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Fuel consumption model for heavy duty diesel trucks: Model development and testing

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ABSTRACT

A simple, efficient, and realistic fuel consumption model is essential to support the development of effective eco-freight strategies, including eco-routing and eco-driving systems. The majority of the existing heavy duty truck (HDT) fuel consumption models, however, would recommend that drivers accelerate at full throttle or brake at full braking to minimize their fuel consumption levels, which is obviously not realistic. To overcome this shortcoming, the paper applies the Virginia Tech Comprehensive Power-based Fuel consumption Model (VT-CPFM) framework to develop a new model that is calibrated and validated using field data collected using a mobile emissions research laboratory (MERL). The results demonstrate that the model accurately predicts fuel consumption levels consistent with field observations and outperforms the comprehensive modal emissions model (CMEM) and the motor vehicle emissions simulator (MOVES) model. Using the model it is demonstrated that the optimum fuel economy cruise speed ranges between 32 and 52 km/h with steeper roads and heavier trucks resulting in lower optimum cruise speeds. The results also demonstrate that the model generates accurate CO_2 emission estimates that are consistent with field measurements. Finally, the model can be easily calibrated using data collected using non-engine instrumentation (e.g. Global Positioning System) and readily implemented in traffic simulation software, smartphone applications and eco-freight programs.

1. Introduction

Transportation activities account for 28% of the total U.S. energy use and 33.4% of carbon dioxide (CO_2, the major component of greenhouse gas (GHG) emissions) production (Davis et al., 2015; EPA, 2015). Consequently, numerous efforts are being tested in an attempt to reduce transportation-related energy use and GHG emissions in response to global energy and environmental issues (e.g. global warming). As the largest emitter of CO_2 (42.7%) in the transportation sector, passenger cars have attracted significant attention in the past decade, and reduction in fuel consumption and emission levels have been achieved through the development of relevant regulations and technical solutions. As a counterpart, however, the investigation of heavy duty diesel truck (HDDT) fuel consumption behavior is relatively less mature compared to that of gasoline passenger cars. Although HDDTs make up only a fraction of the total vehicle population, they are major contributors to GHG emissions, accounting for 22.8% of the total CO_2 production in the transportation sector (EPA, 2015).

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Currently, HDDTs are receiving increasing attention from legislators, the government and society at large. For example, in September 2011, the National Highway Traffic Safety Administration (NHTSA) and the U.S. Environmental Protection Agency (EPA) jointly promulgated the first-ever federal regulations mandating improvements in fuel economy of heavy-duty commercial vehicles (Harrington and Krupnick, 2012; NHTSA, 2011). Furthermore, researchers have been committed to developing road eco-freight strategies (Pindilli, 2012; Lattemann et al., 2004; Dzenisiuk, 2012; Takada et al., 2007) in order to support "green transportation" policy making.

An accurate and efficient fuel consumption model is needed to provide robust fuel estimates in support of quantifying potential reductions in fuel consumption and emission levels induced by implementing eco-friendly strategies, such as developing eco-routing (Rakha et al., 2012; Boriboonsomsin et al., 2012; Ahn and Rakha, 2013) or eco-driving systems (Schall and Mohnen, 2017; Saboohi and Farzaneh, 2009; Soylu, 2014; Barkenbus, 2010; Ahn et al., 2011) and utilizing advanced fuel techniques (Wayne et al., 2004; Guo et al., 2015; Onat et al., 2015) or alternative fuels (Rakopoulos et al., 2015; Balat and Balat, 2009; Demirbas, 2007; López et al., 2009). Among the existing modeling efforts, most are operated at a macroscopic or microscopic level. The macroscopic models, such as MOBILE 6.2 (Arbor, 2003), were demonstrated to produce unreliable estimates due to their inability of capturing transient vehicle activities (Ahn and Rakha, 2008). Consequently, they are incapable of being utilized for the energy and environmental assessment of traffic operational projects. Microscopic models were introduced in order to better capture the variability in fuel consumption and GHG emissions associated with vehicle dynamics. A wide range of instantaneous models have been developed using in-laboratory or field data, and some of them are applicable to modeling HDDTs, such as MOVES, VT-Micro (Rakha et al., 2004), the Passenger Car and Heavy Duty Emission Model (PHEM) (Hausberger et al., 2010), VERSIT (Smit et al., 2007), and the Comprehensive Modal Emissions Model (CMEM) (Barth et al., 2000, 2004).

The majority of the aforementioned models, however, have intrinsic limitations. For example, MOVES, which was developed as an inventory model based on a wide range of data sources, is capable of providing robust estimates. Nonetheless, it requires massive user inputs for each run, which significantly increases the time required to run multiple scenarios and large networks. CMEM generally underestimates fuel consumption levels for acceleration maneuvers; more importantly, it characterizes fuel consumption as a linear function of vehicle power (positive power section), which produces a bang-bang type of control system. A bang-bang control may arise when the partial derivative of the response with respect to the control variable is not a function of the control variable (a more detailed description of a bang-bang control system is provided in Section 2). The fuel estimate module for CMEM is addressed in Eq. (1):

$$FR = \frac{K \cdot N \cdot V + P/\eta}{43.2} \cdot [1 + b_1 \cdot (N - N_0)^2] \quad (1)$$

Here FR is the fuel rate in g/s, K is the engine friction factor, N is engine speed in (revolutions per second), V is engine displacement in liters, η is the efficiency for diesel engines, b_1 equals to 1×10^{-4}, N_0 is a constant related to engine displacement, 43.2 kJ/g is the lower heating value of a typical diesel fuel, and P is the vehicle power which is the control variable of the fuel model. Since the fuel rate is linearly related to the vehicle power, its partial derivative with respect to power is independent of the power. This may suggest that drivers accelerate at full throttle to reduce acceleration time in order to minimize their trip fuel consumption levels. Similarly, PHEM and VERSIT produce a bang-bang control as well. VT-Micro is capable of circumventing the bang-bang control; however, it requires a large amount of in-laboratory or field data to be calibrated, which is cost-prohibitive and time-consuming.

Overall, the existing models either produce a bang-bang type of control (either full throttle or zero throttle input) system or cannot be easily calibrated or efficiently used. Consequently, a simple, accurate and efficient model is needed. Rakha et al. (2011) developed the Virginia Tech Comprehensive Power-based Fuel consumption Modeling (VT-CPFM) framework by characterizing fuel consumption levels as a second-order polynomial function of vehicle power to circumvent the bang-bang control problem. Furthermore, the model offers a unique ability to be calibrated using publicly available data (a more detailed description of the calibration procedure is provided in Rakha et al. (2011) withou data collection. Recent efforts have validated the applicability of the model for light duty vehicles (LDVs) (Park et al., 2013) and transit buses (Wang and Rakha, 2016a,b) under real-world driving conditions; however, it has not been expanded to HDDTs yet. Consequently, the paper is intended to develop the VT-CPFM-based model for HDDTs in order to circumvent the bang-bang problem in the family of heavy duty truck (HDT) fuel consumption modeling tools. The developed model will be applied to develop eco-routing and eco-driving systems in future studies.

2. A bang-bang control system

Minimizing fuel consumption levels, from the system perspective, is essentially an optimal control problem that attempts to compute the optimal solution with the control variable restricted to being between a lower and an upper bound. In optimal control problems, a bang-bang solution may occur when a control switches abruptly from one extreme to the other. To mathematically give a complete picture of the bang-bang control, the minimum-fuel problem is described in Eq. (2), which is derived from Pontryagin's Maximum Principle (Pontryagin, 1987; Saerens et al., 2010):