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Incorporating refuelling behaviour and drivers' preferences in the design of alternative fuels infrastructure in a city

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ABSTRACT

The purpose of this article is to present an optimization model to plan the deployment strategy for hydrogen refuelling stations in a city when Origin–Destination (OD) data are not available. This model considers two objectives: to maximize the traffic covered by the selected hydrogen refuelling stations and minimize the average distance of the city's inhabitants to the nearest hydrogen refuelling station. As OD data are assumed to be unavailable, the clustering of stations in the highest traffic zones is prevented by a new constraint that takes into account information on the distribution of existing conventional refuelling stations. This model is applied to Seville, a city in Southern Spain of about 140 km^2 with a population of around 700,000. This application uses the results of a survey of more than 200 Sevillian drivers on their current refuelling tendencies, their willingness to use alternative fuel vehicles and their minimum requirements (regarding maximum distance to be travelled to refuel and number of stations in the city) when establishing a network of alternative refuelling stations.

1. Introduction

So far the transportation energy system has been based mainly on the use of fossil fuels. However, the pressing environmental problems involved in the production, transport and use of these fuels, the increasing energy demand, and the need for countries to improve energy security and reduce dependence on foreign energy sources are leading countries to promote the use of alternative fuels in the transport sector (see, for example, European Commission, 2011).

Some of these alternative fuels are produced domestically; some of are obtained from renewable sources. In most cases, they are less polluting than fossil fuels. In spite of these advantages, the market penetration of vehicles powered by these fuels has been slow because their performance (in terms of speed, range, refuelling time, acceleration, etc.) was globally worse than that of fossil fuel vehicles and because their costs (vehicle and fuel costs) were usually much higher (Brey et al., 2007).

However, the size of this technological gap and cost differences is becoming increasingly smaller, and it is only to be expected that alternative fuel vehicles (AFVs) will soon be serious competitors of conventional vehicles. A good example of this is the Toyota FCV Mirai (Toyota, 2014), a produced in series fuel cell vehicle, launched in 2014 by Toyota. Its perfor-

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mance is on a par with that of conventional fossil fuel vehicles: more than 650 km autonomy, 175 km/h maximum speed, and full tank refuelling in less than 3 min. It can be leased for less than 500 USD a month, and this is within the price range of conventional sedans and the hydrogen price per km is analogue to that of conventional fuels.

However, there are still other factors that hamper the use of AFVs. One of the most important is fuel availability (Sperling and Kitamura, 1986; Melendez, 2006; Shin et al., 2015). Potential buyers are reluctant to buy AFVs if they feel they could face a relatively high risk of running out of fuel some distance from a refuelling station (Achtnicht et al., 2012). This is not only a matter of number of refuelling stations; their geographical location is also very important, especially if the high costs associated with the deployment of alternative fuels infrastructure are to be minimized.

Both key factors in the design of an alternative refuelling station network (number and location of refuelling stations) should be influenced, to a greater or lesser extent, by drivers' preferences. Drivers must feel comfortable regarding the number of available refuelling stations. Network design should respond to the refuelling behaviour of potential early adopters in the first stages of the alternative infrastructure deployment, and converge to general drivers' refuelling behaviour in the final stages.

Literature on AFV drivers' choices of refuelling locations is rather limited. Most of these papers focus on plug-in electric vehicles; however, the longer refuelling time required by this technology makes it difficult to extrapolate these studies to other (alternative) fuels with a refuelling time similar to that of conventional vehicles (Kelley and Kuby, 2013). This paper will consider the case of fuel cell vehicles (a fast refuelling technology), although the results obtained in this paper could be easily extrapolated to any other fast refuelling technology of similar performance.

Sperling and Kitamura (1986) and Kitamura and Sperling (1987) carried out two surveys with revealed and stated questions in California: a larger survey of 1528 drivers of gasoline vehicles and a smaller survey of 107 drivers of diesel vehicles, which was treated as a proxy for potential AFV drivers. They found that stated convenience to work, home and school was the primary reason for selecting a refuelling station in 56% of the cases for diesel vehicle drivers, compared to the 29% for gasoline vehicle drivers. Anyway, proximity is also important for the larger sample, since in this sample they found that 71.9% of refuelling locations are less than 5 min from their origin or destination, whereas around 60% of trips take 15 min or longer. Since in their sample most trips involving refuelling originate or terminate at home or workplace, these authors state that it is not surprising that location of refuelling choices tends to be close to home or the workplace. Moreover, these authors point out that a diesel network 10% the size of the gasoline network should be more than enough.

Instead, Nicholas (2010) found that the volume of gasoline dispensed in an area of California was most correlated with the vehicle-kilometres travelled than with population. Kelley and Kuby (2013), using a revealed preference survey of 259 drivers of compressed natural gas (CNG) vehicles at five CNG stations in Southern California, concluded that early infrastructure should focus on high-volume commuting routes, regardless of proximity to home locations.

All this previous research was focused mainly in the US. However, drivers refuelling behaviour varies between countries since it is contingent on many factors such as country's size, population distribution, road infrastructure, cultural background and socioeconomic factors. In Netherlands, Bunzeck et al. (2010) carried out a survey of 12 revealed and stated questions to 2970 respondents. In their survey, almost 75% of drivers stated that they refuel just after leaving home on the way to their destination or vice versa (that is, shortly after leaving a point of departure), almost 20% make a round trip to refuel, and 58% of the drivers refuel their car within 5 min of their origin. Their survey thus indicates that is rather unusual to refuel halfway.

These different refuelling behaviours can be modelled by means of different models (Kelley and Kuby, 2013). Point-based models (ReVelle and Swain, 1970; Church and ReVelle, 1974; Wang, 2007; Lin et al., 2008) locate facilities considering distance to demand nodes. These types of models would be more appropriate if AFV drivers show preferences for refuelling close to their origin or destination (home, workplace, etc.) instead of on their way. By contrast, flow-based models (Hodgson, 1990; Kuby and Lim, 2005; Kuby et al., 2009; Zeng et al., 2010; Wang and Wang, 2010; Kim and Kuby, 2012; Capar et al., 2013; You and Hsieh, 2014; Riemann et al., 2015) locate facilities considering the flow within the network arcs. These models typically make use of Origin–Destination (OD) data. They are more suitable to model cases where drivers refuel en route between origin and destination regardless of proximity to origin or destination. Hodgson and Rosing (1992) integrate both approaches (proximity to home and traffic flows) into a single model by assigning weights to each objective and assuming knowledge of the OD matrix. These authors apply their model to a simulated case for a generic type of facility.

This paper aims to contribute to the literature on the deployment of AFV infrastructure and drivers' preferences. This paper is organised as follows. Section 2 presents a model to locate AFV refuelling stations in a city based on the Hodgson and Rosing model, but adapted to the case where OD data is not available. The case of a city is considered in this paper because Directive 2014/94/EU on the deployment of alternative fuels infrastructure of the European Union (European Commission, 2014) points out the importance of the deployment of an adequate AFV infrastructure in urban agglomerations in order to achieve a higher penetration market of AFVs. This paper considers the case of fuel cell vehicles (FCVs), since, as previously mentioned, this technology is expected to become a serious competitor of conventional vehicles in the medium term. However, this model could be similarly applied to any AFV of similar characteristics.

In Section 3, the proposed model is applied to the case of Seville, one of the most populated cities of Spain. This application benefits from a survey aimed at obtaining information about Sevillians refuelling behaviour and their preferences as to some key aspects on the design of an AFV infrastructure. Section 4 presents the results and discussion. Finally, Section 5 contains the conclusions.