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A hybrid heuristic approach to the problem of the location of vehicle charging stations

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ABSTRACT

In order to reduce the negative impact of fuel-powered vehicles on the environment, the use of alternative-fuel vehicles (AFVs), which produce far less pollution than traditional fuel-powered vehicles, is being introduced in many countries around the world. However, compared to the fuel-powered vehicles, AFVs such as electric vehicles require frequent recharging of their electrical energy storages (batteries), which results in a short vehicle driving range. Thus, AFV users who want to travel from home to a terminal location and back again must consider whether their AFVs can be recharged on the way. One of the approaches to solve this problem is to install alternative fuel charging stations on suitable locations to provide recharging services. However, when the budget is limited, the selection of locations and the types of alternative fuel charging stations becomes a decision problem, since it will directly affect the number of potential AFV users that can be served. This paper develops a mixed-integer programming model to address this problem and to maximize the number of people who can complete round-trip itineraries. A hybrid heuristic approach is proposed to solve this model. Numerical results show that the proposed heuristic approach only requires a small amount of CPU time to attain confident solutions.

1. Introduction

Transport services play an important role in daily life. These services include: (1) land transportation, using automobiles, bikes, trains, etc., (2) water transportation, using ships, boats, barges, steamers, etc., and (3) air transportation, using air-craft, and airships. These services may vary in terms of the distance covered, vehicle types used, routes and timetables. Of the land transport options, fossil fuel-powered vehicles are usually used for transport in urban areas, or to and from the suburbs to population centers. These services are often parts of a network, centered on an urban center, or across a city, and usually involve a fixed route and schedule. The use of fuel-powered vehicles produces some gases such as carbon dioxide, nitrogen oxides, ozone and microscopic particulate matters. These waste gases cause air pollution and harm our health and the environment. As reported by the WRI (2006), 65% of global CO2 emissions come from energy use, and 21% comes from transportation, which is dependent on fossil fuels. Thus, decreasing CO2 emissions has been viewed as an important policy around the world, from USA to European Union and to China and Japan in Asia (Lund & Clark, 2008).

Since electric-powered vehicles produce far less pollution than traditional fuel-powered vehicles, they seem not to cause harm to our environment or public health. Thus, electric-powered vehicles are called as partial zero-emission vehicles, even though they still emit pollutants. Accordingly, many countries have begun to introduce electrically powered vehicles in their public transport services, to reduce the gaseous emissions from fossil fuel-powered vehicles. With all the efforts expended on green initiatives and protecting the environment, it is little wonder that electric-powered vehicles have become a popular alternative to traditional fossil fuel-powered vehicles. However, they still have some limitations (Electric vehicle site, 2011). One of the limitations is their limited driving range. Thus, users must consider how many miles can be covered before a recharge is needed. There is no doubt that this restricts their use as transport tools. So for electric-powered vehicles to be practical, the provision of enough alternative fuel vehicle stations is an important issue. This study deals with the problem of refueling locations for alternative-fuel vehicles.

The refueling location problem is a facility location problem. The key questions commonly faced by facility planners include: (1) the number of facilities, (2) the locations of these facilities and (3) the types of facilities (in terms of size, product variety

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and other design aspects). Aboolian, Berman, and Krass (2007) dealt with the competitive facility location and design problem (CFLDP) by simultaneously optimizing the locations and designs of a set of new facilities under a budget constraint and pre-existing competitive facilities. They developed a solution with an adjustable error bound. Frick, Axhausen, Carle, and Wokaun (2007) investigated the problem of the placement of stations for compressed natural gas in Switzerland. Two scenarios for possible distributions of these stations were studied. In the first case, the scoring function was given in terms of the filling station owners' investment costs and their attractiveness for CNG car drivers. In the second case, the scoring function approximated the results of a social cost-benefit analysis, which focused on the investment costs as well as the environmental and user benefits. The results from the two cases show that the social and commercial outcome of an investment can be quite different, depending on the optimization strategy pursued.

Most location models focus on either minimizing the average cost of travel (the median problem) or minimizing the maximum cost of travel (the center problem). A large number of these models assume that the demand for service originates from the nodes of the network. In other words, this assumption implies that customers make a dedicated trip to a specific facility to obtain a service. One popular model for this problem is the p-median model. The p-median model locates a given number of facilities on a network and allocates demand nodes to each facility, in order to minimize the total weighted distance traveled. Nicholas, Handy, and Sperling (2004) developed a GIS model for the location of hydrogen fuel stations in Sacramento County, California, under the assumption that the existing petrol infrastructure is strongly related to the required hydrogen infrastructure of the future. A greedy algorithm, adding two stations at a time, was used for the model. Lin, Ogden, Fan, and Chen (2008) developed a fuel-travel-back approach to deal with the station-siting problem. The only data required for this approach are the distribution of traveled vehicle miles. Their proposed fuel-travel-back problem is treated as a typical transportation problem, which can be solved by a mix-integer-programming model. Wang (2007) developed a recreation-oriented facility location model to economically set the slow recharging stations at scenic spots, for electric scooters traveling on a single O–D (origin–destination) trip using multi-stop refueling. Later, Wang (2008a) extended this model to a case with multiple O–D trips, under the assumption that the length of a trip was also within the vehicle range. The purpose of his model was to optimally site the refueling stations to cover overall passing flows on the paths of interest, instead of the O–D flow data. Wang (2008b) proposed a simulation model to deal with a deterministic location problem for the identification and assessment of the service capacity and performance of a tourism/recreation-oriented electric scooter recharging system with random demands.

In practice, retail facilities such as gas stations and convenience stores also try to capture flow-by customers. In other words, in urban or intra-city travel, demand in a network is fixed-point type and flow-type (Goodchild & Noronha, 1987; Hodgson, 1990; Hodgson & Rosing, 1992). One popular model for the optimal location of alternative-fuel stations to capture flow-by customers is the flow-refueling model, proposed by Hodgson (1990) and Berman, Larson, and Fouska (1992) who referred to it as a flow-intercepting model. In flow-capturing location models (FCLM), demand consists of paths through a network, instead of points of origin for trips to the facility and back. These models are structurally similar to the maximum-coverage problems, which locate a given number of facilities in a network, so as to maximize the traffic flow passing by the facilities. These models are used to locate discretionary facilities, such as ATMs, convenience stores and fast food outlets, at which people stop on their way to somewhere else, rather than making a special trip from home to the facility and back (Kuby et al., 2009). Berman, Hodgson, and Krass (1995) surveyed the works on the optimal facility location, based mainly on flow-by customer traffic. These models were firstly introduced by Berman et al. (1992) and Hodgson (1990). They assume that customers who make an origin to destination trip (for example, from home to the work place) for a certain purpose may also obtain other services if they pass through other facilities. Averbakh and Berman (1996) developed two flow-capture models to address two-location problems. The first problem was the minimization of the number of facilities required to ensure the maximum level of consumption. The second problem was to maximize consumption subject to a given number of facilities. The assumption that facilities only rely on pre-existing customer flows is made in most of the flow interception models, and the assumption that facilities rely exclusively on dedicated trips is made in most of the traditional median and center models.

Many real-life retail facilities rely not only on special trip purchases, but also on intercepting passing customers. Thus, several hybrid models have incorporated these two cases. Berman and Krass (1998) studied a facility location problem in which demand came from both customers with special-purpose trips and customers passing by a facility while en route to another destination on the network. They developed a branch-and-bound scheme and a tight upper bound for their model. Berman and Krass (2002) proposed a spatial interaction model to investigate the competitive facility location problem with considering the effects of market expansion and cannibalization. Hodgson (1990) and Berman et al. (1992) explored the flow capturing location–allocation problem with the purpose of capturing most of the flow-type demand (short distance trips via one-stop refueling) on the paths under budget restrictions. Kuby and Lim (2005) extended the problem of Hodgson (1990) and Berman et al. (1992) to the flow refueling location problem by considering the limited driving range of alternative-fuel vehicles (AFV) when undertaking long-distance trips and using multi-stop refueling.

The FCLM assumes that a single facility on a path is sufficient to serve the demands. However, even though a single facility is located on a path, the single station may not be enough to complete a long-range trip, due to limited driving range. Accordingly, one or more stations must be located on a path to refuel a vehicle so that it does not run out of fuel. Thus, the flow-refueling location model (FRLM), which considers the distance of a path, was proposed to extend the flow-capturing model proposed by Hodgson (1990) and by Berman et al. (1992). FRLM is a path-based demand model that locates a given number of stations in order to maximize the number of trips on the shortest paths that can be refueled. The purpose of the FRLM models is to locate a given number of refueling stations so that the maximum volume of traffic flows traveling on their shortest paths from origins to destinations can be refueled. In the flow-refueling location model, instead of nodes, demand covered is in terms of O–D pairs. Kuby and Lim (2005) dealt with the optimal location for fueling stations. However, their work does not set out to serve origin–destination demands. Kuby and Lim (2007) developed a FRLM model to extend the flow-capturing/intercepting problem by incorporating a driving limitation. Lim and Kuby (2010) presented a flow-refueling location model and developed a genetic algorithm to find the optimal station locations for alternative-fuels, so as to maximize the flow that can be refueled in a given number of facilities. Wang and Wang (2010) developed a mixed integer programming model to study a refueling station location problem for an emerging and/or monopolistic automotive market of alternative fuel vehicles. The objective function of their model minimizes the facility cost and maximizes the population coverage. Upchurch and Kuby (2010) compared the p-median and flow-refueling models for alternative-fuel location