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The effects of urban driving conditions on the operating characteristics of conventional and hybrid electric city buses

Seref Soylu *

Sakarya University, Faculty of Engineering, 54187 Sakarya, Turkey

HIGHLIGHTS

- Operating characteristics of conventional and hybrid electric buses were examined.
- Recovery of braking energy offers an excellent opportunity to improve fuel economy.
- Speed and altitude profiles of routes have dramatic impacts on the energy recovery.
- Capacity of the auxiliary power source has a dramatic impact on the energy recovery.
- Round-trip efficiency of the regenerative braking system was calculated to be 27%.

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ABSTRACT

The basic operating characteristics of a conventional bus (CB) and a hybrid electric bus (HEB) were examined under urban driving conditions. To perform this examination, real-time operating data from the buses were collected on the Campus-Return route of the Sakarya Municipality. The main characteristics examined were the traction, braking, engine, engine generator unit (EGU), motor/generator (M/G), and ultracapacitor (Ucap) energies and efficiencies of the buses.

The route elevation profile and the frequency of stop-and-go operations of the buses were found to have dramatic impacts on the braking and traction energies of the buses. The declining profile of the Campus-Return route provided an excellent opportunity for energy recovery by the regenerative braking system of the HEB. However, owing to the limits on the capacities and efficiencies of the hybrid drive train components and the Ucap, the bus braking energies were not recovered completely. Braking energies as high as 2.2 kW h per micro-trip were observed, but less than 1 kW h of braking energy per micro-trip was converted to electricity by the M/G; the rest of the braking energy was wasted in frictional braking. The maximum energy recovered and stored in the Ucap per micro-trip was 0.5 kW h, but the amount of energy recovered and stored per micro-trip was typically less than 0.2 kW h for the entire route. The cumulative braking energy recovered and stored in the Ucap for the Campus-Return route was 52% of the available brake energy, which was 13.02 kW h. Consequently, the round-trip efficiency of the regenerative braking system, between the wheels and Ucap, was determined to be 27%. Finally, although the brake engine energy (BEE) of the CB was 1.18 times higher than its positive traction energy (PTE), the BEE of the HEB was only 1.07 times higher than its PTE. In fact, it is normal to expect the BEE to be higher than the PTE owing to power train losses, but the energy recovered by the regenerative braking system was found to cover most of the power train losses and even improve the energy efficiency of the HEB.

1. Introduction

Both the European Commission (EC) and the United States Department of Energy (USDOE) are taking serious actions to drastically reduce CO_2 emissions, with the goal of keeping climate change below 2 °C. The EC has suggested that to reach that goal,

Abbreviations: CB, conventional bus; HEB, hybrid electric bus; EGU, engine-generator unit; M/G, motor/generator; Ucap, ultracapacitor; PE, power electronics; Gen, generator; FE, fuel energy; BEE, brake engine energy; GE, generator energy; PTE, positive traction energy; NTE, negative traction energy; EC, European Commission; USDOE, US Department of Energy; CO_2, carbon dioxide; GHG, greenhouse gases; VTP, vehicle technology program; PEMS, portable emission measurement system; GPS, global positioning system.

* Tel.: +90 5359788982.
E-mail addresses: ssoylu@sakarya.edu.tr, serefsoylu@gmail.com

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the transport sector needs to reduce its greenhouse gas (GHG) emissions by at least 60% by 2050, compared to the levels of 1990 [1,2]. Similarly, the USDOE is taking actions to reduce CO_2 emissions through its vehicle technology program (VTP), in partnership with automotive industry leaders, national laboratories, and universities [3,4]. The main goals of the VTP are to enable the US to significantly reduce fossil fuel consumption, GHG emissions, and local emissions. GHG emissions are expected to be reduced from 2005 levels by over 40% by 2030 and by over 80% by 2050. Improving the energy efficiency of vehicle power trains by hybridizing them appears to be one of the most promising and cost-effective approaches to achieving these goals [5–8]. It has been reported in literature that more than 30% fuel saving can be expected from commercial vehicles when coupled with hybrid electric power trains [9,10].

The energy efficiency and emissions of city buses operating under urban driving conditions are highly dependent on their operating conditions [11–16]. If operated at cruising conditions on flat routes without auxiliaries (e.g., heating and air conditioning), buses need only enough energy to compensate for rolling and aerodynamic losses, but real-world operations of buses are far from such idealized conditions. Depending on the traffic and road conditions, which may require many short micro-trips with accelerations, decelerations and various road grades, braking energy losses and auxiliaries can increase energy consumption dramatically and reduce fuel economy.

Electrical hybridization of city buses, on the other hand, can be a remedy for excessive fuel consumption under urban driving conditions. In comparison to CBs, HEBs can easily save fuel and reduce emissions, for two main reasons. First, the vehicle kinetic energy, which is normally wasted during braking in the case of CBs, can be recovered and stored in the form of electricity during braking in the case of HEBs. Second, since HEBs do not necessarily have mechanical links from their engines to their wheels, their engines can always operate in the optimum region of the fuel consumption map. Therefore, they have very high potential to minimize both fuel consumption and emissions.

Computer modeling and simulation programs are highly effective and economical tools for use in examining the effects of design alternatives and energy management strategies on hybrid vehicles before construction of a prototype begins [17–20]. Barrero et al. [21] simulated and compared several power flow management strategies for hybrid city buses using a quasi-static “backward/forward-looking” simulation program. The simulation results indicated that the energy savings that can be achieved are in the range of 32.6% (when using the kinetic strategy and a 0.3-kW h energy storage system) to 40% (when using the ICE on–off strategy and a 0.65-kW h energy storage system). Xiong et al. [22] developed an energy management strategy for a series–parallel hybrid city bus using a forward-facing simulation program based on the Matlab/Simulink software. The simulation results indicated that the engine operation can be maintained in the high-efficiency range and that a theoretical improvement in fuel economy 30.3% can be achieved, compared to that of a conventional bus, over the driving cycle of a transit bus. Ahn et al. [23] simulated a regenerative braking system in a hybrid electric vehicle under various driving conditions using Matlab/Simulink and observed that hybrid electric vehicles with regenerative braking can improve fuel economy by 20–50%.

All these modeling efforts have indicated that electrical hybridization of city buses provides various degrees of benefits in terms of energy efficiency and emissions. In order to confirm and quantify the benefits under real-world urban driving conditions, a research project entitled “Measurement and Modeling of Hybrid City Bus Emissions under Real-World Operating Conditions” was initiated at Sakarya University, with the support of the Turkish Ministry of Science Technology and Industry and TEMSA R&D, which is the research and development department of a local bus manufacturer. Confirmation of vehicle emissions levels under real world driving conditions is a requirement by EC regulation [24]. In the first phase of the project, real-time data on the basic operating characteristics of a conventional 12-m city bus were collected under real-world urban driving conditions and analyzed. In the second phase, similar data were collected and analyzed for hybrid electric versions of the bus. Initial tests and reports on the project indicated that the energy efficiencies of the buses are highly dependent on the elevation and speed profiles of the bus routes [25–27]. In the present study, the benefits and barriers of HEBs were further clarified by examining the PTE, NTE, EGU, M/G, and Ucap energies and efficiencies of the HEB under real world urban driving conditions. The results are expected to be a reference for researchers who design and simulate the next generation of city buses.

2. Experimental setup

The test vehicles were TEMSA-brand city buses. The buses were 12 m in length and weighed 15 tons when loaded. The CB was powered by a 6.7-liter Euro 4 CUMMINS diesel engine. It has a ZF 6 HP 504 C gear box and a ZF AV 132/80 rear axle. The HEB, which was designed based on body of the conventional bus, had a SIEMENS ELFA hybrid drivetrain system. The hybrid bus was powered by a 6.7-liter Euro 5 CUMMINS diesel engine. The Euro 4 and 5 engines have the same power and torque characteristics. Figs. 1a and 1b are schematic diagrams of the conventional and HEB drivetrains. The basic specifications of the ELFA drivetrain components and the engines are given in Table 1.

There are mainly series and parallel power train configuration alternatives for HEBs. However, in order to increase braking energy recovery rate with regenerative braking, series hybrids are generally preferred for city bus applications due to their frequent stop and go operations. As the schematics illustrate, the HE drivetrain (Series Hybrid) does not have a mechanical link from the engine to the wheels. Instead, the engine drives the generator that feeds the M/G. Therefore, the engine can operate in the most efficient regions of its fuel consumption map. Additionally, the Ucap, which can be charged by regenerative braking or by the generator, feeds the M/G, especially during acceleration of the bus.

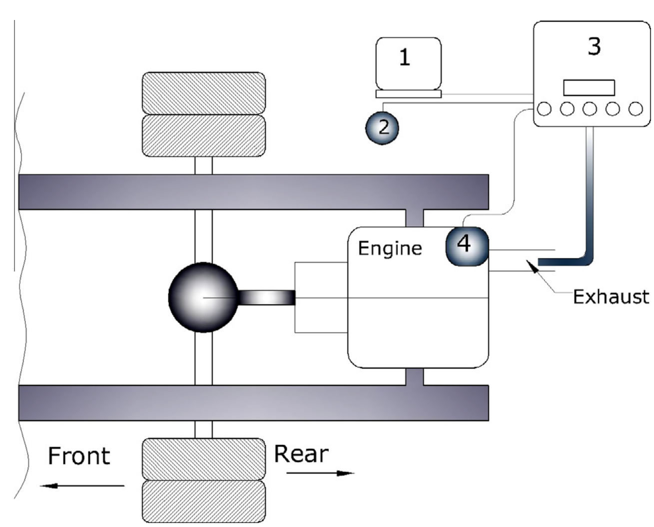

Fig. 1a. Schematics of the conventional drivetrain and its instrumentation (1. Computer, 2. GPS, 3. SEMTECH DS, 4. Engine).