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Optimization of hydrogen stations in Florida using the Flow-Refueling Location Model

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ABSTRACT

This paper develops and applies a model that locates hydrogen stations to refuel the maximum volume of vehicle flows. Inputs to the model include a road network with average speeds; the origin–destination flow volumes between each origin and destination; a maximum driving range between refueling stops; and the number of stations to build. The Flow-Refueling Location Model maximizes the flow volumes that can be refueled, measured either in number of trips or vehicle-miles traveled. Geographic Information Systems and heuristic algorithms are integrated in a spatial decision support system that researchers can use to develop data, enter assumptions, analyze scenarios, evaluate tradeoffs, and map results. For the Florida Hydrogen Initiative, we used this model to investigate strategies for rolling out an initial refueling infrastructure in Florida at two different scales of analysis: metropolitan Orlando and statewide. By analyzing a variety of scenarios at both scales of analysis, we identify a robust set of stations that perform well under a variety of assumptions, and develop a strategy for phasing in clustered and connecting stations in several stages or tiers.

1. Introduction

Many studies have highlighted refueling infrastructure as one of the most formidable barriers to the transition to a hydrogen-based road transportation system [1–4]. Given the high cost of building new fueling stations, it is essential to coordinate the locations of the initial stations in a network that facilitates the maximum utilization by consumers. Numerous models have been proposed to optimize a network of fueling stations [5–16]. This paper uses one such model, the Flow-Refueling Location Model developed by Kuby and Lim, to plan how to phase in a network of refueling stations for intra-city trips in the Orlando metropolitan area and for statewide intercity travel across Florida.

This research was conducted for the Florida Hydrogen Initiative, Inc. (FHI), a non-profit organization established to aid the development of a robust hydrogen industry in Florida. In addition to optimizing a station network, our project for FHI analyzed the feasibility of a hydrogen rental-car business based at the Orlando International Airport (OIA) [17,18]. The rental car analysis is closely related to the station analysis because most car renters in Orlando visit only a small handful of destinations,

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Nomenclature

CNG	compressed natural gas
FCLM	Flow-Capturing Location Model
FDOT	Florida Department of Transportation
FHI	Florida Hydrogen Initiative
FRLM	Flow-Refueling Location Model
GIS	Geographic Information System
MILP	mixed-integer linear program
NREL	National Renewable Energy Laboratory
OD	origin-destination
OIA	Orlando International Airport
OR	operations research
SDSS	spatial decision support system
TAZ	traffic analysis zone
VMT	vehicle-miles traveled

making it possible for a small number of refueling stations to meet the needs of most rental car customers.

Section 2 of this paper reviews other efforts underway worldwide to develop initial networks—consisting of clusters or corridors—of hydrogen refueling stations. Section 3 reviews the literature on approaches to planning and modeling the best locations for a network of refueling stations. Section 4 introduces our approach using the Flow-Refueling Location Model (FRLM) to optimize and compare various strategies for developing an initial hydrogen-refueling infrastructure for Florida. The model uses operations research (OR) and Geographic Information System (GIS) techniques, along with sophisticated and detailed transport databases, to locate a coordinated set of stations. The model maximizes the potential for consumers to refuel as many trips (or, alternatively, vehicle-miles traveled) as possible. Section 5 describes the data used. We then apply the model to a number of scenarios for the statewide network (Section 6) and the Orlando area (Section 7). In Section 8, we synthesize the two sets of scenarios with findings from our companion study of a hydrogen rental-car business in Florida to develop a strategy for phasing in a network of refueling stations. This strategy prioritizes and coordinates station development in Orlando and statewide into several tiers or stages. Section 9 offers some brief conclusions.

The emphasis in this paper is on developing a coordinated system of multiple stations, rather than choosing suitable parcels of land for particular station sites. Site criteria have been studied elsewhere, and include accessibility, traffic, fleet operations, safety, host partners' experience with gaseous fuels, hydrogen supply, adequate space, logistical factors, energy sources, and zoning [19].

2. Hydrogen refueling infrastructure developments

Many regions in the US and around the world have begun planning and deploying initial networks of hydrogen refueling stations in order to break the well-known chicken-and-egg cycle. As of June 2008, there were an estimated 172 stations worldwide, with 37% in the US, 15% in Germany, and 13% in Japan [20]. By the end of 2008, the number of stations worldwide was projected to reach 200 [21].

California has forged ahead of any other region in the world in developing a refueling infrastructure. By mid-2008, 32 hydrogen stations were built and operating in California, with 16 more planned [20], though not all are open to the public. Initially (in April 2004), California proposed a statewide Hydrogen Highway with 200 refueling stations spaced 20 miles apart by 2010 at a cost of up to $100 million [19]. Though California backed off from this ambitious goal, current plans for Phase 1 call for 50–100 stations by 2010. The existing stations are clustered mainly in the Los Angeles and San Francisco–Sacramento regions [22,23]. The idea is to provide a higher level of service to a smaller but densely populated and polluted area, thus maximizing the number of more-likely buyers. Stations connecting these clusters along rural interstate highways are targeted for Phase 2. The State of California allocated $6.5 million to develop stations in both 2005 and 2006.

New York's H2-NET hopes to open 20 stations between New York City and Buffalo and add hydrogen-fueling capability to 70 existing CNG stations by 2020. Illinois is planning a 2H2 Hydrogen Highway, and the Northern H Fuels Network in the Great Plains region of the US and Canada proposed 12 stations spaced 200 km apart by 2012.

At the national scale, the National Renewable Energy Laboratory (NREL) analyzed the potential development of a national backbone network to make long-distance, interstate trips possible by 2020 [24]. They estimated that 284 stations are needed, at a total construction cost of $837 million. Fourteen of these stations are suggested for Florida, including six at existing CNG stations. At the same time, a team of researchers from Oak Ridge National Laboratory and National Renewable Energy Laboratory is recommending to "concentrate on establishing networks of fueling stations in a limited number of urban centers during the transition period. Strategically placing stations in major urban centers will maximize coverage and permit a cost-effective approach to providing the early infrastructure" [25, p. xii]. They target Los Angeles and New York for the earliest clusters. President Bush and the U.S. Department of Energy set 2015 as the date for reaching a variety of technical and commercial targets to allow the private sector to make a commercialization decision [26].

Outside of the USA, the European Union's Joint Technology Initiative hopes to kick-start commercialization by 2015 [27]. The Scandinavian Hydrogen Highway Project consisting of HyNor (Norway), Hydrogen Link (Denmark) and HyFuture (Sweden) will link Oslo with Copenhagen. In Canada, a Hydrogen Highway will connect Vancouver to Whistler Ski Resort for the 2010 Olympics.

There are currently two hydrogen-fueling stations in Florida, both in the Orlando area. The Boggy Creek Hydrogen Refueling Station opened near the Orlando airport in May 2007 to refuel rental-car shuttle buses. The other station, a mobile refueling station operated by Progress Energy near suburban Oviedo, opened in December 2007 but was scheduled for decommissioning.

3. Prior research on refueling infrastructure modeling

In recent years, a large number of papers and reports have addressed the infrastructure needs for the transition to hydrogen energy. While numerous studies have examined the supply chain from production to delivery to fueling stations [15], or the total number of initial hydrogen stations needed [28,29], our focus here is on methods used to solve optimally for the locations of a coordinated network of stations. We group these approaches into GIS models and operations research (OR) models.

Melaina [30] proposed a GIS method that yields exact station locations and station sizes based on the idea of condensing the existing network of gasoline stations into clusters. The NREL study discussed above [24] used GIS to develop a national network of stations to enable long-distance trips on interstate highways. They selected heavily traveled interstates with over 20,000 vehicles per day, narrowed that set by choosing major north–south and east–west routes, and then placed stations along those routes guided by other GIS data layers such as hydrogen production plants, other alt-fuel stations, population, and US highway intersections. Stations were placed no more than 50 miles (80.5 km) apart in the east and in urban areas, and no more than 100 miles (160.9 km) apart in the west.

Although GIS is a powerful tool for integrating detailed spatial data layers, it is not ideal for "combinatorial optimization," in which the model must choose a combination of locations from a large set of candidate sites. Given the astronomical number of combinations that are possible for many real-world problems, many researchers turn to operations research (OR) techniques. One of the earliest OR papers for locations of gasoline stations developed a model to open and close gasoline stations to maximize a company's market share [5]. They based market share on two kinds of demand: home-to-facility trips, and traffic volumes on network links. Bapna et al. [6] used multiobjective programming to locate reformulated gasoline stations in India. One objective minimized the sum of travelers' costs and station investment costs, while the second maximized the population on enabled links. These objectives are optimized subject to a constraint that it is possible to travel from every node to every other node by at least one route given the driving range of vehicles. The fuel-travel-back model, which uses VMT data as the demand, locates stations to minimize the average refueling travel time for a random motorist [12]. Bersani et al. [13] developed a competitive multiobjective model for a petrol company to minimize its investment cost for converting some existing stations to hydrogen while maximizing the demand that can be satisfied. In their model, demand is related to existing gasoline sales, storage capacity, and distances to competitors.

Several papers have used a variant of the *p*-median model to locate hydrogen-refueling stations in various urban areas in California [5,7,9,12,31]. The *p*-median model—one of the most widely used OR models for facility location—locates a given number (*p*) of stations so as to minimize the total distance from population nodes to their nearest open station [32,33].

Beginning in 1990, researchers began developing a new approach to facility location, known as "flow-capturing" or "flow-intercepting" models [34–48]. In Flow-Capturing Location Models (FCLM), demand consists of paths through a network instead of points of origin for trips to the facility and back. The FCLM locates facilities conveniently on the origin-to-destination routes that drivers use on trips they already make. The basic model locates *p* facilities so as to intercept as many trips as possible. These models have been used for locating "discretionary" facilities, such as ATMs, convenience stores, and fast food, at which people stop on their way to somewhere else rather than make a special trip from home to facility and back. In our opinion, the FCLM provides a realistic behavioral basis for locating alternative-fuel stations because people tend to refuel on their way to somewhere else.

Kuby and Lim [8,49] modified the basic FCLM for the purpose of locating hydrogen-refueling stations. The FCLM assumes that a single facility anywhere on a path is enough to capture that demand. For serving long trips, however, a single station may not be enough to refuel a trip from an origin to a destination and back again because vehicles have a finite driving range. US DOE has set a target of 300 miles for the driving range of hydrogen vehicles, but the practical limit, or what drivers would be comfortable with, may be far less. For reference, the 2009 Honda FCX Clarity has a driving range of 240 miles. To deal with fuel limitations, Kuby and Lim adapted the FCLM by incorporating a driving range parameter. The resulting Flow-Refueling Location Model (FRLM) is a mixed-integer linear programming problem (MILP) that maximizes the number of trips that can potentially be refueled with a given number of stations *p*:

$$\max Z = \sum_{q \in Q} f_q y_q \tag{1}$$

Subject to:

$$\sum_{h \in H} b_{qh} v_h \geq y_q, \quad \forall\ q \in Q \tag{2}$$

$$a_{hk} x_k \geq v_h, \quad \forall\ h \in H;\ k \in K \tag{3}$$

$$\sum_{k \in K} x_k = p \tag{4}$$

$$x_k, v_h, y_q \in \{0, 1\}, \quad \forall\ k, h, q \tag{5}$$

where:

q = index of OD pairs (and, by implication, the shortest paths for each pair)
Q = set of all OD pairs
f_q = flow volume on the shortest path between OD pair q (number of vehicle-trips per time period)
$y_q = \begin{cases} 1, & \text{if } f_q \text{ is captured} \\ 0, & \text{otherwise} \end{cases}$
k = potential facility location
K = set of all potential facility locations
$x_k = \begin{cases} 1, & \text{if a facility is located at } k \\ 0, & \text{otherwise} \end{cases}$
p = the number of facilities to be located
h = index of combinations of facilities

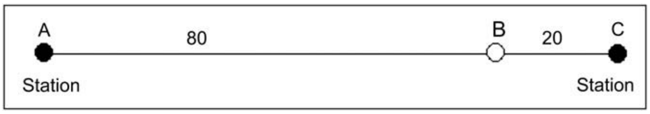

Fig. 1 – Example showing it is not possible to complete a round trip from A to B and back assuming a 100-mile driving range.

H = set of all potential facility combinations

$$a_{hk} = \begin{cases} 1, & \text{if facility } k \text{ is in combination } h \\ 0, & \text{otherwise} \end{cases}$$

$$b_{qh} = \begin{cases} 1, & \text{if facility combination } h \text{ can refuel OD pair } q \\ 0, & \text{otherwise} \end{cases}$$

$$v_h = \begin{cases} 1, & \text{if all facilities in combination } h \text{ are open} \\ 0, & \text{otherwise} \end{cases}$$

Constraint (2) prevents a trip on path q from being counted as refueled (variable $y_q = 1$) unless a valid combination of stations h is open (variable $v_h = 1$) that can refuel a vehicle on path q given the driving range specified (coefficient $b_{qh} = 1$). The driving range assumption is embedded in the b_{qh} coefficients. A subroutine developed by Kuby and Lim [8] uses the driving range parameter to determine whether a particular combination h of stations is capable of refueling a vehicle on the round trip on path q without running out of fuel. If so, the coefficient b_{qh} is set to 1. Constraint (3) ensures that a combination of stations h is considered open ($v_h = 1$) only if *all* of the individual stations k in that combination are open ($x_k = 1$). The coefficients a_{hk} indicate whether a station k is a member of station combination h. Constraint (4) sets the number of stations to p, a user input. Finally, (5) stipulates that a station or a combination of stations is either open or not, and likewise that any origin-destination flow can be considered either refuelable or not. The objective function (1) maximizes the flow volume (number of vehicle trips) that can be refueled. Upchurch et al. [14] developed an alternative objective (6) that multiplies each trip q by its distance d_q. This objective is measured in vehicle-miles traveled. It gives preference to siting stations to refuel longer trips, which would consume more hydrogen than shorter trips:

$$\max\ Z = \sum_{q \in Q} f_q d_q y_q \tag{6}$$

The vehicle driving range is related to, but not equivalent to, station spacing. For example, assume a driving range of 100 miles and stations located 100 miles apart at nodes A and C (Fig. 1). A round trip between nodes A and C could be completed without running out of fuel, as could the round trip between B and C. The round trip from A to B, however, would require 160 miles without refueling and thus could not be completed.

4. A spatial decision support system for the flow refueling location model

For the FHI, we integrated the FRLM into a GIS interface using ArcGIS software and Microsoft Visual Studio.net. The resulting Spatial Decision Support System (SDSS) performs three primary tasks [17]:

1. Processing transport network data from GIS sources into a format suitable for the solution algorithms.
2. Solving the FRLM for a given driving range and number of facilities.
3. Displaying the outputs in map and graph form.

The SDSS is implemented by extending the ArcGIS Desktop interface using the ESRI ArcObjects and Microsoft .NET technologies. It provides an intuitive user interface for data input, data conversion, model execution options, and display results. For the preprocessing stage, the SDSS uses five main input map data layers: a point layer of population centers, which are used as the origins and destinations of trips; a point layer of road junctions; a point layer of candidate facility sites; a line layer of road network arcs; and a line layer of shortest paths. Non-spatial input data to the SDSS includes the vehicle range, the number of facilities to be built, and a trip table for all OD pairs. The SDSS uses ESRI ArcMap and ArcCatalog to create GIS data in the ESRI personal geodatabase format. It generates the shortest path between all OD pairs using the ArcGIS Network Analyst tool. It also converts all GIS data, with real-world locations and shapes, into a simplified and connected network of nodes, arcs, and paths for the solution algorithms, which have no need for real-world location information.

While MILP software can solve small versions of the FRLM optimally, we developed two heuristic solution algorithms to solve larger, more realistic cases of the model—although they are not guaranteed to find the global optimal solution in every case. For this paper, we used a greedy-adding-and-substitution algorithm [50,51]. A simple greedy algorithm—without substitution—would add one facility at a time at the site that increases the objective function the most, that is, that refuels the most flow volume above and beyond what the previous facilities were able to refuel. The simple greedy algorithm, however, has been shown to be suboptimal for the FRLM [8]. The greedy substitution algorithm, on the other hand, allows the model to swap unused candidate sites for chosen candidate sites at each iteration. So if, for instance, after choosing the 1st to 8th sites, the 3rd site becomes partly redundant, the substitution algorithm could swap another site for it, and possibly perform several additional substitutions, before moving on to add the 9th site. The second solution algorithm in the SDSS is a genetic algorithm, but it was not used to generate the results here. Both algorithms allow the user to set certain parameters:

1. A driving range for vehicles (a distance).
2. The number of stations to locate (p).
3. The objective function to be maximized (either the number of trips or vehicle-miles traveled that can potentially be refueled).
4. Any stations the analyst wishes to force into the solution (either pre-existing or desired).

After completing a model run, the solution algorithms output the results directly to text files, the Access database, and directly to the open ArcMap window. The selected facilities and the refuelable paths are displayed directly on the map with real locations and shapes. These optimal facilities and covered paths can be saved as separate layers for each scenario, making it easy to visually compare results for different scenarios. The percentage of trips or VMT covered by each solution is output to a table from which tradeoff graphs such as Fig. 8 can be made.

5. Data

The three universities involved in this project worked closely together to build, simplify, check, and calibrate detailed and realistic GIS network databases for the Orlando and statewide case studies (see [17] for details). For each case study, we obtained GIS road network databases and then corrected topology errors in the raw network and simplified the road network by eliminating minor and duplicative roads while retaining needed connectivity. Next we aggregated nearby traffic analysis zones (TAZs) together, being careful to ensure contiguity and compactness, and selected a single origin–destination (OD) point to represent each area, considering the locations of major intersections and traffic generators (for other TAZ aggregation in flow-intercepting models, see [46–48]). The OD points are a subset of the larger set of road junctions. Once each network was built, we generated shortest paths minimizing travel time between each OD pair (e.g., Fig. 2). Our Florida-based researchers checked many paths one by one to see if they followed realistic routes that drivers would take, and calibrated the speeds associated with different classes of roads, added missing road links, or changed OD locations accordingly.

The Orlando study area includes all of Orange and Seminole counties and the northwest region of Osceola county including the cities of Kissimmee and Saint Cloud (Fig. 3). We obtained GIS highway networks and maximum speed data from the Florida Department of Transportation (FDOT), and detailed street networks from ESRI, Inc. FDOT divides the Orlando study area into 358 traffic analysis zones (TAZs), which we aggregated to 102 larger zones. We obtained a matrix of weekday OD trip volumes from FDOT, which we aggregated into a 102×102 matrix, ignoring short intra-zonal flows. Speeds on arterial streets were reduced from posted speed limits by 15% to reflect slower driving conditions.

For intercity travel, the study area included the entire state of Florida (Fig. 4). Using ESRI and FDOT road networks, we included all interstate highways, toll roads, and US highways, as well as selected state highways important for intercity trips. We reduced the speeds on all roads other than limited-access highways by 15%. For modeling intercity trips, the basic

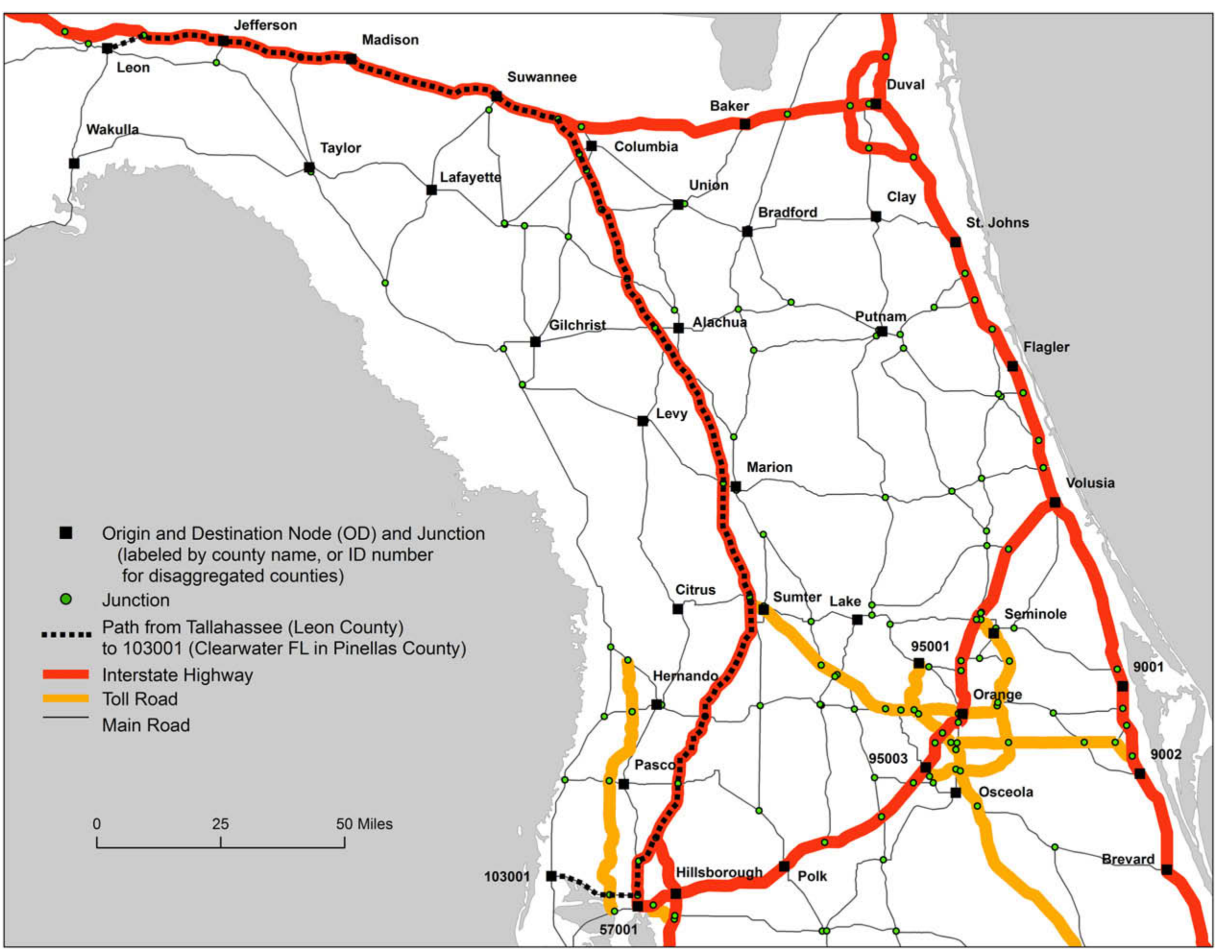

Fig. 2 – Sample path from Tallahassee (Leon County) to Clearwater (103011).

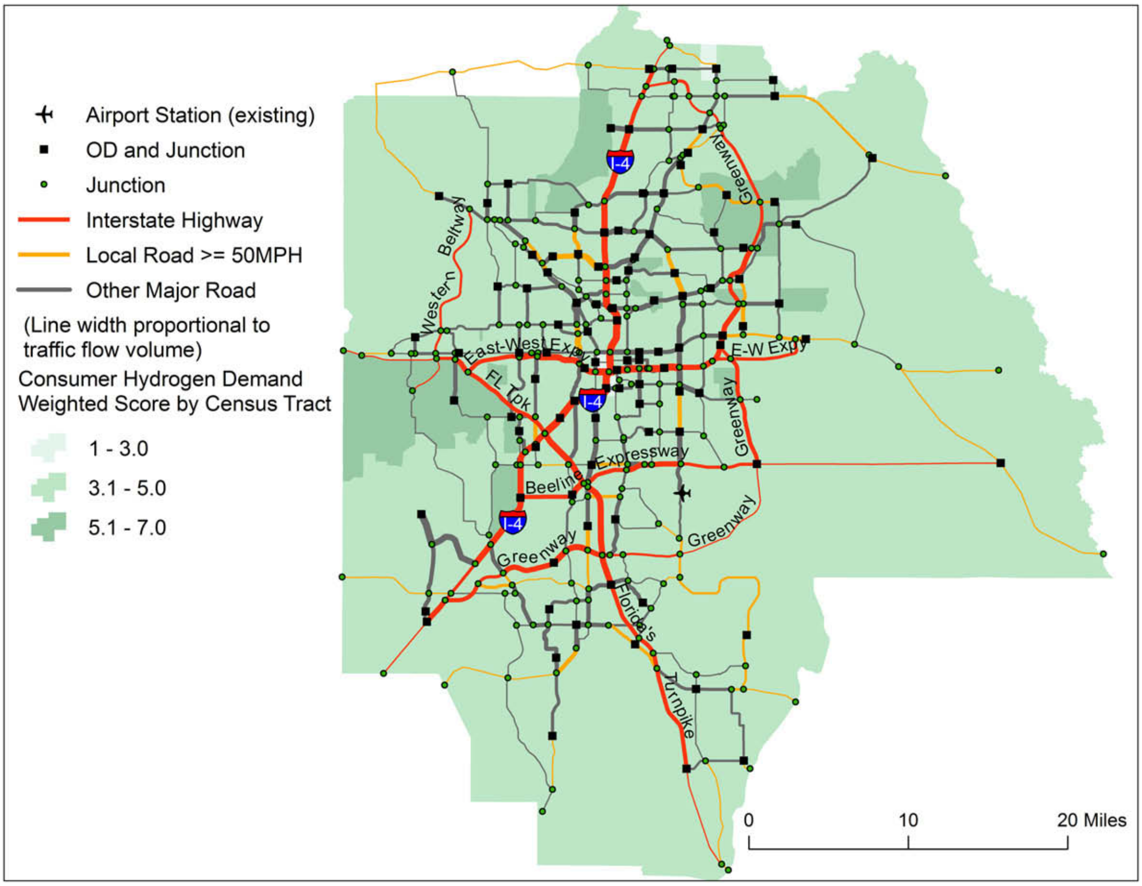

Fig. 3 – Network for the Orlando case study. Orlando's central business district is near the intersection of I-4 and the East–West Expressway.

level of spatial aggregation was by county, with some exceptions. Large urban counties consisting of several distinct urban areas in the Miami, Orlando, and Tampa areas were further subdivided into separate ODs, and some small rural counties were aggregated together. In all, Florida was aggregated into 74 ODs.

The FDOT trip data used for the Orlando study does not include statewide travel flows. We therefore used a spatial interaction or gravity model [52,53] to estimate intercity flows T_{ij} based on zone populations P_i and P_j and a friction function FF_{ij} for the route from i to j:

$$T_{ij} = P_i \times P_j \times FF_{ij} \tag{7}$$

We used a friction function for intercity home-based social-recreational and vacation trips from Michigan's statewide travel forecasting model [54], cited by a Federal Highways Administration guidebook [55] as an example of best practice in statewide travel forecasting:

$$FF_{ij} = 50 \times GC_{ij}^{-0.114} \times e^{-0.03GC_{ij}} \tag{8}$$

where GC_{ij} is the generalized cost between zones i and j, calculated as $0.75 \times \text{miles} + 0.5 \times \text{minutes}$. To estimate trip volumes, we applied equations in (7) and (8) to each OD pair, plugging the travel time and length of the shortest path into the generalized cost formula and the aggregated populations of i and j into (7). The resulting T_{ij} values were then standardized to a percentage of the statewide total and used as the intercity trip volumes f_q. This study does not include out-of-state flows to or from Florida.

For the base cases for the Orlando and statewide models, the trip volume data consider trips made by all Orlando and Florida residents. All consumers, however, are not equally likely to purchase hydrogen vehicles in the early stages of commercialization. Therefore, we also ran the model with demand weighted by a hydrogen demand factor. Our method was loosely based on a 2006 report by NREL [56]. We used their variables, relative weights, and 7-point scales whenever possible, but adapted their method to estimate *per capita* demand factors that could be used as multipliers on the f_q vehicle flow total. Based on Table 1, we calculated a weighted average hydrogen demand score on a scale from 1 to 7 for each aggregated TAZ (see base layer in Figs. 3 and 4). Then, after linear conversion to a multiplier between 0 and 1, we computed a weighted average multiplier for each origin–destination pair and multiplied the number of origin–destination trips by it. Given that "there is no single best data classification method," and that NREL modified the number of classes and weights in a subsequent publication [10, p. 4] these scenarios should be interpreted mainly as a way to assess the

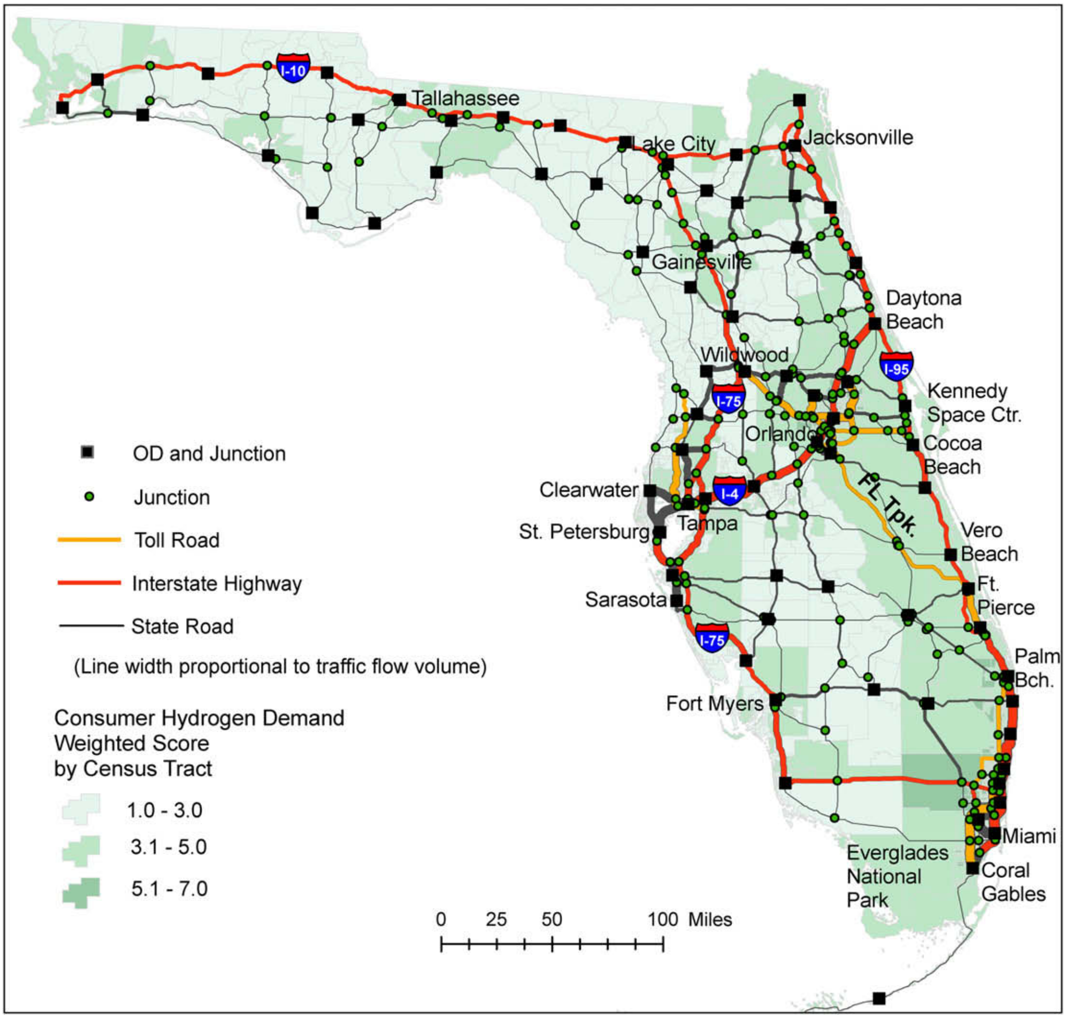

Fig. 4 – Network used for the statewide case study.

sensitivity of the optimal locations to assumptions about demand levels.

The base case scenario for both statewide and Orlando case studies uses 100 miles as a reasonable or ''safe'' vehicle range. This number represents a distance drivers would feel comfortable traveling between stations on a round trip, rather than the technological maximum range of the vehicle, currently around 180–300 miles for today's prototypes. The NRC [2] assumes a 300-mile driving range for their infrastructure scenarios, and the US DOE has set 300 miles as the goal for 2015 [26]. The original California Hydrogen Highway plan was to space stations every 20 miles along interstates, although their current thinking is closer to 50 miles. The NREL national analysis spaces stations 100 miles apart west of the Mississippi River but 50 miles apart in the eastern US and urban areas, because interstates in the east are ''used extensively for short trips'' [24]. We adopt NREL's 100-mile assumption as a reasonable driving range that allows for driver error, suboptimal vehicle performance, improper filling, side trips, detours, and closed stations. With the FRLM, however, we do not need to assume NREL's more conservative 50-mile spacing as a proxy for capturing shorter trips because the model uses data for both short and long intercity trips. If capturing short trips that would otherwise fall between stations justifies spacing stations closer than 100 miles apart, the model will recognize that. We also ran scenarios assuming a 50-mile and 75-mile range.

6. Florida state-scale results

We ran a variety of scenarios locating stations optimally for intercity trips within Florida. Scenarios varied by objective function (trips, VMT, weighted trips, weighted VMT), driving range (100, 75, 50 miles), and whether or not stations were forced into the solution for ''non-model-based'' reasons. For 5 stations, the model locates four in SE Florida and one in Tampa (Fig. 5). These five stations are capable of refueling 62% of the estimated intercity trips in Florida. The large number of intercity trips in this area of 5.4 million people is the result of many large population nodes with short distances between them. Clustering stations in the greater

Table 1 – Hydrogen consumer demand scoring and weighting system.

Data layer	Spatial units	Weight (%)
Median household income	Census tract	23
Percentage of households with 2 + vehicles	Census tract	23
Pct. of workers age 16+ who commute more than 20 min	Census tract	18
Percentage of people with bachelor's degrees	Census tract	18
Clean cities coalitions	County	18

Miami-Palm Beach area is therefore a smart strategy for serving many trips with a few stations. In addition, the linear arrangement of cities along the coast means that most intercity trips travel north and south on the main highways, and by stringing the stations along the coast, the arrangement of these four stations allows trips to be made that are longer than 100 miles round trip. Outside of this cluster, the other station in Tampa facilitates round trips between the area's largest city and some large surrounding cities such as St. Petersburg, Lakeland, Sarasota, and Clearwater.

The optimal system of ten stations for maximizing unweighted trips includes two major clusters: a linear one in SE Florida and another connecting the Tampa–St. Petersburg (2.6 million people) and Orlando (1.9 million) metropolitan areas. Each cluster now has five stations, and the stations that were optimal with only five stations remain optimal with 10 (Fig. 5). These 10 stations are able to refuel 77% of the estimated intercity trips in Florida. With 15 stations, the model adds three stations to the Orlando–Tampa cluster, one station to southeast Florida, and one in Jacksonville (population 1.2 million). The stations that were optimal within the first five and the first 10 remain optimal with 15, which is not always the case with this kind of model, adding confidence to these priorities. As we saw before in the case of Tampa, the single station in downtown Jacksonville potentially enables trips from central

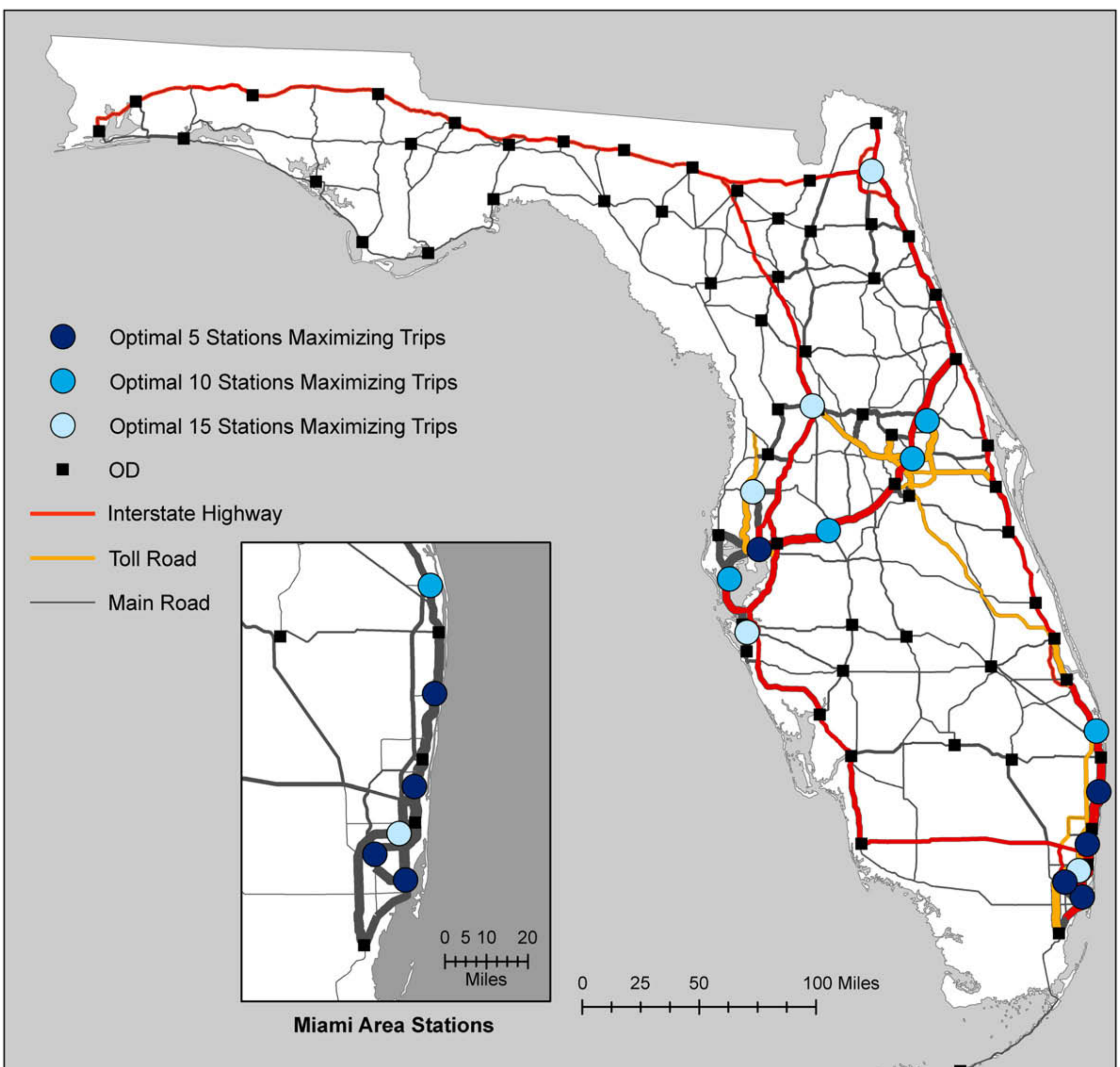

Fig. 5 – Optimal 15 stations maximizing trips with 100-mile vehicle range.

Jacksonville to the five surrounding counties. These 15 stations refuel 84% of estimated intercity trips (Fig. 5).

A new strategy emerges when expanding the network to 20 stations (not shown). The model begins adding some connecting/bridging stations, such as on I-95 at Daytona, Cocoa Beach, and Vero Beach, facilitating north–south trips among nearly every pair of cities from Coral Gables in the south almost to the Georgia border in the north. Despite enabling trips up and down the east coast and further down the west coast, these five stations only increase the percentage of refuelable intercity trips from 84% to 89%, because people make fewer long-distance trips than short-distance trips. With 25 stations, the model adds stations as far north as Gainesville (University of Florida main campus), and adds to the clusters in the Orlando, Tampa, and Miami areas (Fig. 6). Note the lack of stations in the Florida Panhandle, and the fact that some stations that were optimal with 5–15 stations are no longer optimal with 25.

Next, we maximized vehicle-miles traveled (VMT) instead of the number of trips. The VMT objective multiplies the number of trips on each shortest path by its distance in order to prioritize serving longer trips that use more fuel. The results are surprisingly similar (Fig. 6). Twelve of the locations that were optimal for maximizing trips remain optimal for maximizing VMT, while others shift only slightly. There continue to be clusters of stations around Miami, Orlando, and Tampa, as well as a station in Jacksonville. The priority order, however, is different, with one of first five stations shifted to Orlando to make the 170-mile Orlando–Tampa round trip possible. Despite the increased emphasis on serving longer trips, however, there would still not be enough VMT served in the Panhandle to justify placement of scarce refueling infrastructure there.

Two examples highlight the differences in the trips and VMT solutions. The VMT model locates a station on I-75 crossing the Everglades, because of the higher weight placed on long-distance trips between the Miami and Tampa–St. Petersburg conurbations. To support this strategy, several stations in the Miami area shift location slightly in order to be at key junctions where trips funnel towards I-75 while still

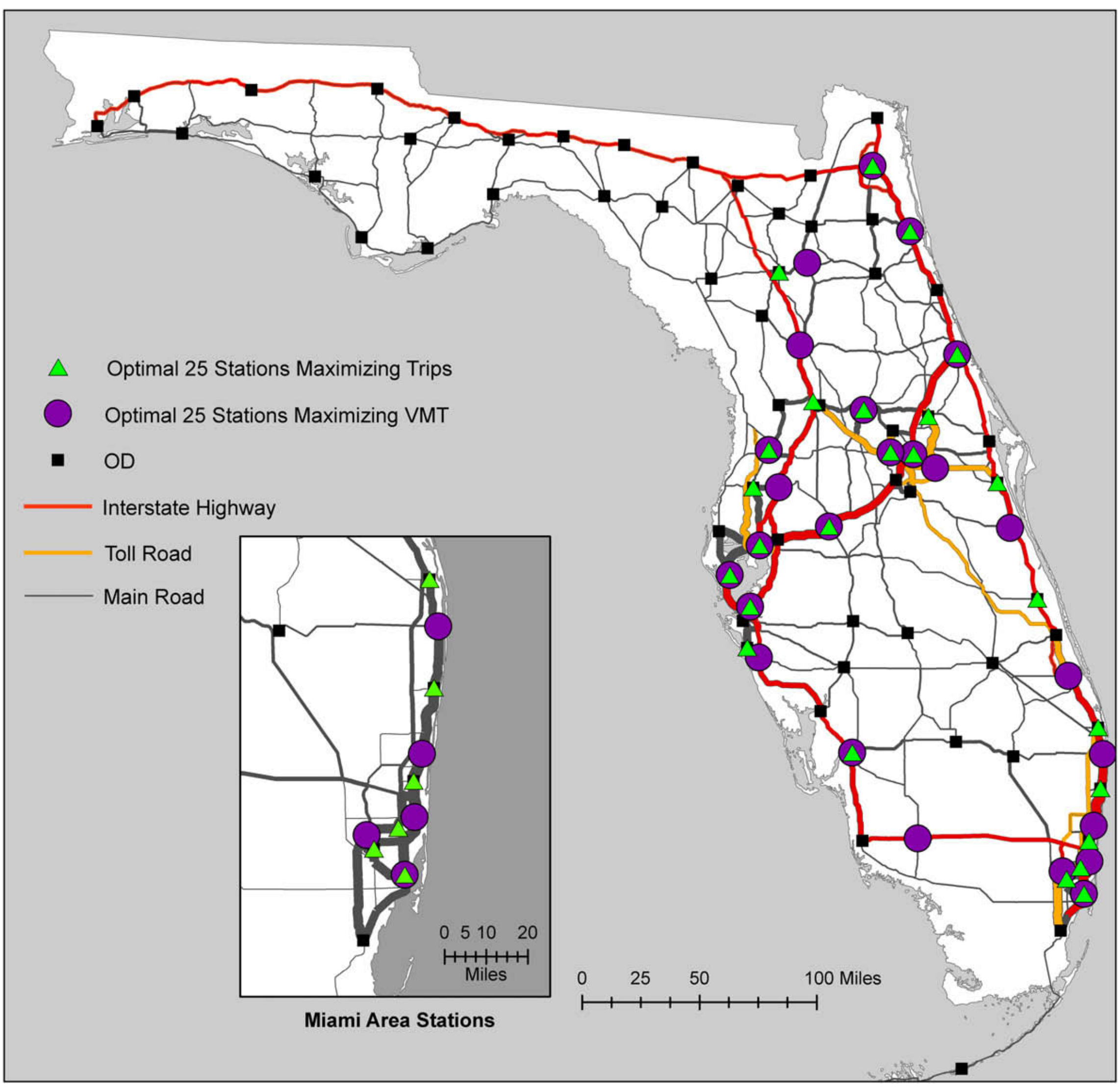

Fig. 6 – Comparison of optimal networks of 25 stations maximizing trips and VMT, for a 100-mile vehicle range.

being able to serve short intercity trips within southeast Florida. The second notable change is that the station in Gainesville in the max-trips scenario shifts eastward onto US-301, the fastest route between Jacksonville and Tampa. While Gainesville has a larger population than this node, a station in Gainesville would serve primarily shorter intercity trips, whereas the station on US-301 facilitates fewer but longer trips.

Fig. 7 presents results for 25 stations maximizing trips, assuming driving ranges of 50 miles compared with 100 miles. With a 50-mile range, the optimal network of 25 stations breaks up into two independent clusters in the greater Miami and Tampa–Orlando areas, with a single station in Jacksonville. With the shorter range, more stations are needed to provide connectivity in the two main clusters, leaving too few stations to provide linkages between these clusters.

Fig. 8 shows tradeoff curves for both the max-trips and max-VMT objectives for driving ranges of 50, 75, and 100 miles. First, as expected, all curves show a general pattern of diminishing marginal returns. Each subsequent station tends to add fewer trips than the previous station, as the best locations are used up. Previous research [8,57] has shown, however, that returns are not strictly diminishing, because sometimes it takes two additional stations to be able to refuel a high-volume but longer trip. This is visible in the curve for maximizing trips assuming a 50-mile range, although it is also possible that the concavity at 7–8 facilities could be examples of the substitution algorithm being unable to find the global optimal solution. Second, the curves for the shorter range are lower than the curves for the longer range, simply due to the need for spacing stations closer together to serve the same long-distance trips. Third, a given number of stations can potentially refuel a higher percentage of trips than of VMT because the latter consists more of long trips that require more stations to serve. Note that the percentage of trips or VMT enabled is to some extent an artifact of the structure of the network constructed by the analysts. With a more-detailed network and more origin and destination nodes, the same set of stations would likely intercept a smaller percentage of intercity routes.

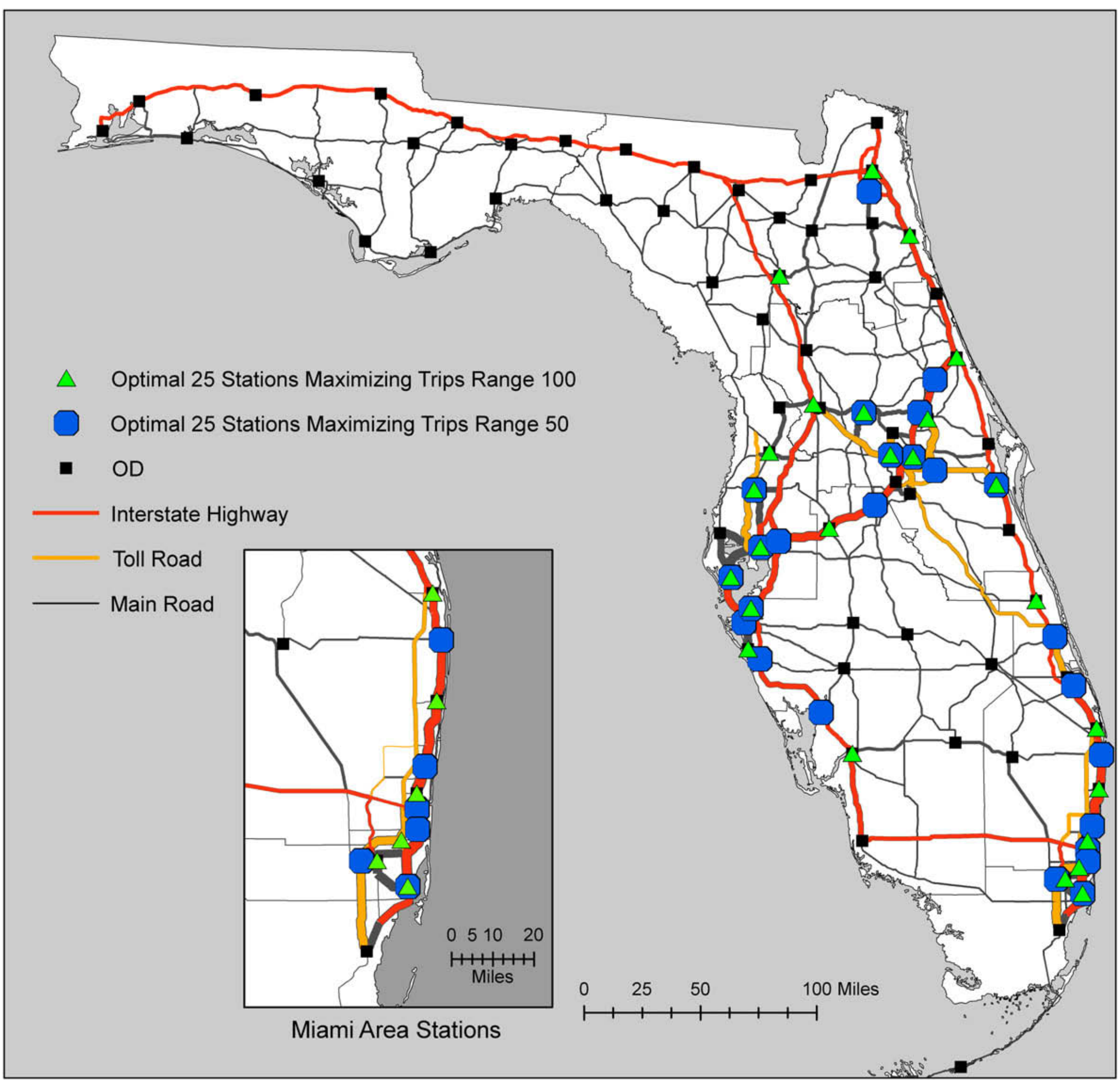

Fig. 7 – Optimal 25 stations with 100-mile and 50-mile driving range assumptions.

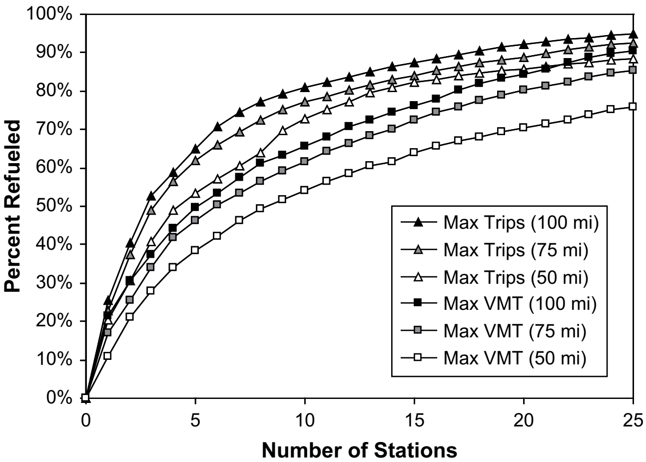

Fig. 8 – Tradeoff between number of stations and percent of demand able to be refueled for the statewide network.

The station networks in the previous scenarios were optimized with no *a priori* assumptions about any particular station being part of the network. There may, however, be certain locations that decision-makers wish to include for tourism, political, or scientific reasons, even though the model based on intercity estimated trip demand does not select them. In another part of the FHI study [18], we found that the bundles of trips made by approximately 64% of car renters at Orlando International Airport (OIA) could be serviced by three stations: at OIA (station already exists), downtown Orlando, and the theme parks. Of these, only downtown Orlando was consistently chosen by the model based on intercity trips. Many trips to the theme parks and OIA are intra-city trips that are not modeled in the statewide network. Yet these two stations play a key role in a possible hydrogen rental-car business model. Likewise, no scenarios with 25 or fewer stations selected Tallahassee based on the *intercity* trips to, from, or through it, yet a station in Tallahassee may be justified on other legitimate grounds. As the site of Florida State University, a station in Tallahassee may be important for scientific research and environmental education. Similarly, a station near the state capital in Tallahassee could be important for demonstrating hydrogen technology and for fueling governmental fleets. Finally, a station in Tallahassee may be justified by the intra-city trips of the highly educated workforce there. Similar considerations point to a station in Gainesville near the University of Florida at I-75. For this reason, we ran some scenarios in which these three rental-car stations and two university stations are forced into the solution, and the rest of the station network was optimized around these five fixed stations.

Forcing the placement of these five stations involves a large sacrifice in terms of the number of intercity trips served—but only in the early stages of infrastructure development. Alone, these five stations serve only 7% of intercity trips estimated by the gravity model, versus 65% for the five stations optimally located in southeast Florida and Tampa. However, adding 20 optimal stations in coordination with the five fixed stations, it is possible to serve 94% of the estimated intercity trips, only 1% less than if all 25 stations were optimized freely. The un-modeled benefits of early university adopters and the possible tourist rental-car market in the Orlando area may more than make up for the loss of 1% of intercity travelers. In any case, 17 stations in the maximizing trips scenario and 10 stations in the maximizing VMT scenario remain in exactly the same locations, showing that these are robust locations regardless of whether the rental-car stations and university stations are forced into the top 25.

Finally, we ran a number of infrastructure scenarios using the weighted hydrogen consumer demand factors based on NREL's GIS model, with and without forcing the three rental stations and two university stations into the solution, and maximizing weighted trips or weighted VMT. All weighted demand scenarios assumed a 100-mile driving range. In the weighted demand scenarios, the Miami-Palm Beach and Orlando metropolitan areas are predicted to have higher consumer demand than the Tampa and Jacksonville areas mainly because they have Clean Cities coalitions to facilitate adoption, but also because of demographics and longer commutes. As a result, there is slightly more clustering in these two urban areas and earlier connecting stations between them. Overall, however, many locations remain the same, which helps lead us to a robust final set of priorities for the initial hydrogen-refueling infrastructure in Florida.

7. Orlando metropolitan-scale results

The Orlando area was chosen as the study area for analysis at the metropolitan scale because it was the focus of our feasibility study on hydrogen rental cars [18], and is home to Florida's first two hydrogen stations. We treat the station located at OIA as existing in all scenarios, but the mobile refueling unit in Oviedo, scheduled for decommissioning in late 2008, is not treated as existing in any scenario. The main difference between analysis at the state and local scales is that the range of the vehicle becomes a non-factor. Hardly any round trips in Orlando exceed the 100-mile safe vehicle range in length. Therefore, one station anywhere on a path can refuel almost any OD pair.[1]

The base case for the Orlando network is maximizing trips based on the FDOT trip table, with only the airport location locked into place. Fig. 9 shows the optimal locations for 25 stations, color-coded by priority. We generated these priorities by first solving the model for five stations, then 10 stations, and so on up to 25 stations. Only two stations are substituted for others during the greedy-substitution algorithm, and only one is not part of the final optimal solution for 25 stations (see Fig. 9 caption for explanation). The fact that these are the only two substitutions suggests that if stations

[1] For those few round trips longer than 100 miles, the path is likely to follow a major highway, and a single station anywhere near the middle of the path could easily serve the trip by refueling it in both directions. For a round trip of, say, 110 miles (the longest in our Orlando network), the only way that a single station would not be able to refuel the vehicle before it reached the 100-mile mark is if the station were located within five miles of either the origin or destination. For applications such as these where the vehicle range exceeds the longest round trip distance, the FRLM reduces to the simpler flow-capturing model.

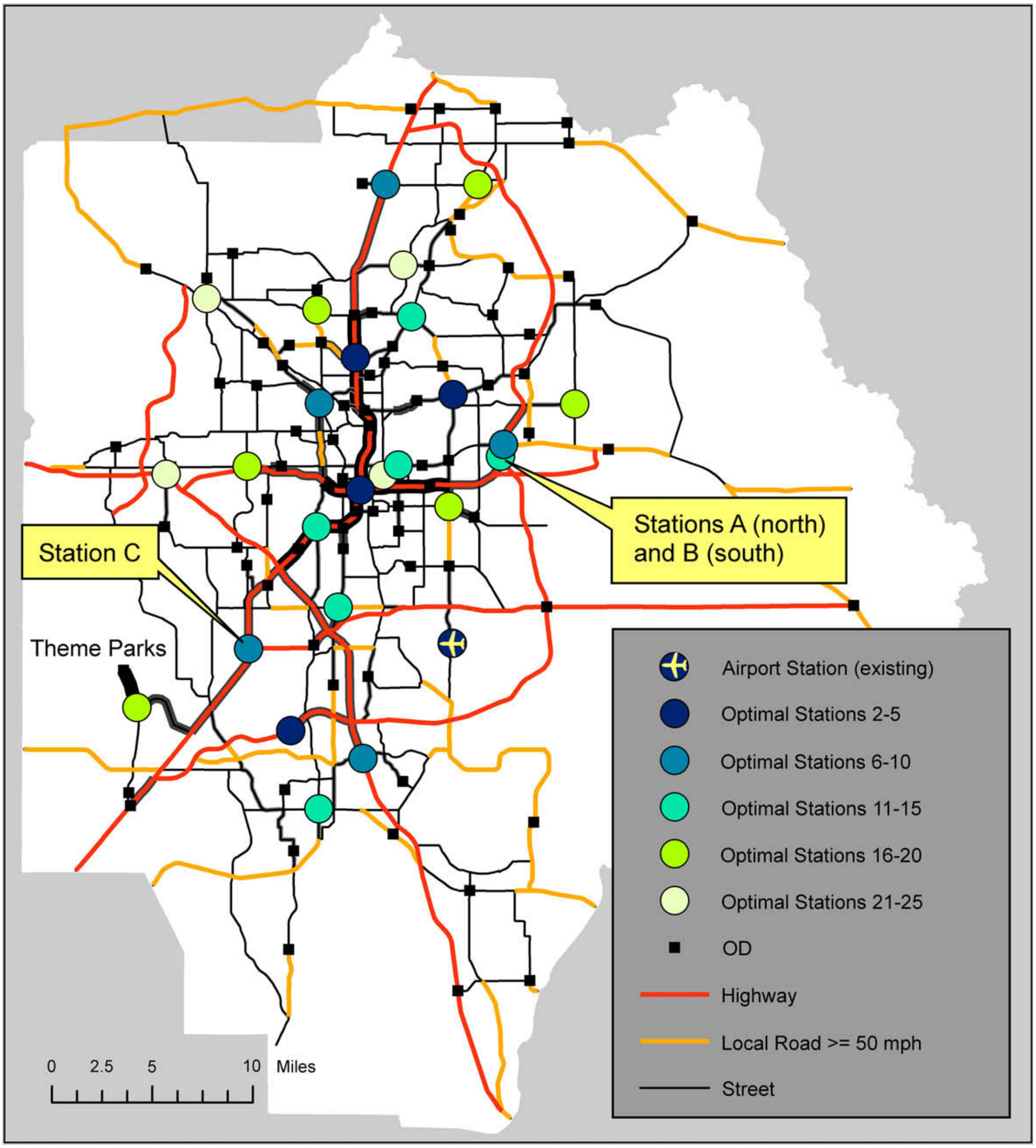

Fig. 9 – Optimal 25 stations in the Orlando area maximizing trips with 100-mile vehicle range. The color shown for each location indicates the highest priority level at which it was ever selected. The reason why *six* new stations are shown as optimal for $p = 11–15$ and $p = 16–20$, and only *four* for $p = 21–25$, is due to substitutions during the greedy adding-with-substitution algorithm. Station A was optimal for 6–10 facilities, but shifts its location less than a mile south to B for 11–15 stations and remains there for 16–20 and 21–25 facilities. Meanwhile, Station C, at a freeway exit east of the theme parks, is shown as first appearing in the optimal solution for 6–10 stations. It remains optimal for 11–15 stations, is replaced by a different site for 16–20, and re-emerges as optimal for 21–25 stations. The station that replaced C in the 16–20 solution remains optimal for 21–25.

are developed in this order, future stations are not likely to cannibalize the demand of earlier stations. After the existing station at OIA, the best location is in downtown Orlando, near the intersection of I-4 and the East–West Expressway, which could intercept and potentially refuel 14% of the daily trips.

Of the eight next best station locations, six are on major freeways with high passing traffic volumes as well as high crossing traffic flows and/or originating and ending flows. While these freeway sites are on high-traffic roads, they are not necessarily at the *next highest* traffic sites in the network. What is more important is that they intercept high-traffic flows that were not captured by the previously chosen stations. The freeway stations in the top 10 are located a substantial distance away from each other. A certain amount of cannibalization of demand is inevitable, but the FRLM tries to maximize the unique flow volume that can be refueled with each additional station, and does not consider any benefits of redundancy. The model also places two of the top 10 stations at heavy-traffic intersections of major arterial streets.

As important as where the model locates stations is where the model does *not* locate stations. In contrast with other methods such as the *p*-median model, the FRLM does not necessarily try to spread the locations evenly around metro Orlando to minimize the average distance from residential zones to their nearest stations. Many OD nodes remain far from any of the top 10 sites, and large areas *appear* to be underserved; however, appearances can be deceiving. Many trips may start from neighborhoods without a station but pass by stations in other areas. In fact, 53% of trips pass through at least one of the top 10 station sites.

After these first 10 stations, the subsequent sets of five add 13%, 9%, and 7% as diminishing returns set in. Not surprisingly, fewer ''freeway funnel'' points remain to intercept large volumes of passing flows that were not already intercepted by previous locations. Thus, the model eventually begins to adopt a different strategy, spreading stations 16–25 around Orlando in more suburban locations on arterial streets.

There is empirical evidence that consumers prefer to refuel near their homes [31,58]. This raises the question whether the FRLM or the *p*-median model is more behaviorally realistic. When presented with a choice of many stations along their driving route, we agree that most drivers would prefer a station near home, all else being equal. Stations near home are more familiar, and by refueling near home drivers can avoid getting off the freeway to refuel and then getting back on. Locating stations in each and every neighborhood, however, is a luxury that may not be affordable when building the first set of hydrogen stations at $1–3 million apiece. For the initial refueling infrastructure, we argue that it is most important to locate on the routes of as many trips as possible. With only a handful of stations, we believe that early adopters will be willing to refuel far from home as long as the station is on their regular commuting or shopping route and does not require a detour. A station far from home but on the way may in fact be more convenient than a station that is closer but requires a special trip or detour to reach. Stations next to highways with large passing flow volumes can enable refueling by a larger share of potential adopters.

We also ran scenarios maximizing VMT, using weighted demands based on the strength of consumer demand, and forcing in the stations needed for a rental-car business. Because we already treat the airport station as fixed, and the downtown station is always the first station added, the station at the center of the theme parks is the only one that needs to be forced in to optimize the refueling network around the three targeted rental-car stations.

8. Priorities for Infrastructure in Florida and Orlando

In planning an initial hydrogen refueling infrastructure in Florida, our team of researchers synthesized the results of a large number of model scenarios for both the statewide and Orlando networks using our judgment and local knowledge to arrive at a prioritized list of stations coordinated across the two scales of analysis. This approach recognizes that the FRLM is capable of analyzing tens of thousands of origin–destination pairs and sorting through trillions of possible station combinations in ways that are impossible without the benefits of OR and GIS. At the same time, we recognize the limitations of the model and the datasets, and the importance of factors that are not included in the models. In addition, no single scenario can determine the best station network. The final factor dictating this approach is that the Orlando trip table was based on FDOT data while the statewide trip table was based on gravity model estimates, which meant that the Orlando and statewide refueling networks had to be analyzed separately and coordinated exogenously.

For this reason, we looked for station locations that consistently perform well across a variety of scenarios. The most robust locations can coordinate well with a variety of other stations in refueling short trips by themselves and longer trips in combination with other stations, regardless of vehicle range, demand weighting, and whether we are maximizing trips or VMT. In devising a strategy for the Orlando area, we had to take into account that some stations would also serve the intercity and rental-car trips in addition to the intra-Orlando trips. Thus, any station included in the final statewide network had to also be included in the final Orlando network at the same location. Finally, our team of four professors—with expertise in transport modeling, geography, and tourism and a combined 60 years living and driving in Florida—weighed the importance of various factors not included in the model to develop the location strategy presented below.

Table 2 lists the higher-priority stations and their highest rank in various scenarios. The full table, including every station that was optimal in at least one scenario, can be found in [17]. Rows represent stations, columns represent model scenarios, and cells relate whether the station was optimal in the scenario, and if so, in which tier.[2] Based on all the model results, we sort the stations into tiers of overall Top 5, Top 10, and so on through Top 25 as in Table 2. In ranking them, we consider synergies, spacing, timing, and local intra-city consumer demand. We do not attempt to rank stations within each tier of five. For the statewide network of intercity trips, we place greater emphasis on the scenarios that include the three stations in Orlando needed for serving rental-car trips and the two flagship university stations. We also put more emphasis on the weighted demand scenarios and the 100-mile range scenarios. Finally, because our focus in the statewide network is on facilitating *long-distance* trips, we place more emphasis on maximizing VMT.

Our final priorities for 25 stations are quite close to the ''Max VMT-Range 100-Weighted Demand-Five Required Sites'' scenario in the last column of Table 2, with the substitution of Kennedy Space Center for the Shady Hills station, some minor relocations among nearby sites, and some shuffling of stations among the tiers. These 25 higher-priority stations generally perform very well across the board, coordinate well

[2] Some scenarios were solved separately for 5, 10, 15, 20, or 25 stations, which allowed us to prioritize the stations into Top 5, Top 10, and so on. Others were solved only for $p = 10$ and 25.

Table 2 – Statewide infrastructure strategy.[a]

Jct	City	Intersection	Max trips range 100	Max VMT range 100	Max trips range 50[b]	Max trips range 75[c]	Max VMT range 75[b]	Max Trips range 100 five required sites	Max trips range 100 weighted demand	Max trips range 100 weighted demand five required sites[b]	Max VMT range 100 weighted demand five required sites
First tier – top 3 locations											
190	Orlando Int'l Airport	Boggy Creek Rd.						Existing		Existing	Existing
183	Orlando Downtown	I-4 & East West Expwy	Top 10	Top 5	Top 25	Top 10	Top 25	Required Rental Station		Required Rental Station	Required Rental Station
197	Orlando Theme Parks	Epcot Ctr Dr. between I-4 & World Dr.						Required Rental Station		Required Rental Station	Required Rental Station
Second tier – top 10 locations											
242	Delray Beach	I-95 & W Atlantic Ave	Top 5	Top 15			Top 25	Top 10			Top 15
256	Ft Lauderdale	I-95 & Sunrise Blvd	Top 5	Top 5	*			Top 10			Top 10
266	Miami Lakes	I-75 & Palmetto Expwy	Top 5	Top 10		Top 10		Top 10	Top 5	Top 25	Top 10
107	Tampa	I-4 & I-275	Top 5	Top 5	Top 25	Top 25		Top 10	Top 5	Top 25	Top 10
155	Gainesville	I-75 & W Newberry Rd	Top 25					Required University Station	Top 25	Required University Station	Required University Station
163	Wildwood	I-75 & Florida's Tpke	Top 15	Top 10		Top 25	Top 25	Top 20	Top 20	Top 25	Top 15
292	Tallahassee	Tennessee St & Monroe St						Required Univ./Govt. Station		Required Univ./Govt. Station	Required Univ./Govt. Station
Third tier – top 15 locations											
109	Mango	I-4 & I-75			Top 25		Top 25	Top 15		Top 25	Top 15
270	Miami	I-95 & I-195	Top 5	Top 5	Top 25		Top 25	Top 10			Top 10
169	Sanford	S Orlando Dr & Eastern Beltway	Top 10	Top 15	*		*	Top 15	Top 10	Top 25	Top 20
209	St. Petersburg	I-275 & 5th Ave N	Top 10	Top 10	Top 25	Top 10	Top 25	Top 15	Top 10	Top 25	Top 15
	Kennedy Space Center	Visitor's center, not included in statewide network.									
Fourth tier – top 20 locations											
93	Daytona Beach	I-95 & I-4	Top 20	Top 25		Top 25	Top 25	Top 25		Top 25	Top 25
217	Fort Pierce	St Hwy 70 between I-95 and Florida's Turnpike			Top 25			Top 25	Top 15	Top 25	
82	Jacksonville	I-95 & I-10	Top 15	Top 25		Top 25	Top 25	Top 15	Top 15	Top 25	Top 25
149	June Park (near Melbourne)	I-95 & Coast Hwy		Top 15				Top 20	Top 15	Top 25	Top 15
232	Palm Beach Gardens	I-95 & PGA Blvd	Top 10					Top 15	Top 25		Top 25

Fifth tier – top 25 locations											
201	Kissimmee	Osceola Parkway between Florida's Tpke and Orange Blossom Trail				Top 25		Top 25		Top 25	Top 25
263	Miramar	Florida's Tpke & County Line Rd	Top 15	*			*	Top 20			Top 20
98	Pasco	I-75 & St Hwy 52	Top 15	*	Top 25	Top 25	Top 25	Top 25	Top 15	Top 25	
81	Sarasota	I-75 & St Hwy 72	*	Top 25	Top 25	*	*	Top 25	*	*	*
50	Solana	I-75 & Duncan Rd			Top 25	Top 25	Top 25				Top 20

a Indicates that another location within the same city was in the Top 25 for the scenario in question. The other location(s) can be found further down in the table. Does not apply to large cities such as Miami, Orlando, and Jacksonville, where different locations may be far apart.
b Stations in these columns are not ranked. Only one scenario (for $p = 5$) was analyzed.
c Stations in this column are either Top 10 or Top 25. Other p values were not analyzed.

with each other for serving longer distance trips, and cannibalize each other's demand as little as possible.

As can be seen in Fig. 10, we propose developing clusters of stations and connecting stations along major interstates in stages, so that as each tier is constructed, the clusters and the connections between them grow in a coordinated way. The first tier of three stations consists of the airport, downtown, and theme park stations in Orlando needed for the hydrogen rental-car business. Given Orlando's head start in the hydrogen industry with its existing station at the airport, we see it as the key to getting hydrogen moving in Florida. The second tier of seven stations rounds out the Top 10. It creates a hydrogen corridor from Miami Lakes to Ft. Lauderdale to Delray Beach, as well as a connected triangle between Tampa, Orlando, and Gainesville. The third tier fleshes out the Orlando, Tampa, and Miami clusters. The fourth tier completes the network up I-95 from Palm Beach Gardens to Jacksonville. The fifth tier extends the I-75 network north and south of Tampa–St. Petersburg, as well as adding to the Miami and Orlando clusters and shortening the distance between stations on Florida's Turnpike. Fig. 10 shows that the spacing of the connecting stations between the clusters along I-95, I-4, and Florida's Turnpike never exceed 100 miles.

We ranked the two university stations in the second tier. The Gainesville station was actually optimal in a number of scenarios, based on intercity trips to and from Gainesville and along I-75. It becomes a higher priority considering the hydrogen research program at the University of Florida, as well as university vehicle fleets and the greater likelihood of staff and students as early adopters. Similar arguments apply to Florida State University in Tallahassee, minus the through-traffic benefits but plus the benefits to state government fleets and for purposes of political demonstrations and leadership. A number of other universities around the US have hydrogen stations (e.g., Penn State, UC-Davis, UCLA, UC-Irvine, UC-Riverside, and CSU-LA).

Kennedy Space Center is placed in the third tier, even though we assume the station would be at the NASA Visitor Center. To be conservative, we assumed it is too far out of the way to refuel trips along I-95. Nevertheless, we include it in the third tier because of its importance to the proposed rental-car business, its attractiveness as a tourist destination to technophiles, its use of hydrogen for rockets, and the availability of hydrogen for a station. Daytona is another location of particular interest because of its car-racing heritage. Although it was rarely chosen in the Top 20, it was consistently in the Top 25 and we moved it up to the 4th tier in order to phase in the I-95 connecting stations as a group. About 5% of car renters included it in their bundle of trips with the Orlando theme parks and/or downtown Orlando, and it is also a popular weekend destination from Orlando.

In prioritizing stations for Orlando intra-city traffic flows, we consider scenarios using the likely-consumer-demand multipliers to be the most important. Secondly, we consider maximizing trips more important than maximizing VMT for the urban network. In the urban network, in contrast to the statewide network, it is actually easier to refuel the longer trips, because the long trips are more likely to use freeways and more likely to encounter at least one station somewhere along the route. Our emphasis, therefore, is on refueling as

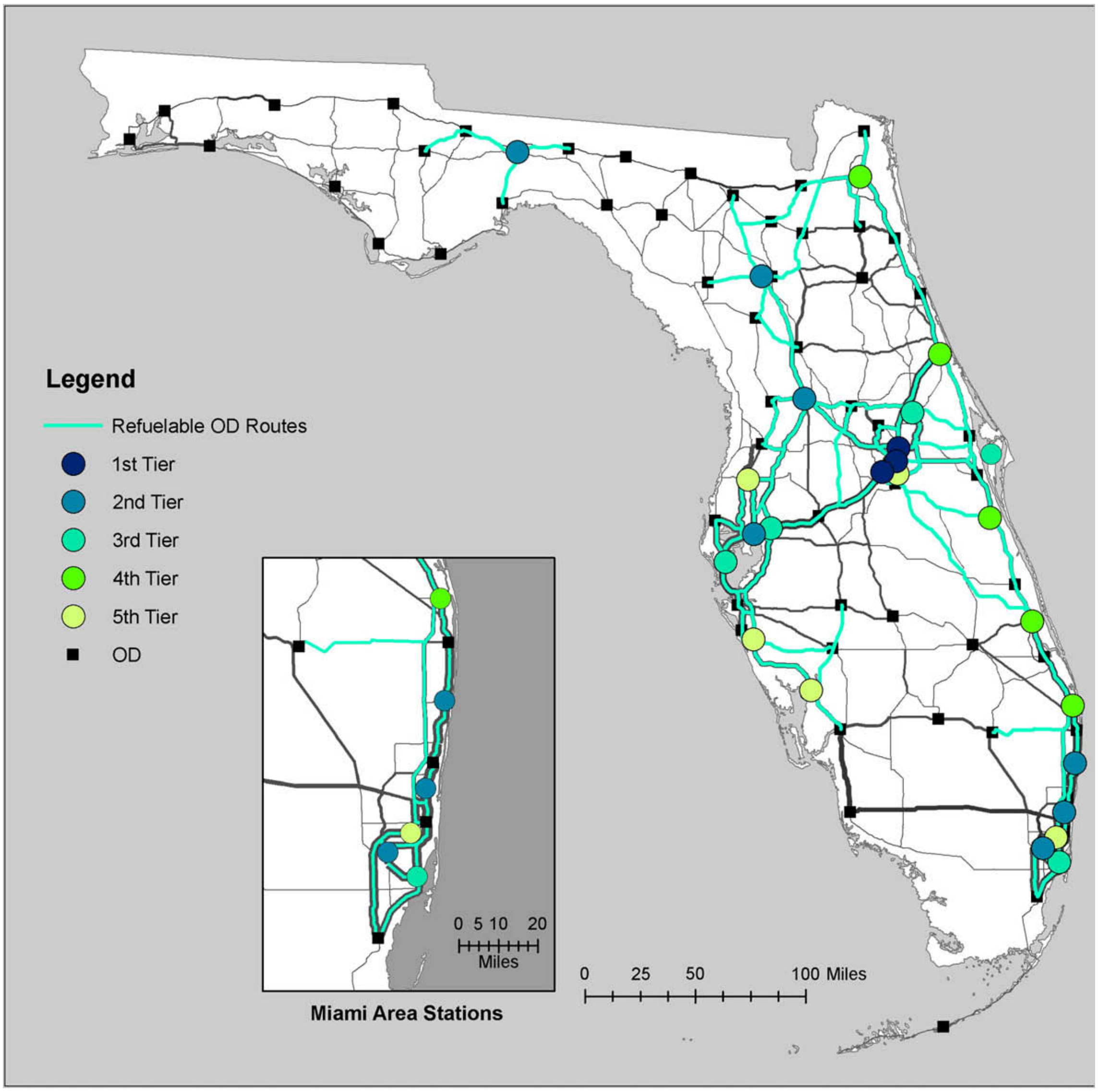

Fig. 10 – Statewide refueling infrastructure strategy.

many trips as possible, both short and long. An initial network of 11 hydrogen-refueling stations prioritized into two tiers could refuel about 54% of weighted trips (Fig. 11; Table 3). Development in coordinated stages is less important than in the statewide network because distances within the metro area are not long enough to require multiple refuelings on any given trip. The stations are grouped into tiers mainly according to their potential to add to the total trips that can be refueled. Five of the stations are also important in the statewide network.

Compared with the statewide network, there is more consistency across Orlando scenarios, leading to a robust plan with reduced uncertainty. Eleven stations are included because there are 10 that capture substantial amounts of traffic and/or play key roles in the rental-car business model, and an 11th station is needed at a key highway intersection for the statewide network. Eight of the 11 stations are consistently in the Top 10 in every scenario and are robust choices. The three stations needed for the rental business are joined in the Top 5 by stations at funnel points of the network that capture many trips not otherwise refueled by the downtown, airport, and theme-park stations. We propose placing the theme park station near I-4 so it would be accessible to through traffic for the statewide network. Detailed explanations for the other high-priority stations and a full list of all stations that were optimal in any run can be found in [17].

9. Conclusions and future research

Having already summarized the station location priorities for the Florida statewide network and Orlando metropolitan travel, a number of general policy conclusions can be drawn from these analyses that may be useful for other regions in their transition to hydrogen vehicles. First, although the FRLM does not assume either a clustering or bridging strategy, the

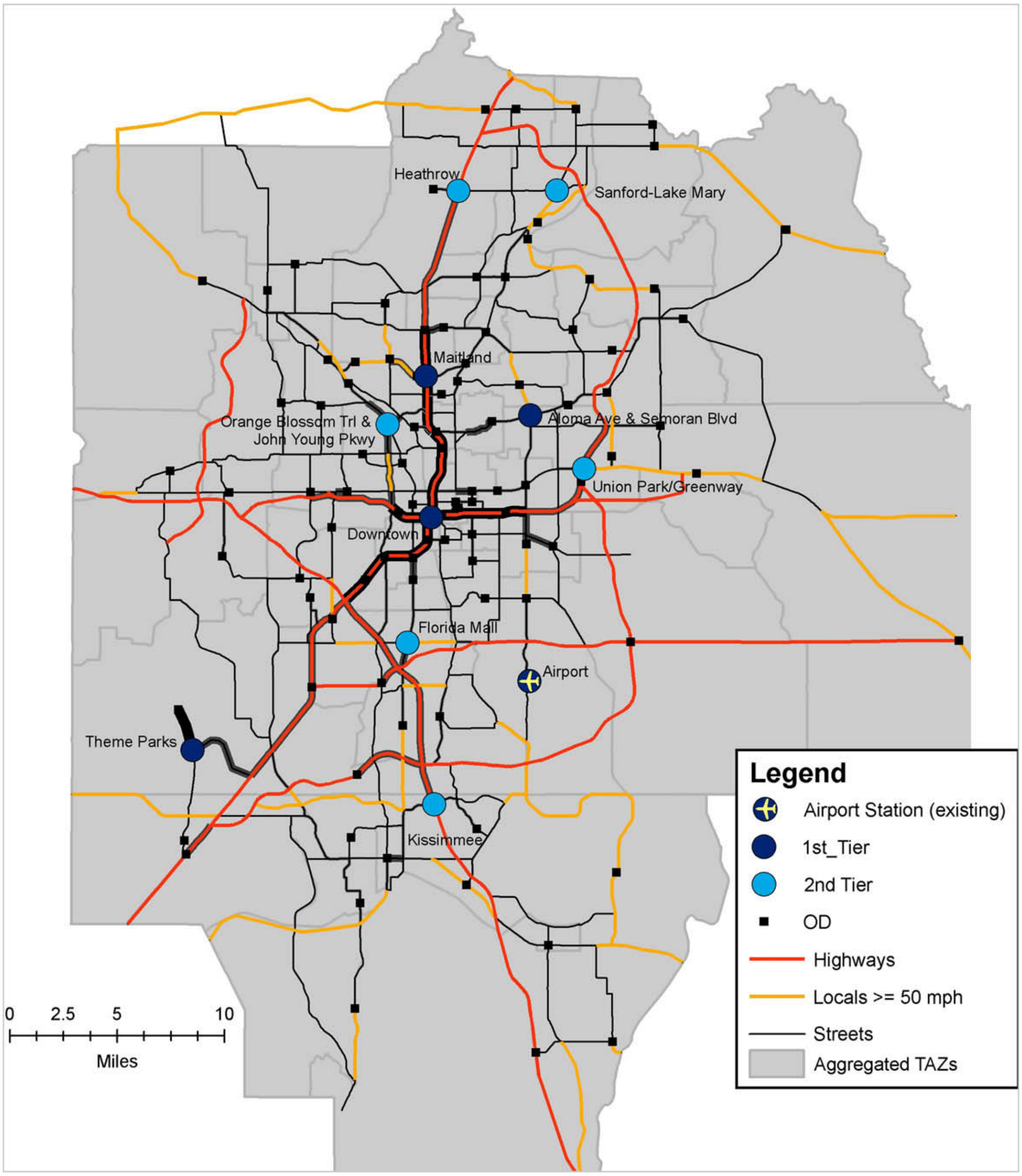

Fig. 11 – Orlando refueling infrastructure strategy.

results appear to suggest a strategy somewhat similar to California, beginning with clusters in the major cities and later building bridging stations to facilitate trips between urban regions.

The initial clusters in and near large metropolitan areas can refuel the high trip volumes between heavily populated nodes that are close together. Clustering also enables the stations to work together to refuel medium-length trips that require multiple stations along the travel route.

There is no consistent formula or guideline to determine when bridging stations should be added to connect the clusters. Given the high cost of building hydrogen stations, it is important to use a model such as the FRLM to determine this critical component of the strategy considering the distance, trip volumes, and network structure of the region in question. It is important to place bridging stations where they can also serve crossing traffic flows and local traffic flows.

Careful thought and planning must be given to the spacing of bridging stations. Spacing stations too far apart could lead to emergency situations and stranding of vehicles that could compromise safety and generate bad publicity. On the other hand, spacing stations too closely sacrifices coverage of trips elsewhere and could lead to duplication and underutilization. Our choice of a 100-mile driving range is consistent with NREL's assumptions, and should be adequate for dealing with detours, getting lost, incomplete refueling, and station

Table 3 – Orlando infrastructure strategy.

Jct	Intersection	Place	Max Trips Airport	Max Trips Airport + Disney	Max Trips Airport + Disney weighted demand	Max VMT Airport + Disney weighted demand
First tier – top 5						
29	Aloma Ave & Semoran Blvd	East of Winter Park	Top 5	Top 5	Top 5	Top 10
144	Epcot Ctr Dr between I-4 & World Dr	Theme Parks	Top 20	Required Rental Station	Required Rental Station	Required Rental Station
176	I-4 & W Maitland Blvd	Maitland	Top 5	Top 5	Top 5	Top 10
202	I-4 & East-West Expwy	Downtown	Top 5	Top 5	Top 5	Top 5
305	S Access Rd & Airport Blvd	Orlando International Airport	Existing	Existing	Existing	Existing
Second tier – top 11 stations						
66	Orange Blossom Trail & N John Young Pky	Northwest Orlando	Top 10	Top 10	Top 10	Top 10
126	S Orange Blossom Trail & Sand Lake Rd	Florida Mall	Top 15	Top 15	Top 15	Top 20
148	S Orlando Dr between Cent Florida Greenway & Lake Mary Blvd	Sanford - Lake Mary	Top 20	Top 20	Top 15	Top 25
168	I-4 & W Lake Mary Blvd	Heathrow	Top 10	Top 10	Top 10	Top 5
180	Cent Florida Greenway & E Colonial Dr	Union Park	Top 10	Top 10	Top 10/25	Top 10/15/25
210	Osceola Pky between Florida's Tpke & Orange Blossom Trail	Kissimmee	Top 10	Top 10	Top 10	Top 20

closures. A smaller driving range, such as 50 miles, would lower the percentage of intercity trips and VMT that can be refueled by a given number of stations, perhaps unnecessarily. It would also further cluster the optimal 25 stations and reduce coverage for other areas. Whatever the driving range, it should be enforced as a maximum spacing only. Strict regular spacing will waste scarce resources.

To get the most benefit out of the initial infrastructure rollout, it is important to locate stations at funnel points on the road network through which many trips pass, from many origins to many destinations. This is best achieved by locating many of the first stations on major freeways with high volumes of *passing* traffic, where they intersect with other freeways or major arterials with high volumes of *crossing, originating, or ending* traffic. It is equally important that these funnel points duplicate or cannibalize each other as little as possible. Thus, stations on major freeways should not be too close together. At the intra-metropolitan scale, the highest priority locations will not necessarily be spread evenly across the network to minimize average distance from where people live to their nearest stations. As more stations are added, however, optimal locations are increasingly spread around to smaller and smaller funnel points in suburban areas, and the overall network gradually begins to resemble an evenly spread distribution that would minimize average distance to stations but favor freeway locations.

While other empirical research has shown that consumers tend to refuel their conventional vehicles near their homes, we caution against concluding that the initial set of hydrogen stations should be located according to that principle. We believe it is more important to locate the early set of stations along the routes people travel rather than locate them near their homes, especially because the first 10 or so stations can only truly be near a small fraction of residents' homes, but can be directly en route for over half of all trips.

Not all residents are equally likely to purchase hydrogen vehicles when they become available. NREL has estimated geographic differences in consumer demand, and market analysis may reveal certain neighborhoods as "hot" markets for alternative-fuel vehicles. Regardless of whether a model uses flow demands like the FRLM or point demands like the *p*-median, some scenarios should be conducted using weighted demands reflecting consumer preferences.

Finally, we recognize that factors not included in the model's data set should be taken into consideration. In the case of Florida, unique synergistic opportunities exist with a possible OIA rental-car business, Florida's flagship universities, Kennedy Space Center and Disney, and the state capital in Tallahassee. Other regions will offer their own unique opportunities that are not reflected in their trip tables, and thus it is important that the decision support system be able to solve a variety of scenarios quickly and display the results visually. Tradeoff curves based on model results can help decision-makers visualize the diminishing marginal returns typical of these kinds of problems, but the number of stations to build is ultimately a political decision.

Additional research could improve on these results in a number of ways. To begin with, a more detailed analysis of the Miami and Tampa metropolitan areas, similar to the Orlando network analysis, should be performed. In the statewide network, the Miami-Palm Beach area is represented by nine OD nodes, while the Tampa area stretching from Sarasota to Pasco County to Lakeland is represented by eight nodes, compared with over 100 nodes in the Orlando intra-city network. Modeling these two metropolitan areas at the same level of detail as Orlando was beyond the limited scope of this project. Future research could also incorporate out-of-state trips, which were omitted from these data, limiting the traffic in the Panhandle.

We are working on several enhancements to the FRLM model. First, the model could allow drivers to detour from their shortest paths up to some limit or with decreasing willingness, as it has been incorporated in flow-intercepting models [37]. Second, models need to account for the different fixed cost of different sites, based on land prices and co-location possibilities with fuel depots, hydrogen production facilities, and other alt-fuel stations [24]. Third, the FRLM and the *p*-median models could be combined into a multiobjective model to identify solutions in which stations can refuel many paths *and* minimize distance from stations to residential areas [36]. Fourth, we need to develop consistent trip tables to optimize local-scale and state-scale networks simultaneously.

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REFERENCES

[1] US Dept of Energy. National hydrogen energy roadmap. Washington, DC: US Dept of Energy; 2002.
[2] National Research Council. The hydrogen economy: opportunities, costs, barriers, and R&D needs. Washington, DC: The National Academies Press; 2004.
[3] Melendez M. Transitioning to a hydrogen future: learning from the alternative fuels experience. Golden, CO: National Renewable Energy Laboratory; 2006. Technical Report No. NREL/TP-540-39423.
[4] Ogden JM. Prospects for building a hydrogen energy infrastructure. Ann Rev Energy Environ 1999;24:227–79.
[5] Goodchild MF, Noronha VT. Location–allocation and impulsive shopping: the case of gasoline retailing. In: Ghosh A, Rushton G, editors. Spatial analysis and location–allocation models. New York: van Nostrand Reinhold; 1987. p. 121–36.
[6] Bapna R, Thakur LS, Nair SK. Infrastructure development for conversion to environmentally friendly fuel. Eur J Oper Res 2002;142(3):480–96.
[7] Nicholas MA, Handy SL, Sperling D. Using Geographic Information Systems to evaluate siting and networks of hydrogen stations. Transp Res Rec 1880;2004:126–34.
[8] Kuby MJ, Lim S. The flow-refueling location problem for alternative-fuel vehicles. Socio Econ Plann Sci 2005;39: 125–45.
[9] Nicholas MA, Ogden J. Detailed analysis of urban station siting for California hydrogen highway network. Transp Res Rec 1983;2006:121–8.
[10] Melendez M, Milbrandt A. Regional consumer hydrogen demand and optimal hydrogen refueling station siting. Golden, CO: National Renewable Energy Laboratory; 2008. Report No.: NREL/TP-540-42224.
[11] Melaina M, Bremson J. Refueling availability for alternative fuel vehicle markets: sufficient urban station coverage. Energy Policy 2008;36(8):3223–31.
[12] Lin Z, Ogden J, Fan Y, Chen C. The fuel-travel-back approach to hydrogen station siting. Int J Hydrogen Energy 2008;33(12): 3096–101.
[13] Bersani C, Minciardi R, Sacile R, Trasforini E. Network planning of fuelling service stations in a near-term competitive scenario of the hydrogen economy. Socio Econ Plann Sci 2009;43(1):55–71.
[14] Upchurch C, Kuby MJ, Lim S. A capacitated model for location of alternative-fuel stations. Geog Anal 2009;41:127–48.
[15] Conzelmann G: Cirillo R, Mintz M, Macal C, North M. In: Modeling the evolution of a new hydrogen infrastructure using a complex adaptive using a complex adaptive systems approach. Proceedings of the National Hydrogen Association, Los Angeles, CA; April 26–30 2004.
[16] Ogden JM. Developing an infrastructure for hydrogen vehicles: a southern California case study. Int J Hydrogen Energy 1999;24(8):709–30.
[17] Lines L, Kuby MJ, Schultz R, Xie Z. Hydrogen refueling infrastructure and rental car strategies for commercialization of hydrogen in Florida, Final report to Florida Hydrogen Initiative. US Dept of Energy; June 30, 2007. FHI Agreement No. 2005-01, Grant Award No. DE-FC36-04G014225.
[18] Lines L, Kuby MJ, Schultz R, Clancy J, Xie Z. A rental car strategy for commercialization of hydrogen in Florida. Int J Hydrogen Energy 2008;33(20):5312–25.
[19] California hydrogen blueprint plan, vols. 1 and 2. California Environmental Protection Agency. Available from: www.hydrogenhighway.ca.gov/plan/plan.htm; May 2005 [Last accessed March 31, 2007].
[20] Worldwide hydrogen fueling stations. Fuel Cells. Available from: www.fuelcells.org/info/charts/h2fuelingstations.pdf; 2000 [Last accessed July 24, 2008].
[21] Huleatt-James N. Hydrogen infrastructure survey. 2008; Available from: www.fuelcelltoday.com/media/pdf/surveys/2008-Infrastructure-Free.pdf [Last accessed July 24, 2008].
[22] California Fuel Cell Partnership. Driving for the future, Available from: www.fuelcellpartnership.org/ [Last accessed April 30, 2004].
[23] California Fuel Cell Partnership. 2004–2007 plans: the next four years. Available from: www.fuelcellpartnership.org/fact_sheets/factsheet_04-07.html [Last accessed March 31, 2007].
[24] Melendez M, Milbrandt A. Analysis of the hydrogen infrastructure needed to enable commercial introduction of hydrogen-fueled vehicles. National Renewable Energy Laboratory; 2005. Report No. CP-540-37903.
[25] Greene DL, Leiby PN, James B, Perez J, Melendez M, Milbrandt A, et al. Analysis of the transition to hydrogen fuel cell vehicles and the potential hydrogen energy infrastructure requirements. Oak Ridge, TN: Oak Ridge National Laboratory; March 2008. Report No. ORNL/TM-2008/30.

[26] Hydrogen, fuel cells & infrastructure technologies program: multi-year research, development and demonstration plan. US Dept of Energy, Office of Energy Efficiency and Renewable Energy; 2007.

[27] Adamson KA, Crawley G. Fuel cell today, 2007 automotive infrastructure survey. Hertfordshire, UK: Royston. Available from: www.fuelcelltoday.com/FuelCellToday/FCTFiles/FCTArticleFiles/Article_1187_Automotive%20Infrastructure.pdf; 2007.

[28] Melaina MW. Initiating hydrogen infrastructures: preliminary analysis of a sufficient number of initial hydrogen stations in the US. Int J Hydrogen Energy 2003;28(7):743–55.

[29] Melaina MW. Turn of the century refueling: a review of innovations in early gasoline refueling methods and analogies for hydrogen. Energy Policy 2007;35(10):4919–34.

[30] Melaina MW. Estimating relative station sizes in early hydrogen station networks. In: Proceedings of the National Hydrogen Association, Washington, D.C.; 2005.

[31] Nicholas MA, Handy S, Sperling D. Hydrogen refueling network analysis using Geographic Information Systems. In: Proceedings of the National Hydrogen Association, Los Angeles, CA; April 26–30 2004.

[32] Hakimi SL. Optimum locations of switching centres and the absolute centres and medians of a graph. Oper Res 1964;12:450–9.

[33] Revelle CS, Swain R. Central facilities location. Geogr Anal 1970;2:30–42.

[34] Hodgson MJ. A flow capturing location allocation model. Geogr Anal 1990;22:270–9.

[35] Berman O, Larson RC, Fouska N. Optimal location of discretionary service facilities. Transp Sci 1992;26:201–11.

[36] Hodgson MJ, Rosing KE. A network location–allocation model trading off flow capturing and *p*-median objectives. Ann Oper Res 1992;40(1-4):247–60.

[37] Berman O, Hodgson MJ, Krass D. Flow intercepting models. In: Drezner Z, editor. Facility location: a survey of applications and methods. New York: Springer; 1995. p. 389–426.

[38] Berman O, Krass D, Chen WX. Locating flow-intercepting facilities: new approaches and results. Ann Oper Res 1995;60:121–43.

[39] Hodgson MJ, Rosing KE, Leontien A, Storrier G. Applying the flow-capturing location–allocation model to an authentic network: Edmonton, Canada. Eur J Oper Res 1996;90(3):427–43.

[40] Averbakh I, Berman O. Locating flow-capturing units on a network with multi-counting and diminishing returns to scale. Eur J Oper Res 1996;91(3):495–506.

[41] Hodgson MJ, Rosing KE, Zhang J. Locating vehicle inspection stations to protect a transportation network. Geogr Anal 1996;28:299–314.

[42] Berman O. Deterministic flow-demand location problems. J Oper Res Soc 1997;48(1):75–81.

[43] Berman O, Krass D. Flow intercepting spatial interaction model: a new approach to optimal location of competitive facilities. Location Sci 1998;6(1–4):41–65.

[44] Wu TH, Lin JN. Solving the competitive discretionary service facility location problem. Eur J Oper Res 2003;144(2):366–78.

[45] Yang J, Zhang M, Chen X. Class of the flow capturing location-allocation model with service radius. Xitong Gongcheng Lilun yu Shijian/Syst Eng Theory Practice 2006;26(1):117–22.

[46] Zeng W. GIS based facility location planning with different types of consumers. J Dissert 2007;1(2).

[47] Zeng W, Hodgson MJ, Castillo I. The pickup problem: consumers' locational preferences in flow interception. Geogr Anal 2008;41:3–22.

[48] Zeng W, Hodgson MJ, Castillo I. A generalized model for locating facilities on a network with flow-based demand. Netw Spat Econ; doi: 10.1007/s11067-008-9073-8.

[49] Kuby M, Lim S. Location of alternative-fuel stations using the Flow-Refueling Location Model and dispersion of candidate sites on arcs. Netw Spat Econ 2007;7(2):129–52.

[50] Daskin MS. Network and discrete location analysis. New York: John Wiley and Sons; 1995.

[51] Lim S, Kuby M. Heuristic algorithms for siting alternative-fuel stations using the Flow-Refueling Location Model, Unpublished results (under review); 2008.

[52] Black WR. Transportation: A geographical analysis. New York: Guilford; 2003.

[53] Hanson S, Giuliano G. In: The geography of urban transportation. 3rd ed. New York: Guilford; 2004.

[54] Statewide travel demand model: update and calibration, phase II. Ann Arbor, State of Michigan: KJS Associates; 1996.

[55] Center for Urban Transportation Studies, University of Wisconsin–Milwaukee. Guidebook on statewide travel forecasting. Washington, DC: Federal Highways Administration, US Dept of Transportation; 1999.

[56] Melendez M, Milbrandt A. Geographically based hydrogen consumer demand and infrastructure analysis. Golden, CO: National Renewable Energy Laboratory; 2006. Report No.: NREL/TP-540-40373.

[57] Kuby MJ, Lim S, Wang K. A model for optimal location of hydrogen refueling stations: an Arizona case study. In: Proceedings of the National Hydrogen Association, Los Angeles; April 26–30, 2004.

[58] Kitamura R, Sperling D. Refueling behavior of automobile drivers. Transp Res A Pol 1987;21A(3):235–45.