Appendix I: A Literature Review of Factors Determining Siting of Hydrogen Fueling Stations

The absence of Hydrogen infrastructure in terms of Hydrogen storage, distribution and refueling capacities had been a significant barrier to the large-scale entry of hydrogen fuel cell vehicles (HFCVs) in the market and their on-road deployment. Some countries, including the U.S., U.K., Germany, Norway and Canada, have launched initiatives to develop hydrogen refueling facilities on expressways (He *et al.*, 2017). The demonstration projects were unable to increase the rate of hydrogen vehicle adoption because the high rates of hydrogen production and resultant high cost of HFCVs remained economically unfeasible for most parties. Site selection and design of hydrogen refueling plants could reduce hydrogen delivery costs per HFCV, therefore being an important criterion for selection. Future initiatives need to focus attention on deriving maximum value from investments made to meet the capital and operation costs for refueling stations (He *et al.*, 2017).

The California Hydrogen Highway Project was a government-sponsored project dedicated to the development of Hydrogen infrastructure to support the on-road deployment of HFCVs (California Energy Commission, 2010). Locations for refueling stations was an important component of the project to ensure that HFCV deployment could occur over an extended range. The refueling stations were initially clustered around the deployment zone (California Air Resources Board, 2008).

The station capacity, which was governed by daily fuel dispensation rate (kg/day), remains a critical characterization parameter for refueling stations. In order to account for the heightened traffic during daylight hours, which lead to underutilization and longer wait times, SAE came up with a modified dispensation rate in terms of peak kg/hour to characterize the refueling stations (Society of Automotive Engineers, 2009).

Brown *et al*. (2012) analyzed the operational parameters of a hydrogen refueling station, established as part of the California Hydrogen Initiative. This station had dual dispensing pressures (35 and 70 MPa) and an extended storage capacity. Due to an increased demand for refueling, this station had operated significantly above its design capacity with a long wait time. Despite the station remaining open for 24 hours, the refueling was concentrated during waking hours. The hydrogen, delivered in a liquid state, was stored in three storage tubes capable of storing a total of 52 kg hydrogen at 54 MPa by means of a compressor. For refueling 35 MPa vehicles, hydrogen was first dispensed from the lowest pressure storage tubes while the higher-pressure tubes came into operation once the pressure in the vehicle tank equalizes the pressure in the low-pressure storage tube. The refuelling of higher capacity vehicles having 70 MPa capacity required the existing low-pressure storage tube at 54 MPa to be further pressurized to 80 MPa by means of a reciprocating pump (Brown *et al*., 2012). The high-pressure compression requires that additional heat dissipation equipment be encompassed in the infrastructural needs.

Enhanced operation of the hydrogen refueling station during certain hours of the 24-hour operation causes the consumption rate to be higher than the average (2 kg/hr), resulting in a shortage of hydrogen. The main constraints to increasing the hydrogen dispensation included the type, rate and scheduling of filling events. Long waiting times and inadequate filling due to low pressure were key issues faced by both the 35 MPa and 70 MPa capacity vehicles. There was an additional requirement of pre-cooling for the 70 MPa capacity vehicle. Higher

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temperatures from the combination of ambient and high-pressure dispensing resulted in an automatic cut-off of dispensing until the temperature cooled down (Brown *et al.*, 2012).

A behavioural trend was observed, whereby 70 MPa capacity vehicle owners opted for lower range 35 MPa to avoid longer waiting times. From 2007-2011, there was an increase in the total hydrogen dispersed per year, average hydrogen dispersed per day, average hydrogen per fill and maximum hydrogen dispensed in one day. It was also observed that the nominal design dispensing capacity of 25 kg/day (based on compressor capacity of 2 kg/hour with 50% duty cycle) was exceeded for 40% of the working days in 2011. Various physical processes, such as compression, refrigeration, dispensing, control systems and lighting, utilized electric energy at an almost linear rate of 5.18 kWh per kg of hydrogen dispensed. In terms of the power requirements, 35 MPa and 70 MPa refilling leads to a peak load of 12 kW and 30-35 kW, respectively (Brown *et al.*, 2012).

Melaina (2003) highlighted the key underlying factors which have remained instrumental in determining the location of refueling stations: 1) proximity to regions with high traffic volume; 2) ease of accessibility to potential first HFCV buyers; 3) ability to fuel vehicles for long distance trips; and 4) proximity to high profile areas to increase public awareness. This work demarcated the hydrogen fuel refueling stations into metropolitan oriented or interstate oriented with the realization that the metropolitan oriented stations would be the “prime” stations while the interstate oriented stations would be “placeholder” stations, ensuring hydrogen availability for rare events or long-distance trips (Melaina, 2003).

This work chronologically divided the hydrogen vehicle adoption process into two stages - the first involved the installation of enough refueling stations to support environmentally sensitive individuals adopting HFCV, and the later stage involved the installation of a larger number of refuelling stations to cater to the general public. A phased increase in the production volumes of HFCV is expected, to match the predicted high sales when Phase 2 arrives (Melaina, 2003).

Ni *et al.* (2005) utilized population density, car ownership, market penetration rate, and fuel use from GIS maps to estimate hydrogen demand. A clusterization approach is utilized to demarcate areas with demand density greater than a given threshold, to represent regions of high hydrogen demand (Ni *et al.*, 2005). Melendez & Milibrandt (2005) also planned a network of hydrogen refueling stations on highways to enable interstate travel based on HFCVs. This was achieved by estimating the HFCV demand and the corresponding hydrogen refueling station requirement through literature review and through interviews with experts. Various parameters were evaluated to gauge consumer’s potential interest in buying a HFCV and were assigned weights to account for consumer’s preferences. The sum total of all weights is considered a measure of consumer’s potential interest (Melendez & Milibrandt, 2005). This technique, involving the division of geographical area into distinct entities while ensuring equal distribution of households followed by quantifying relevant numerical or behavioral parameters for assessment, has been utilized in further studies (Greene *et al*., 2008; Kuby *et al*., 2009).

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