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Locating refuelling stations for alternative fuel vehicles: a review on models and applications

Joonho Ko[a], Tae-Hyoung Tommy Gim[b] and Randall Guensler[c]

[a]Department of Transportation Systems Research, The Seoul Institute, Seoul, South Korea; [b]Graduate School of Environmental Studies, Seoul National University, Seoul, South Korea; [c]School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, USA

ABSTRACT
The recent concerns on environmental issues have expedited the technological development of alternative fuel vehicles (AFVs), but the deployment of AFVs still remains at the initial stage mainly because of the lack of refuelling facilities. Recognising this, researchers have conducted various studies, proposing a variety of approaches to strategically locating refuelling stations. This paper presents a comprehensive review of the approaches, focusing more on applications than computational issues. The review identifies two main elements of the approaches: location modelling and refuelling demand estimation. Examining how the elements were handled in refuelling location studies, this paper suggests that future refuelling location models should properly reflect the intricate and various perspectives of three major AFV stakeholders: drivers, government agencies and refuelling service providers. This study is expected to help researchers efficiently set up their refuelling location problems and identify critical factors for seeking the solutions.

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1. Introduction

1.1. Background

It is known that about 25% of worldwide CO_2 emissions are attributable to the transportation sector and road transport such as cars and trucks represents a significant portion (about 75% worldwide) of the emissions (Chapman, 2007; IEA, 2009). Numerous studies have pointed out that travel behaviour changes and technological innovations are crucial for reducing the CO_2 emissions (Chapman, 2007; Choi, Nakagawa, Matsunaka, Oba, & Yoon, 2013; Kim, Lee, & Choi, 2015; Ko, Park, Lim, & Hwang, 2011; Lee & Suzuki, 2016). Concerning the technological innovations, more and more attention has been paid to alternative fuel vehicles (AFVs) such as hydrogen, electric, natural gas and biofuel vehicles. In fact, studies have illustrated that the wide use of AFVs with appropriate strategies can contribute to significantly reducing the dependency on fossil fuels, the major contributor of greenhouse gases, requesting governments' vigorous and consistent

CONTACT Joonho Ko jko@si.re.kr Department of Transportation Systems Research, The Seoul Institute, 57 Naumbusunhwan-ro 340 gil, Seocho-gu, Seoul 06756, South Korea

supports for the diffusion of AFVs (Shafiei, Davidsdottir, Leaver, Stefansson, & Asgeirsson, 2015; Thomas, 2009). Because of this reason, many cities and countries have actively encouraged citizens to use AFVs, especially electric vehicles (EVs), by implementing various policy actions including EV purchase subsidies (IEA, 2012).

It is recognised that the major hurdle to the wide use of AFVs is the lack of public refuelling infrastructure as well as the high price of AFVs. Researchers describe the infrastructure-related issue as the "chicken and egg" problem (Lim & Kuby, 2010). Without adequate refuelling infrastructure, people will not accept AFVs. Conversely, adequate refuelling infrastructure will not be built without sufficient refuelling demand. Under this circumstance, how to provide an adequate level of refuelling infrastructure is an important issue for decision-makers to encourage the use of AFVs.

The decision on refuelling locations is significantly complex since there are various factors affecting the decision. The factors include vehicle characteristics (e.g. driving range, battery capacity and charging time), refuelling facility type (e.g. battery exchange stations, rapid chargers and hydrogen stations), total number of AFVs, budget constraint and geographic scale. For example, Wang and Lin (2009) pointed out that the driving range of AFVs plays a critical role when determining the number of refuelling stations needed to be sited for long-distance trips made in Taiwan. In addition, AFVs with different operational characteristics, for example, commercial vehicles like taxis need different strategies for locating refuelling stations in order to minimise their operation time loss induced by frequent charging (Jung, Chow, Jayakrishnan, & Park, 2014). Note that this paper uses the words "refuel" and "recharge" interchangeably as well as "tank" or "battery".

The questions of this study include how existing studies specify AFVs' refuelling location problems and which factors are considered. In addition, this study examines refuelling demand estimation approaches, considering that the demand location and amount can directly affect the refuelling location and capacity needed. Several studies appear to have already attempted to discuss the issues. Dagdougui (2012) reviewed models and approaches for planning the future hydrogen supply chain composed of three stages: production, storage and transportation. Agnolucci (2007) and Agnolucci and McDowall (2013) reviewed relevant studies concerning the design of hydrogen infrastructure in the transport sector. Agnolucci and McDowall's (2013) study is particularly notable, in that it discussed the spatial distribution of hydrogen filling stations and refuelling demand, which is similar to the scope of this study. However, their study scopes were confined to hydrogen vehicles and planning approaches to providing their refuelling infrastructure as an element of the supply chain. Demir, Bektaş, and Laporte (2014) conducted a literature review on fuel consumption models from the perspective of freight route planning. Gnann and Plötz (2015) attempted to review combined models handling AFVs' market diffusion and their refuelling infrastructure together, without intensively covering the issue of the location or spatial distribution of the infrastructure. Some studies discussed the issue of AFVs, simply considering AFV as an element of sustainable transportation systems (Janic, 2006) or examining only a single type of AFV, such as bus (van der Straten, Wiegmans, & Schelling, 2007). Therefore, this study is rather unique, in that it attempts to review the location problems of AFVs' refuelling stations in a comprehensive manner considering refuelling demand together. The results of this study are expected to help researchers efficiently set up their refuelling location problems and identify critical factors for seeking their solutions.

1.2. Study approach

The first step of this study is to identify literature relevant to AFV refuelling location problems. For this, three electronic databases – Web of Science Core Collection, SCOPUS and Transportation Research International Database – were searched, using the keywords of “alternative fuel vehicle”, respectively, combined with “refuelling”, “recharging” and “infrastructure”. The search was confined to the peer-reviewed articles which were published over the past 10 years (January 2006–March 2016) and written in English. Although conference papers and technical research reports can be surely good sources of knowledge about the topic, they were excluded because of the potential difficulty in tracing them (due to language issues and their voluminous work). Moreover, capturing the research trend was deemed to be fully possible with more than 150 articles that the search identified.

This study intends to review the approaches for locating AFVs’ refuelling stations and their real-world applications, paying more attention to problem definition and less attention to computational issues such as efficient solution methods. This intention excluded more than half of the initially selected articles from the review. Meanwhile, in spite of the literature search strategy, the initial review suggested that some older articles published before 2006 and some conference/technical papers that were heavily cited by the identified articles should be also examined. This approach was expected to reduce a possibility for this study to exclude the relevant work that is essential for the better understanding of the research trend.

2. Elements of refuelling station location problems

Some examples of the reviewed literature, in particular those with empirical applications, are illustrated in Table 1, revealing that alternative fuels considered in the literature are mostly battery-powered electric and hydrogen. Moreover, most recent studies tended to deal with EVs for their applications, although they pointed out that proposed approaches may be applicable to other types of AFVs with a limited driving range and insufficient refuelling infrastructure. This situation renders this study more or less focused on EVs among the AFVs.

The type of refuelling facilities is a factor that should be considered in location problems, which is particularly critical for EV charging infrastructure. In fact, EV chargers have three types from Level 1 to 3 depending on the level of voltage and current (Nie & Ghamami, 2013; Yilmaz & Krein, 2013). The Level 1 charging method typically requires long charging times – more than several hours – and was intended to be used at home or places where the vehicle can stay for an extended period of time. Meanwhile, the Level 3 chargers can deliver a power ranging between 50 and 100 kW, usually offering the possibility of charging less than one hour (Yilmaz & Krein, 2013). The charging time is likely to influence the location and amount of charging facilities as suggested in Wang (2007). The research, based on a simulation model locating recreation-oriented scooter recharging stations, concluded that a faster charging method would significantly reduce the number of recharging stations as well as cost for constructing the stations. However, it should be noted that the reduced number of charging stations does not always result in cost savings in particular when the faster charging facilities are expensive.

Table 1. Selected case studies for locating refuelling stations.

Literature	Refuelling facility	Alternative fuel vehicle	Charging demand	Approach for refuelling location decision	Studied area
Nicholas and Ogden (2006)	Hydrogen stations	Hydrogen vehicle	Population of the census tract (home-based refuelling)	p-median	Metropolitan areas in California, U.S.
Frick et al. (2007)	CNG filling stations	CNG vehicle	Estimated city-level CNG vehicle ownership	Social cost minimisation	Switzerland
Schwoon (2007)	Hydrogen stations	Hydrogen vehicle	Intercity trips estimated by gravity model	Considering driver and filling station owner behaviour	Trunk roads in Germany
Wang (2007)	Level 1	ES	Recreation trips with single tour path	Flow-based set covering model	Penghu Island in Taiwan
Lin et al. (2008)	Hydrogen stations	Hydrogen vehicle	Road-based VMT	Fuel-travel-back approach	Southern California, U.S.
Wang (2008)	BES	ES	Recreation trips with multiple tour path	Flow-based set covering model	Penghu Island in Taiwan
Kuby et al. (2009)	Hydrogen stations	Hydrogen vehicle	OD flows weighted by household income, car ownership and education	Flow-refuelling location model	Florida, U.S.
Wang and Lin (2009)	Fast chargers	Not specified	Intercity trips	Flow-based set covering model	Taiwan
Frade et al. (2011)	Slow charger	BEV	Census block or TAZ-based work and return home trips	Maximum set covering model	Neighbourhood with mixed land use, Lisbon, Portugal
Wang (2011)	Level 1	ES	Recreation trips with multiple tour path	Flow-based set covering model	Penghu Island, Taiwan
Chen et al. (2013)	Level 2	BEV	TAZ-level parking demand	p-median	Seattle metropolitan area, U.S.
Mak et al. (2013)	BES	BEV	Trips entering freeway with a Poisson process	Considering construction cost and return-on-investment	San Francisco Bay Area, U.S.
Nie and Ghamami (2013)	Level 1, 2, 3 and BES	BEV	Trips along a corridor (measured by vehicles per mile)	Social cost minimisation	A 150-mile intercity corridor
Sathaye and Kelley (2013)	Level 2	BEV	Traffic volume on the corridors and population and attraction sites in the study area	Minimising deviation along the corridor	Five highway corridors in Texas, U.S.
Xi et al. (2013)	Level 1, 2	BEV	Work, school, shopping trips/Tour-based vehicle trips	Maximum set covering model	Ohio, U.S.
Dong et al. (2014)	Level 1, 2, 3	BEV	445 GPS-equipped vehicles' daily trips	Minimising failures of refuelling	Seattle metropolitan area, U.S.
Jung et al. (2014)	Fast chargers/BES	Electric taxis	Stochastic taxi trip demand	Bi-level approach (Simulation and p-median)	Seoul, South Korea
Chung and Kwon (2015)	Fast chargers	BEV	Trips on highway/Multi-period demand	Multi-period flow-refuelling location model	Nationwide expressways, South Korea
Hwang et al. (2015)	LNG filling stations	LNG truck	Truck OD flows on a directed road network	Maximising covered traffic	Pennsylvania Turnpike, U.S.
Brey et al. (2016)	Hydrogen stations	Fuel cell car	Population and VKT aggregated by census track	p-median and maximal set covering	Seville, Spain
Tu et al. (2016)	Level 2	Electric taxis	Taxis' spatial and temporal demand	Maximise covered demand and minimise charging wait time	Shenzhen, China

Note: BEV, battery electric vehicle; CNG, compressed natural gas; BES, battery exchange station; ES, electric scooter and TAZ, traffic analysis zone.

Yilmaz and Krein (2013) reported that an installation of a Level 3 charger costs between \$30,000 and \$160,000 while the cost of a Level 2 charger lies between \$1000 and \$3000.

A consideration of trip characteristics such as travel distance, trip purpose and travel mode is also important for locating refuelling stations. The longer travel distance requires more visits to refuelling facilities although the frequency of the visit varies depending on the AFV's driving range. Trip purpose (e.g. tourism, shopping and commute) is strongly related to parking duration that can affect the decision on the type of refuelling facilities with different refuelling speeds. Unlike personal vehicles, commercial vehicles such as taxis and trucks may need different strategies for locating refuelling facilities. Erdoğan and Miller-Hooks (2012) pointed out that alternative refuelling stations for a fleet of commercial/service vehicles should be located so as to eliminate the risk of running out of fuel while maintaining low-cost routes. In addition, the different spatial coverage of the refuelling facility network requests different input data. For example, studies which attempted to plan a refuelling network on a highway corridor illustrated that simple origin–destination (OD) trips between highway entries/exits or link-based traffic volume data were enough for inputs of refuelling demand estimation (Hwang, Kweon, & Ventura, 2015; Nie & Ghamami, 2013). Meanwhile, spatial socio-economic information has often been applied when a whole city or region is the target area (Brey, Brey, Carazo, Ruiz-Montero, & Tejada, 2016; Chen, Kockelman, & Khan, 2013). Along with policy goals and planners' perspectives, a proper definition of such trip characteristics is expected to help analysts effectively to establish location modelling approaches. Indeed, Table 1 shows that a variety of modelling approaches have been applied reflecting the context of the problem.

Knowing where the potential refuelling demand exists is another issue since the refuelling stations located near high demand areas are more likely to be fully utilised and, at the same time, the total travel distance (weighted travel distance by demand) to the stations are minimised. The refuelling demand may be reasonably estimated considering traffic volume on roadways or parking demand of the area studied. Understanding parking activities, in particular parking duration, is crucial for determining the refuelling facility types such as slow or fast chargers as well as their locations (Chen et al., 2013; Ghamami, Nie, & Zockaie, 2016; Gimenez-Gaydou, Ribeiro, Gutierrez, & Antunes, 2016; Xi, Sioshansi, & Marano, 2013). Besides, it has long been understood that there are mutual interactions between AFV market and infrastructure supplies (Gnann & Plötz, 2015). This implies that understanding factors that affect AFV ownership is also crucial for properly establishing the location problems.

The review on elements of refuelling station location problems indicates that two aspects, location modelling approaches considering trip characteristics and refuelling demand estimation are major issues in the literature. In the following sections, these two issues are discussed in more detail.

3. Refuelling location model

3.1. Approaches for location model

The basic idea for determining refuelling locations is to minimise the associated cost (i.e. travel time or distance to refuelling locations) or maximise the demand served (ReVelle & Eiselt, 2005), as implemented in general location problems. Location problems can be roughly divided into four categories: set covering problem, maximum covering problem, *p*-centre problem and *p*-median problem (Daskin, 1995). Among these problems, *p*-median is the most commonly applied one in the literature (Upchurch & Kuby, 2010). A *p*-median problem is to locate *p* facilities and allocate each weighted demand point to its nearest facility to minimise the sum of travel costs (Daskin, 1995). The application of a *p*-median problem is observed in Chen et al. (2013), Jung et al. (2014), Ko and Shim (2016), Lin, Ogden, Fan, and Chen (2008) and Nicholas and Ogden (2006).

The other common model is the maximal covering problem, which seeks the maximum demand that can be served within a stated service distance (or time) given a limited number of refuelling facilities. The solution to this problem specifies both the largest amount of demand that can be covered and the *p* facilities that achieve maximum coverage (Church & ReVelle, 1974). The application of a maximal covering problem is observed in Frade, Ribeiro, Goncalves, and Antunes (2011) and Gimenez-Gaydou et al. (2016). The flow capturing location model (FCLM) and its variants, which will be explained in the next section, are also under this realm. Meanwhile, the application of set covering problem is observed in Wang and Lin (2009). He, Kuo, and Wu (2016) applied all the three location models – set covering, maximal covering and *p*-median models – for locating public EV charging stations in Beijing, China, comparing the performance of the three models. Based on the comparison, they argued that *p*-median solutions are more effective, in that the model locates charging stations near the communities with higher EV demand, thus higher degree of accessibility for most EV users.

Unlike the approaches above, some studies did not follow the approaches of general location problems. For example, Nie and Ghamami (2013) developed a model determining only the required number of EV charging facilities, evenly allocating the facilities over a corridor studied. In the case of Schwoon (2007), hydrogen refuelling stations were allocated over the German trunk road network, balancing the behaviours of driver and station owners. The driver behaviour includes possibilities of buying fuel cell vehicles, which is influenced by the density of hydrogen stations. Conversely, the density of hydrogen stations was assumed to be affected by the refuelling demand, so hydrogen station owners are to add an H_2-pump only when sufficient refuelling demand is observed.

3.2. Point- and flow-based models

Point-based models assume that refuelling demand can be located at nodes representing, for example, home or workplace. The approach usually takes into account the origins and destinations of the vehicle trips for the candidate refuelling locations rather than considering paths between ODs. Thus, the characteristics of the nodes, for example, their population size, number of jobs and penetration rate of AFVs, are critical elements for determining the location of refuelling stations. Parking activity is another important factor in the models, as parking demand can be easily converted to refuelling demand in particular for facilities requiring an extended time of recharging. For defining the characteristics of the node, researchers have used traffic analysis zone or census block for their geographic unit of analysis considering the data availability (Chen et al., 2013; Frade et al., 2011).

In contrast to one-dimensional point-based models, "flow-based" models consider two-dimensional flows, paths, or trips as refuelling demand. The FCLM, proposed by Hodgson

(1990), is the classical flow-based model. The model, a variant of a maximum covering problem, locates p facilities so as to intercept as many trips as possible. After Hodgson (1990), the FCLM was further developed and applied to various location problems (Zeng, Hodgson, & Castillo, 2008). Yet, the FCLM has a limitation to fully reflect the characteristics of AFVs, that is, the limited driving range, since it allows flows to be captured by a single facility anywhere along their paths regardless of trip distance. AFVs with a limited driving range need multiple stops for refuelling when their trip distances exceed their driving range.

Reflecting AFV's limited driving range, Kuby and Lim (2005) extended the FCLM by proposing a flow-refuelling location model (FRLM). In the FRLM, a flow is not considered captured (refuelled) unless it is possible to travel from the origin to the destination and back without running out of fuel, which, given AFV's limited driving range, may require multiple refuelling stations properly spaced along a covered OD flow path. To extend the FRLM, researchers proposed approaches to locating refuelling stations along arcs (Kuby & Lim, 2007) and allowing deviation from fixed routes or shortest paths (Kim & Kuby, 2012). The latter, named deviation-flow-refuelling location model (DFRLM), is meaningful, in that it attempts to reflect AFV drivers' willingness to deviate to a refuelling station off their pre-planned path. Such driver behaviour seems acceptable and realistic when a refuelling network is sparse, which may be often observed at the initial stage of AFV deployment. Recently, the DFRLM was enhanced for more applicability to larger networks (Yildiz, Arslan, & Karasan, 2016). Huang, Li, and Qian (2015) further applied the concept of deviation, allowing multiple paths including the shortest and deviation paths and seeking the locations that minimise the cost of refuelling stations. In addition, the FRLM was extended to reflect the gradual provision of charging infrastructure over time as formulated in Chung and Kwon (2015). The formulated model, named "multi-period flow-refuelling location model" (M-FRLM), was mainly based on the work of MirHassani and Ebrazi (2013) and applied to a nationwide expressway system, showing its validity. Furthermore, Li, Huang, and Mason (2016) demonstrated that both the concepts of multi-path and multi-period can be applied for determining the locations of public electric charging stations, and they named it M^2PRLM. Hwang et al. (2015) proposed another location problem considering separate refuelling stations serving each side of one-way motorways with limited access. The research was motivated by the fact that previous research considered only dual-access facilities usually located at interchanges. Researchers further attempted to improve the FRLM by mitigating computational issues and enhancing the flexibility of the model, expanding its applicability to a variety of situations, for example, with a larger network and multiple objectives (Capar & Kuby, 2012; Capar et al., 2013; MirHassani & Ebrazi, 2013). As another type of flow-based approach, Wang and Lin (2009) proposed a model following the concept of a set covering problem, relaxing the constraint of trip length under a vehicle range. The complete covering requirement is helpful, in that it allows the analyst to use the distance matrix of OD pairs instead of OD flow data or the spatial distribution of vehicle miles travelled (VMT) which are usually difficult to obtain. Figure 1 illustrates how the FRLM has evolved over time, incorporating various conditions in the decision process.

Upchurch and Kuby (2010) tested how well the facilities located by p-median or FRLM perform on the other's objective function (proportion of flow refuelled for FRLM; demand weighted distance for p-median), showing that the result of flow-based model is rather

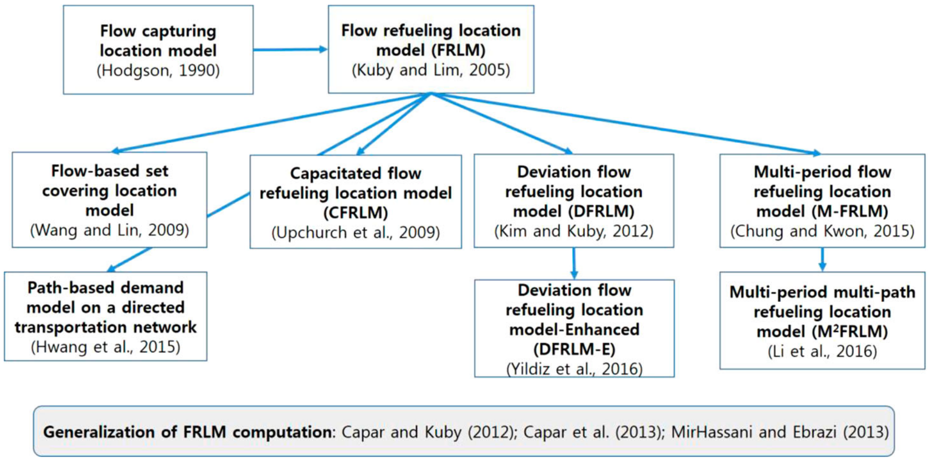

Figure 1. Evolvement of the FRLM.

more stable than that of point-based model. In particular, the FRLM was found to perform noticeably better for a larger geographic scale (i.e. state vs. metropolitan area). The researchers argued that the stability of the refuelling locations may be beneficial at the early stage of deployment since the selected (stable) locations are likely to remain good even when more stations are added.

In addition to point-based models such as the *p*-median and flow-based models such as the FRLM, researchers have recognised a third class of arc-based models. The arc-based models relate demand to arcs of the road network and assess their magnitude separately, with the number of stations along each arc being proportional to arc lengths and demand. Recent studies have further developed flow-based models towards tour-based ones, which can be considered a fourth category of refuelling location models. Indeed, Jung et al. (2014) proposed an itinerary-intercept model where refuelling is scheduled into a trip chain. This type of approach has a potential when detailed space–time vehicle activity data are available as shown in Dong, Liu, and Lin (2014), Tu et al. (2016) and Xi et al. (2013).

3.3. Model objectives and assumptions/constraints

3.3.1. Objectives

Approaches for deciding refuelling locations are mostly to minimise social costs represented by extra travel time for travelling to the nearest refuelling stations (Lin et al., 2008; Nicholas & Ogden, 2006) or construction cost for refuelling facilities (Nie & Ghamami, 2013; Wang & Lin, 2009). In other cases, the locations were determined so as to maximise the coverage of users (Gimenez-Gaydou et al., 2016; Xi et al., 2013) or to minimise the number of missed trips defined as the trip of which distance is longer than the remaining battery range (Frade et al., 2011). The FRLM by Kuby and Lim (2005) maximises covered vehicle trips by strategically locating a predefined number of stations in a network. Meanwhile, the capacitated FRLM (Upchurch, Kuby, & Lim, 2009) maximises VMT by adding a weight factor of the shortest distance between OD pairs, ensuring that longer trips have priority for refuelling. This approach may best reduce the use of traditional fuels since VMT is generally proportional to fuel consumption. Mak, Rong, and Shen (2013) proposed approaches with objectives from the perspective of battery-swapping service providers: (1) minimising costs associated with station construction and operations and (2) maximising the probability of meeting a target of return on investment.

Multi-objective location models can be beneficial when the location decision cannot be made by a single dominant factor. Wang and Wang (2010) developed a hybrid model with dual objectives simultaneously considering minimum station cost and maximum coverage, extending the work of Wang and Lin (2009). Similarly, Brey et al. (2016) proposed a location model with an objective function composed of two terms: (1) minimising the total distance from users' homes to the nearest station (*p*-median problem) and (2) maximising VMT within the range of each station. Capar and Kuby (2012) also showed that the FRLM can be generalised by incorporating a multi-objective model that combines the *p*-median or maximum covering model with the FRLM. Brey et al. (2016) illustrated that a driver preference survey can be applied for systematically constructing a trade-off curve that explains the relationship between two different objectives.

3.3.2. Assumptions/constraints

Most studies have assumed that refuelling stations have an unlimited capacity, thus no delay for charging service (Chen et al., 2013; Dong et al., 2014; Gimenez-Gaydou et al., 2016; Wang & Lin, 2009). The rationale of these uncapacitated refuelling stations is that at the early stage of AFV deployment, the shortage of refuelling capacity is unlikely to be observed because of insufficient demand. However, refuelling demand can be concentrated at particular stations even at the initial stage of AFV deployment depending on travel patterns, exceeding the refuelling capacity (in particular for slow charger stations). When a limited capacity is considered, queue delay should be regarded as a decisive factor (Bae & Kwasinski, 2012; Jung et al., 2014; Upchurch et al., 2009).

Another common assumption is that fuel would be consumed at a constant rate with travel distance regardless of driving and vehicle conditions (Wang & Lin, 2009). However, as found by Wu, Freese, Cabrera, and Kitch (2015) for the case of EVs, fuel efficiency may vary depending on driving conditions; driving on in-city routes are more efficient than driving on freeway routes. The opposite is generally true for gasoline-powered vehicles that do not have regenerative braking systems and are more efficient in a higher gear. In addition, an empirical study suggested that a battery discharge rate may vary depending on vehicle age: generally, a higher discharge rate for older cars (Tian et al., 2014). An initial charging (or tank level) strategy is another issue to be assumed. Researchers have assumed an initial full charge (Li et al., 2016; Wang & Lin, 2009; Wang & Wang, 2010), half full charge (Capar & Kuby, 2012; MirHassani & Ebrazi, 2013) or random one (Jung et al., 2014). A proper assumption, however, should be taken considering the context of the study condition; for example, if there is a refuelling station at the origin, the model may reasonably assume an initial full charge. This implies that, in particular for EVs, the issue of home charging that can complement public chargers should be taken into account for deciding charger locations and numbers.

A budget constraint is also often considered in various location problems (Dong et al., 2014; Gimenez-Gaydou et al., 2016; Mak et al., 2013; Xi et al., 2013) as well as in the FRLM and its variants. In this case, the budget controls the size (the number of refuelling stations) and composition (charger types) of a refuelling station network. If the refuelling station construction cost varies location by location, the budget constraint would significantly affect the decisions on refuelling station location. The assumption of the varying cost is found in the studies of Wang and Lin (2009) and Wang and Wang (2010). In addition, Capar et al. (2013) showed that an analysis without considering the varying cost may result in suboptimal solutions, advising infrastructure providers to properly take the cost and budget into account. The reviewed literature also shows that numerous assumptions have been taken for establishing efficient models and relaxed later for more flexibility and applicability: for example, multiple types of recharging stations rather than a single type in Wang and Lin (2013) and uncertain refuelling demand rather than fixed one in Hosseini and MirHassani (2015).

4. Refuelling demand estimation

4.1. Refuelling behaviour

Understanding driver's refuelling behaviour is the starting point of refuelling demand estimation. Such effort is found in Kitamura and Sperling's (1987) study, where a survey was addressed to more than 1500 drivers in northern California, U.S., asking where they refuel their cars. The survey revealed that most drivers prefer to refuel 5 minutes from their origin or destination and that they tend to refuel at the beginning of trips, inferring that drivers tend to refuel before making trips to less familiar areas. The researchers named it "risk-averse behaviour". Nicholas (2010) tested how gasoline consumption is related to population and traffic pattern. The research introduced a metric of "population-traffic", redistributed population from the population centre to a path from the population centre to the nearest highway entrance, identifying that it has a stronger correlation with gasoline consumption than population or traffic alone. This research effort illustrates that refuelling demand may be estimated by considering both population and traffic together.

An empirical study using a questionnaire-based survey was conducted to investigate refuelling patterns by comparing drivers of gasoline and CNG vehicles (Kuby, Kelley, & Schoenemann, 2013). At the time of study, only 60 CNG stations, representing only 0.02% of the 3200 gasoline stations in the region, were open to the general public. The survey found that CNG vehicle drivers more frequently fill their tanks and detour out of their way to refuel than gasoline vehicle drivers. Concerning the locations of AFV refuelling stations, the study concluded that refuelling stations should be located on the way to destinations or to freeway entrances rather than places close to home, suggesting that flow-based optimal location models would be appropriate at the early stage of AFV deployment. A similar research effort is observed in Kelley and Kuby (2013), where 259 drivers of CNG vehicles were interviewed in Southern California, U.S. in order to explore their refuelling behaviour. Focusing on whether the respondents select stations nearest to home or on routes that require the least deviation, the research concluded that it would be better for AFV refuelling stations to be located along frequently travelled paths of drivers, such as home–work commute routes. In contrast, a survey conducted in Seville, Spain in 2015 revealed that drivers were more willing to refuel close to origin or destination (57.0%) rather than on the way (28.5%). Other drivers (14.5%) responded that they would make special round trips to refuel depending on the characteristics of the stations (Brey et al., 2016). Martin, Shaheen, Lipman, and Lidicker (2009) also showed that Californian drivers were willing to travel 5–10 minutes to find a hydrogen station. To know at what tank level AFV drivers refuel is also important since it is able to provide insights into determining the distribution of refuelling stations. Kuby et al. (2013) found that CNG drivers tend to refuel with more left in their tanks than gasoline vehicle drivers.

As EVs become available, empirical studies concerning refuelling behaviour under real-world context have been conducted. Smart and Schey (2012) investigated EV's driving and charging behaviour using data collected from 2903 EVs under a demonstration, called "The EV project", operated in U.S. cities. The study reported that EV users started to recharge at a 20% or higher state of charge level and 82% of charging events were conducted at drivers' home. Similarly, Turrentine, Gosselin, Kurani, and Sperling (1992) suggested that EV users usually leave 20 miles as the spare range for a 100-mile range battery. Based on this finding, Nie and Ghamami (2013) used 80% as the parameter for tolerance range. Charging patterns of electric taxis are also interesting as shown in Tian et al. (2014), in which 600 EV taxis operated in Shenzhen, China were monitored using GPS devices. After comparing the EV taxis' operation patterns with conventional taxis', the study found that EV taxi drivers prefer to operate around the charge stations and to recharge during the time period with less passenger requests.

4.2. Alternative fuel vehicle ownership

It is plausible that the region with more potential AFV buyers requires more refuelling stations, and thus estimating AFV ownership has been a critical step in the process of refuelling demand identification (Frick, Axhausen, Carle, & Wokaun, 2007; Gimenez-Gaydou et al., 2016; Schwoon, 2007; Xi et al., 2013). In some cases, AFV ownership is simply estimated by multiplying an assumed AFV penetration rate and the number of cars operated in the area (Frade et al., 2011; Ghamami et al., 2016). However, the penetration rate is likely to be influenced by numerous factors. Studies have shown that some socio-economic factors such as education, income, gender, age and car ownership are related to the willingness to purchase or use environmentally friendly vehicles including AFVs (Campbell, Ryley, & Thring, 2012; Erdem, Şentürk, & Şimşek, 2010; Potoglou & Kanaroglou, 2007; Sangkapichai & Saphores, 2009; Skippon & Garwood, 2011; Williams & Kurani, 2006; Zhang, Yu, & Zou, 2011). Generally, studies indicate that people with college education, middle- and high-income groups and households with more than one car have a tendency to more easily accept AFVs (Gimenez-Gaydou et al., 2016). In addition, a longer commute distance might exert a negative impact on the preference for AFVs because of their limited fuel availability, as illustrated by a stated preference study conducted in a Canadian urban area, Hamilton in Ontario (Potoglou & Kanaroglou, 2007).

Policy incentives can also affect the AFV ownership, which has been often reported in the literature. For example, Kelley and Kuby (2013) reported that 63% of the survey respondents replied that their primary reason for owning a CNG vehicle is the unrestricted use of high occupancy vehicle (HOV) lanes. Similarly, Californians replied that an important reason for considering hybrid EVs is the possibility of using HOV lanes while driving alone, especially for people with potentially long commutes to work (Sangkapichai & Saphores, 2009). A survey conducted in Germany also demonstrated that such governmental incentives as vehicle tax exemptions, free parking and bus lane access could boost AFV ownership (Hackbarth & Madlener, 2016). The consideration of policy incentives may be important for determining the locations of refuelling stations when the policy actions are only limited to a specific area, for example, free or discounted downtown congestion charge for AFVs. A comprehensive review of consumer AFV adoption behaviour is found in Rezvani, Jansson, and Bodin (2015) and Zhang et al. (2011).

4.3. Demand estimation approaches

Refuelling demand estimation can be made in numerous ways. For example, mathematical models may be applied for the identification of a refuelling demand profile. The profile can provide useful information about the spatial and temporal distribution of fuel consumption demand, as illustrated by Bae and Kwasinski (2012). The study proposed a framework applying fluid traffic model and queuing theory for determining the location and size of refuelling stations with rapid EV chargers on a highway using traffic speed and volume. Real-world high-resolution vehicle operation data, which become more and more available in particular for commercial vehicles equipped with position tracking devices, can also provide information on potential refuelling demand. Tu et al. (2016) illustrated how such real-world data, obtained from one-week taxi operation database, can be applied to optimise electric taxi charging locations, considering both the spatial and temporal distribution of charging demand. Travel survey data would be another important source for estimating charging demand over space and time (Dong et al., 2014; Kang & Recker, 2009).

Such alternative vehicles as EVs may need several hours for recharging, depending on charger types. Therefore, drivers may prefer recharging their vehicles during parking at workplaces or shopping malls, implying that identifying locations of refuelling stations is closely associated with parking demand. This "parking-based" refuelling location problems are found in Chen et al. (2013), Ghamami et al. (2016) and Xi et al. (2013). In particular, Chen et al. (2013) proposed a stepwise model in which parking location and duration models were developed for the first step of a public charging location identification process. This "parking-based" approach is useful in particular for serving daytime refuelling demand (Frade et al., 2011). The daytime activities or trips considered in literature include work, shopping, university and tourism. Interestingly, the "parking-based" approach can be combined with the FRLM as illustrated by Wang and Lin (2013). In their model, the number and location of slow-refuelling stations for tourist attractions were determined based on the tourists' average length of stay at those attractions and complete refuelling at every stop was not assumed.

The most common approach to estimating refuelling demand is to use OD trips. In the approach, driving distances between OD pairs are usually estimated using shortest path algorithms and candidate locations for refueling are assumed to be at destinations or fixed facilities (Wang, 2007, 2008, 2011). The flow-based approach is another form of "OD-based" approach since it utilises OD trips for constructing paths along which candidate stations are located (mostly at nodes or arcs) (Kuby & Lim, 2007). However, constructing a flow-based model using OD trips is rather complicated and burdensome, in that it requires network flow data, which are not always easy to obtain, especially when the network's geographic coverage is wide. To mitigate this issue, an approach requiring only the distribution of VMT was proposed and applied for locating hydrogen stations (Lin et al., 2008). This VMT application, under a situation where OD trips were unavailable, is also found in Brey et al. (2016). In the study, researchers defined two concentric circles with different radii around each hydrogen station and considered the VMT within the circles, assigning higher weights to road segments in the inner circles.

Since the OD trips of AFVs may not be easily available, it has been simply assumed that the flow pattern of AFVs follows that of general traffic, and thus a homogeneous adoption rate was applied regardless of geographic areas where the OD trips depart or arrive (Chung & Kwon, 2015). Meanwhile, Kuby et al. (2009) applied heterogeneous adoption rates for hydrogen demand. In the study, each OD pair was assigned a different demand weight depending on residents' income, car ownership, commute distance and education.

In the approach proposed by He, Wu, Yin, and Guan (2013), the refuelling demand for plug-in hybrid EVs is somewhat differently defined. The approach adopted a destination route choice model for EV trips, assuming that the choice is affected by charging opportunity (measured by the number of charging facilities at the destination), charging expense and travel time. The charging expense or the price of electricity varied across locations, with the price being affected by charging demand and the electricity power network setting. Frick et al. (2007) assumed that CNG filling stations would have high refuelling demand when they are located near the region with good network connections to/from other regions and high car density. In addition, the study related the refuelling demand to station characteristics such as whether it has a shop and its operating hours.

Meanwhile, the demand estimation procedure in Jung et al. (2014) is somewhat unique, in that they consider the stochastic demand of shared EV taxis over time, producing a detailed demand profile for each charge station. In doing so, the research attempted to reflect the operational characteristics of a shared taxi dispatch system and evaluate the system performance. Another case considering the stochastic demand is observed in Hosseini and MirHassani (2015). Proposing a two-stage stochastic refuelling station location model, they first identified permanent refuelling stations based on deterministic demand and then sought the locations of portable stations from stochastic demand.

5. Conclusions

5.1. Future research directions

As more attention is given to AFVs due to their sustainability and environmentally friendliness, their refuelling infrastructure planning becomes an important topic in the field of transportation research. With an aim to identify future research agendas in the area, this study conducted a comprehensive literature review on approaches to locating AFV refuelling facilities. As a result, the review identified that numerous factors and issues affect decisions on locating refuelling stations as illustrated in Table 2.

The table shows that the issues can be classified into five categories: AFV type, refuelling facility type, demand estimation, location problem optimisation and spatial coverage. The first two categories are dependent on each other, but, for EV charging, the facility type can be independently determined considering vehicle trip characteristics such as trip distance and parking duration. Concerning the facility type, a number of proposed models appear to have already considered fast- and slow-refuelling methods together with

Table 2. Issues in the studies of locating refuelling stations.

	Facility type			Optimisation for location problems		
Type of AFV	Type	Capacity consideration	Refuelling demand estimation	Minimisation	Maximisation	Spatial coverage
• Electric cars (including scooter and taxi) • Hydrogen • CNG • LNG trucks	- Electric cars • Level 1 (Slow charger) • Level 2 (Standard charger) • Level 3 (fast charger) • Battery exchange station - Hydrogen station - CNG station - LNG station	• Capacitated • Uncapacitated	• Drivers' willingness to accept AFVs: income, education and car ownership, etc. • Travel distance • Trip purpose • Parking patterns and behaviour • Traffic volume • Vehicle miles travelled • Penetration rate of AFVs • Locations of attraction sites • Government incentives	• Travel time for refuelling • Facility construction cost • Unserved users • Delay in queue Constraints • Budget • Number of refuelling stations • Driving range (battery capacity) • Charging time • Predetermined candidate sites • Minimum service coverage • Construction cost for a refuelling station • Single-/multi-path for an OD pair • Initial fuel tank level	• Coverage of users	• Nationwide • Region • City • Multiple corridors • Single corridor

refuelling capacity. Thus, a major issue would be the reasonable setting of refuelling capacity, ensuring an adequate level of refuelling service in terms of wait time both during refuelling and in queue. In particular, by applying queuing theory and considering facility cost, the capacity constraint issue should be properly addressed when refuelling demand is expected to be overloaded for particular stations. In the near future, this capacity issue is likely to be critical as more AFVs, thus greater refuelling demand, are expected.

In addition, future studies are encouraged to explicitly consider roadway congestion effects. Congestion is likely to aggravate "range anxiety" in particular for AFVs with a limited driving range (i.e. EVs with a low-capacity battery) as congestion incurs more fuel consumption and unreliable travel times. Thus, on roadways with unstable traffic conditions, more refuelling stations should be located to support AFVs' reliable operations. Consequently, practices using simple travel distance or average travel time as a performance measure are less likely to be dependable when traffic congestion is unpredictable and severe. Congestion modelling procedures, therefore, will be imperative when developing more general and realistic models.

Some studies have applied multi-objective processes as a way to reflect the complicated decision-making mechanisms of AFV stakeholders: drivers (price and convenience), government agencies (budget and social benefits) and refuelling service providers (profitability). Future studies are expected to further develop and fine-tune the multi-objective approaches by generating Pareto-optimal trade-off curves that sufficiently represent real-world situations. For this, researchers need to identify the interactions among the objectives of interest for a better model formulation. In-depth interviews or surveys addressed to target stakeholders may be helpful for the identification.

More importantly, researchers need to recognise that a sound understanding of AFV driver behaviour is critical for properly designing a refuelling facility network. Concerning refuelling demand estimations, empirical evidence is still insufficient and thus the estimated demand is likely to inevitably retain substantial uncertainties. Even though some research attempted to incorporate the uncertainty into modelling processes (Hosseini & MirHassani, 2015; Sathaye & Kelley, 2013), the issue seems to still remain unsolved. In the near future, the uncertainty is expected to be alleviated when AFVs are often used as a mode of daily transportation and thus relevant data are easily available. Moreover, real-world vehicle operation data, as shown in Tu et al. (2016), will be a useful source for tracing AFVs' activities. It is suggested that based on such data, future studies should reveal the intricate AFV driver behaviour, answering the questions raised in the existing literature. The questions include AFV purchase likelihood, route deviation behaviour (e.g. how much deviation in terms of distance and time is acceptable), AFV trip purpose, and typical refuelling time and place. Researchers also need to empirically measure the convenience or inconvenience of users (e.g. distance to stations, wait time in queue and refuelling frequency). These efforts will surely enhance the understanding of AFV user behaviour, in turn substantially contributing to building well-framed location models. The development of an effective research framework, including data collection methods and analytical methodologies, is also a subject of future tasks.

Most studies have assumed that demand estimation processes are separate from the optimisation problem. However, it is likely that the presence of refuelling stations would impact demand (Sathaye & Kelley, 2013). This phenomenon was considered to some degree in the studies of He et al. (2013) and Schwoon (2007). However, most existing literature fails to reflect the mutual dependence between demand and refuelling facility provision, requiring a new type of modelling framework that is able to address the issue. The understanding of the mutual dependence may also guide government agencies to plan subsidies to generate public interest in purchasing AFVs before the market matures.

Finally, researchers need to capture potential changes induced by the wider diffusion of refuelling facilities. The changes may include decreasing concerns about refuelling. Actual users of AFVs tend to have less difficulty in finding refuelling stations than they thought prior to AFV purchase, resulting in different behavioural responses to refuelling by time. In fact, a survey result showed that concerns over refuelling availability diminished rapidly after about 10% of existing stations provided the alternative fuel (Nicholas, Handy, & Sperling, 2004). Thus, current modelling frameworks may not properly work once the refuelling facility diffusion reaches a certain level. Another potential change is the type of refuelling facility. Melaina and Bremson (2008) noted that "outlet" type refuelling facilities (e.g. a single charger for EVs) can be replaced by "station" type facilities developed based on business models (e.g. multiple chargers and retail stores), as observed in the history of gasoline retailing. Also, it is worthwhile to note the finding of Brey et al. (2016). They found based on a survey that some drivers tend to seriously consider the particular characteristics of refuelling stations such as price, fuel quality, or the existence of full service when choosing where to refuel. (In fact, Frick et al. (2007) reflected this tendency in their model.) This finding surprisingly implies that the current practice which assumes that AFV drivers will choose the refuelling stations located near their origins/destinations or "on the way" may not be always a perfect approach when various types of refuelling stations are introduced. Further research is required to incorporate potential future changes into location models as more refuelling facilities are provided.

5.2. Study limitations

The literature search results pointed out that the research in this field has flourished in recent years. This situation actually motivated this study, but, at the same time, imposed a challenge to covering a wide range of AFV refuelling issues by a single study. In fact, this study did not attempt to review in detail the issue of AFV routing that finds the shortest or optimal routes given the vehicle's driving range and refuelling station locations (Erdoğan & Miller-Hooks, 2012; Yildiz et al., 2016). Clustering refuelling facilities in a small geographic area is another issue not explicitly covered in this study. Locating clusters of facilities can be a reasonable strategy under particular situations: (1) AFV users are limited to a specific group during the early deployment, (2) the vehicle's driving range is short and (3) the number of stations to be located is small (Capar et al., 2013; Melaina & Bremson, 2008). In addition, computational issues in location models such as solution algorithms were excluded from the review regardless of their theoretical and practical importance. Considering that there is still much room for improvement in the area, future studies are expected to comprehensively examine the computational issues.

Lastly, it should be noted that the literature search method confining to peer-reviewed English journal papers might prevent this study from fully capturing various aspects of AFVs/refuelling stations. As a result, AFV types considered in the empirical studies were limited to mostly electric/hydrogen fuels and private vehicles rather than commercial ones. Besides, the method might exclude geographic information system-based location models, which are practically useful when relevant spatial data are available, as illustrated in Melendez and Milbrandt (2005).

Disclosure statement

No potential conflict of interest was reported by the authors.

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