Transportation Research Part D 55 (2017) 91–98

Contents lists available at ScienceDirect

Transportation Research Part D

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

# Life cycle GHG emissions and lifetime costs of medium-duty diesel and battery electric trucks in Toronto, Canada

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ARTICLE INFO

*Article history:*
Available online 27 June 2017

*Keywords:*
Life cycle assessment
GHG emissions
Medium-duty trucks
Fuel consumption
Lifetime costs

ABSTRACT

Battery-electric trucks (BET) are an alternative to diesel trucks and have the potential for lower life cycle greenhouse gas (GHG) emissions and total lifetime costs (TCO). This study compares a Class 6 medium-duty BET with a Class 6 medium-duty diesel truck. Vehicle fuel consumption is simulated for Toronto driving conditions, based on different drive cycles, operating temperatures and payloads. The base case results show the BET has lower life cycle GHG emissions and higher lifetime TCO than the diesel truck, but this does not hold across all conditions. GHG emissions of the BET are higher than those of the diesel truck under 100% payload in driving conditions with infrequent stops, while the results are less sensitive to operating temperature. The lifetime cost of the BET can be lower than that of the diesel truck in situations that have driving with frequent stops/starts and with low payloads and low battery and charging station costs. These variables also affect estimated GHG abatement costs, which are highly relevant as carbon pricing is being introduced in the province.



## 1. Introduction

Medium-duty trucks (MDT), Classes 4–6, have gross vehicle weight ratings between 6351 kg and 11,793 kg. These trucks are mainly used for vocational purposes, such as emergency, delivery and dump trucks (Freightliner, 2016). The total energy used by MDTs in Canada increased by 19% from 1990 to 2011, despite average diesel fuel consumption decreasing 17%. The U.S. Energy Information Administration (EIA) estimated that MDTs had the highest average annual growth rate (2.2%) in energy use from 2009 to 2035 among commercial transportation modes (e.g., buses and heavy-duty trucks) (EIA, 2011). The increasing delivery demand and the rising sales and market share of MDTs may have resulted in the growth in energy consumption despite the efficiency improvements (Natural Resources Canada, 2011; Statistics Canada, 2013).

The battery electric powertrain is a promising technology to reduce energy consumption and life cycle greenhouse gas (GHG) emissions in both passenger vehicles and commercial trucks (National Research Council, 2010). Duran et al. (2014) noted that last-mile delivery fleets: (1) travel mostly in conditions with frequent stopping (where the greatest fuel consumption reduction occurs when using a battery electric truck (BET) compared to a diesel truck), (2) can have fixed routes for delivery and travel relatively short distances, and thus may be able to operate within the constraints of BET battery capacities, and (3) can return to a central location at the end of the day, where charging infrastructure can be located. Therefore, battery electric MDTs are candidates for last-mile fleets. This is beginning to be reflected in policies incentivizing the pur-

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http://dx.doi.org/10.1016/j.trd.2017.06.019
1361-9209/

chase of battery-electric vehicles. The Province of Ontario, for example, plans to give financial incentives for electric commercial trucks (Ontario Minister of Environment and Climate Change, 2016). However, before such policy actions are taken it is important to investigate whether a BET is expected to be a good alternative to a diesel truck with respect to reducing fuel consumption, GHG emissions and operating cost in the province.

Many studies have demonstrated that the drive cycle affects the life cycle GHG emissions and fuel consumption of vehicles (e.g., Sharer et al., 2007; Fontaras et al., 2008; Raykin et al., 2012; Ercan and Tatari, 2015; Ercan et al., 2015; Bachmann et al., 2014). Ercan et al. (2015) concluded that a battery-electric bus reduces life cycle $CO_2e$ emissions by 50–68% compared with a diesel bus depending on the transit drive cycle (Manhattan, Central Business District, and Orange County Transit Authority). Generally, electrification of vehicles results in higher reductions of GHG emissions in city, rather than highway, driving conditions compared with conventional vehicles (Raykin et al., 2012; Karabasoglu and Michalek, 2013; Lee et al., 2013). Some studies have also examined MDTs including Tong et al. (2015) who found that BETs can achieve GHG emissions reductions of 31–41% compared with diesel trucks and Lee et al. (2013) who concluded that the BET reduces GHG emissions more in the New York City Cycle than the City-Suburban Heavy Vehicle Cycle.

Along with drive cycle, operating temperature is another crucial factor affecting energy consumption of both conventional and battery-electric vehicles. Researchers from Argonne National Laboratory found that both gasoline and battery electric light-duty vehicles operated in low (−7 °C) and high (35 °C) temperatures had higher fuel consumption than when operating at 20 °C (Lohse-Busch et al., 2013). Yuksel and Michalek (2015) found that life cycle GHG emissions associated with battery-electric vehicles may increase in places with cold climates, even when operated off of the same electricity grid.

As shown in many studies, the electricity generation mix has a major effect on life cycle GHG emissions of battery-electric vehicles. Several studies have assumed the average U.S. regional electricity generation mix and found that battery-electric vehicles emit less GHG emissions than the average gasoline vehicle, but the degree of reduction depends on where the vehicle is charged (Anair and Mahmassani, 2012; Yawitz et al., 2013; Zivin et al., 2014; Zhao et al., 2016a, 2016b; Ercan et al., 2016). Yuksel and Michalek (2015) found battery-electric vehicle life cycle GHG emissions vary with U.S. regional grid mix, which results in the GHG intensity of vehicles in the Upper Midwest being three times higher those of the Pacific Coast.

Life cycle GHG emissions and vehicle fuel consumption can vary widely because these metrics are highly dependent on drive cycle, operating temperature, payload, and truck configuration (Fleetcarma, 2013; Lohse-Busch et al., 2013; Taptich and Horvath, 2014; U.S. National Research Council (NRC), 2014; Yuksel and Michalek, 2015; Zhao et al., 2016b). However, no previous studies of MDTs that we are aware of compare the impacts of drive cycle, operating temperature and payload on energy consumption of diesel and battery-electric MDTs. Studies of MDTs either use average fuel consumption data from the literature, or use standard test drive cycles, which may not reflect real traffic conditions (Amirjamshidi and Roorda, 2015; Tate et al., 2008). These studies fail to capture the interactions of drive cycle, payload and temperature on fuel consumption and life cycle GHG emissions.

The objectives of this study are: (1) to address the above gaps by investigating impacts of fuel/powertrain type, payload, drive cycle, and operating temperature on energy consumption and life cycle GHG emissions, and (2) to estimate lifetime total cost of ownership (TCO) for diesel and battery-electric MDTs for a case study of Toronto. The results of the study have the potential to inform government agencies of benefits/costs of extending battery electric vehicle incentive programs to MDTs, and to inform commercial fleet owners of benefits/costs of investment in BETs.

## 2. Methods

The medium-duty diesel and BET fuel consumption are simulated using Autonomie (Argonne National Laboratory, 2016) vehicle simulation software on different drive cycles, payloads, and temperatures. Fuel consumption data are then used to estimate life cycle GHG emissions using GHGenius (Natural Resources Canada, 2013), a Canadian life cycle assessment model for fuels and vehicles. Calculations of lifetime total costs of ownership are then estimated based on different scenarios. Finally, the cost of GHG abatement of the BET is calculated based on the incremental lifetime total costs of ownership, as well as the life cycle GHG emissions reduced.

### *2.1. Vehicle fuel consumption*

Autonomie (Argonne National Laboratory, 2016) is a vehicle simulation software that is suitable for automotive control system design (Vijayagopal et al., 2010). It performs customized vehicle simulations for particular vehicle specifications, drive cycles and temperatures. Autonomie is used in the U.S. Department of Energy FreedomCAR and Vehicle Technologies Program, and by more than 140 companies and research facilities (Karbowski et al., 2012). In Autonomie, a user can select a variety of commercially available vehicle components and adjust the peak power of components by linearly scaling the operating maps and component weights accordingly (Lewis et al., 2012).

#### *2.1.1. Vehicle models*

We use Autonomie to simulate energy consumption for both the diesel truck and BET. The diesel truck is similar to the Ford F-650 Super Truck (Ford, 2009) and the BET is similar to the SmithNewton BET (Smith Newton, 2013). Both vehicles are Class 6 trucks, whose specifications are listed in Table S1 in Appendix A.