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Original Research Article

A computer model for optimizing the location of natural gas fueling stations

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ABSTRACT

High levels of fine particulate matter and ozone in many major cities are causing increased respiratory problems, increased asthma attacks and premature death. Natural gas vehicles have been reported to emit up to 95% less particulate matter than diesel powered vehicles and up to 90% less ozone-producing carbon monoxide and reactive hydrocarbons. The adoption of natural gas vehicles, therefore, could play a large role in improving air quality in many cities. Because of the many costs associated with the introduction of a new fueling infrastructure, optimum distribution of fueling stations will play a major role in widespread use of natural gas vehicles, especially in the early stages of market penetration. A model was developed that can be used to optimize fueling station placement-based on traffic volume using a Monte Carlo algorithm. In particular, the Monte Carlo method allows for the placement of the fueling stations based upon their proximity to high volume traffic flow and the placement of all the fueling stations are optimized simultaneously. Traffic volume data from Pittsburgh, PA was used in the model simulations.

Background

Many U.S. leaders have suggested that the U.S. should strive for energy independence, while the transportation sector in the U.S. is still highly dependent on fuel imports. According to the Energy Information Administration, in 2011 the U.S. imported approximately 4.2 billion barrels of petroleum, 45% of the total U.S. petroleum consumption and 65% of the total petroleum that is consumed in the transportation sector [1]. These statistics represent an unsustainable national energy policy, especially considering that a significant portion of the exporting countries that are relied upon have volatile diplomacy. The transition of the U.S. transportation refueling infrastructure to natural gas is a major step toward the reduction of dependence on petroleum fuels and therefore a reduction in imported oil. The U.S. domestically produced 85.8% of its total consumed natural gas in 2011, up 1.5% from the previous year, and as the development of Marcellus and Utica shale continues this domestic production percentage should increase even further [1]. A transportation sector dominated by natural gas vehicles (NGVs) would provide a huge step toward energy independence, but this is not the only advantage of NGVs. NGVs significantly lower carbon monoxide, nitrogen oxide, non-methane hydrocarbon, particulate matter, and greenhouse gas emissions when compared to gasoline and diesel vehicles [2]. During operation, NGVs emit 60–90% less smog producing pollutants, such as particulate matter, and 30–40% less Greenhouse Gases (GHGs) [3]. Although there are additional costs associated with NGV conversion systems and the relatively immature NGV business sector, there are substantial savings to be attained in the operation of the vehicles. The fuel cost of natural gas is approximately one quarter of the cost of the pump price of gasoline and diesel fuel [4].

The development and construction of the natural gas refueling station infrastructure is a pivotal change that would initiate the long term transition from liquid fossil fuels to cleaner gas-based transportation fuels, potentially facilitating a future transition to hydrogen fuels by way of on-site steam methane reformation. Natural gas is a fossil fuel that is extracted from underground wells, in turn adding to the overall carbon in the atmosphere, but Renewable Natural Gas (RNG) can be produced with much less carbon related emissions and can be used as a direct replacement for natural gas. RNG, also known as biogas, is chemically identical to fossil natural gas and can be produced in a number of ways, including fixed bed reactors, fluidized bed reactors, anaerobic digesters, and landfill gas collection [5]. The feedstock used to produce the RNG is organic matter and therefore was a carbon sink before being

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processed into RNG. Argonne National Laboratory estimated an 81–91% reduction in GHG emissions for the production of anaerobic digester-based compressed natural gas when compared to petroleum gasoline on a per MJ basis [6]. Another advantage to RNG is that the gases from the natural decomposition of the organic matter is traditionally allowed to vent to the atmosphere, but through the collection and use as a fuel, a portion of the extracted natural gas can be displaced by the RNG. The future potential use of hydrogen as a transportation fuel, which could make use of existing natural gas infrastructure, would further reduce GHG emissions to zero during vehicle operation [7]. Natural gas fueling stations and infrastructure could provide a natural transition to the eventual conversion of natural gas fueling stations to hydrogen by way of on-site steam methane reformation. Currently 95% of the hydrogen that is produced in the U.S. is made by natural gas reforming and could potentially be reformed on-site at the fueling station; therefore a station could provide natural gas and hydrogen to ease the transition to a hydrogen economy [8].

Introduction

The transition from traditional to alternative fuels is an important topic for future energy consumption and greenhouse gas reductions. Many studies have focused on this transition and how important refueling stations are to the transition [9–12]. Optimal locations of alternative refueling stations will play a major role in the success of the transition from fossil to alternative fuels, especially early in the transition. The optimization of refueling locations depends upon many variables, but the ultimate goal is have refueling stations that are as easily accessible and as close to consumers as possible.

The determination of optimized locations for fueling stations and other consumer facilities is not a new topic. Multiple research groups have developed classical location models. Facility location models, a sub-category of the classical location models, focus on optimal locations related to public facilities and retail stores [13–16]. Another sub-category of classical location modeling is covering modeling where the primary goal is to optimally locate a system of facilities. The covering models focus on either minimizing the number of locations necessary to ”cover” the demands or to minimize the distance between coverage areas [17–19]. One of the most widely used models in the field of refueling station location optimization is the p-median model, where the model chooses locations for a set number of facilities (p) and then allocates demand nodes (i) to facilities (j) with the goal of minimizing the distance traveled from the consumer to the facilities [20,21]. The p-median model has been applied to fueling stations by Goodchild et al. and to alternative-fueling stations by Goodchild and Noronha [22], Nicholas and Ogden [23], Nicholas et al. [24]. Lin et al. developed an approach that is similar to the p-median model, but focuses on the notion that, ” where you drive more is where you more likely need refueling.” The fuel-travel-back approach that Lin et al. developed only requires data of Vehicle Miles Traveled (VMT) spatial distribution [25]. Any point along the road network acts as a possible location for refueling, where the probability is a function of the VMT distribution or fuel consumption. The objective is to minimize the time of travel for the consumer to reach a refueling station. It has been suggested by Nicholas that the ”population-traffic” metric correlates with fuel sold better than both population and VMT [26].

Another important category of models in the field of refueling station location are the flow-based demand models. These models examine the flow paths between multiple locations or nodes. Flow-based models have been used to determine optimal locations for convenience stores, billboards, automated teller machines and refueling stations [27–29]. A refueling flow models assumes that if a vehicle passes through a node, which is used to represent a refueling station, the vehicle flow is captured by the node. The vehicle's origin could be close to the node or very far from the node, as in the case of a vehicle making multiple refueling stops during a long journey. The flow-refueling model accounts for the differences in likelihood of stopping at a close proximity node versus a farther proximity node through the demand volume at a particular node in relation to the vehicle's origin and/or destination. Unlike the flow-based demand models, this research makes use of a coverage radius from the refueling station, where a gaussian distribution represents the effective coverage for each refueling station. A vehicle that lies within the coverage radius of the refueling station will have a probability of refueling at that station that is defined by the gaussian distribution. The closer the vehicle is to the station, the more likely the vehicle is to refuel there.

The model that we have developed simultaneously optimizes station location for any given number of fueling stations within the given geographic region, and therefore the placement of each station changes the amount of traffic volume that is available for each other station that occupies a neighboring space. The location of fueling stations effectively evolves toward an optimum configuration. In this manner, the computational time approximately scales linearly with the number of fueling stations and our model can efficiently optimize the location of a large number of fueling stations simultaneously.

Methodology

The current model uses a Monte Carlo algorithm to optimize the positioning of a set number of fueling stations. The location of all fuel stations are then optimized simultaneously. Here we assume the optimum location of fueling stations will be in close proximity to traffic density. While the optimum location of a fueling station will indubitably depend on socioeconomic factors and the presence of petroleum fueling stations, for simplicity, here we concentrate on the volume of traffic flow in order to exhibit our technique. In particular, we discretize the Pittsburgh area onto a 800×800 grid (an area of $80 \times 80\ \mathrm{km}^2$ with a 100 m spatial discretization) and define the vehicle miles traveled (VMT) by all vehicles in each discretized region of space. The location and annually averaged traffic flow for the roads around Pittsburgh were obtained from the Pennsylvania Department of Transport (PennDOT). We consider the average flow of traffic in each grid section and combine all roads to obtain the average distance driven within that grid point. A contour plot of this traffic flow is depicted in Fig. 1a, which clearly shows the main arteries of traffic in the Pittsburgh region, with downtown Pittsburgh located in the center of the figure.

Next we consider the coverage of a fueling station that is placed somewhere in this region. For simplicity, we assume that the coverage of a fueling station is a Gaussian function centered on the location of the fueling station (see top inset Fig. 1a for such a two-dimensional Gaussian). In other words, traffic flow close to this fueling station is considered to have access to the fueling station, but the coverage offered by a fueling station will decrease with distance. The traffic flow, $F(x,y)$, is taken to have access to the Gaussian coverage of the ith fueling station, $C_i(x,y)$, via the following expression for the fueling station access

$$\Phi(x,y) = \frac{\sum_i^N [C_i(x,y)F(x,y)C_i(x,y)]}{\sum_i^N C_i(x,y)} \tag{1}$$

where the summation is over all fueling stations. $C_i(x,y)$ is included twice in the numerator, once as part of the optimization of $C_i(x,y)F(x,y)$ and a second time to take into consideration that some of the traffic might also be covered by neighboring fuel stations. Re-