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A parametric study of light-duty natural gas vehicle competitiveness in the United States through 2050

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HIGHLIGHTS

- NGVs are economical, but limited by infrastructure and OEM model availability.
- NGVs compete more with EVs than conventional vehicles.
- By displacing EVs, NGVs offer little or negative GHG reduction benefits.
- Public refueling infrastructure is a better investment than home CNG compressors.
- Bi-fuel vehicles can be a bridge technology until infrastructure build-out.

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ABSTRACT

We modeled and conducted a parametric analysis of the US light-duty vehicle (LDV) stock to examine the impact of natural gas vehicles (NGVs) as they compete with electric vehicles, hybrids, and conventional powertrains. We find that low natural gas prices and sufficient public refueling infrastructure are the key drivers to NGV adoption when matched with availability of compressed natural gas powertrains from automakers. Due to the time and investment required for the build out of infrastructure and the introduction of vehicles by original equipment manufacturers, home natural gas compressor sales and bi-fuel NGVs serve as bridge technologies through 2030. By 2050, however, NGVs could comprise as much as 20% of annual vehicle sales and 10% of the LDV stock fraction. We also find that NGVs may displace electric vehicles, rather than conventional powertrains, as they both compete for consumers that drive enough miles such that fuel cost savings offset higher purchase costs. Due to this dynamic, NGVs in our LDV stock model offer little to no greenhouse gas emissions reduction as they displace lower emission powertrains. This finding is subject to the uncertainty in efficiency technology progression and the set of powertains and fuels considered.

1. Introduction

Recent advances in drilling technologies and new domestic shale gas discoveries have dramatically increased natural gas (NG) production in the United States (by 15% from 2008 to 2012). This boom in domestic supply has dropped the price of natural gas significantly (by 50% from 2008 to 2012) [1,2]. The attractiveness of natural gas is due not only to its low price, but also its lower carbon content relative to other fossil fuels (roughly 55% of the carbon per unit energy as coal and 73% of petroleum) [3,4]. In the US energy economy, the usage of natural gas in the residential, commercial, industrial, and electricity generation sectors is growing and even finding new niches [1]. One sector of the US economy where natural gas does not currently play a large role is transportation (0.1% of total delivered energy in 2011) [1]. The technology has long existed for natural gas to serve as a transportation fuel in the form of compressed natural gas (CNG), which can be stored on the vehicle at high pressure, or in a cooled environment as liquid natural gas (LNG) [5]. There are also other, less established pathways for natural gas to serve as a transportation fuel. Natural gas can be chemically refined into liquid fuels, such as ethanol, methanol, gasoline, and diesel. However, creating drop-in replacement fuels from natural gas requires more processing than other fossil fuel feedstocks, meaning it is more expensive and less efficient [3]. Finally, natural gas can also be processed with steam methane reforming to produce hydrogen for hydrogen fuel-cell vehicles [6]. In the scope of this work, however, the only natural gas derived fuel pathway considered is CNG, as the others

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are less well established and must still overcome some technological and regulatory hurdles.

The lack of refueling infrastructure, the high incremental price of NGVs, and limited CNG powertrains offered by automakers have historically suppressed demand [5]. However, this reality is rapidly changing for short-range, heavy duty vehicles (HDVs) that are centrally refueled, such as buses, refuse haulers, or delivery trucks. For these vocations, fleet owners can build a private refueling infrastructure and offset higher vehicle purchase costs with fuel cost savings in three years or less. There is also interest in strategically placing CNG or LNG refueling stations along interstate highways to enable long-haul, publicly refueled HDVs to rely on natural gas as well [3]. The merits of heavy-duty NGVs, however, are not the focus of this work, rather we focus on light-duty NGVs.

For light-duty vehicles (LDVs), natural gas is used as a transportation fuel almost exclusively as CNG, since LNG is impractical for multiple reasons. This includes the need for a large, thermally insulated fuel storage tank and high-mileage, continuous operation to minimize the impacts of LNG evaporation [3]. Similar to HDVs, the early adopters of light-duty NGVs will likely be fleet operators that can establish their own infrastructure, such as government fleets, taxis, and delivery vans [5]. However, for the broader light-duty personal automobile market, the dearth of refueling infrastructure is not as easily overcome, and the lower annual vehicle miles traveled (VMT) compared to HDVs leads to longer payback periods for consumers (on the order of 10 years versus 1–2 years) [3,7]. At the same time, LDV consumers are far less focused on lifetime ownership costs compared to fleet owners, and therefore only consider a few years worth of costs in their purchase decisions [8–11]. Moreover, light-duty NGVs will have to compete with improved efficiency conventional vehicles (such as clean diesel or plugless hybrid electric vehicles, HEVs), as well as other alternative fuel vehicles (AFVs), such as plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), or E85 flex-fuel vehicles (FFVs). Many of these powertrains also face similar challenges to NGVs. Thus, in order to gain significant market share, NGVs must therefore be an economically viable alternative to the established and more efficient gasoline-fueled car, and also a more attractive option than other AFVs.

Earlier surpluses in natural gas combined with high oil prices and growing concerns about air quality and energy security garnered much interest in NGVs in the 1980s and 1990s [12–22]. In particular, the Department of Energy's Alternative Motor Fuels Act gave rise to a number of reports that examined alternatives to gasoline and diesel and discussed their costs, displacement potential, and infrastructure challenges [23–25]. Many of these studies highlight the same issues and challenges NGVs face today. A couple recent studies have also assessed the viability of light-duty NGVs in the US [3,5]. These studies concur that the fuel price differential between oil and natural gas makes NGVs attractive to consumers. However, they also agree that until CNG refueling infrastructure becomes more widespread and automakers offer more CNG models (thereby reducing incremental manufacturing costs), the high purchase price will remain prohibitive. In these studies, one limitation of the analysis approaches used is that NGVs were considered as a single alternative to conventional vehicles, instead of one of many alternative powertrains. One exception is the National Petroleum Council study [5], which considered a range of portfolios that included one or more other AFVs. Another common analysis shortcoming is the limited set of scenarios considered to understand the thresholds of natural gas price, gasoline price, technology progress, and consumer behavior for which NGVs succeed or fail in the marketplace. Our work expands upon these analyses by considering a broad parametric exploration of this trade space, in addition to allowing NGVs to compete with all other types of powertrains available.

The path forward for light-duty NGVs in the US must traverse a number of uncertainties. There are uncertainties associated with policies that drive the growth of refueling infrastructure, and future regulation of carbon emissions [3]. There is also economic uncertainty given the price volatility of oil and natural gas [5], both of which determine the fuel cost savings offered by NGVs. Additionally, there is technological uncertainty in the performance and cost of future NGVs (as well as other alternatives such as PHEVs and BEVs), and in the long-term potential for shale gas to produce significant natural gas volume in a cost effective manner. These uncertainties motivate this work to take a parametric approach to the analysis, similar to [26]. Thus, instead of dissecting a limited number of future scenarios that differ by one or two key parameters, we explore a broad trade space to ascertain the set of conditions that promote or discourage light-duty NGV adoption in the US. Moreover, this work examines the future prospects of NGVs in the context of the entire portfolio of powertrains (both alternative and improved efficiency). This proves to be a key point in the analysis, since these technologies will compete with each other in addition to competing with conventional gasoline vehicles.

2. Methods

The model tracks the evolution of the light-duty vehicle stock in the US, its fuel usage, and corresponding demand for raw energy stocks. The model is broken down into four sub-components, a vehicle sub-model, a fuel production sub-model, an electricity grid sub-model, and an energy supply sub-model. The sub-models exchange price and demand information for the energy supply stocks and fuels considered. The model uses system dynamics concepts (i.e. stocks, flows and feedback loops) to track the changes in various quantities over time and the interactions between variables. No predetermined market share targets are assumed, thus technologies compete directly in the marketplace and are allowed to flourish or fail. The LDV stock is segmented by driver demographics such as population density [27], daily trip distance distributions [28], and housing type [27], as well as vehicle descriptors such as state of registration [29], age [30], size [31], and powertrain [32]. Fuel and commodity prices also vary regionally. A detailed description of the model is found in [33], which builds upon an earlier version of the model presented in [26]. More detailed extensions of the previously published model to account for CNG powertrains and home compressors are found in Appendix A.

Some of the essential model assumptions are reflected in the results, and therefore worth summarizing here. We assume that vehicles per capita is constant in time, thus the LDV stock grows at the same rate as population, 0.9%/year [27]. This also implies that the new vehicle sales rate and scrapping of older vehicles are also fixed in time. Similarly, we assume that the proportion of vehicle size classes is fixed over time. Furthermore, while miles traveled by each vehicle (VMT) varies across different descriptors of the vehicle and the driver, there is no change in VMT over time. The total mileage driven by all vehicles in the LDV stock nevertheless increases as the number of on-road vehicles increases.

The vehicle *cost* to consumers is a generalized utility encompassing purchase costs, fuel costs, incentives, and econometric penalties for range and infrastructure limitations. This cost is amortized over a required payback period for consumers (due to high implicit discount rates [10]) and then normalized by VMT. We use the term, *required payback period*, for consumers in this paper to refer to the number of years of ownership costs that consumers consider when purchasing a vehicle. Note that the default value of 3 years is far shorter than the true time it takes for fuel cost savings to offset purchase premiums. Due to their inherent