Applied Energy 154 (2015) 143–159

Contents lists available at ScienceDirect

Applied Energy

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

Assessment of alternative fuel and powertrain transit bus options using real-world operations data: Life-cycle fuel and emissions modeling

Yanzhi Xu *, Franklin E. Gbologah, Dong-Yeon Lee, Haobing Liu, Michael O. Rodgers, Randall L. Guensler

School of Civil and Environmental Engineering, Georgia Institute of Technology, United States

HIGHLIGHTS

- We present a practical fuel and emissions modeling tool for alternative fuel buses.
- The model assesses well-to-wheels emissions impacts of bus fleet decisions.
- Mode-based approach is used to account for duty cycles and local conditions.
- A case study using real-world operations data from Atlanta, GA is presented.
- Impacts of alternative bus options depend on operating and geographic features.

ARTICLE INFO

Article history:
Received 26 February 2015
Received in revised form 27 April 2015
Accepted 27 April 2015

Keywords:
Energy consumption
Mode-based emissions modeling
Life-cycle assessment
Transit
Alternative fuels

ABSTRACT

Hybrid and electric powertrains and alternative fuels (e.g., compressed natural gas (CNG), biodiesel, or hydrogen) can often reduce energy consumption and emissions from transit bus operations relative to conventional diesel. However, the magnitude of these energy and emissions savings can vary significantly, due to local conditions and transit operating characteristics. This paper introduces the transit Fuel and Emissions Calculator (FEC), a mode-based life-cycle emissions modeling tool for transit bus and rail technologies that compares the performance of multiple alternative fuels and powertrains across a range of operational characteristics and conditions. The purpose of the FEC is to provide a practical, yet technically sophisticated tool for regulatory agencies and policy analysts in assessing transit fleet options. The FEC's modal modeling approach estimates emissions as a function of engine load, which in turn is a function of transit service parameters, including duty cycle (idling and speed-acceleration profile), road grade, and passenger loading. This approach allows for customized assessments that account for local conditions. Direct emissions estimates are derived from the scaled tractive power (STP) operating mode bins and emissions factors employed in the U.S. EPA's MOVES (MOtor Vehicle Emissions Simulator) model. Life-cycle emissions estimates are calculated using emissions factors from the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model. The case study presented in this paper applies the FEC to second-by-second GPS position data collected from buses operating in metropolitan Atlanta, GA. These operations, from two different transit agencies, feature distinctly different transit service types: local transit bus operations and longer-distance express bus operations. The results illustrate that the decision as to which bus technology-fuel combination produces the least greenhouse gas emissions is a function of location and route characteristics. For the express bus operations monitored, the case study shows that CNG vehicles offer greater emissions reductions than Biodiesel (B20). For local bus services, battery electric buses show the greatest emissions savings in the fuel cycle, as long as range limitations can be met for the specific routes. The amount of these emissions savings is, however, highly dependent on the power generation mix. Among CNG, B20, parallel hybrid, series hybrid, and fuel cell buses, the least emitting option varies by location, due to complex interactions of factors such as duty cycle, meteorology, and terrain.

1. Introduction

Transit operations play an important role in greenhouse gas reductions and air quality improvements [1]. There are more than

* Corresponding author at: 790 Atlantic Drive Northwest, Atlanta, GA 30332-0355, USA. Tel.: +1 (404) 723 0543.

E-mail address: yanzhi.xu@ce.gatech.edu (Y. Xu).

http://dx.doi.org/10.1016/j.apenergy.2015.04.112
0306-2619/

Abbreviations

AZ	Arizona
B2	2% biodiesel blend with diesel
B5	5% biodiesel blend with diesel
B10	10% biodiesel blend with diesel
B20	20% biodiesel blend with diesel
B100	100% biodiesel
BEV	battery-electric vehicles
CA	California
CARB	California Air Resources Board
CMAQ	Congestion Mitigation and Air Quality Improvement
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
DEQ	Diesel Emissions Quantifier
DPF	diesel particulate filter
E85	85% ethanol blend with gasoline
eGRID	Emissions and Generation Resource Integrated Database
EM	electric motor
EPA	Environmental Protection Agency
FCV	fuel-cell vehicles
FEC	Fuel and Emissions Calculator
FTA	Federal Transit Administration
GA	Georgia
GHG	greenhouse gases
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GRTA	Georgia Regional Transit Authority
GPS	Global Positioning System
H_2	Hydrogen
HEB	hybrid-electric buses
HEV	hybrid-electric vehicles
ICE	internal combustion engine
kg	kilogram
kJ	kilojoule
km	kilometer
kWh	kilowatt-hour
LCA	life-cycle assessment
LNG	liquefied natural gas
LPG	liquefied petroleum gas
MARTA	Metropolitan Atlanta Rapid Transit Authority
MOVES	MOtor Vehicle Emission Simulator
MPO	metropolitan planning organization
NG	natural gas
NRC	National Research Council
NREL	National Renewable Energy Laboratory
NOx	oxides of nitrogen
NTD	National Transit Database
OCTA	Orange County Transit Authority
PHEV	plug-in hybrid-electric vehicles
PM	particulate matter
$PM_{2.5}$	particulate matter less than 2.5 μm in diameter
PM_{10}	particulate matter less than 10 μm in diameter
SAE	Society of Automotive Engineers
SOC	state of charge
STP	scaled tractive power
UCD	University of California at Davis
U.S.	United States
VOC	volatile organic compounds

800 transit agencies in the United States, with nearly 65,000 buses in operation [2]. At the national and regional levels, a low-emission or zero-emission transit fleet would curb both greenhouse gas (GHG) emissions and improve air quality. In a study that compared the metropolitan areas of San Francisco, Chicago, and New York City, Chester et al. [3] found that New York City had the lowest life-cycle energy and emissions footprints of passenger transportation, attributable to its large share of transit ridership. At the local level, reducing transit emissions could also help relieve social and environmental equity concerns. For example, transit riders, often with low income and limited mobility options, are currently disproportionately exposed to criteria and toxic pollutant emissions from bus operations. Alternative fuel and powertrain buses are excellent prospects for helping to achieve these multiple policy goals over a broad range of operating conditions.

A growing number of transit agencies are purchasing alternative fuel and/or powertrain buses. According to the National Transit Database [2], in 2012 there were 9253 compressed natural gas (CNG), 3974 hybrid-diesel, 174 hybrid-gasoline and 52 battery-electric buses operating in transit agencies across the United States. Manufacturers have introduced a broad array of alternative fuels and powertrains [4]. With an increasing number of technology options, there is a need for a comprehensive evaluation tool designed to assess fuel and emissions benefits. Transit equipment purchases and operations in the United States are highly subsidized with public funds [5] and decisions by transit agencies regarding fleet purchases are often heavily scrutinized to ensure that prudent decisions are made. Multiple factors must assessed in fleet purchase decisions and many desirable characteristics such as fuel savings, reduced life-cycle costs, and reduced emissions of criteria pollutants and greenhouse gases can vary considerably based on local conditions, including fuel supply, sources of electricity generation, terrain, meteorology, and the onroad operating characteristics of the transit system.

There are generally two modeling approaches to estimate fuel consumption and emissions: the fuel-based, top-down approach, and the vehicle activity-based, bottom-up approach [6]. On a national or regional level, both approaches should closely match each other [7]. However, the evaluation of transit vehicle purchases often needs to focus on a specific geographic area, and sometimes on specific routes. Fuel receipts or fuel economy data are not available at the route level. Moreover, the fuel-based approach does not allow the evaluation within the context of local operating characteristics, such as speed/acceleration profile and number of stops. The vehicle activity-based bottom-up approach, on the other hand, is capable of analyzing the effects of different operating scenarios in a specific area. The bottom-up approach also provides better estimates of emission species that are more dependent on fuel and vehicle standards than fuel consumption, such as GHGs other than CO_2 [7].

A number of previous studies have attempted to evaluate alternative bus technologies through environmental and economic life-cycle assessment (LCA), incorporating various components of the fuel cycle (also known as well-to-wheels, including well-to-pump and pump-to-wheels) and the vehicle cycle. Table 1 summarizes the findings from recent comparative studies on the energy consumption and emissions of alternative fuel and powertrain buses. Table 1 showcases the divergent conclusions from existing studies, depending on the life-cycle components analyzed, the objectives of the comparison, the geographic context and the type of bus operations. Many studies have acknowledged the complexity and uncertainty inherent in such comparative