Determining Hydrogen Filling Station Allocation Strategies in Tainan City, Taiwan

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Abstract: Hydrogen is considered as a potential energy form to replace gasoline in the future. Due to the high cost of hydrogen filling station (HFS) construction, to have an efficient HFS deployment in the initial phrase is essential. This study aimed at tackling this issue using Tainan City, Taiwan as an example. The P-median model was applied to minimize the total weighted driving time between 752 administrative neighborhoods and 167 candidate HFS sites. Accurate driving times were acquired from Google Maps. The origin-destination trip data extracted from the official household travel survey database were employed as weights to represent the uneven population distribution. The technique of Monte-Carlo simulation was used to search for the best HFS allocation strategies under different scenarios. This study demonstrates a powerful, flexible and efficient process to explore the tradeoffs between driving time and HFS numbers, and accordingly suggest the HFS deployment scenarios and strategies.

Keywords: Hydrogen Filling Station, Allocation, P-Median Model, Monte-Carlo Simulation, Google Map Distance Matrix API

1. INTRODUCTION

Hydrogen is considered a high-potential source of future energy. It is an environmentally-friendly energy to mitigate climate change as the burning process produces water only, no greenhouse and other harmful gases emitted. In addition, hydrogen fuel can be produced locally and from multiple sources, helping a country reduce its dependence on imported energies.

Following the trend of green energy, the automotive industry has developed several desirable replacements for gasoline vehicles. Among these replacements, hydrogen vehicles have advantages over other alternatives such as using less time to refuel and has longer distances driven on a single refueling. It offers a similar driving experience to that of the gasoline vehicle. Hence, this energy type has been attracting the attention all over the world.

However, to promote hydrogen energy, one of the major obstacles is the distribution of the fuel itself. As the cost of constructing a hydrogen filling station (HFS) is four times higher than the cost of constructing a gas filling station (GFS) (Yen, 2015), such a high cost cannot be balanced by its economic benefit in the initial phase of promotion. In addition, given that there are no adequate HFSs available initially, few customers would purchase hydrogen

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vehicles, which would, in turn, lead to a chicken and egg dilemma (Melaina, 2003). To solve this dilemma, an efficient deployment for HFSs in the initial phase is crucial.

In Taiwan, there is no existing HFS nowadays. The issue of HFSs allocation has not been investigated. It is unknown that how many of HFSs are needed, where they should be located, and what kind of policies need to be formulated. The present study aims to address these questions and hence these issues are considered: first, the efficient deployment of HFSs; secondly, construction of a HFS location model; and thirdly, development of future deployment strategies.

This paper is structured as follows: Section 2 reviews the regulations and allocation models for HFSs. Section 3 describes the methods used in this research, elaborating on the data collection techniques and the allocation methods. Section 4 presents the results and Section 5 presents the conclusion of this study.

2. LITERATURE REVIEW

This section discusses previous studies on regulations for HFSs in Taiwan, and location-allocation models.

2.1 Regulations for Hydrogen Filling Stations

HFSs are built in the same form as GFS in order to comply with safety regulations and to store a specific volume of hydrogen fuel. In Taiwan, regulations for HFSs have not be legislated. Hung and Huang (2016) analyzed the Building Act, Fire Services Act, management regulations, and safety regulations in Taiwan, Japan, and the United States. They indicated that “Regulations Governing the Gas Filling Station” in Taiwan are clear enough to be set as the frame of future HFS regulations, and suggested using “Regulations Governing the Gas Filling Station” as a foundation to legislate the regulations for HFS. In addition, from the experience in Japan, it is suggested that placing both hydrogen and gasoline filling equipment within a single station is permitted. (Yen, 2015).

Based on the above reviews, in the present study, HFS candidate sites were assumed to be upgraded from the existing GFSs. It was also assumed that the siting regulations for HFSs are the same as the regulations for GFSs. In Taiwan, all siting regulations for GFSs are listed in the “Enforcement Rules of Urban Planning Law Art,” “Regulations Governing the Gasoline Filling Station,” and “Regulations Governing the Gas Filling Station” (Ministry of Justice, 2016), which can be summarized as:

1) GFSs cannot be placed in residential areas in urban planning zones.
2) The maximum required area is 3000 m^2 and the minimum area is 300 m^2.
3) The breadth of the station should be more than 20 m.
4) The road to the main entrance should be more than 12 m wide.
5) Distances to schools, crossings, tunnels, and interchanges should exceed 100 m.

2.2 Hydrogen Filling Stations Allocation Model

An efficient deployment of HFS plays a key role in the initial phase of the promotion of hydrogen vehicles (Melaina, 2003). To formulate policies to introduce an efficient HFS network through policies, subsidies, and collaboration with private companies, allowing people to easily access the energy is of crucial importance in promoting hydrogen vehicles. Therefore, the efficient deployment of stations is the first step of the initial phase. To assist in

deployment, an HFS location-allocation model is needed. For policy purposes, this model should focus on public benefits and creating an accessible deployment of HFS.

Kitamura and Sperling (1987), and Greene (1998) have used consumer behavior surveys to estimate the necessary quantity of alternative fuel filling stations (AFFS). Their results showed that the baseline quantity of alternative energy station is around 10 - 20% of the existing GFSs. However, surveys cannot show specific AFFS locations on a real map. Other models are required to develop an AFFS network.

When choosing a GFS to refuel, people tend to go to a GFS in the vicinity of their workplaces or homes. Commuting drivers tend to disrupt their trips to refuel closer to their origins and destinations than in the middle of such trips (Kitamura and Sperling, 1987). While others suggested that people choose to go to a GFS on their way, rather than making a trip to refuel their vehicle (Upchurch and Kuby, 2010). Both concepts are reasonable and may describe driver refueling behavior.

A group of scholars applied the P-median model to deploy the optimal locations for HFSs. This model assumes that people choose GFSs around their workplaces or homes. The model aims at minimizing the weighted distance from customers to facilities. Nicholas *et al.* (2004) found that 18 - 30% of the existing GFSs is the critical number by which to achieve the accessibility to gasoline. Nicholas and Johnson (2005) compared the future HFS coverage between urban and rural areas by splitting their research area into urban and rural areas based on census data. The results showed that around 30% of urban GFSs and 57% of rural GFSs are required for the HFS service to meet a 90% satisfaction level compared to the existing GFSs. Nicholas and Ogden (2007) applied the model among four metropolitan areas in California, USA, and suggested that population density leads to different results among different cities. Denser regions require fewer HFSs compared to less dense regions. Lin *et al.* (2008) introduced the fuel travel-back approach in southern California, USA. The model used quantified vehicle-miles-traveled data to replace the population density as the weight. The result showed that only 18% of the existing GFSs is needed.

Another group of scholars posited that people refuel on their way rather than making a special trip for refueling. They introduced a series of flow-capturing location models to examine future AFFS deployment (Hodgson, 1990; Kuby and Lim, 2005; Upchurch et al., 2009). The model focused on capturing as much as traffic flow as the located stations could. Kuby and Lim (2005) modified the flow-capturing location model into the flow-refueling location model to consider a limited driving range for alternative fuel vehicles. This flow-refueling location model was designed to suit the geographical scale of the United States or intercity travel. Upchurch *et al.* (2009) introduced the capacitated-flow refueling location model by adding a capacity constraint on the number of vehicles refueled at each station. The model provides a more realistic scenario of refueling limitations. Kim and Kuby (2012) considered the possible situation where drivers might deviate to refuel by applying a deviation-flow refueling location model to make the flow-refueling location model a more precise model.

Upchurch and Kuby (2010) compared the results of the p-median model and the flow-refueling location model for locating HFSs. They could not conclude which model offered a better solution, but the flow-refueling location model provided a more behaviorally realistic basis. In addition, they also found that the difference of performances between the two models was small in high population density areas. The P-median model was more unstable when the number of stations increased because the model is less influenced by the need of exact locations. However, the P-median model has some benefits. First, stations can be sited at specific locations in the P-median model while they can be sited anywhere along a given path to capture flows in the flow-based model (Upchurch and Kuby, 2010). Secondly,

the P-median model has a simpler data requirement. Demographic data and road network information can be easily acquired in most countries, yet the O-D travel data are not (Upchurch and Kuby, 2010). Thirdly, using the P-median model by adding a constraint to the candidate stations with specific traffic volumes rules out the possibility of placing stations in the middle of nowhere (Melaina, 2003). Finally, the results of the P-median model can be easily understood by people. A recognizable figure helps policymaker understand the effects of promoting alternative energy, and also helps citizens compare the refueling experiences between using gasoline and new fuel. The concept of minimum driving time is similar to maximum public benefits, with the purpose of allocating AFFSs in the initial promotion phase.

In the present study, the P-median model was applied to allocate future HFS locations. Despite the fact that both models can provide future HFS distribution scenarios, the flow-location models were restricted by their data requirements. Fewer cities in Taiwan have completed O-D travel surveys, which indicates the limitation of the flow-location models on future applications. In addition to the data requirement, Taiwan is a densely populated country. The population density gap between urban and suburban areas is not as huge as that of the United States. In addition, daily driving distance in Taiwan is shorter than that in the United States. Shorter commute routes and more compact development leads to traffic flow dispersion and in turn increases the difficulties related to applying the flow-location models. Besides, to maximize public benefits, the P-median model can serve a more persuasive point of view. It could provide quantifiable, understandable results for policy purposes.

3. METHODS

Based on the assumptions and problems stated in Section 2, an HFS location-allocation model was developed to create efficient HFS deployment. The design of the P-median model and the construction of the calculation process are discussed in this section.

3.1 Study Area and Data Collection

Tainan city, Taiwan was chosen as the study area. Tainan city encompasses an area of 2,191 km^2 and has 752 administrative neighborhoods (ANs). There were 168 GFSs within the Tainan city on 25th May 2016, in which 167 were candidate HFSs, filtered by the regulations mentioned in Subsection 2.1 by using the official land use investigation data through the calculation of a Geographical Information System (GIS).

The Google Map distance matrix API (Application Programming Interface) service was applied to acquire accurate driving time estimation based on its comprehensive recommended routes as compared to the conventional shortest route method (Google Developers, 2017). Driving time from every HFS candidate site to every administrative neighborhood center was acquired using the Google Map Distance Matrix API. The present study developed a program written in Python to send requests to Google Maps. Each request was composed of the parameters such as origins, destinations, and optional parameters, e.g. travel mode, arrival time, and transit routing preference. All the optional parameters were set as defaults. A total of 125,584 requests that consisted of data from 167 candidate HFS locations to 752 ANs were sent and the driving time for each pair were acquired.

3.2 The Weight of the P-Median Model

A weight was applied to represent the uneven population distribution in the P-median model. Conventionally, studies might apply the population or the number of households as the weight. In this study, the activity level was applied to describe how many auto trips were generated or finished in a given administrative neighborhood. Some areas, such as science parks and industrial areas, attract trips during the daytime, but there are very few dwelling houses. The conventional weights therefore cannot reflect such work-based trips as people tend to refuel near their home, workplace, and activity locations (Kitamura and Sperling, 1987). To describe the spatial distribution of auto trips more precisely, the number of auto trips from or to an administrative neighborhood was applied to represent the activity level. The auto trip data were acquired from the official household travel survey database (The Third Approach Management Consultants, 2011). The driving time matrix and the weighted driving time matrix of 167 HFS candidate sites by 752 ANs were calculated.

3.3 The Monte-Carlo Simulation

A Monte-Carlo simulation was introduced to approach the minimal weighted driving time for the P-median model. The Monte-Carlo simulation is often applied to generate random sampling to approximate the optimized results or to calculate a probability distribution or numerical integration problem using a computer. Despite the fact that the Monte-Carlo simulation might not calculate the optimized result, this method was chosen because of its time efficiency and flexibility.

In the present study, a program written in Java was used to run the Monte-Carlo simulation. The program is able to generate several million random sets of HFS candidate combinations according to the given constraints or scenarios, and then, to calculate their weighted driving time between these HFS candidate sites and the ANs to approximate the best solution. In comparison with the conventional approach, which has to solve the optimization problem using mathematical or statistical techniques, the Monte-Carlo method offers a more efficient and flexible way to approach the solutions.

4. Results

4.1 The Number of HFS Deployment and the Utility Curve

The model calculated all the optimized approach results for a different designated number of HFS deployment. Some of the key numbers are shown in Table 1. In the scenario of designated only one HFS, people take an average of 19.1 minutes to go from their homes to this HFS. When 10% of the current GFSs are upgraded, i.e. 17 HFSs deployment, the average driving time to get to the nearest HFS drops dramatically to 7.2 minutes. , as compared to the time required to get to the nearest GFS. When 20% of the current GFSs are upgraded, i.e. 34 HFSs deployment, the average driving time drops to 5.7 minutes. The marginal effect of deploying a HFS shrinks as the number of HFS deployment increases. In the scenario of upgrading all the current 167 GFSs to HFSs, the average driving time drops to 3.7 minutes, which is the approximate level of service of current 168 GFSs. By listing all the scenarios of HFS deployment numbers, a utility curves of optimized results is found, as shown in Figure 1.

Studies in the literature have shown that 10-30% of GFS upgrades is vital to HFS deployment. However, the information provided in the literature is insufficient for supporting

policy decisions. The results of the present study reveal the relation between driving time and the number of HFS deployment. In the case of Tainan City, the utility curve in Figure 1 shows that the marginal effect shrinks after around 20% of GFS upgrades (34 HFS deployment). The average driving is an acceptable 5.7 minutes. This provides information for policy making.

Table 1. Optimized average driving time

HFS deployment		Average driving time (min)
No.	(%)	
1	1	19.1
3	2	13.6
5	3	11.5
7	4	9.9
9	5	8.9
17	10	7.2
34	20	5.7
50	30	5.1
75	45	4.5
100	60	4.2
125	75	4.0
150	90	3.7
167	100	3.7

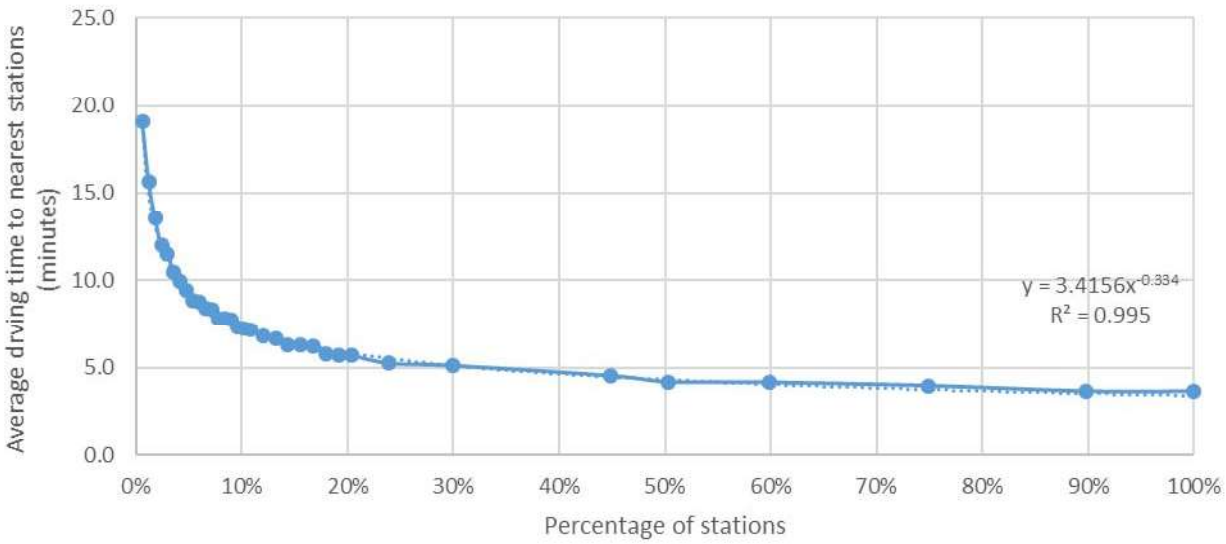

Figure 1. The utility curve of driving time and HFS deployment percentage

4.2 Decision Making under Constraints

One of the advantage of the procedure proposed in the present study is its flexibility. The Monte-Carlo simulation is a powerful tool for testing scenarios. Programming for altering scenarios is straightforward and no complicated mathematical and statistical techniques are needed, this makes the updates of candidate HFS sites and constraints easily when simulating different scenarios based on different requirements. The whole procedure gives flexibility for future applications and creates future scenarios conveniently.

Figure 2 demonstrates a scenario of decision making under given constraints. In phase 1,

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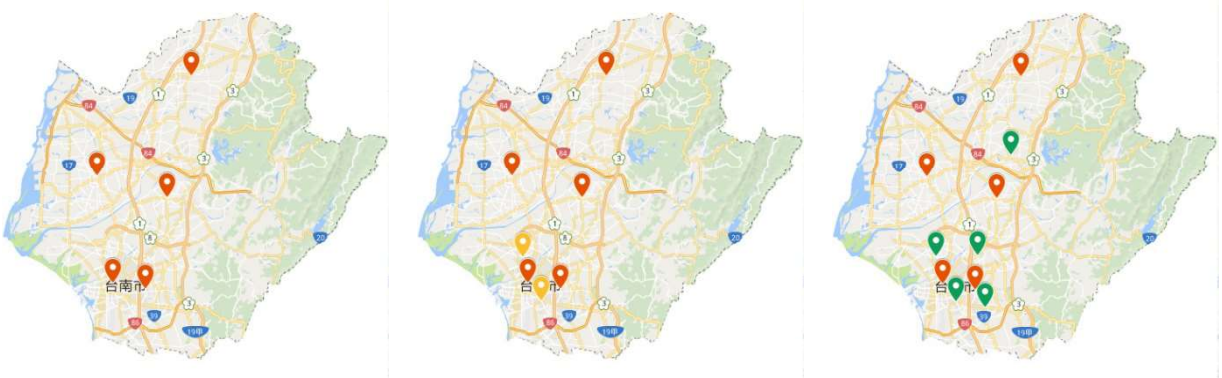
a given condition is that the private sector builds five HFSs based on entrepreneurial approach. In phase 2, the municipal government would like to promote hydrogen energy with limited budget, adding two HFSs based on public benefits. In phase 3, another three HFSs are added by the government based on public benefits. The procedure proposed in the present study has the flexibility to deal with the challenge of optimal deployment strategy for later phases under the given constraints in the previous phases.



Phase 1: the given 5 HFSs built by private entrepreneurship

Phase 2: optimized allocation of 2 HFSs, added according to public benefits

Phase 3: optimized allocation of another 3 HFSs, added according to public benefits

Figure 2. Demonstration of decision making for HFS deployment

4.3 Participation of Players in the Initial Phase of Promotion

In Taiwan, there are two major companies processing and offering gasoline: the CPC Corporation and the Formosa Petrochemical Corporation. Most GFSs belong to these two companies directly or are franchised. The CPC Corporation, which is a government-owned business, is the most likely to be designated for promoting hydrogen energy in the future.

There is currently a total of 56 CPC direct operating stations in Tainan City. More than half of these (33 stations) are located within the downtown areas. Some GFSs are deployed to remote areas to serve rural citizens.

This scenario assumes that only the CPC Corporation participates in the initial phase of promotion, i.e. only the CPC direct operating stations are listed as the HFS candidate sites. The deployment efficiency loss of such scenario was tested. The results are shown in Figure 3. The difference line (grey line) indicates the percentage of the difference between the CPC scenario and the optimized scenario. When less than 10 stations are allocated, the gap between these two scenarios is smaller than 10%. Yet when more than 10 GFSs offer hydrogen filling services, the gap becomes larger. The difference is around 20% with 20 HFSs, reaching a maximum of 28% when around 41 HFSs are built. This test shows the efficiency loss when a part of the potential HFS sites does not participate in the initial phase of promotion.

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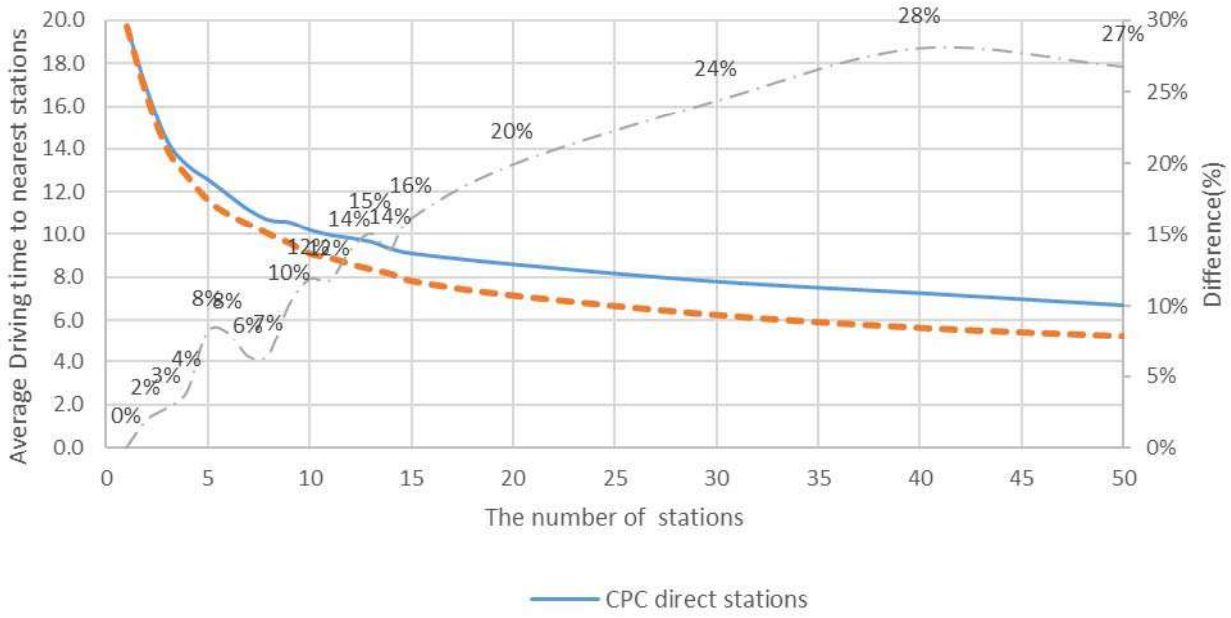

Figure 3. The CPC direct operating station scenario

5. Conclusion

To promote alternative energies for vehicles, an efficient deployment of HFS is needed. The present study aimed at constructing a suitable model to create an efficient HFS network. The P-median model was applied by using accurate driving times acquired from the Google Map Distance Matrix API as the main variable. The origin-destination trip data extracted from the official household travel survey database were employed as weights to represent the uneven population distribution. To create flexible scenarios, a Monte-Carlo simulation was applied to effectively evaluate the results.

The procedure proposed in the present study is powerful and flexible in terms of developing optimal allocation strategy. It is of crucial importance in the promotion of clean energy and policy making. This procedure is able to search for the best allocation strategies under different scenarios of HFS deployments. One of the main contributions is to reveal the relationship between driving time and the number of HFSs, i.e. the utility curve. The marginal effect shrinks after around 20% of GFS upgrades (34 HFS deployment). In addition, this paper demonstrates the flexibility of the proposed procedure in decision making under different phases of constraints, and the capability of evaluating the efficiency loss when a part of the potential HFS sites does not participate in the initial phase of promotion.

Future studies may investigate drivers' refueling behavior to determine the most acceptable driving time. Hence, the critical number of HFSs at the initial phase can be decided.

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