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# Energy policy considerations in the design of an alternative-fuel refueling infrastructure to reduce GHG emissions on a transportation network☆

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ABSTRACT

This paper presents a bi-criteria binary linear programming model for locating alternative-fuel refueling stations on a directed transportation network with two conflicting objectives of maximizing the total vehicle-miles traveled (VMT) per year covered by the stations and minimizing the capital cost for constructing the refueling infrastructure. The proposed model is validated with an application to the Pennsylvania (PA) Turnpike System regarding the location of liquefied natural gas (LNG) refueling stations on existing service plazas. A regression model is developed to accurately estimate construction costs for LNG refueling stations on the turnpike. To solve the bi-objective model, the second objective (capital cost) is treated as an infrastructure budget constraint and the model is run considering a range of infrastructure budget values. Given that alternative fuels and fuel economy legislation dates back to the Clean Air Act Amendment of 1970, which created initiatives to reduce mobile sources of pollutants, further analysis is performed on the case study to estimate the potential reduction of pollutants on the PA Turnpike as a function of the LNG infrastructure cost.

## 1. Introduction

Beginning with the Air Pollution Control Act in 1955 (U.S. Congress, 1955), the U.S. government has passed a number of laws and regulations to address the importance of air quality. The subsequent passage of the Clean Air Act in 1963 (U.S. Congress, 1963), as well as significant amendments to the Act in 1970, 1977, and 1990, expanded the government's ability to research and establish standards to regulate the emission of air pollutants. These national laws and standards are reinforced through international agreements established by the 1992 United Nations (UN) Framework Convention on Climate Change (United Nations, 1992), the 1997 Kyoto Protocol (United Nations, 1998), and the 2015 Paris Agreement (United Nations, 2015) to reduce greenhouse gas (GHG) emissions and prevent the consequences of climate change.

In this study, we investigate the reduction of GHG emissions for the case of establishing liquefied natural gas (LNG) refueling stations on the Pennsylvania (PA) Turnpike System, with the goal of converting Federal Highway Administration (FHWA) Classes 6–10 heavy-duty vehicles, classified by number of axles (Federal Highway Administration FHWA, 2012), from diesel to LNG as an alternative-fuel (AF). These vehicles correspond to the U.S. Environmental Protection Agency (EPA) Class 8a and 8b combination trucks (Environmental Protection Agency and Department of Transportation, 2016). When considering the impact of GHG emissions from the transportation sector, we follow the lead of the EPA and National Highway Traffic Safety Administration (NHTSA) and focus on four main gases: carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), and hydrofluorocarbons (HFCs). The first three gases are produced through the fuel cycle as byproducts of fossil fuel combustion and we will consider the impact of these emissions when evaluating the shift from diesel-fueled heavy-duty vehicles (HDVs) to LNG-fueled HDVs. The fourth category of GHG, HFCs, is typically emitted from air conditioning units within the vehicles, and we will assume that any improvements that can be made to reduce the emissions from this source could be applied equally across trucks which consume any fuel type. The European Union has already begun to phase down the use of fluorinated gases through regulation (European Commission, 2016). Furthermore, $N_2O$ emissions can be mitigated using on-vehicle emission control technologies, and the EPA expects that both diesel and LNG vehicles can be fitted with the same emission control technologies, eliminating any significant difference between the $N_2O$ emissions for the two fuel types (Environmental Protection Agency, 2003).

When discussing the impact of GHG emissions, it is common to use a scaling factor to compare the potential for different GHGs to have an impact on climate change. This factor is referred to as the global

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**Table 1**
Climate impacts of GHGs for targeted gases.

| GHG | Lifetime in Atmosphere (years)[a] | GWP | | % Responsible for Man-Made Global Warming[b] |
|---|---|---|---|---|
| | | 20 year[a] (scaled to $CO_2$Eq) | 100 year[a] (scaled to $CO_2$Eq) | |
| Carbon Dioxide ($CO_2$) | 30–95 | 1 | 1 | 64% |
| Methane ($CH_4$) | 12 | 72 | 25 | 17% |
| Nitrous Oxide ($N_2O$) | 114 | 289 | 298 | 6% |

[a] Environmental Protection Agency (2016a).
[b] European Commission (2016).

warming potential (GWP) for a gas, and the factor enables the comparison between the impact of a gas and the reference GHG, $CO_2$. This allows the measurement of GHG emissions to be standardized from the collection of emitted GHGs to a single measure of carbon dioxide equivalence ($CO_2$Eq). Table 1 shows the GWP values for the three main GHGs we will consider in this paper for transportation emissions resulting from fossil fuel combustion.

GHG emissions in the U.S. in 2014 totaled 6870.5 million metric tons (MMT) $CO_2$Eq (Environmental Protection Agency, 2016a), with 76% of this total coming from the combustion of fossil fuels like coal, natural gas, and petroleum products (diesel and gasoline), predominantly used for energy, industrial, and transportation purposes. In 2014, the transportation sector emitted 1810.3 MMT $CO_2$Eq, accounting for 26.3% of the total GHG inventory in the country for that year. Of this total, 95.9% (1737.6 MMT $CO_2$Eq) was the result of burning fossil fuels like diesel (typically used in HDVs and long-haul trucks), gasoline (typically used in passenger cars and light trucks), compressed natural gas (typically used in vocational vehicles like local busing and delivery vehicles), and LNG, which is an emerging fuel in this sector for long-haul trucks and HDVs, and is the focus of this study. The transportation sector is the largest contributor of $CO_2$ emissions, having recently surpassed the electricity sector (Energy Information Administration, 2017), where energy consumption is higher but less carbon-intensive. Despite being only 4% of the registered vehicles on the road in the U.S., HDVs accounted for nearly 23% of the GHG emissions from transportation in the U.S. (White House, 2014), so reducing the consumption of GHG-emitting fuels from this sector would significantly reduce in GHG emissions.

It is also important to mention the effect of importing and using petroleum-derivative fuels, most notably energy security and economic development. According to the U.S. Energy Information Administration (EIA), the U.S. imported 9.45 million barrels of petroleum per day in 2015, about 78% of which were crude oil for refining, consumption, and distribution (Energy Information Administration, 2016a). At a cost of about $45 per barrel (Energy Information Administration, 2016b), this amounts to nearly $425 million of petroleum imported from foreign sources daily. A reduction in U.S. petroleum imports reduces the risk of disruption of petroleum supply due to local distribution issues in source countries, which is a worthy mitigation target given the potential for political instability and security issues in the regions that distribute much of the world's oil, notably the Middle East and Northern Africa, which produce approximately 30% of global petroleum supply (Environmental Protection Agency and Department of Transportation, 2016). Although imports of petroleum have decreased in recent years as the U.S. has increased oil production, the exploration of alternative domestic energy resources has also created the possibility that other fuels could be used for energy production and transportation, further reducing the need to import fossil fuels from foreign states. Most notably, exploitation of natural gas resources in the northeastern U.S. offers just such an opportunity, enabling the adoption of CNG and LNG as transportation and energy fuels at competitive prices and with abundance to supply industries for decades.

The adoption of LNG as an alternative to diesel fuel can potentially reduce $CO_2$ emissions due to its lower carbon content, but natural gas, comprised mostly of $CH_4$, creates an additional problem that needs to be addressed. As shown in Tables 1, 1 kg of $CH_4$ emissions has the same GWP as 25 kg of $CO_2$ over a 100-year study period. Although $CH_4$ spends less time in the atmosphere, the 25- and 100-year potentials suggest that $CH_4$ is arguably a more hazardous gas to emit in the near term. Fugitive emissions from vehicle drivetrains, refueling operations, and boil-off of LNG expanding to CNG in a fuel tank may offset the $CO_2$ reduction potential of LNG by contributing more impactful GHG emissions from $CH_4$ (Environmental Protection Agency and Department of Transportation, 2016). We will return to this consideration in Section 4, where we will estimate the total GHG emissions impacts, and in Section 5, where we will suggest policy and mitigation strategies to address this concern.

Current literature offers an avenue to relate the location of AF refueling stations to the problem of mitigating the effects of GHG emissions from transportation sources. For this purpose, based on the modeling framework proposed by Hwang et al. (2015), we formulate a bi-criteria binary linear programming model for locating AF refueling stations on a directed transportation network with two conflicting objectives: maximizing the total vehicle-miles traveled (VMT) covered by the stations and minimizing the capital cost of constructing the refueling infrastructure. The proposed model is applied to the PA Turnpike to optimize the development of an LNG refueling infrastructure considering service plazas as potential station locations.

In the succeeding sections of this paper, we begin with a literature review in Section 2 on location models for the development of AF refueling infrastructures in transportation networks. In Section 3, we describe the modifications to the original model with the goals of maximizing VMT and minimizing infrastructure cost, where the original construction cost objective is relegated to the constraint set as a budget constraint. Section 4 presents the case study on the PA Turnpike, where we analyze the resulting LNG refueling station locations for a variety of construction budgets while maximizing VMT and estimating the GHG emissions changes for $CO_2$ and $CH_4$. The construction costs for the candidate LNG refueling stations are estimated using a regression model developed with estimates from a previous study (Myers et al., 2013). In Section 5, we draw conclusions and recommend policy actions that may be taken to advance the development of a natural gas refueling infrastructure and potential research and development targets to maximize the environmental benefits realized through the transition to LNG vehicles.

## 2. Literature review

In this section, we review the relevant literature for AF infrastructure development within the context of refueling station location in a transportation network. Hodgson (1990) and Berman et al. (1992) developed the initial concept of the path-based flow-capturing location model (FCLM) to select optimal station locations with the objective of maximizing coverage of frequently traversed paths in a network, instead of optimizing to serve or cover demands assumed to be generated from the nodes of a network.

Due to the growing demand for AF vehicles over the last two decades, Kuby and Lim (2005) expanded the FCLM to the flow-refueling location model (FRLM) to incorporate the vehicle driving range on the design of an AF refueling infrastructure. Later, Lim and Kuby (2010) proposed heuristic algorithms to solve the FRLM efficiently. These heuristic algorithms were integrated into a geographic information system to locate hydrogen stations in Florida (Kuby et al., 2009). Upchurch et al. (2009) introduced the concept of capacitated stations to the FRLM, and changed the objective to maximizing the VMT of captured flow instead of their trip volumes. Capar and Kuby (2012) proposed a new formulation for the FRLM based on covering nodes along edge path, while Capar et al. (2013) achieved even greater