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The heavy-duty vehicle future in the United States: A parametric analysis of technology and policy tradeoffs

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HIGHLIGHTS

- We present a parametric analysis of factors U.S. Class 7–8 trucks through 2050.
- Conventional diesels will be more than 70% of U.S. heavy-duty vehicles through 2050.
- CNG trucks are well suited to large, urban fleets with private refueling.
- Ultra-efficient long haul diesel trucks are preferred over LNG at current fuel prices.

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ABSTRACT

We present a parametric analysis of factors that can influence advanced fuel and technology deployments in U.S. Class 7–8 trucks through 2050. The analysis focuses on the competition between traditional diesel trucks, natural gas vehicles (NGVs), and ultra-efficient powertrains. Underlying the study is a vehicle choice and stock model of the U.S. heavy-duty vehicle market. The model is segmented by vehicle class, body type, powertrain, fleet size, and operational type. We find that conventional diesel trucks will dominate the market through 2050, but NGVs could have significant market penetration depending on key technological and economic uncertainties. Compressed natural gas trucks conducting urban trips in fleets that can support private infrastructure are economically viable now and will continue to gain market share. Ultra-efficient diesel trucks, exemplified by the U.S. Department of Energy's SuperTruck program, are the preferred alternative in the long haul segment, but could compete with liquefied natural gas (LNG) trucks if the fuel price differential between LNG and diesel increases. However, the greatest impact in reducing petroleum consumption and pollutant emissions is had by investing in efficiency technologies that benefit all powertrains, especially the conventional diesels that comprise the majority of the stock, instead of incentivizing specific alternatives.

1. Introduction

In the United States, heavy-duty vehicles (HDVs) accounted for 12.1% of total petroleum consumption in 2012 (Davis et al., 2014) and transported 70% of freight by tonnage (U.S. Department of Transportation Bureau of Transportation Statistics and U.S. Department of Commerce Census Bureau, 2012). These fractions are anticipated to grow in the future (U.S. Department of Transportation Federal Highway Administration, 2010). Accordingly, the efficiency and types of fuels used by HDVs are of increasing interest as the U.S. addresses climate stabilization and energy independence issues. Current federal efforts related to HDV efficiency include technology development, technology commercialization, and issuing regulatory standards. Examples of technology development and commercialization include the U. S. Department of Energy's 21st Century Truck Partnership, a public–private cooperative that has accelerated the pace of HDV efficiency improvements (National Research Council, 2012; U.S. Department of Energy, 2013), and the SuperTruck program, which has made substantial progress toward demonstrating a 50% more freight efficient (measured in ton-miles per gallon) Class 8 tractor-trailer (TA Engineering, Inc., 2012). Example regulations include the new HDV fuel efficiency and greenhouse gas (GHG) emissions standards that took effect for model year 2014–2018 trucks (U.S. Environmental Protection Agency and U.S. Department of Transportation, 2011b). While fuel economy standards have been in place for light-duty vehicles (LDVs) since the 1970s, the diversity in construction, use, and ownership of HDVs has made it difficult to institute similar regulations for this segment of vehicles. Thus,

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these new regulations represent a significant accomplishment on behalf of both government and industry. Due to the short time horizon of the first round of regulations, the regulatory impact analysis focused on technologies that would be widely available in 2014, but did not consider more advanced efficiency technologies, hybridization, or alternative fuel vehicles (AFVs) (U.S. Environmental Protection Agency and U.S. Department of Transportation, 2011a). However, additional Presidential direction was issued to the EPA and the Department of Transportation in February 2014 to establish follow-on regulations by March 2016 that would begin to take these factors into consideration (The White House, 2014). Finally, interest in reducing HDV emissions and fuel consumption has also occurred at the state level. Prior to the enactment of federal fuel economy standards, the California Air Resources Board instituted regulations for tractor-trailers operating in California. These regulations require SmartWay certification (an EPA program that verifies technology performance) for new sleeper-cab tractors as well as adoption of other SmartWay technologies for both tractors and trailers(California Environmental Protection Agency, Air Resources Board, 2012).

Meeting stricter efficiency and emissions standards will require the continuous development of advanced technologies. A number of studies exist in the literature that attempt to quantify the range of efficiency and emissions benefits of individual, and groups of, technologies (National Research Council, 2010; Cooper et al., 2009; Silver and Brotherton, 2013; Zhao et al., 2013; Gao et al., 2013; Delorme et al., 2009). These studies play a key role in supporting near-term regulatory decisions as individual technologies must be considered in the context of specific use cases, given the diversity of HDV truck types and operational patterns. For instance, aerodynamics improvements of a long haul truck reduce fuel consumption by up to 11.5%, but have far less impact on a refuse truck (National Research Council, 2010). Conversely, hybridization would have much greater utility for a refuse truck than for a long haul truck (National Research Council, 2010).

Alternative fuel HDVs represent both another potential pathway to meeting regulatory standards and could provide cost savings to fleet operators in their own right (Werpy et al., 2010; Whyatt, 2010). Well-informed commercial consumers are prepared to recognize and capitalize on the financial opportunities presented by low cost fuels, such as natural gas. The consistent usage patterns of some vocational vehicles and the capital resources of large fleets can enable the construction of on-site, private refueling infrastructure. Thus, the switch from diesel to an alternative fuel can happen rather quickly for a given fleet. Additionally, long haul trucks rely predominately on refueling infrastructure along highway corridors, thereby limiting the number of public alternative fuel stations necessary to support alternative fuel HDVs. Moreover, the high mileage of long haul vehicles enables their owners to recoup any initial capital outlay relatively quickly from a fuel price differential.

The short term decisions made today by policy makers and fleet owners to respond to the evolving environment of technology, regulations, economic growth, and commodity prices will have a lasting impact. The longer term, continuing evolution of the heavy-duty transportation sector will be sensitive to the uncertain trajectories of the same factors. As mentioned above, the literature includes studies of near-term impacts of specific technologies but is more limited in terms of long term projections or tradeoff studies. Long term studies that do exist (Cooper et al., 2009; National Petroleum Council, 2012; U.S. Energy Information Administration, 2014) are scenario-based and offer only a few possible futures, despite the extensive uncertainty in model inputs values. Furthermore, while numerous models have been developed to assess the long term fuel consumption and emissions trajectory of the LDV sector, due to the heterogeneity of the HDV sector and the relatively limited data availability, few models have considered the HDV sector in detail. To address these gaps, this paper presents a detailed HDV consumer choice and stock model to investigate the factors driving fleet adoption of efficiency technologies and alternative fuel vehicles. The results aim to provide insight into the inhibitors and drivers toward reduced petroleum consumption and emissions in the HDV sector. Critical to this analysis is the parameterization of inputs to capture uncertainties, determine sensitivities, and illustrate long term tradeoffs in these objectives.

2. Methods

The model tracks the evolution of the heavy-duty vehicle stock in the US, its fuel usage, and corresponding demand for raw energy stocks. A diagram of the model is shown in Fig. 1 and is based on a similar implementation for light-duty vehicles described in Barter et al. (2013). The model is broken down into three subcomponents: a vehicle sub-model, a fuel production sub-model, and an energy supply sub-model. The sub-models exchange price and demand information for the energy supply stocks and fuels considered. No predetermined market share targets are assumed, thus technologies compete directly in the marketplace and are allowed to flourish or fail. The model is implemented using system dynamics concepts (i.e., stocks, flows and feedback loops) to construct a set of interacting algebraic and differential equations using Python and the Numpy library. Solutions are generated using a third-order Runge–Kutta algorithm with fixed step size.

2.1. Model scope

Gross Vehicle Weight (GVW) Class 7 and 8 vehicles are the largest heavy-duty consumers of fuel and comprised 17% of 2012 U.S. transportation petroleum use (12% of total U.S. petroleum use) (Davis et al., 2014). By contrast, Class 3-6 vehicles consumed only 4% of transportation fuel use in 2012. The model therefore focuses exclusively on Class 7 and 8 heavy-duty vehicles in the US with the following exclusions:

- Public vehicles whose adoption is often politically motivated and/or based on individualized circumstances (3.9% of Class 7 and 8 petroleum consumption R.L. Polk & Co., 2012).
- Emergency vehicles which have very specific operating conditions and purchasing considerations (0.5% of Class 7 and 8 petroleum consumption R.L. Polk & Co., 2012).
- Recreational vehicles which are not typically commercially operated or purchased with business considerations.
- Short-term rental vehicles for which the user is frequently changing and always different than the permanent owner (6.4% of Class 7 and 8 petroleum consumption R.L. Polk & Co., 2012).
- Off road vehicles, construction equipment, and farm equipment which are separately regulated and have unique operating conditions.

The model currently considers natural gas as the only alternative fuel due to the availability of suitable engines and industry interest in natural gas as a fuel for commercial fleets. Compressed natural gas (CNG) and liquefied natural gas (LNG) are considered separately due to their applicability to different niches. LNG has a higher-energy density that is well suited for long distance travel, but it also requires expensive liquefaction and handling

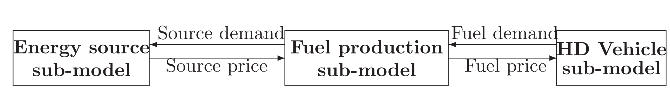

Fig. 1. High-level diagram of the model components.