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Infrastructure development for alternative fuel vehicles on a highway road system

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ABSTRACT

A new mathematical model for positioning alternative fuel (AF) refueling stations on directed-transportation networks with the objective of maximizing the coverage of path flow volume is proposed. This model is especially designed for developing an AF infrastructure on toll roads and other highways, where vehicles do not need to exit the road network for refueling, some candidate station locations are not located at interchanges, and some stations may only service vehicles on one driving direction. The proposed model is applied to the Pennsylvania Turnpike System using the 2011 truck traffic data and considering different vehicle driving ranges.

1. Introduction

Over 164,000 miles of National Highway System (NHS) roadways, comprising the Interstate Highway System and other roads important to the nation's economy and defense, are a central component of the U.S. ground logistics. Using NHS, trucks carried almost 69% of U.S. domestic freight movements in 2014 (McNally, 2014). In order to achieve fuel cost savings and environmental benefits in the freight transportation sector, the ground logistics industry has made significant efforts to transition from traditional petroleum fuel (gasoline and diesel) trucks to alternative fuel (AF) trucks, which are powered by engines that do not involve only gasoline or diesel. AF trucks are becoming a high priority for transportation companies, truck manufacturers, and also government institutions due to several factors, including environmental concerns, high oil prices, development of cleaner fuels, and advancement in power system technology. For example, United Parcel Service of North America, one of the major logistics companies in the world, has been researching trucks powered by electric motors and natural gas engines since 1998 (UPS Pressroom, 2014).

Various types of AF trucks are currently available. The first type includes battery-electric trucks. A battery-electric truck runs with an electric motor operated by a large and heavy battery pack. The limited battery capacity restricts the driving range of electric trucks between 100 and 200 miles, which is the main concern of transportation companies (Gallo and Tomić, 2013). Hydrogen fueled trucks comprise another type of AF technology. In this category there are two kinds of trucks available in the market: hydrogen internal combustion engine (ICE) trucks and hydrogen fuel cell trucks (FCTs). Hydrogen ICE trucks burn hydrogen in the engine to produce mechanical energy, and hydrogen FCTs run their electric motor by reacting hydrogen with oxygen in built-in fuel cells (Shukla et al., 2011). Both kinds of hydrogen fueled trucks are eco-friendly in that they produce near-zero harmful pollutants. Since hydrogen has a wide range of flammability, it needs to be stored in a large and safe tank, which causes an increase in truck price and a slight drop in fuel efficiency (Gillingham, 2007, Paster et al.,

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2011). Therefore, using hydrogen for long distance transportation is inefficient with the current technology of hydrogen storage. Trucks using biofuel, such as bioethanol or biodiesel form another type of AF technology. Bioethanol and biodiesel are produced from a wide range of waste vegetables and animal oils, which are less expensive than fossil fuels. Biofuel trucks burn these fuels in the same way that gasoline- or diesel-powered trucks do, but the biofuel trucks emit significantly fewer toxins and less carbon dioxide (Börjesson and Mattiasson, 2008). For example, when the biofuel is used instead of diesel, greenhouse gas emissions are averagely reduced by 60% (Official Report of the Swedish Government, 2007). Another type of AF for trucks that can provide economic and environmental benefits is natural gas with two basic options: compressed natural gas (CNG) for return-to-base, short mileage vehicles, and liquefied natural gas (LNG) for long-haul on-highway classes 8 to 10 trucks, based on the Federal Highway Administration vehicle classification scheme (Cambridge Systematics, 2007, Appendix A). LNG trucks with high-pressure direct injection system engines enable the same driving range as mid- and heavy-duty trucks with a driving range of approximately 300 miles, which is recommended for long distance transportation (Burnham, 2013). Hybrid electric trucks can also be categorized as AF trucks. This type of truck uses hybrid electric vehicle (HEV) technology for propulsion, instead of using only an internal combustion engine. Furthermore, using an AF in combination with hybrid drive propulsion systems in heavy duty trucks can further displace petroleum but the technology has not yet come together naturally in the market place.

Nevertheless, due to an insufficient AF infrastructure on most road networks, logistics companies hesitate to replace their traditional fuel trucks with AF trucks for their over-the-road trucking business. For example, in the U.S., only about 860 public natural gas stations are currently in operation, compared to over 120,000 gasoline stations (National Renewable Energy Laboratory, 2014; US Census Bureau, 2014). In order to invigorate the use of AF trucks in the ground logistic industry, it is necessary to develop AF infrastructures along a road system to maximize the refueling coverage. In this research work, we consider the development of an AF infrastructure on a highway. Highway road networks have special characteristics compared to other transportation road networks. In general, highway roads are divided into two driving directions by a median divider island, such as a traffic barrier or grass. Also, for uninterrupted high speed traffic flow, they do not have traffic signals or at-grade intersections. Since vehicles are able to access the highway system only at interchanges, drivers can only use built-in facilities on the system to take breaks and refuel their vehicles without exiting onto other roads. This road network usually comprises two types of service facilities: (i) single-access facilities which provide service to one-way traffic, and (ii) dual-access facilities which can serve traffic on both sides of the roadway. We can observe these directional service facilities on several highways. For example, 22 single-access facilities are being operated along Ontario's highways in Canada (Nichols and Elzen, 2010). Also, highways in South Korea run approximately 2500 miles in 2013, and most facilities are open to serve one-way traffic (Korea Expressway Corporation, 2013). In the U.S., toll roads consisting of interstate highways and other principal arterials have their own service facilities. In particular, the Pennsylvania (PA) Turnpike Commission currently operates 14 single-access facilities and 3 dual-access facilities along the turnpike. Thus, locating an AF refueling station at candidate sites to cover vehicle round trips on a highway road network must be determined not only by their placements but also by the directional access of the sites. We take into account the driving direction (path) in the specific road segment where each refueling station is located. This issue has not been considered in previous research. Kuby and Lim (2005) introduced the first path-based model for AF vehicles taking into account their limited driving range, but they assumed that all stations could be designed as dual-access facilities. In this article, we present a mathematical model that locates AF refueling stations on a directed-transportation network to maximize the coverage of traffic flow in vehicle round trips per time unit. Also, in order to efficiently apply the model to large-scale networks, we use different types of constraints to cover a specific origin–destination flow depending on the corresponding travel distance.

In the next section, we review the existing research on location problems for AF refueling stations. In Section 3, we describe assumptions and define sets of refueling station locations on each driving path that are necessary to formulate the model, and then propose the mathematical model that locates a given number of refueling stations with the objective of maximizing the coverage of traffic flow on a directed-transportation network. In Section 4, we apply the proposed model to the PA Turnpike using the 2011 truck traffic data to set up LNG refueling stations for trucks considering various vehicle driving ranges. Then, two greedy algorithms are developed and implemented to find the best sequence to build the AF refueling stations on the selected locations. The last section provides conclusions and directions for future research.

2. Literature review

In this section, we classify the literature about network location-allocation models for refueling stations into three categories according to the demand type, including node-based, arc-based, and path-based demand models (MirHassani and Ebrazi, 2012). Firstly, node-based demand models designate each node as a demand point (i.e., population in a city) and assume that demand can be covered by dedicated trips to the closest refueling station. Nicholas et al. (2004) and Nicholas and Ogden (2006) use the *p*-median model, which is one of the node-based demand models, to locate refueling stations that minimize a weighted sum of driving time to the closest station. Chan et al. (2007) also use the *p*-median formulation as a pricing model to locate gasoline stations in Singapore. Lin et al. (2008) apply the *p*-median model to the fuel-travel-back concept and propose a mixed integer linear programming formulation that minimizes the total fuel-travel-back time. Instead, Bapna et al. (2002) use the maximum set covering model, which is another node-based demand model, to find the optimal locations for unleaded gas stations that maximize the number of vehicles refueled during their inter-city trips in India considering the driving range of vehicles. The main advantage of using node-based demand models to determine the