FLORIDA HYDROGEN INITIATIVE

HYDROGEN REFUELING INFRASTRUCTURE AND RENTAL CAR STRATEGIES FOR COMMERCIALIZATION OF HYDROGEN IN FLORIDA

FINAL REPORT

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Executive Summary

A recent study by the National Renewable Energy Laboratory found that government fleets of hydrogen vehicles are not enough to jump-start the hydrogen industry. “Finding a way to transition from fleets to consumers,” they concluded, “is equally critical.” In this report, we address this critical need by developing strategies for Florida’s early stages of hydrogen-powered consumer transportation. In particular, we investigate urban and statewide networks of refueling stations and the feasibility of a hydrogen rental-car fleet based in Orlando. These two ideas are linked by the potential for a few stations, properly located, to serve the needs of a surprisingly high percentage of car renters in Orlando.

Hydrogen Rental-cars. The vision for a hydrogen rental-car business based at the Orlando International Airport is compelling. Orlando is the country’s #1 tourist destination, but most of those tourists visit only a few local destinations. Central Florida has a reputation for innovation, with its unique theme parks and the hydrogen-powered space program at Cape Kennedy. Visitors could have a positive first exposure to hydrogen vehicles with no commitment, and become hydrogen advocates in their home regions and potential early adopters. The rental-car business combines the logistical advantages of a fleet operation while reaching large numbers of consumers. A hydrogen powered rental-car fleet at OIA can provide guaranteed demand to the initial rollout of a hydrogen-refueling infrastructure in the area.

To investigate the feasibility of a hydrogen rental-car business at the Orlando International Airport, we surveyed rental-car customers to understand the demand side. Our survey of 435 renters found that half would be willing to pay more to rent a hydrogen car, and over 80% would be willing to detour a mile or more for a station. Most importantly, we found that three stations at the airport, theme parks, and downtown Orlando would enable 80% of car renters to complete trips to all of their destinations, increasing to 85% with a fourth station at Kennedy Space Center.

From the rental company’s point of view, major barriers to a successful hydrogen rental-car business model include: viable consumer target markets; a steady revenue stream via rental of conventional vehicles; a means of identifying customers willing to upgrade to hydrogen; adequate range and refueling locations; breakdown and insurance coverage; the status value of hydrogen cars; the resale market for used vehicles; and most importantly, the availability of hydrogen cars to purchase at a reasonable (subsidized) price. Solutions to each of these issues are proposed here. Synergies with NASA or Disney, refueling stations, and auto manufacturers have the potential to overcome these problems. The strongest evidence that a hydrogen rental-car business is a realistic possibility is the recent announcement by Hertz of a plan to rent a small number of hydrogen vehicles in Iceland. Given this new development and accelerated plans for producing hydrogen vehicles by major automobile manufacturers, planning for the hydrogen rental business and associated refueling infrastructure should begin now. A hydrogen rental-car start-up in the 2012-2015 timeframe would place Florida at the forefront of the hydrogen industry.

Modeling Hydrogen Refueling Infrastructure. Given the high cost of the initial refueling stations, locating a limited number of stations as efficiently as possible will be a key to early success of the industry in Florida. We developed a model that locates stations optimally to serve the maximum consumer demand possible, and quantifies the tradeoff between the number of stations and how much potential demand can be served. The foundation of the model is a road network and a set of traffic analysis zones within a geographic information system (GIS). Using GIS, we find the shortest path (in travel time) from every origin to every destination. Then, given the flow volume on each path, a driving range (in miles) that hydrogen vehicles can be reasonably driven between refuelings, and the number of stations to build, the model uses operations-research (OR) techniques to solve for the optimal set of locations that maximize the amount of transport demand that can be served. Transport demand is measured either in number of trips or vehicle-miles traveled. The GIS and OR models are integrated in a spatial decision support system that researchers can use to develop data, enter assumptions, analyze various 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: a metropolitan Orlando network, and a statewide network.

Statewide Infrastructure. To maximize the potential for drivers to use the first set of stations, the model suggests clustering the first ten stations in the Miami-West Palm Beach corridor and the Tampa-Orlando I-4 corridor, followed by filling in and connecting these clusters. In the statewide analysis, we assume a driving range of vehicles of 100 miles, which allows a large safety margin compared with the expected technical range of hydrogen vehicles of around 300 miles per fill-up. The 100-mile range should be treated as a maximum: it is important to place connecting stations where they can also serve crossing traffic flows and local traffic flows, rather than spacing them at regular 100-mile intervals. We also analyzed scenarios of 75- and 50-mile vehicle range, in which optimal station networks were progressively more clustered and less connected.

Orlando Infrastructure. To get the most benefit out of the initial refueling infrastructure in Orlando, the model locates stations at funnel points on the road network through which many trips pass, from many origins to many destinations. This strategy wins out over spreading the stations evenly across the metropolitan area. 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 stations can only truly be near a small fraction of Orlando residents' homes, but can be right on the route of over half of all trips.

Recommendations. We recommend developing a statewide network of 25 stations in five stages or tiers, 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.

For Orlando, we recommend working towards an 11-station network, which could capture 54% of intra-city trips. The first tier or stage includes the airport, downtown, and theme park stations that are essential to the rental-car business, as well as two other stations on the northern side of town at traffic funnel points that capture heavy traffic flows not otherwise captured by the other three stations. The second tier of six stations includes stations in Kissimmee and Sanford that are recommended for the statewide network.

Next Steps. Future modeling research could focus on a more detailed analysis of the Miami and Tampa metropolitan areas similar to the Orlando network analysis, and an extension of the model to deal with drivers' deviations from their shortest paths. Next steps for the rental-car business plan are to begin discussions with rental-car companies, as well as energy companies that build stations, and possible partners at Disney and NASA.

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We could not have done this work without the brilliant efforts of several students. Ph.D. candidate Seow Lim at Arizona State University (ASU) programmed the greedy and genetic algorithms that solve the FRLM. Ph.D. student Jong-Geun Kim at ASU worked closely with Seow Lim to develop the GIS components of the Spatial Decision Support System, and worked closely with the faculty team to build and test the networks and data bases. Ph.D. student James Clancy at ASU was instrumental in interviewing key people in the hydrogen and rental-car industry for understanding the barriers and solutions from the corporate point of view. Marissa Williams, who recently graduated from Rollins College, did a tremendous job interviewing car renters at the Orlando airport and compiling the data.

Several people in the industry have been extremely generous with their time. Yongqiang Wu of the Systems Planning Office at the Florida Department of Transportation, Roberto Miquel of Cambridge Systematics in Tallahassee, and Dennis Hooker of MetroPlan Orlando provided essential transportation data and GIS layers. Margo Melendez and Anelia Milbrandt of the National Renewable Energy Laboratory in Golden, Colorado have provided data, advice, and encouragement. Bob Kelley of EV Rentals in Phoenix, AZ generously shared his insights and experience regarding renting alternative-fuel vehicles. Karen Faussett of the Michigan DOT provided information about their statewide forecasting model. We also thank the following for information they shared: John Masiello of Progress Energy in Orlando; Nicole Barber of Florida DEP; Herman Everett of NASA; Gerry Paulus of City of Mesa; and Ray Hobbs of Arizona Public Service. We have learned much about the hydrogen industry from discussions with Gene Nemanich, former President of the National Hydrogen Association; about hydrogen station location from Michael Nicholas and Marc Melaina of UC Davis; and about flow-capturing models from M. John Hodgson and Weiping Zeng of University of Edmonton. Max Wyman, of Terragenesis, Inc. in Tempe, AZ provided the original inspiration for this work.

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1. INTRODUCTION

Widespread problems associated with the fossil fuel economy, such as the availability of fossil fuels, reliance on oil imports from Middle-Eastern countries, and greenhouse gas emissions, have motivated the vision and effort to transition from a fossil fuel economy to a hydrogen economy. Barriers to the hydrogen economy, however, are high. These barriers include the cost of building the infrastructure, the maturity of hydrogen production, delivery, and storage technologies, and perceived safety risks [1, 2].

As Florida considers the transition to a hydrogen economy, it would do well to learn from past experiences with other alternative fuels. A 2006 study by the National Renewable Energy Laboratory (NREL) [3] studied the lessons that can be learned from other alternative fuels and applied to hydrogen. The study ranked the various barriers in three ways: a comprehensive literature review, rankings by NREL scientists and engineers, and rankings by Clean Cities coordinators. All three rankings agreed that the #1 barrier is the availability of alternative fuel infrastructure—or lack thereof. The high cost of purchasing alternative-fuel vehicles (AFVs) and the availability of AFVs were also identified as major barriers by NREL and Clean Cities coordinators.

These two sets of barriers—refueling infrastructure and available/ affordable vehicles—are closely interrelated. It is often said that the transition to hydrogen faces a chicken-and-egg quandary [1-5]. Manufacturers will not be able to sell mass-produced vehicles until consumers are able to refuel the cars when traveling between their desired origins and destinations. Likewise, hydrogen-fuel producers and distributors will have no market for hydrogen until manufacturers begin mass-producing vehicles.

The typical solution to this chicken-and-egg dilemma is (a) government-subsidized initial alternative-fuel infrastructure and (b) incentives or mandates for government and industry fleets of AFVs. This two-pronged approach is meant to provide guaranteed initial demand for both vehicles and stations. Yet, a major message from the NREL study of barriers [3] was that the fleet market, while undoubtedly important, "was not sufficient to generate significant sales for vehicle manufacturers." The study concluded that "finding a way to transition from fleets to consumers is equally critical."

To this end, our research focuses on a unique integration of two closely related solutions to these two related sets of barriers for the transition to consumer use of hydrogen vehicles in Florida. We analyze an optimal network of refueling stations for intra-city trips in the Orlando metropolitan area and for statewide, intercity travel. In addition, we evaluate the feasibility of a hydrogen rental-car business based at the Orlando International Airport. The rental-car business model has most of the logistical advantages of a fleet approach to introducing AFVs, with the additional benefit of reaching the consumer market. Orlando is the country's number one tourist destination, attracting millions of tourists from all over the US and the world. A hydrogen rental-car fleet based in Orlando would attract worldwide attention and introduce thousands of potential buyers to hydrogen vehicles in a fleet-like situation. The hydrogen rental-cars would provide a base level of guaranteed demand for the initial set of hydrogen stations in and around

Orlando. Orlando's tourism industry is uniquely well-suited for a hydrogen rental-car business; in that most of these tourists visit only a handful of local destinations, making it possible to serve most visitors with a small number of well-placed hydrogen stations.

The first part of our report provides a brief overview of both sides of the chicken-and-egg problem in Florida, the US, and worldwide. Section 2.1 reviews the efforts underway worldwide to develop initial networks of hydrogen refueling stations, while Section 2.2 reviews the current timetables for hydrogen vehicle production by major carmakers.

Section 3 analyzes the feasibility of a hydrogen rental-car business based at the Orlando International Airport. Section 3.1 presents the results of a survey conducted of 435 car renters in Orlando, while Section 2.2 then uses these survey results and other sources of information to assess the barriers to a hydrogen rental-car operation and propose some practical solutions.

The final part of our study focuses on the optimal refueling infrastructure for hydrogen-powered vehicles in Florida. The emphasis here is on developing a coordinated system of multiple stations, rather than choosing an exact suitable parcel of land for a station site. 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 [6]. Section 4.1 reviews the literature on approaches to planning and modeling the best locations for a *network* of refueling stations. Section 4.2 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 and GIS techniques, along with sophisticated and detailed transport data bases, to locate a coordinated set of stations so as to maximize the potential for Florida consumers to refuel as many trips, or replace as much gasoline consumption, as possible. Section 4.3 describes the data sources and data preparation steps. Sections 4.4 and 4.5 then apply the model to a statewide network and to the Orlando area, respectively. Section 5 integrates the two sets of results and the hydrogen rental-car analysis into a final set of recommendations for developing a refueling network.

2. HYDROGEN REFUELING INFRASTRUCTURE DEVELOPMENTS AND VEHICLE PRODUCTION PLANS: DOMESTIC AND FOREIGN

2.1 Hydrogen Refueling Infrastructure Developments

As the State of Florida plans for a hydrogen future, it is useful to provide a brief overview of the efforts of other regions to develop networks of refueling stations. Many regions in the US and around the world have begun planning or deployment of an initial network of hydrogen refueling stations in order to break the well-known chicken-and-egg cycle, by which the lack of vehicles inhibits station development, and vice versa.

We begin this review in California, where due to air-quality problems, the state of California has forged ahead of any other region in the world in developing a hydrogen-refueling infrastructure. As of the end of 2006, 24 hydrogen stations were built and operating in California, with 13 more planned for 2007. Of these 24 stations, 15 are available for public use. Initially, in April, 2004, California proposed a statewide Hydrogen Highway (CAH2NET) with 200 refueling stations spaced 20 miles apart by 2010 at a cost of up to $100 million [6]. Though California has backed off somewhat 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, with a few others in San Diego, Palm Springs, and Lake Tahoe [7,8]. 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 who could refuel their hydrogen vehicles on most of their trips. Stations connecting these clusters along rural interstate highways are targeted for Phase 2. The State of California allocated $6.5 to CAH2NET to develop stations in both 2005 and 2006. The December, 2006 Report to the Legislature also identified 126 vehicles and 55 hydrogen-related businesses in California [9]. Supporting the development of the CAH2NET is the California Fuel Cell Partnership, a coalition of 31 auto and energy companies, government agencies, and technology companies that work together to promote commercialization of hydrogen vehicles.

Other regions are also developing or planning networks of hydrogen stations. There are over 140 stations worldwide, with 48% in the US, 14% in Japan, and 13% in Germany [10,11]. By the end of 2007, the number of stations worldwide will surpass 160 [12]. In the United States, New York's H2-NET hopes to have 20 stations by 2015-2020 to facilitate travel from New York City to Buffalo. They also plan to add hydrogen-fueling capability to 70 existing CNG stations, and replace 5% of conventional fuel demand with hydrogen 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 proposes 12 stations 200 km apart by 2012. Discussions are ongoing in South Carolina, in Connecticut, and for a Denver-to-Los Angeles network.

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 [13]. They estimated that 284 stations are needed, at a total construction cost of $837 million. The cost per station ranged from $248,000 to $5.1 million depending on the estimated demand and technology. They concluded that many of the stations could be economically self-sustaining in the near term based on "aggressive assumptions" of 1% penetration of hydrogen light-duty vehicles in 2020 increasing to 20% in 2030. Fourteen of these stations are suggested for Florida, including six at existing natural gas stations and eight at new sites. (The methods used in this study are reviewed in the following section.) At the same time, DOE is putting greater emphasis in 2007 on developing clusters of stations rather than corridors [14].

Outside of the US, many countries are seeding initial refueling infrastructures. In Canada, British Columbia hopes to have a Hydrogen Highway in place connecting Vancouver to Whistler Ski Resort in time for the 2010 Winter Olympics. Five stations are already open. The Canadian federal government has provided CDN$33 million of funding to the Transportation Fuel Cell Alliance. The European Union has a Joint Technology Initiative with the stated goal to kick-start commercialization by 2015 [12]. The Scandinavian Hydrogen Highway Project consisting of HyNor (Norway), Hydrogen Link (Denmark) and HyFuture (Sweden) is trying to link Oslo with Copenhagen.

In the less-developed world, India has developed a National Hydrogen Roadmap, and both Singapore (SINERGY) and China have opened two stations each. In China, the Shanghai Hydrogen Lighthouse Program aims to build a small network of stations for fueling 90 taxis and ten fuel-cell buses by 2010 [12].

Most stations being developed recently provide gaseous hydrogen. Very few provide liquid hydrogen. A recent trend is to build more multi-fuel stations rather than dedicated hydrogen stations. Developing stations to sell hydrogen as well as CNG and other alternative fuels—and possibly even conventional gasoline—is a way to share investment costs and minimize technology risks [12]. One refueling infrastructure project in Europe, called HyChain MiniTrans, is investigating the possibility of selling hydrogen canisters from a dispenser.

Recent Developments in Orlando and Florida

There are currently two hydrogen refueling stations in the Orlando metropolitan area: the Boggy Creek Hydrogen Refueling Station near the Orlando International Airport and a mobile refueling station at Progress Energy's Jamestown Operations Center near Oviedo.

The Boggy Creek Hydrogen Refueling Station is the result of a collaborative project involving the State of Florida, Chevron Technology Ventures, Ford Motor Company, and Progress Energy. Built and operated by Chevron Technology Ventures, the Boggy Creek station (natural gas reformation) opened in May of 2007. Initially it will refuel four hydrogen-powered airport shuttle buses (Ford V-10, E-450). Four additional H2 shuttle buses will be in service by 2008. Under the current plan, the Boggy Creek station is scheduled for decommissioning in May of 2010.

The mobile refueling station at Progress Energy's Jamestown Operation Center opened in September of 2005 and is scheduled for replacement by a fixed electrolysis station in late 2007. This test site is part of a US Department of Energy Demonstration Project: *Ford and BP Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project*. The station currently provides power for six Ford Focus hydrogen fuel cell vehicles operated by Progress Energy and Florida's Department of Environmental Protection. Under the current plan, this station is scheduled for decommissioning in late 2008.

In 2004, the Florida Hydrogen Business Partnership was formed by 27 companies and government agencies with a mission to "establish Florida as a center of hydrogen technology commercialization for the Americas" [15]. The Partnership targeted Orlando as the site for five operating hydrogen stations by 2007. The State of Florida aims to develop the nation's first one-stop permitting standard for hydrogen fueling infrastructure by creating a single, uniform permitting standard and consistent safety codes across all jurisdictions in Florida, and its Energy Plan 2006 calls for sales and corporate income tax credits for hydrogen vehicles and fueling infrastructure [16].

2.2 Hydrogen Vehicle Production Plans

Lack of refueling infrastructure is only half of the chicken-and-egg problem for hydrogen. Florida must also account for the timetables for the manufacture of hydrogen vehicles. While researchers have developed a variety of models for predicting the co-evolution of infrastructure and vehicles, the following section is based on announcements by auto manufacturers rather model simulations.

In their February 2007 survey of the light-duty vehicle market [12], Fuelcelltoday.com, an industry website that publishes annual market surveys, concludes that major manufacturers have in some cases accelerated their timetables for commercializing fuel-cell vehicles (Table 2.1).

General Motors expects to begin production of a fuel-cell version of its Chevrolet Volt, possibly as early as 2010, and they could hit showrooms before 2020 [17]. They are transferring 500 fuel cell engineers from the research department to production. According to Autocar.co.uk, "the world's second largest car company now views hydrogen fuel cell power as the 'the end game,' according to its director of advanced technology vehicle concepts Dr Christopher Borroni-Bird" [18]. GM predicts that FCVs could match conventional vehicles in affordability by the time the scale of production reaches about 1 million units.

Honda has announced it will launch a limited number of fuel-cell vehicles based on the FCX concept car by 2008 in Japan and the US [19]. Hyundai aims to market an affordable FCV by 2015, and boldly forecasts a 90% market share for FCVs by 2050. Renault is reported to begin production of FCVs in India by 2010. Toyota recently announced they would be providing Hertz with Prius hybrids converted to run on hydrogen for a hydrogen rental car operation in Iceland by April, 2008 [20].

Several manufacturers are banking on the internal combustion engine (ICE). BMW advertises that they will begin selling cars using liquid hydrogen in ICEs by 2008. Mazda is developing a rotary engine that can run on gasoline or hydrogen—a development that could potentially remove major concerns about running out of hydrogen when not in the vicinity of a hydrogen station [21].

Table 2.1 Automobile Manufacturers' Hydrogen Vehicles [17-23]

Company	Technology	Driving Range	Future Plans
BMW	ICE	240	Currently introducing series production hydrogen-fueled internal combustion engine Hydrogen 7 vehicles.
GM	Fuel Cell (Chevrolet Volt)	200-300 miles	Begin production of a fuel-cell version of its Chevrolet Volt, possibly as early as 2010.
Hyundai			"Wants to sell a hydrogen powered vehicle at an affordable price by 2015."
Honda	Fuel Cell ("FCV, FCX")	235 miles	"Plans to introduce a limited number of second generation FCX vehicles to the Japanese and US markets in 2008."
Mazda	Dual Fuel ICE ("RX-8 Hydrogen RE")	62 miles on hydrogen and 341 miles on gasoline	Currently leasing prototypes.
Nissan	ICE		Early 2010s
THINK	Fuel Cell ("city vehicle")	180 miles	
PSA Peugeot Citroen	Fuel cell concept vehicle	300 miles	

At its Scenario Analysis Meetings in January, 2007, Dr. Sigmund Gronich, Transition Strategy Manager of DOE's Hydrogen, Fuel Cells, and Infrastructure Technologies Program, presented three scenarios for hydrogen vehicle production in the United States, as shown in Table 2.2, with hundreds to thousands produced by 2012 [14].

Table 2.2 DOE Scenarios for Hydrogen Fuel Cell Vehicle Production

Scenario	By 2012	By 2015	By 2018	By 2021	By 2025
1	100s-1000s		10,000s		2 million
2	1,000s	10,000s	100,000s		5 million
3	1,000s			1,000,000s	10 million

3. HYDROGEN RENTAL-CAR FEASIBILITY STUDY

This section introduces and analyzes a new strategy for creating a base level of demand for an initial refueling infrastructure that may be uniquely well suited for the Orlando area—namely a hydrogen rental-car fleet based at the Orlando International Airport. Generating a base level of demand for hydrogen is a key to overcoming the chicken-and-egg quandary outlined in the previous sections. The risk in rolling out the refueling infrastructure first to short-circuit the chicken-and-egg problem is that the stations may initially be underutilized. While government vehicle fleets will undoubtedly provide some underlying demand for the initial set of stations, the transition from government and industry fleets to consumer vehicles may stall without a strategy to get consumers into hydrogen vehicles. A hydrogen rental-car fleet has the potential to overcome this obstacle, especially one based in Orlando, the number one tourist destination in the United States. In addition, as Box 1 shows, we are not the only ones who think that a hydrogen rental-car fleet is a feasible idea whose time has come.

> Box 1. In breaking news, Icelandic New Energy (INE), an organization promoting hydrogen-powered transportation in Iceland has announced plans to introduce a small fleet of hydrogen-powered rental-cars in April of 2008 [19]. The vehicles will be H2 converted Toyota Prius models, available through Hertz Car Rental in Iceland.

Orlando attracts millions of tourists each year from all over the US and the world. Furthermore, Orlando has a reputation of being on the cutting edge, with its innovative theme parks, the planned town of Celebration, and the nearby Kennedy Space Center. Visitors and Florida residents alike could be introduced to hydrogen-powered vehicles in Orlando with no long-term commitment on their part. Their first experience with hydrogen could be a positive one because of the worry-free availability of centralized service by rental companies and convenient location of refueling stations. In fact, a very small number of stations would be needed to serve most rental-car trips. Benefits would be felt locally, nationally, and worldwide, as renters would become hydrogen advocates in their home regions, and would be more likely to purchase hydrogen vehicles. Florida would benefit by developing a base level of demand for its infrastructure, as well as hydrogen expertise and a reputation for being on the cutting edge of hydrogen deployment.

To examine barriers to using hydrogen as a fuel source for the rental-car market and propose some possible solutions, we pursue two primary lines of research. First, to understand the consumer point of view, we conducted a personal intercept survey of 435 potential car renters. Second, we explored the feasibility of a rental-car business model from the corporate point of view by reviewing literature and conducting interviews with key people in the hydrogen and rental-car industries about barriers to a rental-car business and some possible solutions to those barriers.

3.1 Survey of Car Renters

Consumer attitudes will clearly play a pivotal role in any effort to develop a hydrogen-based rental-car fleet at the Orlando International Airport (OIA). To better understand what is needed to develop a hydrogen rental-car option at OIA we conducted a personal intercept survey of 345 potential car renters at the OIA and 90 visitors to Orlando's theme park attractions at International Drive. The airport surveys were conducted in the OIA rental-car terminal between March and June of 2006. The International Drive visitor surveys were conducted in the shuttle bus waiting areas during August-September, 2005.

The survey instrument (Appendix 1) focused on each respondent's knowledge and awareness of hydrogen technology, reasons for and against renting a hydrogen vehicle, willingness to pay more to rent a hydrogen vehicle, willingness to drive out of their way to refuel, intended destinations in the Central Florida region, and socio-demographic characteristics.

Our typical survey respondent was 43 years of age and female, married with two children, and college educated (see Table 3.1). The majority of respondents were employed in either private industry/business or government/education, with an annual household income considerably higher than the US median household income of $46K. The survey included visitors from 14 different countries (most notably Canada and Great Britain); however, the majority of survey respondents (80%) were from the United States.

Table 3.1 Socio-economic Characteristics of Survey Respondents (n=435)

Average age:	43		
Gender	Female: 59%	Male: 41%	
Marital status:	Married: 80%	Single: 20%	
Number of children:	None: 14%	One: 13%	Two: 41%
	Three: 20%	Four: 7%	Five or more: 5%
Education:	Less than high school: 0%		
	High school graduate: 27%		
	College graduate: 53%		
	Post-graduate degree: 20%		
Occupation:	Student: 3%	Private industry/business: 39%	
	Government/education: 21%	Military: 1%	
	Retired: 6%	Other: 30%	
Household income:	Under $30K: 6%	$30K-49K: 15%	
	$50K-99K: 43%	Over $100K: 36%	
Country of origin:	United States: 80%	United Kingdom: 10%	
	Canada: 6%	Other 11 countries: 4%	

Within our group of survey respondents there was considerable variation in the general understanding of hydrogen vehicle and fuel-cell technology. Despite the wide variation in responses, a significant proportion of the respondents possessed some knowledge of the technology and a familiarity with how it works (see Figure 3.1). This moderate level of knowledge of hydrogen technology may reflect recent media coverage of alternative energy technologies. It may also reflect the high level of educational attainment for our survey respondents (73% are college graduates).

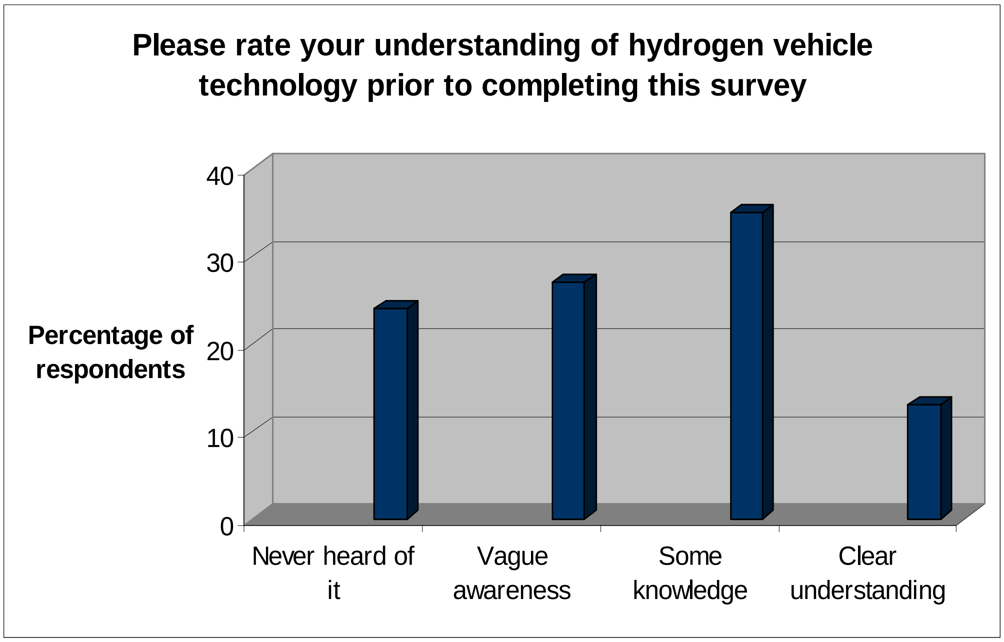

Figure 3.1 Consumer understanding of hydrogen fuel-cell technology

On the question of consumer willingness to pay more to rent a hydrogen vehicle, our survey respondents were evenly divided (49% responding positively). Of the total number of visitors surveyed, 21 percent indicated that they were willing to pay an additional \$5 to \$10 per day to rent a hydrogen car (see Figure 3.2). Roughly 6% of all respondents were willing to pay an additional \$15 to \$20 per day to rent a hydrogen vehicle.

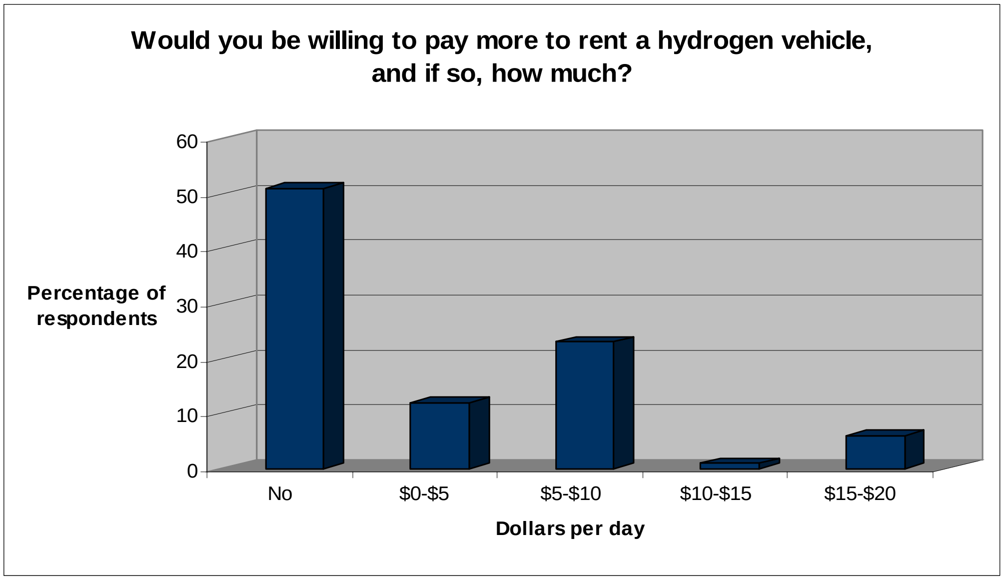

Figure 3.2 Consumer willingness to pay more to rent a hydrogen vehicle

The willingness of car renters to consider a hydrogen vehicle is clearly influenced by a number of different factors. To better understand these considerations in the consumer decision-making process, we asked our survey respondents to rate the importance of a number of features in convincing them to rent a hydrogen vehicle (see Table 3.2). These features reflect a wide range of potential renter concerns including vehicle performance, cost, convenience, customer support, and vehicle safety. Survey respondents rated the importance of each feature on a scale from **1** (not important) to **5** (very important).

Table 3.2 Features influencing consumer decision to rent a hydrogen vehicle

Feature	Average response Scale: **1** (not important) to **5** (very important)
Map of refueling stations in Florida and Orlando	4.3
Ability to exchange for a gasoline car at no extra cost	4.0
Priority parking at theme parks	3.9
Using a pollution-free vehicle	4.4
Fuel cost per mile comparable to gasoline	4.4
Opportunity to experience a new technology	4.0
Opportunity to test drive before renting	3.8
Vehicle performance (e.g., acceleration, noise)	4.1
Driving range of vehicle	4.4
Availability of insurance	4.3
Full-service refueling by a trained attendant	4.0
On-call, roadside repair/refueling service	4.4

The most interesting aspect of the results displayed in Table 3.2 is that respondents rated all features as important. Features considered most important included the driving range of the vehicle, fuel cost per mile, availability of an on-call roadside repair/refueling service, and the opportunity to use a pollution-free vehicle. Other important features were the availability of vehicle insurance and an obtainable map of refueling stations in Florida and Orlando. The responses to this question reflected an interesting mix of practical concerns (e.g., vehicle performance) and wider motivations (e.g., using a pollution-free technology) surrounding the decision to rent a hydrogen vehicle.

Perhaps most significant in our survey of potential car-renters are the questions centered on the intended destinations of Orlando visitors and their willingness to drive out of their way to refuel a hydrogen vehicle. The question on intended destinations—"Which of the following destinations did you (or will you) visit on your trip to Orlando"—provided each respondent with a list of twelve major destinations (see Table 3.3). The responses to this question provide a snapshot of where our potential car renters are driving, and perhaps more importantly, where they are not driving (note: since most respondents identified multiple destinations, summed percentage values exceed 100 percent).

Table 3.3 Intended destinations of potential hydrogen car-renters

Destination	Percentage of respondents identifying this destination
Magic Kingdom	63
Universal Studios	42
EPCOT	40
Sea World	35
Other theme park	21
Downtown Orlando	20
Port Canaveral (cruises)	10
Kennedy Space Center	9
Tampa-St. Petersburg	9
Daytona Beach	8
Miami-Palm Beach area	3
Everglades region	3

As expected, a significant proportion of our respondents identified at least one of the major Orlando theme park attractions as an intended destination. Somewhat surprising were some of the low response rates for destinations beyond the Orlando area such as Daytona Beach (8 percent) and Tampa-St. Petersburg (9 percent). This immediately raised a number of follow-up questions. What percentage of visitors to Orlando are renting vehicles and driving beyond the Orlando area? What specific set or "bundle" of destinations is typical for a car renter at the Orlando International Airport? The answers to these questions have important implications for the initial planning and rollout of a hydrogen-refueling infrastructure in Orlando.

The average length of stay for the 435 Orlando visitors surveyed in our study is 7.9 days. If we assume that the majority of visitors renting a car will rent that car for the duration of their stay, it becomes important that the vehicle they are renting can get them to their entire bundle of destinations for the week. If the rented vehicle is hydrogen-powered, this bundle of destinations will place a specific set of demands on the refueling infrastructure. For example, a number of widely separated destinations will require a very different refueling infrastructure than a concentrated set of destinations in a confined geographic area. In fact, even a single trip to a more distant destination (e.g. Kennedy Space Center) during the course of an otherwise geographically concentrated week of driving will require a different set of stations to refuel that trip. The ability of the refueling network to refuel such a trip could be the pivotal factor in the consumer's decision to rent, or not rent a hydrogen-fueled vehicle.

To examine this issue, we analyzed bundles of visitor destinations both within and outside of the Orlando metropolitan area (Figure 3.3). Most significantly, 80 percent of the car renters surveyed did not identify an intended destination outside of the theme park areas or downtown Orlando. Only 20 percent of our respondents identified intended travel destinations beyond the Orlando area.

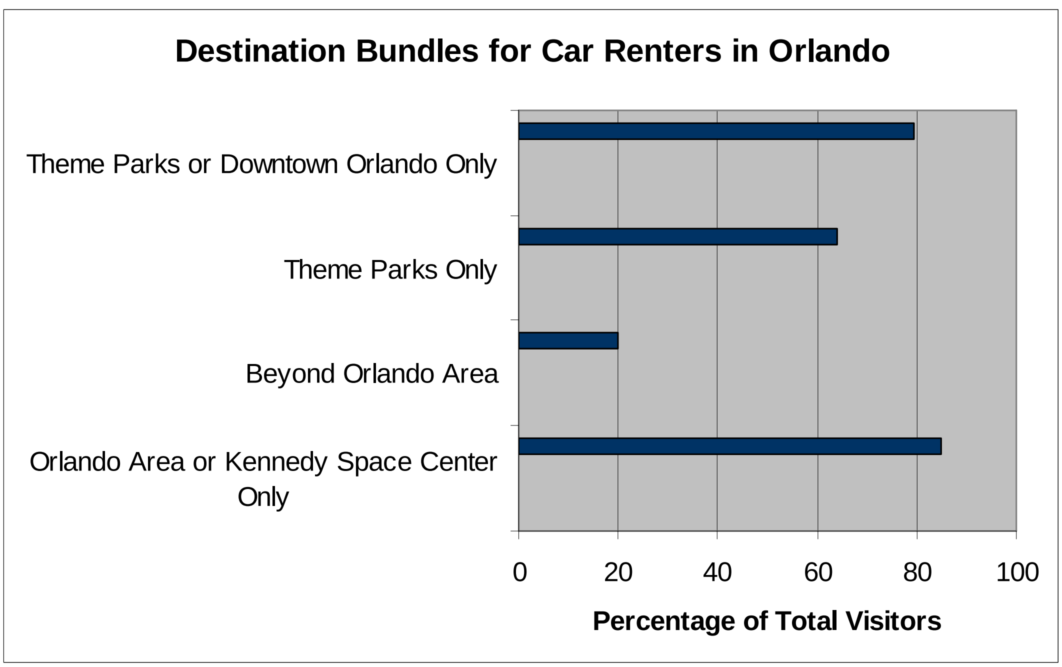

Figure 3.3 Destinations of car renters surveyed at the Orlando International Airport

These findings have important implications for the potential feasibility of a hydrogen-powered fleet of rental vehicles based at OIA. Given that the majority of airport car renters are concentrating their trips in the area of the theme parks and downtown

Orlando, the initial refueling network required to support this fleet of cars could be modest. In fact, our survey data suggests that just *three* refueling stations (located at OIA, downtown Orlando, and Disney) could cover the refueling needs for roughly 80 percent of the car rentals originating from the Orlando International Airport.

We also asked potential car renters how far out of their way they would be willing to drive for a hydrogen refueling station without considering it a hassle. The survey results for this question also support the idea that *three* initial stations in the Orlando area will likely cover the majority of airport car rentals. More than 80% of our survey respondents expressed a willingness to drive more than one mile for a hydrogen refueling station, and 46% were willing to drive more than three miles out of their way (Figure 3.4). These visitors—many of whom are on vacation, and will only need to make this detour once or twice—may exhibit a greater willingness to divert from their optimal driving path than Orlando residents, making the rental-car network more flexible in the refueling of trips.

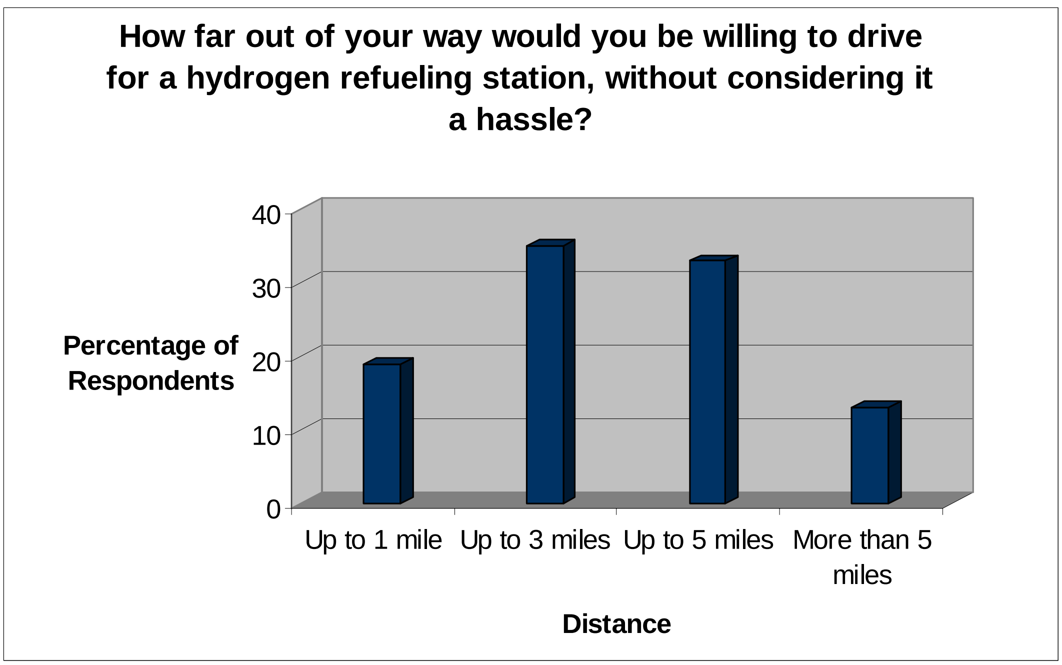

Figure 3.4 Willingness of car renters to go out of their way for a hydrogen refueling station

For all survey questions, we analyzed the results statistically to determine if the demographic characteristics of the renter significantly influenced their responses. We used analysis of variance (ANOVA) to search for relationships between the opinion variables and gender, marital status, education, and income. Our tests, summarized in Appendix 2, were conducted at the 95% confidence level or as alternatively stated, the 5% significance (α) level. We found that people with higher education levels are significantly less concerned about refueling hydrogen vehicles themselves and less concerned about the rental price. Women were significantly more concerned with roadside on-call service, the ability to exchange a hydrogen vehicle for a conventional one, the cost per mile, and the vehicle performance. Males, on the other hand, claimed a better understanding of hydrogen technology and were more concerned with having to detour to a station. Not surprisingly, those with higher education, higher education, and male gender rented cars more frequently.

The survey results outlined in this section have important implications for the initial hydrogen vehicle refueling infrastructure in Florida. Most analysts agree that a major impediment to the introduction of hydrogen fuel-cell technology is the initial cost and individual consumer risk associated with early adoption. Car renters may provide an ideal market for the first wave of hydrogen vehicles in Central Florida. A fleet of hydrogen-fueled rental-cars based at OIA could introduce consumers to hydrogen technology in a setting where their individual costs would be short-term and shared by the rental-car agencies. Since most car-rental trips are concentrated in the area of the theme parks and metro Orlando, the logistical costs associated with consumer support for this rental-car fleet would be quite reasonable.

3.2. Barriers and Solutions from the Corporate Point of View

To understand the barriers to a successful hydrogen rental-car business from the supplier's point of view, and assess solutions to overcoming those barriers, we studied various reports on the hydrogen economy and spoke with a number of key informants. In particular, we interviewed the manager of a rental-car company, EV Rentals, which currently rents hybrid vehicles in partnership with Fox Rent A Car, and previously had experience renting electric and Compressed Natural Gas (CNG) vehicles.

Target Market

Knowing your target market is an important starting point for any new business idea. In the case of renting hydrogen cars, a number of market segments stand out as potential renters of hydrogen vehicles:

1. *Green Consumers.* Ecologically minded consumers have shown a willingness to pay extra for goods and services that allow them to live a more sustainable lifestyle. Such services range from alternative-fuel vehicle purchases, organic foods, renewable electricity, and many others. In addition, EV Rentals has found that green companies, and companies that are marketing to other green companies, are willing to rent alt-fuel and hybrid cars. EV Rentals has found the status value of renting alt-fuel cars to be important to green consumers and companies. Therefore, the car must be easily identifiable by others as a sustainable form of transportation—and not just by a small decal.
2. *Technophiles*. Hydrogen cars capture the imagination of technophiles. Whether it is a fuel cell powering an electric motor, or simply an ICE running on the same fuel that blasts rockets into space, technophiles and car buffs may be very interested in trying out a hydrogen vehicle.
3. *Alt-fuel Privileges.* Some demand for AFVs derives from the privileges associated with them. Use of HOV lanes by single-occupant vehicles is a major incentive in congested areas. EV Rentals noted that some customers in Los Angeles enjoy free

downtown parking with their AFV rentals. We think that priority parking for hydrogen cars at Disney theme parks or Kennedy Space Center might provide an important incentive to rent a hydrogen car, especially if the priority parking also included refueling by a trained technician while they visited the attraction.

In addition, EV Rentals has found it important to also rent conventional vehicles. Conventional vehicles provide a base revenue stream in case demand for alt-fuel cars fluctuates. Offering conventional vehicles would provide the agents with the opportunity to offer upgrades to hydrogen vehicles. Agents can be trained to ask a few key questions that may indicate willingness to upgrade, such as:

"Is this a business or tourist trip?"
"Are you planning to stay within the Orlando area?"
"Are you planning to visit Kennedy Space Center?"
"Would you like priority parking at the theme parks?"

Customer Concerns

While the idea of trying a hydrogen vehicle on a short-term rental basis may be attractive, various concerns may deter potential customers from doing so. Some main concerns, and solutions to overcome these, are listed below:

1. *Safety*. Given that most renters in our survey were middle-aged families with two children and not very knowledgeable about hydrogen, a key concern is likely to be safety. References to the Hindenburg or to "riding a hydrogen bomb" elicit fearful responses. Educational videos comparing the risks of hydrogen to gasoline may help overcome these fears. Videos could be shown on the Internet and at the rental counter. A brief instructional session may be necessary before customers depart with their rented vehicles, and safety brochures should also be placed in each car and on the rental counter and Internet.
2. *Breakdowns*. Advertising can emphasize the lower maintenance requirements of clean-burning hydrogen fuel, but renters are still likely to be concerned about breakdowns and the lack of knowledge and parts at most auto-repair shops. In the survey, on-call roadside repair service was rated as highest in importance to customers with a 4.4 average, and free replacement by a gasoline vehicle was slightly less important at 4.0. In the Orlando area, substitution of another hydrogen vehicle might be possible, but outside of Orlando, quick replacement by a conventional vehicle would seem to be the only viable solution. To make this goal achievable, it is important that the managers of the rental business have experience working with other companies at the Orlando airport, because rental companies often ask each other for help to deliver replacement cars quickly.
3. *Refueling*. In the survey, the driving range of vehicles tied for the highest average importance with 4.4, while a map of refueling stations averaged 4.3, and refueling by a trained mechanic averaged 4.0. Many renters who visit only the theme parks and/or the convention center may not require even a single refueling. Offering customers the ability to return their car empty, without the usual penalty of high fuel fees, might be a major incentive. If refueling could be coupled with parking

at Kennedy Space Center, Disney theme parks, or downtown Orlando, this would provide a large incentive. Ability to "practice" refueling when renting the car might also allay such concerns.

4. *Insurance*. Insurance companies are unfamiliar with hydrogen vehicles, and replacement cost of early vehicles will be high. Customers will undoubtedly be uncertain of whether their regular policy will cover damage to a hydrogen vehicle. The rental-car business must work out the insurance issues for the customer, and government subsidy of supplemental insurance undoubtedly will be necessary in the early going.

Refueling Availability

A customer's ability to rent a hydrogen vehicle hinges on the availability of refueling stations to serve not just one or several of the destinations they are planning to visit, but all of their destinations. A rental-car business based at OIA could be launched with the d as few as three hydrogen stations:

1. At the Orlando International Airport (already exists);
2. Near the cluster of theme parks in southwest Orlando;
3. Downtown Orlando.

This group of stations, along with the airport station, could serve roughly 80% of car renters. A fourth station at Kennedy Space Center would raise this percentage of renters who could make all of their intended trips to around 85%. A station in Tampa would raise this percentage to around 90%.

Purchase of Hydrogen Cars

The supply of hydrogen cars is the biggest barrier to overcome. Currently, all hydrogen cars made by major automakers are custom-made prototypes, with the BMW H7 series soon to be the first production-run hydrogen vehicle sold to the general public. A number of manufacturers, however, have plans to begin production in the 2010-2015 time period (see Section 2.2). The cost of vehicles may dictate when the rental-car business might become feasible. Options are discussed below:

1. *FCVs.* Fuel-cell prototypes currently cost up to $1 million to produce. Automakers have carefully controlled these valuable investments to protect them for continued use and to gain as much information as possible from each user. Until very recently, automakers have been highly circumspect about placing FCVs in the hands of untrained users in uncontrolled situations. One manufacturer suggested to us that even the first generation of production-scale vehicles would be too valuable to use as rental-cars. However, with the recent announcement of Toyota's willingness to provide prototypes of a hydrogen-hybrid Prius for the Hertz/New Icelandic Energy hydrogen rental-car operation in Iceland, it now appears possible that a manufacturer would be willing to provide more-costly pre-production vehicles as rentals.

2. *ICEs*. ICE prototypes are also quite costly, whether hydrogen-only or dual-fuel. It is conceivable, however, that production runs of ICEs will reach the needed scale and cost to supply a subsidized rental business before FCVs.
3. *Converted Conventional Cars*. A number of small businesses currently convert conventional ICEs to burn hydrogen. Though still a custom procedure, a company in the Phoenix, Arizona area quotes $8,000 per conversion. If each hydrogen car could be rented for $10 more per day for 300 days per year, the conversion costs could be paid off in about three years. Liability issues for using converted cars might be a stumbling block.

While purchase costs are the most daunting hurdle facing hydrogen rental-cars, the barrier may not be insurmountable. The free mass media publicity to the manufacturer that supplies the vehicles could easily be worth millions of dollars of advertising. Cross-marketing with Disney could also create substantial buzz. Word of mouth from satisfied rental customers could promote sales throughout the world. In addition, it may be possible to begin with converted ICEs, then move to production ICEs, and eventually to FCVs. It may also be possible to start with just a few hydrogen vehicles added to EV Rental's fleet of other alt-fuel vehicles.

Resale of Used Vehicles

The car rental industry is a low-margin business. A key element of financial success is the ability to resell used vehicles, which are typically retired from rental service at around 30,000 miles. Cars that are in high demand may be kept in service longer, while cars in low demand may need to be sold sooner. Conventional vehicles are typically sold back to manufacturers for sale through their dealers or sold to wholesalers. No such used car market, however, is likely to exist for retired hydrogen rental-cars. EV Rentals had to make their own markets for used electric and CNG cars. Drawing on their experience, here are some solutions to the resale problem:

1. *Environmental Groups.* Used hydrogen vehicles could be marketed to members of large national environmental groups such as the Sierra Club, National Wildlife Society, Audubon Society, Resources for the Future, Nature Conservancy, etc.
2. *Respiratory Health Groups.* Marketing to members of the American Lung Association or the Asthma and Allergy Foundation of America could reach large numbers of potential buyers.
3. *Car Clubs*. Various hobbyist groups are interested in alternative-fuel cars.
4. *State Vehicle Fleets*. The State of Florida might be able to indirectly subsidize the rental-car business by promising to purchase used hydrogen vehicles for some of their fleets. This would keep the cars in use in state and promote continued use of Florida refueling infrastructure, and perhaps provide a reasonably-priced supply of zero emission vehicles (ZEVs) to the state government.
5. *Past Rental Customers*. A database can be maintained of customers who rented hydrogen cars, and used cars could be offered to them first. They will have already test-driven the cars.

A potential unrecognized benefit of developing this business in Orlando is that, with most rental-cars never leaving the Orlando area, hydrogen rental-cars might not reach the 30,000 mile threshold for resale for 3-5 years, thus spreading the cost of cars over a longer time span.

Operator Characteristics

Though financially challenged, a small rental-car company such as EV Rentals might be best suited to run the first hydrogen rental-car business, if the cars were affordable or subsidized. A lean, flexible, and hungry company may be necessary to work around the barriers that are likely to arise. Such companies need to offer products or services that the large rental-car companies do not, and they are likely to test this market first.

Large companies, on the other hand, with their higher revenues, national advertising, and ties with automakers, would have more resources to throw behind such a venture should they choose to do so. Hertz's decision to launch a hydrogen rental-car joint venture in Iceland certainly indicates their willingness to innovate in this direction. Hertz will add 3,400 Prius hybrids by 2008, while Avis is adding 1,000 Toyota Prius hybrid cars to their fleets in California; Portland, Oregon; Seattle, Washington; and Washington, D.C. by July, 2007 [23].

Synergies

A hydrogen rental-car business based in Orlando could benefit from tremendous synergies with other hydrogen initiatives:

1. *Added Demand for Stations.* The rental-cars would provide an additional source of hydrogen demand for certain stations, especially those located near the theme parks, the airport, downtown Orlando, Kennedy Space Center, Daytona Beach, and Tampa. Several of these stations are also recommended stations for the statewide network (see Section 5).
2. *Kennedy Space Center.* Many people associate hydrogen energy with the space program. Hydrogen is burned to launch the shuttle into space, where hydrogen fuel cells generate electricity and drinking water for the shuttle astronauts. Cross-marketing with NASA could give a tremendous boost to the rental-car idea. Priority parking at Kennedy Space Center (KSC) and a highly visible refueling station, perhaps offering tours, would help promote the rental-car business. Officials at Kennedy have informed us that they bleed off approximately 1,000 gallons of hydrogen from their LH2 storage tanks each day. While there are no immediate plans to capture this hydrogen for transportation use, they have indicated to us their intention to do a feasibility study of a hydrogen station at the Visitor Center. There is already a CNG station at KSC.
3. *Airport Station.* A station built and operated by Chevron Technology Ventures (Boggy Creek Hydrogen Fueling Station) opened at the Orlando International Airport in May, 2007. Initially it will refuel four hydrogen-powered airport shuttle buses (Ford V-10, E-450). Four additional H2 shuttle buses will be in service by

2008. Though located off-site on nearby Boggy Creek Road, rental-car employees could drive the cars there for refueling. Advertising on the hydrogen-powered shuttle buses could help promote the new business ("You're already riding in a hydrogen-powered vehicle—now drive one yourself!").

4. *Disney.* Disney theme parks (e.g., EPCOT) have always had a futuristic appeal. Disney might be willing to locate a station at one of their parks. In doing so, they could convert their parking lot trams—which are similar to airport baggage trams—to run on hydrogen. A highly visible station site that also offered priority parking to hydrogen vehicles would aid in cross promotion. Development of a hydrogen-powered space ride at one of their theme parks might someday be possible. Alternatively, a station could be located near I-4 on International Drive or EPCOT Center Drive.
5. *Climate.* Current FCV prototypes reportedly face operational and durability issues in cold weather. The warm Orlando climate is well suited to the large-scale use of an early generation of production vehicles.
6. *Used Rental-cars.* As mentioned earlier, state vehicle fleets could agree to purchase used rental-cars at a discount to the full cost to meet state ZEV goals. In turn, this guaranteed resale market could remove a significant uncertainty from the rental-car business.
7. *Florida Hydrogen Business Partnership.* This alliance of 27 companies and government agencies might find the hydrogen rental-car business in Orlando highly appealing as a way to put Florida and Orlando at the forefront of commercialization of hydrogen.
8. *The Hydrogen Economy.* The renters who completed our survey came from all over the United States and several foreign countries, renting their vehicles for an average of 7.9 days. Some 40-50 individuals a year could rent each hydrogen car, exposing thousands of potential customers to a positive, low-risk experience that could generate positive word-of-mouth and political support for hydrogen power.

3.3 Conclusions

1. A fleet of hydrogen-powered rental-cars based at the Orlando International Airport could play a key role in the initial rollout of a hydrogen refueling infrastructure in Central Florida.

2. Consumer attitudes reflect an interesting mix of practical concerns (e.g., driving range of the vehicle) and wider motivations (e.g., using a pollution-free technology) surrounding the decision to rent a hydrogen vehicle.

3. Our survey results suggest that just *three* refueling stations (located at OIA, downtown Orlando, and Disney) could cover the refueling needs of about 80% of car renters originating from OIA. With a fourth station at Kennedy Space Center, 85% of car renters could be served. The clustered tourist destinations and climate make Orlando the ideal location for a hydrogen rental-car business.

4. The cost of hydrogen vehicles for a rental fleet represents the most difficult barrier to a feasible rental-car business, but Hertz, Toyota, and New Icelandic Energy have recently shown a willingness to overcome that. Starting off with hybrids converted to burn hydrogen instead of gasoline seemingly can enable the business to begin in the early 2010s or as soon as refueling stations can be built. The publicity generated by the rental business, as well as the opportunity for consumers to experience H_2 cars in a low-risk setting, may be an adequate incentive for automakers to subsidize cars to the rental business.

5. Most other hurdles—such as resale of used vehicles, maintenance, and targeting potential markets—should be easier to overcome.

6. Synergies would be plentiful between the rental business and NASA, Disney, energy companies, and other state hydrogen initiatives.

7. The next step for the rental-car business plan is to begin discussions with rental-car companies, as well as energy companies that build stations, and possible partners at Disney and NASA.

4. OPTIMAL REFUELING STATION LOCATION ANALYSIS FOR FLORIDA

The lack of a hydrogen-refueling infrastructure has been pinpointed as the greatest challenge in the transition to a hydrogen economy [3]. Given the high cost of the initial set of refueling stations, locating them as efficiently as possible will be a key to the early success of the industry in Florida. To address this need, we developed a model that locates a given number of stations optimally to serve the maximum consumer demand possible, measured as origin-destination trips, or vehicle-miles traveled [25]. The model, called the Flow Refueling Location Model, takes into consideration the structure of the road network, the routes that people drive regularly from their origins to their destinations, the amount of traffic on those routes, and a reasonable or safe driving range between fill-ups for hydrogen cars. The model then locates the stations optimally and quantifies the tradeoff between the number of stations and how much demand can be served. Operations research techniques and geographic information systems are integrated in a spatial decision support system that researchers can use to develop data, enter assumptions, analyze scenarios, evaluate tradeoffs, and map the 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: a metropolitan Orlando network, and a statewide network.

4.1 Prior Research on Refueling Infrastructure Modeling

In recent years, a large number of academic papers and government reports have addressed the infrastructure needs for the transition to hydrogen energy. While numerous studies have examined the entire supply chain from production to delivery to fueling stations [26], or the total number of initial hydrogen stations needed [4], our focus here is on methods used to solve optimally for the locations of a coordinated network of stations.

The problem of optimally locating refueling stations had attracted little attention in the published literature until the recent push for alternative fuels. In the operations research literature, the lack of earlier published research is likely due to the fact that, by the time the mathematical methods and computer hardware and software needed to address such problems became available, gasoline stations were already ubiquitous in more-developed countries. With the advent of alternative fuels and the need to develop a refueling infrastructure, researchers have recently published several new modeling approaches. We group these approaches into GIS models and operations research models.

Several researchers have been using Geographic Information Systems (GIS) to locate hydrogen-refueling stations. Melaina [27] proposed a GIS method based on the idea of condensing the existing network of gasoline stations into clusters, which yields exact station locations and station sizes. In the NREL study discussed in Section 2.1, Melendez and Milbrandt [13] used GIS to develop a national network of stations to enable long-distance trips on interstate. 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 subjectively placed stations along those routes using other GIS data layers as guides. The other GIS layers included existing hydrogen production plants, other alt-fuel stations, population, and US highway intersections. Stations were placed no more than 50 miles apart in the east and in urban areas, and no more than 100 miles 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 based on linear programming and heuristic solution. One of the earliest OR papers for locations of gasoline stations was by Goodchild and Noronha [28], who developed a model to open and close gasoline stations to maximize a company's market share. They based market share on two kinds of demand: home-to-facility trips, and traffic volumes on network links. Bapna et al. [29] used multiobjective programming to locate reformulated gasoline stations in India. One objective minimized the sum of travelers' costs and station investment costs, wiht costs based on the number of stations needed to make travel possible on each link given the driving range of vehicles. The second objective maximized the population on enabled links.

Several papers have used a variant of the *p*-median model—one of the most widely used OR models for facility location. The *p*-median model locates a given number (*p*) of stations so as to minimize the total distance from residential nodes to their nearest open station [30,31]. Nicholas, Handy, and Sperling [32] used a *p*-median approach to locate hydrogen-refueling stations in Sacramento County, California. Their results show that when the number of hydrogen stations reaches about 30% of the number of existing gasoline stations, the average driving time to the nearest station could be similar to today. Nicholas and Ogden [33] used a *p*-median model to examine hydrogen station needs to achieve equivalent levels of convenience in the four major urban areas of California.

Beginning around 1990, researchers have been developing a new approach to facility location, known as "flow capturing" or "flow intercepting" models [34-42]. 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. Flow-capturing models locate facilities conveniently on the origin-to-destination routes that drivers already use on trips they already make. The basic model locates *p* facilities so as to intercept as many trips as possible. The literature suggests these models are ideal for locating "discretionary" facilities, such as ATMs, convenience stores, and fast food, at which people stop on the way to somewhere else rather than make a special trip from home to facility and back. They have also been applied to billboards and vehicle-inspection stations. In our opinion, the FCLM also provides a realistic behavioral basis for locating alternative-fuel stations.

4.2 Modeling Approach: The Flow Refueling Location Model and the Spatial Decision Support System

Kuby and Lim [25, 43-44] modified the basic FCLM for the purpose of locating hydrogen-refueling stations. Modifications were necessary because the FCLM assumes that a single station anywhere on a path is enough to capture that demand. For refueling longer trips, however, a single station may not be enough to complete a trip from an origin to a destination and back again. Currently, despite their high efficiencies, prototype hydrogen vehicles have a much shorter driving range than conventional vehicles due to the energy density of on-board storage systems. US DOE has set a target of 300 miles for the technical range of hydrogen vehicles, but the safe practical range may be far less. Thus, many intercity trips will require multiple refuelings at reasonable intervals. To deal with fuel limitations, Kuby and Lim adapted the FCLM by incorporating a driving range parameter that can be set by the user. The resulting Flow-Refueling Location Model (FRLM) is the basis for our analysis.

The FRLM maximizes the number of trips that can potentially be refueled with a given number of stations *p,* and can be stated as a mixed-integer linear programming problem:

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

Subject to:

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

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

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

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

where:

q = index of O-D pairs (and, by implication, the shortest paths for each pair)
Q = set of all O-D pairs
f_q = flow volume on the shortest path between O-D pair q
y_q = 1 if f_q is captured
0 otherwise
k = potential facility location
K = set of all potential facility locations
x_k = 1 if a facility is located at k
0 otherwise
p = the number of facilities to be located
h = index of combinations of facilities
H = set of all potential facility combinations
a_{hk} = 1 if facility k is in combination h
0 otherwise
b_{qh} = 1 if facility combination h can refuel O-D pair q
0 otherwise
v_h = 1 if all facilities in combination h are open
0 otherwise

The objective function (1) maximizes the flow volume, in number of trips that can be refueled. Constraint (2) prevents a trip from being counted as refueled unless a valid combination of stations *h* is open that can refuel that path given the safe vehicle range, which is a user input. Constraint (3) prevents a combination of stations *h* from being open unless all the individual stations *j* in that combination are open. Constraint (4) limits the number of stations to *p*, a user input. Finally, (5) stipulates that a station or a combination of stations is considered open or not, and likewise that any origin-destination flow can be considered either refuelable or not.

It is important to recognize that our concept of a "safe driving range" is related to, but not equivalent to, station spacing. If stations are spaced, say, 100 miles apart, it still may not be possible to complete some trips without exceeding a 100 mile driving range. For instance, in Figure 4.1, although stations are 100 miles apart on this highway, it is not possible to travel from A to B and back without exceeding a 100-mile limit.

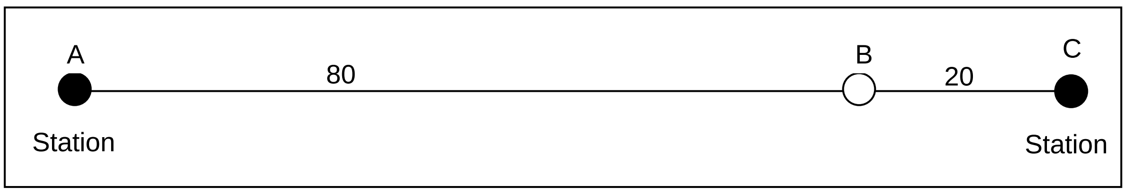

Figure 4.1 Station spacing ≠ safe driving range

For the Florida Hydrogen Initiative, we integrated the FRLM into a GIS interface using ArcGIS software and computer programming software Microsoft Visual Studio.net. The resulting Spatial Decision Support System (SDSS) performs three primary tasks:

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.

Appendix 3 provides additional details about the SDSS.

While linear programming software can solve the FRLM optimally, we developed two heuristic solution algorithms to solve larger, more realistic cases of the model. Heuristic algorithms are able to solve large problems efficiently, although they do not guarantee finding the absolute global mathematical optimum. The first heuristic solution method is the widely used greedy-adding-and-substitution (GAS) algorithm [45]. A greedy algorithm without substitution adds one facility at a time but does not look ahead to where subsequent facilities should be placed. At each iteration, a greedy algorithm places a facility at the site that increases the objective function the most—in this case, the site that refuels the most flow volume above and beyond what the previous facilities were able to refuel. The simple greedy algorithm, which had been used successfully with the FCLM [34], has been shown to be suboptimal for the FRLM [25]. Not looking ahead to where subsequent facilities should go can lead to a suboptimal solution, which the substitution algorithm addresses by allowing 1-4 swaps of unused candidate sites for chosen candidate sites. So, for instance, if after locating the 8^{th} facility at the next best site, the 3rd site has become partly redundant, the GAS algorithm could swap another site for it, and then perform several additional substitutions before moving on to the 9th site. The greedy algorithm with four substitutions generated the results presented in this report.

The second algorithm is a genetic algorithm, so-called because it mimics the process of evolution of genes toward a higher fitness level [46]. If the model is used to locate 25 facilities among 500 candidate sites, for instance, each possible solution consists of a string of 25 "1s" and 475 "0s" in some particular order The genetic algorithm creates a population of random solutions, and then mutates, crosses, and evaluates them in a process mimicking evolution towards a solution that is able to refuel a higher flow volume.

Both algorithms allow the user to set certain common parameters (see Appendix 3):

1. A safe working driving range for vehicles (a distance).
2. The number of stations to locate.
3. The objective function to be maximized. Choices include number of trips refueled, vehicle-miles traveled (VMT=trips*distance) refueled, and number of origin-destination pairs refueled.[1] The VMT objective, first introduced in [47], weights longer trips more heavily than shorter trips, and is useful for maximizing the amount of gasoline potentially replaced by hydrogen. The trips objective, on the other hand, might maximize consumer adoption of hydrogen vehicles, assuming consumers are more likely to purchase a vehicle if they are able to complete more trips with the available stations.
4. The node ID number of any existing stations, or any stations the analyst wishes to force into the solution.
5. For the greedy algorithm, the analyst can set the maximum number of substitutions to perform at each iteration. For the genetic algorithm, the analyst can control a number of evolutionary parameters.

4.3 Data

The three universities worked closely together through an elaborate series of steps to build, check, and calibrate detailed and realistic GIS data bases for the Orlando and statewide case studies (Appendix 4). The process was similar for both case studies, with a few exceptions noted. In each case, we first obtained GIS road network data bases. We also obtained a table of trip volumes among more than 4000 traffic analysis zones (TAZs) from FDOT—though this table did not contain long-distance trips for the statewide analysis. We identified and corrected many topology errors in the raw network and simplified the road network by eliminating minor and duplicative streets while retaining needed connectivity. We then processed the remaining road segments into a topological network consisting of junction nodes and arcs connecting them, which involves substantial editing to split and combine segments as needed and place junction points at

[1]The number of O-D pairs refueled simply sets the f_q in the model to 1 for each O-D pair q. In the dialog box, this objective is called "unweighted routes." It is useful mainly for debugging purposes, and is not used for any of our results because it counts lightly traveled routes and heavily traveled routes the same.

intersections. Next we aggregated nearby TAZs together and selected a single origin-destination (OD) point to represent each area considering the locations of major intersections and traffic generators. The OD points are a subset of the larger set of road junctions. We also aggregated the trips in the trip table corresponding to the aggregation of the TAZs. These two steps—simplifying the network and aggregating TAZs into OD points—had to be carefully coordinated with each other.

Once the network was built, we generated shortest paths minimizing travel time between each OD pair (see example in Figure 2). We checked many paths one by one to see if they followed realistic routes that Floridians would take. If necessary, to make the paths more realistic, we calibrated the speeds associated with different classes of roads, added missing road links, or changed OD locations. Because the FDOT trip table did not include long-distance intercity trips, such as Orlando to Miami, we had to estimate intercity flow volumes using a gravity model. Finally, we ran the models for Orlando and Florida and checked thoroughly for errors that might have caused the model to locate stations in unrealistic locations. Local knowledge by the three researchers based in Florida, including Dr. Lines in Orlando and Drs. Schultz and Xie in Boca Raton, was invaluable in developing and testing these databases.

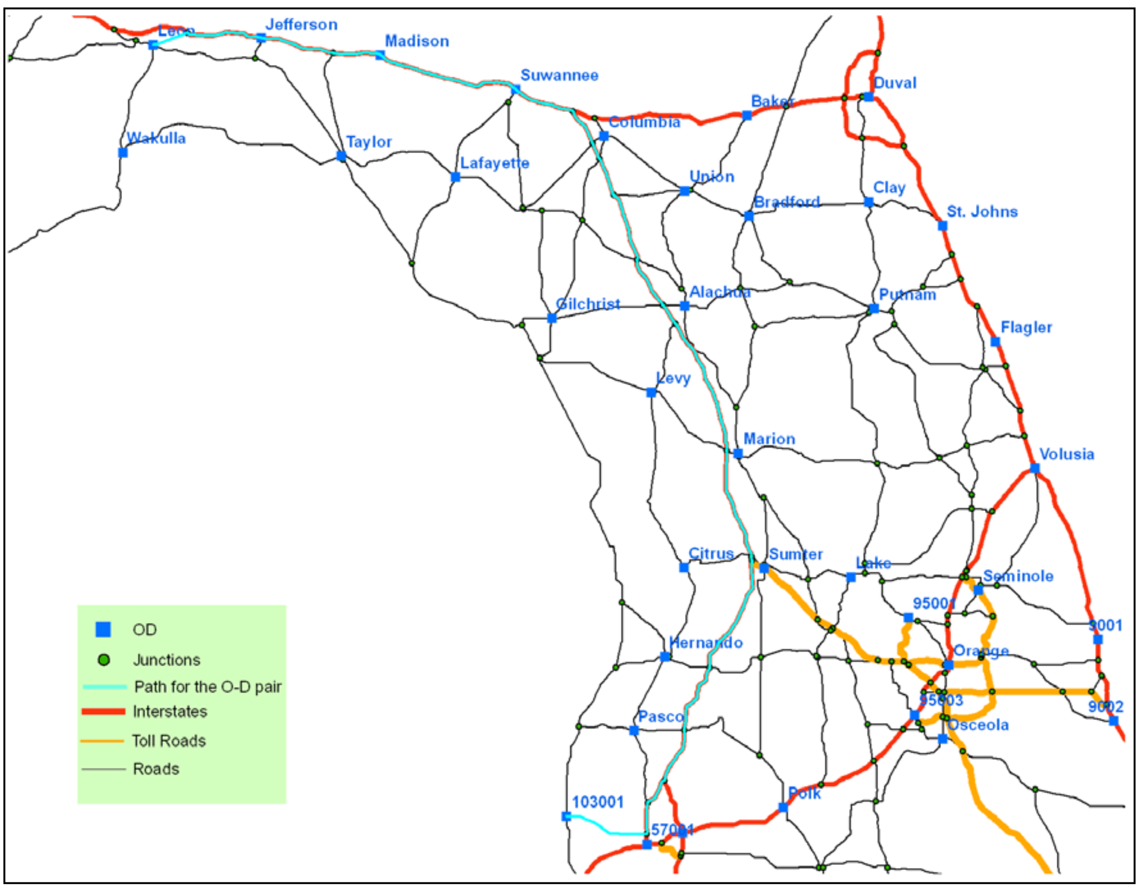

Figure 4.2 Sample path from Tallahassee (Leon County) to Clearwater (103001)

Orlando Data

The study area includes all of Orange and Seminole counties and the northwest region of Osceola including the cities of Kissimmee and Saint Cloud. We obtained highway networks and maximum speed data from FDOT, and detailed street networks from ESRI, Inc. The FDOT research division assisted us in obtaining TAZ to TAZ trips flows from their travel demand models. FDOT divides the study area into 358 TAZs, which we aggregated to 102 larger zones, being careful to ensure contiguity and compactness of the aggregated TAZs. Selection of OD points within each TAZ considered the geometric center of the aggregated TAZ, the spatial relationship between the OD points and the main road network, as well as population density. This resulted in aggregated TAZs that are closer together in denser and more central urban areas. Speeds on arterial streets were reduced from posted speed limits by 15% to reflect normal driving conditions. Figure 4.3 shows the network used for the Orlando case study.

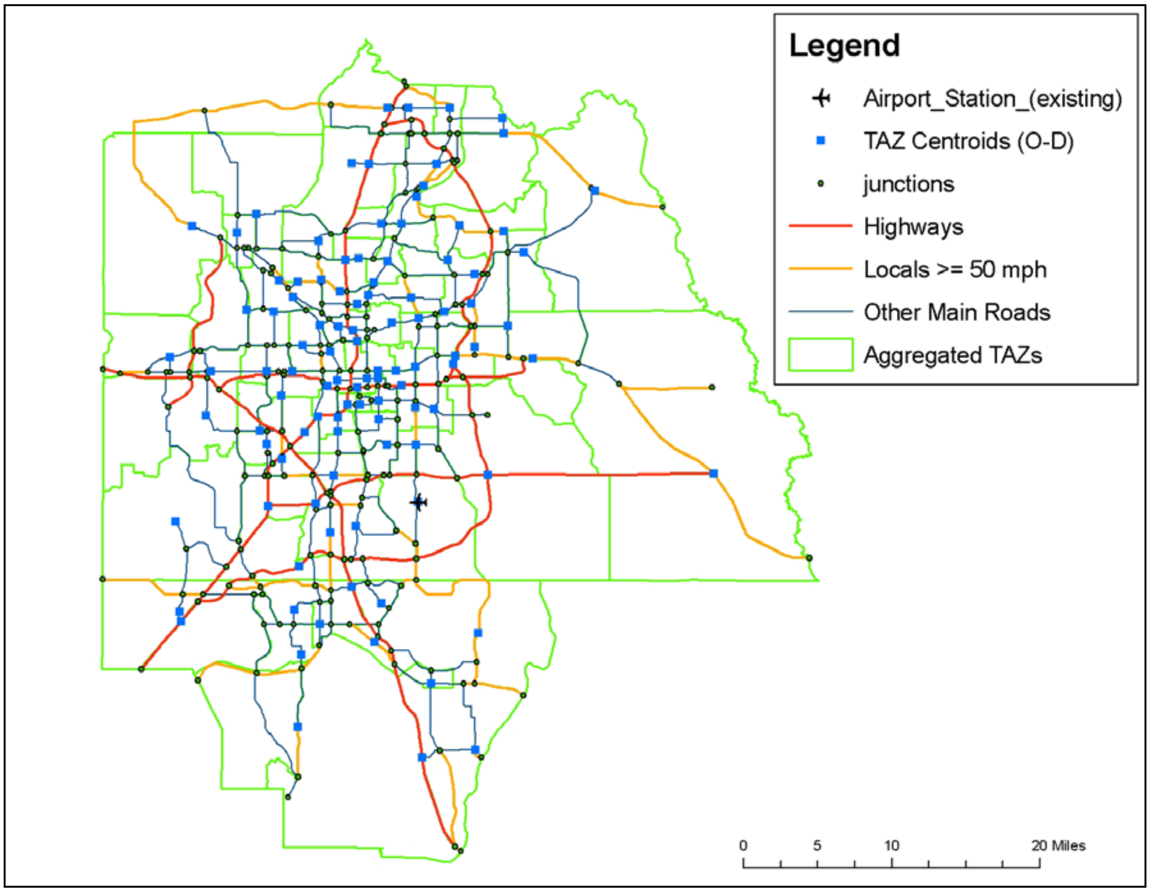

Figure 4.3 Network for the Orlando case study

To create the Orlando trip table, we extracted from the FDOT trip data the trips between 358 original TAZs in the study area. The trips were then aggregated to the 102 aggregated OD points.

Internal flows within each aggregated OD point were excluded from the analysis. These very short but frequent trips would otherwise dominate the trip volumes of the entire network and dictate station locations largely according to how we aggregated the 358 original TAZs into 102 OD points. While intra-zonal trips are sometimes included in transport planning because of their impact on local street congestion, we determined that including them would undermine our purpose of locating hydrogen stations to serve the Orlando metropolitan area.

Florida Data

For modeling stations for statewide, intercity travel, the study area included the entire state of Florida. Using ESRI and FDOT road networks, we included all interstate highways, toll roads, and US highways, as well as other major state highways used for intercity trips, as shown in Table 4.1. We reduced the speeds on all roads other than limited-access highways by 15% from their maximum speed limits to reflect slower driving conditions.

Table 4.1. State Highways Included in the Statewide Network
Florida Turnpike (from I-75 near Wildwood to Homestead)
Suncoast Parkway (State Road 589
Sawgrass Expressway
Beeline Expressway (State Road 528)
Central Florida Greeneway (State Road 417)
East-West Expressway (State Road 408)
State Road 429Lee Roy Selmon Expressway (State Road 618)

For modeling intercity trips, the basic level of spatial aggregation was by county. Large urban counties consisting of several distinct urban areas were further subdivided into separate ODs. Disaggregated counties included Dade, Broward, and West Palm in southeast Florida, Lake near Orlando, and Pinellas and Hillsborough in the Tampa-St. Petersburg area. Similarly, several small rural counties were aggregated into a neighboring county, such as Dixie into Gilchrist. In all, the State of Florida was aggregated into 74 ODs (Figure 4.4).

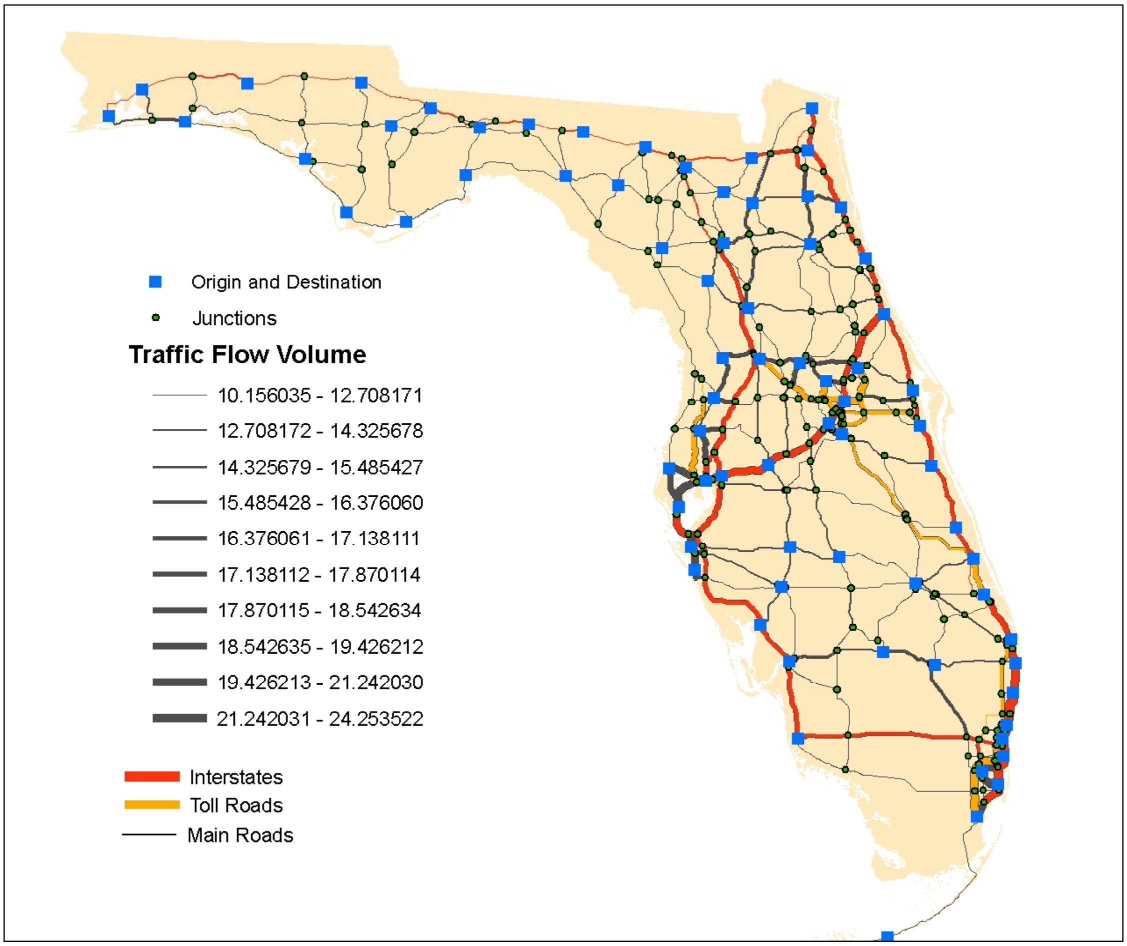

Figure 4.4 Network used for the statewide case study

Only a few US states collect data on long-distance intercity trips and model statewide flows. The FDOT trip data that we used for the Orlando study does not include intercity trips except between nearby cities. We therefore used a spatial interaction or "gravity" model to estimate intercity flows. Spatial interaction models are the most widely used approach in transportation planning to estimate how trips are spatially distributed across a network [48,49]. The formula used is shown in equation (6):

$$T_{ij} = P_i * P_j * FF_{ij} \tag{6}$$

where:

T_{ij} = number of trips between zone *i* and *j*
P_i = population of zone *i*
P_j = population of zone *j*
FF_{ij} = friction function between nodes *i* and *j*

The shape and steepness of the friction (or impedance) function is a key input to a spatial interaction model. We used a friction function from Michigan's statewide travel forecasting model [50], which is touted by a Federal Highways Administration guidebook as an example of best practice in statewide travel forecasting [51]. We adopted the

Michigan friction function developed for intercity home-based social-recreational and vacation trips (see Figure 4.5 and equation 7).

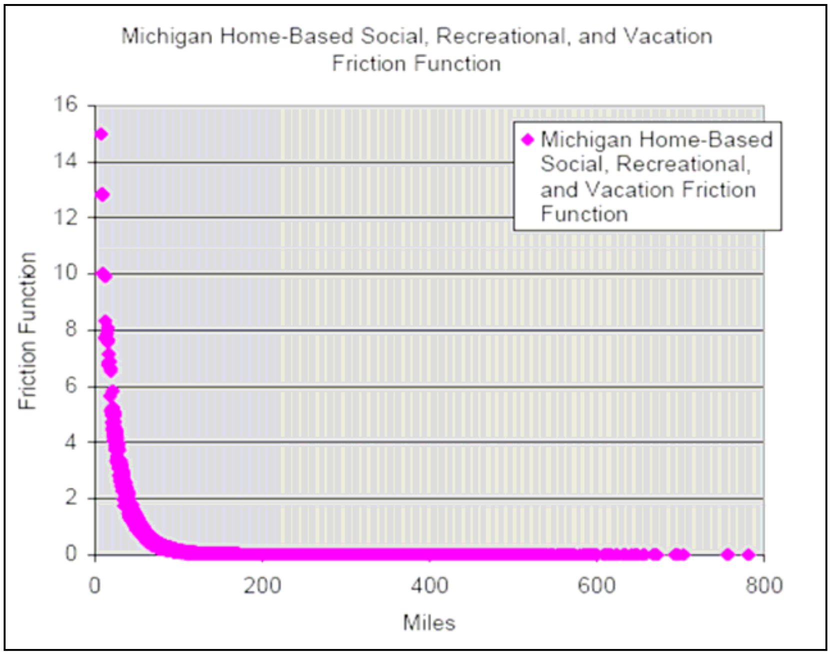

Figure 4.5. Michigan friction function shown as a distance-decay curve

$$FF_{ij} = 50 * GC_{ij}^{-0.114} * e^{-0.03*GC_{ij}} \qquad (7)$$

where:

GC_{ij} = generalized cost between zone i and j = 0.75* miles + 0.5*minutes

To estimate trip volumes, we applied the equations in (6) and (7) to each OD pair, plugging the travel time and length of the shortest pair into the generalized cost formula and the aggregated populations of i and j into (6). The resulting T_{ij} values were then standardized to a percentage of the total. This data set consisting of each OD pair's percentage of the statewide total of intercity trips was used as the trip volumes in the FRLM. Though it is impossible to make a map showing the trip volumes for each of the 2,701 OD paths in the model, the net result of the flows on all these paths can be mapped. Figure 6a aggregates all trip volumes on all paths using each link of the highway network, which can be compared to the actual traffic volume on major Florida roads in Figure 6b. Looking at the rural roads and interstates only—because urban road volumes are inflated by local traffic—the modeled traffic flows on the simplified network appear similar to the actual flows.

This study does not include out-of-state flows because surrounding states may not proceed at the same pace in the transition to a hydrogen economy. Stations justified partly by out-of-state trips could be underutilized if surrounding states transition more slowly. Likewise, trips by Florida residents to neighboring states might not be possible if those states do not develop an infrastructure on their side of the border. Given that out-of-state tourists make up a substantial share of the traffic in the Panhandle region, the number of resident trips there are not proportional to the traffic volumes on roads.

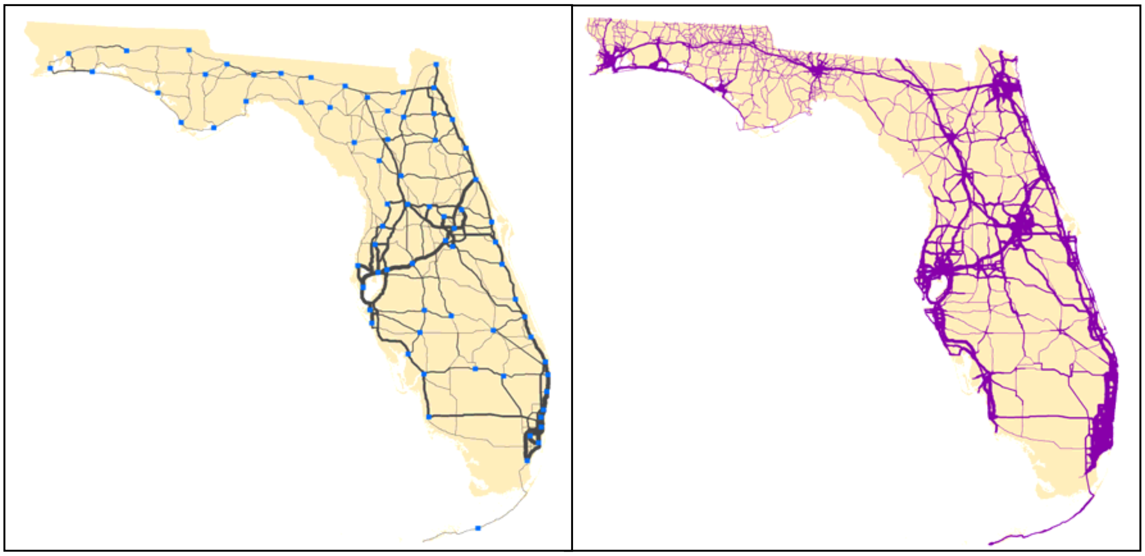

Figure 4.6

(a) Estimated intercity use of the statewide highway network (aggregated from spatial interaction model results).

(b) Actual Florida traffic volumes on road segments (FDOT data)

Hydrogen Demand Factor Scenarios

The base case for both the Orlando and statewide models was based on the total number of trips made by 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 followed the National Renewable Energy Laboratory (NREL) report on *Geographically Based Hydrogen Consumer Demand and Infrastructure Analysis* [52], adapted as needed to be consistent with our modeling approach. NREL developed a GIS model that divides the United States into a 20x20 mile grid and classifies each grid square into seven classes ranging from 7 or “very high” to 1 or “low” on various socioeconomic, transportation, and policy variables. Their model predicts higher total demand in areas with higher median income; more people with bachelor’s degrees or higher; more two-car households; more workers over 16 years old who commute more than 20 minutes one way; air quality non-attainment (at the county level); participation in Clean Cities coalitions (county level); zero-emission mandates and number of state incentives (state level); and more hybrid vehicle registrations (state level). Scores from 1 to 7 are assigned to different levels of each variable. Each variable was assigned a weight (Table 4.2). For each grid square, the score on each variable was multiplied by the weight and summed across all variables, leading to an overall demand classification for each grid square, shown in Figure 4.7. Stakeholders, including car manufacturers and fuel companies, reviewed their choice of variables and the weights on each variable.

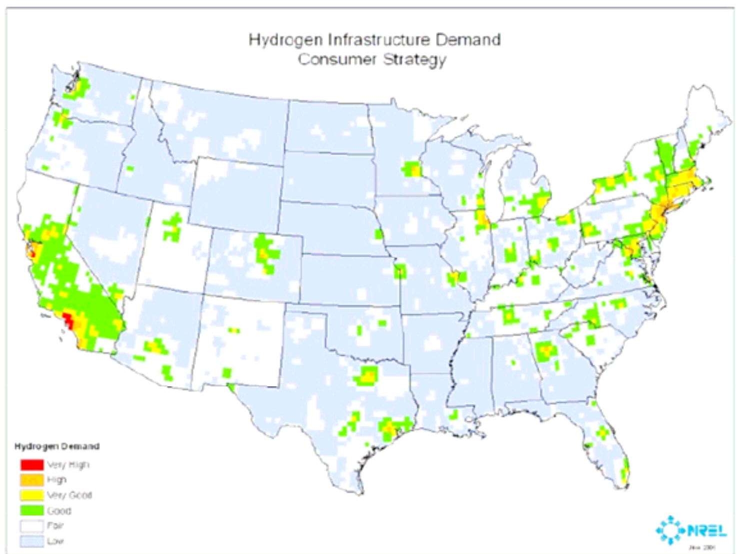

Figure 4.7 Consumer hydrogen demand classes from NREL's GIS model (Source: Melendez and Milbrandt 2006)

To adapt their model for use with our Flow Refueling Location Model in Florida, several changes were required:

1. The NREL model estimates *total* hydrogen consumer demand in each area. Our model, on the other hand, required a *per capita* estimate of consumer demand. Our data set already has the total trips from origin zone to destination zone, so what was needed was a method to weight the total number of trips according to the likelihood of individual consumers in the origins and destinations to purchase a hydrogen vehicle. This necessitated changing variables: from total number of people with bachelors degrees to percentage of people with bachelors degrees; from total households with 2+ vehicles to a percentage of households; and so on.
2. Several variables used by NREL were state-level variables. State incentives, ZEV mandates, and hybrid registration data were by state and therefore did not vary within Florida. In addition, Florida has no counties in non-attainment status for air quality. These variables were dropped and their weights reassigned to other variables.
3. We used an equal-interval classification scheme. We took the range from the high value of each variable to the low value and divided it equally into seven classes. For percentage variables, the top class was extended up to 100% and the bottom class down to 0% to cover all possible values.
4. NREL used a 20x20 mile grid for the entire US. Because our study is at a much finer scale, we used census tracts. Using the weights, a score between 1.0 and 7.0 was calculated for each tract.
5. An average score for each aggregated OD zone (consisting of multiple census tracts or even entire counties) was then calculated from the scores of the constituent census tracts using a spatial weighting procedure similar to the NREL procedure. These average scores were not, however, rounded to integer values, but were treated as continuous variables from 1 to 7.
6. For each OD trip, the scores of the origin and destination zones were averaged.
7. The average score from 1 to 7 for the OD pair was then converted linearly to a weighting factor between 0 and 1. This value was used as a multiplier on the number of trips from the origin to the destination.

Table 4.2 Hydrogen Consumer Demand Scoring and Weighting System: NREL Model and FHI Adaptation

NREL Data Layer (weight - %)	NREL Classes	NREL Rank Score	FHI Data Layer (weight - %)	FHI Classes	FHI Rank Score
Median Household Income (High - 15%)	54,955–86,901	7	Median Household Income (High - 23%)	172,515 – 200,001	7
	43,109–54,954	6		145,029 – 172,514	6
	36,152–43,108	5		117,542 – 145,028	5
	30,673–36,151	4		90,056 – 117,541	4
	24,748–30,672	3		62,569 – 90,055	3
	15,405–24,747	2		35,083 – 62,568	2
	0–15,404	1		0 – 35,082	1
Number of people with bachelor's degrees (Medium – 10%)	943,877–1,770,650	7	Percentage of people with bachelor's degrees (Medium – 18%)	75.7 – 100	7
	415,521–943,876	7		63.1 – 75.6	6
	228,465–415,520	6		50.5 – 63.0	5
	123,779–228,464	5		38.0 – 50.4	4
	51,563–123,778	4		25.5 – 37.9	3
	14,107–51,562	3		12.84 – 25.4	2
	0–14,106	2		0 – 12.83	1
Number of workers age 16+ who commute more than 20 minutes (Medium – 10%)	908,659–1,572,668	7	Percentage of workers age 16+ who commute more than 20 minutes (Medium – 18%)	78.6 – 100	7
	418,740–908,658	7		66.3 – 78.5	6
	219,920–418,739	6		53.9 –66.2	5
	109,577–219,919	5		41.5 –53.8	4
	47,249–109,576	4		29.1 –41.4	3
	12,529–47,248	3		16.8 –29.0	2
	0–12,528	2		0 – 16.7	1
Number of Households with 2+ Vehicles (High – 15%)	179,419–312,470	7	Percentage of Households with 2+ Vehicles (High – 23%)	80.8 – 100	7
	312,471–516,079	7		68.0 – 80.7	6
	118,941–179,418	6		55.2 – 67.9	5
	68,543–118,940	5		42.4 – 55.1	4
	30,240–68,542	4		29.6 – 42.3	3
	8,065–30,239	3		16.6 – 29.5	2
	0–8,064	2		0 – 16.5	1
Clean Cities Coalitions, by county (Medium – 10%)	Yes	7	Clean Cities Coalitions, by county (Medium – 18%)	Yes	7
	No	1		No	1
Air Quality (Medium – 10%)	Severe	7	Not applicable		
	Moderate	6			
	Marginal	5			
	None	1			
State Incentives (Medium – 10%)	Yes	5-7	Not applicable		
	None	1			
ZEV Sales Mandate (Medium – 10%)	Yes	7	Not applicable		
	No	1			
Registered Hybrid Vehicles, by state (Medium – 10%)	1,551-2,875	7	Not applicable		
	686-1,550	6			
	372-685	5			
	169-371	4			
	68-168	3			
	12-67	2			
	0-11	1			

Consumer hydrogen demand scores were calculated for every OD zone in both the statewide network and the Orlando network. The multiplier between 0 and 1 should not be interpreted literally as the percentage of consumers who will buy hydrogen vehicles in the early commercialization stage. Rather, the multipliers should be interpreted in relative terms. For instance, suppose that a given OD pair has demographic and policy variables that give it an average score of 5 on a scale from 1 to 7, which translates to a 0.67 multiplier. Meanwhile, another OD pair has a score of 2 because of some combination of lower income and education, shorter commutes, less car ownership, or not being part of a Clean Cities Coalition. The multiplier for the second OD pair would be 0.167. The interpretation of these two multipliers should be that four times as many consumers are likely to adopt hydrogen vehicles for trips between the first OD pair than for the second OD pair. Demand scores for areas in Florida are shown in Figure 4.8.

As the NREL authors admit, "there is no single best data classification method" [52, p4]. Likewise, different experts would assign weights differently. Our consumer demand weighted scenarios are not meant to be a definitive approach to estimating future hydrogen demand geographically. Rather, they represent one possible and relatively straightforward approach to accounting for the obvious fact that all consumers are not equally likely to adopt hydrogen technology. The main purpose of analyzing scenarios based on these trip multipliers is to determine how sensitive the optimal station locations are to assumptions about the hydrogen vehicle trip volumes between places.

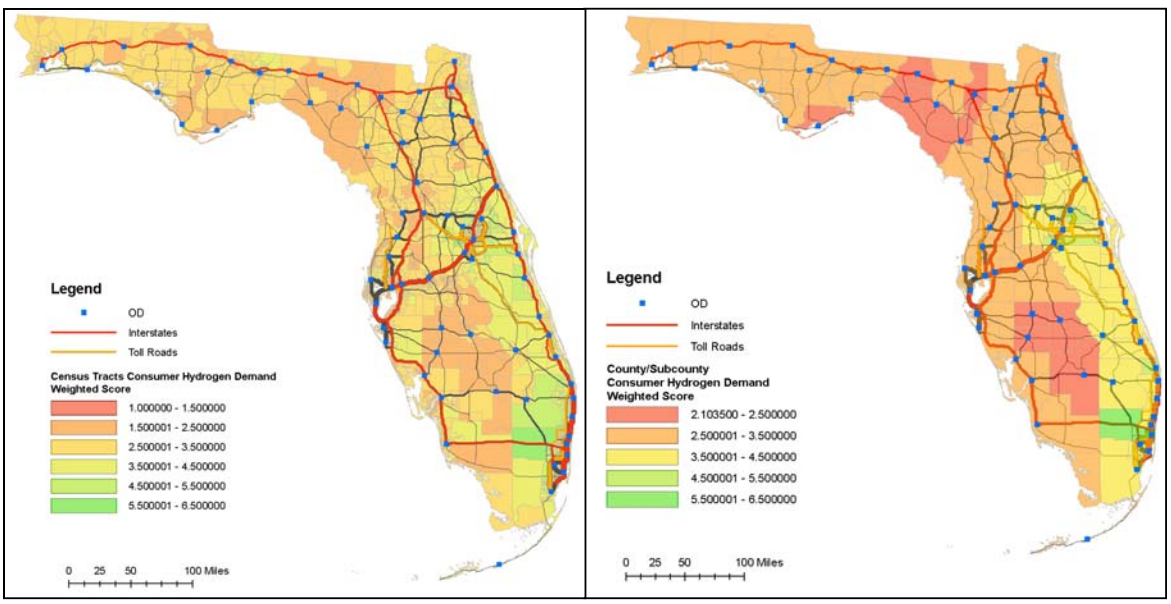

Figure 4.8 Hydrogen consumer demand scoring and weighting results at the (a) census tract level and (b) county level

4.4 Florida Statewide Station Location Analysis

The base case scenario for the Florida statewide analysis uses raw unweighted trip volumes and 100 miles as a reasonable "safe" vehicle range. This number represents a distance drivers would feel comfortable traveling between stations on a round trip, rather than the technological maximum of the vehicle. The technological maximum is substantially higher: prototype vehicles are already being road-tested or planned with driving ranges between 180 and 300 miles (Table 2.1). The National Research Council Report on *The Hydrogen Economy* [2] assumes a 300-mile driving range for their infrastructure scenarios. The original California Hydrogen Highway plan was to space stations every 20 miles along interstates, though their current thinking about station spacing is closer to 50 miles. The NREL national hydrogen network analysis spaces stations 50 miles apart in the eastern US and urban areas, and 100 miles apart west of the Mississippi River [13]. NREL assumed 50 mile spacing in the east, however, because interstates in the east are "used extensively for short trips."

We adopt NREL's 100-mile assumption as a safe driving range of 100 miles that allows for a substantial margin of driver error, suboptimal performance, improper filling, side trips, detours, and stations that may be closed or inoperative. With our model, however, we do not have to assume NREL's more conservative 50-mile spacing as a proxy for capturing shorter trips, because we actually *have* trip data for both short and long intercity trips. If closer station spacing is justified by capturing the shorter trips that would otherwise fall between stations, then the model will space them more closely. In other words, the trips dictate the station spacing, with the assumed safe driving range of 100 miles being strictly a maximum distance between refuelings on each individual trip. We also ran scenarios assuming a 50-mile and 75-mile working range. Any distance can be input into the model.

Base Case and Illustration of How the Model Works: 100 Mile Vehicle Range and Maximizing Unweighted Trips

Figure 4.9 shows optimal locations for five stations in Florida, and the routes they can refuel. The model locates four stations in SE Florida and one in Tampa. These five stations are capable of refueling 62% of the estimated intercity trips in Florida. Clustering stations in the greater Miami-Palm Beach area is a smart strategy for serving the largest number of intercity trips

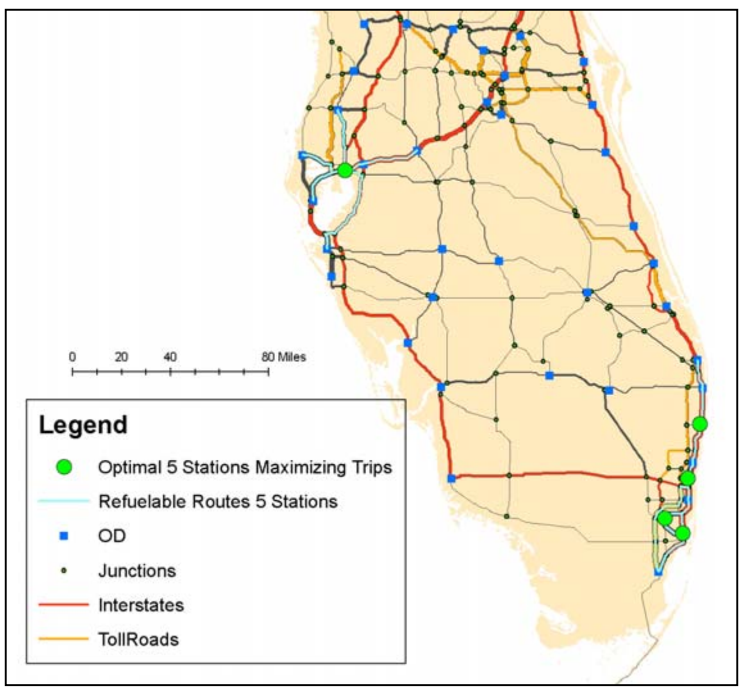

Figure 4.9 Optimal 5 stations maximizing trips with 100-mile working range

with a few stations. The large number of intercity trips in this area of 5.4 million people is the result of large population nodes with short distances between them. (Keep in mind that trip volumes were estimated by a gravity model, and that the number of trips is proportional to the product of the origin and destination populations and inversely proportional to the distance between them). In addition, the linear arrangement of cities along the coast means that most intercity trips travel north and south on the main highways. Furthermore, 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.

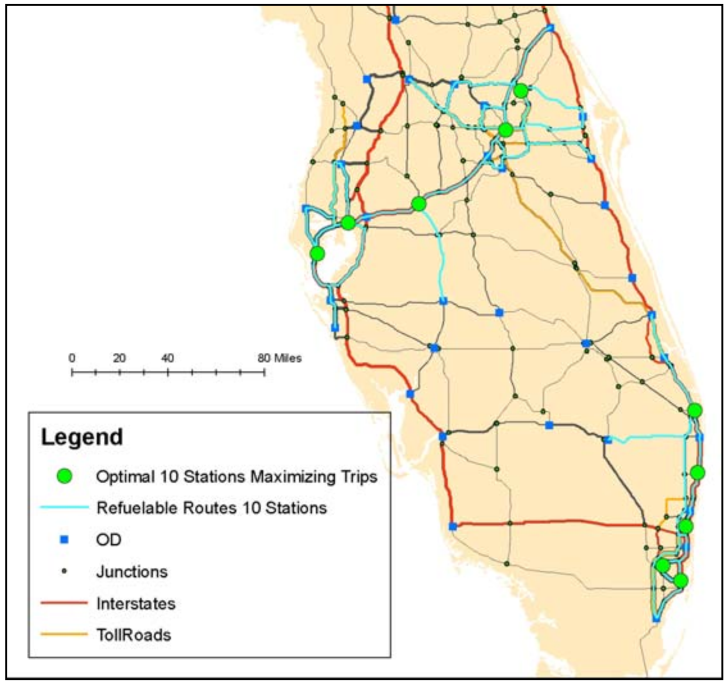

Figure 4.10 Optimal 10 stations maximizing trips with 100-mile working range

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 (Figure 4.10). Each cluster now has five stations, and the stations that were optimal with only five stations remain optimal with ten. These ten stations are able to refuel 77% of the intercity trips in Florida.

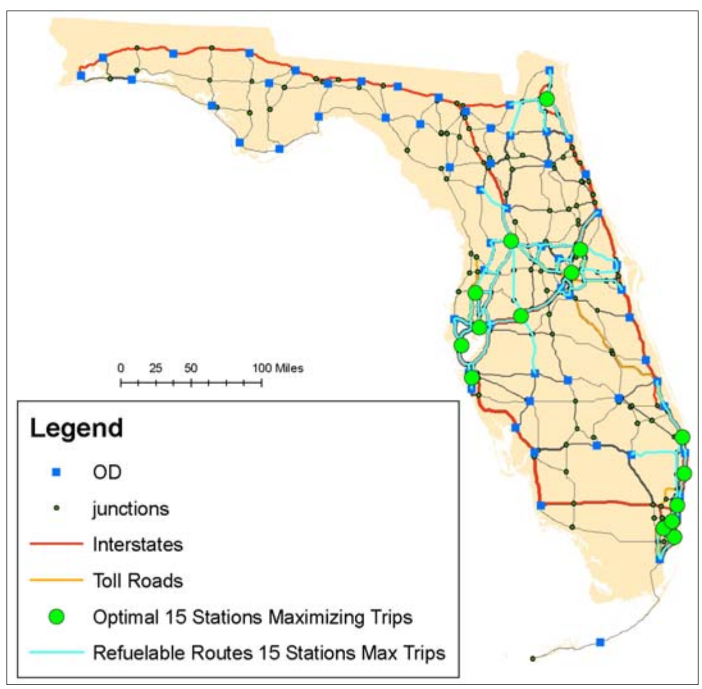

Figure 4.11 Optimal 15 stations maximizing trips with 100-mile working range

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 ten remain optimal with 15, which adds confidence to these recommendations. As we saw before in the case of Tampa, the single station in downtown Jacksonville potentially enables trips from central Jacksonville to the five surrounding counties. These 15 stations refuel 84% of intercity trips (Figure 4.11).

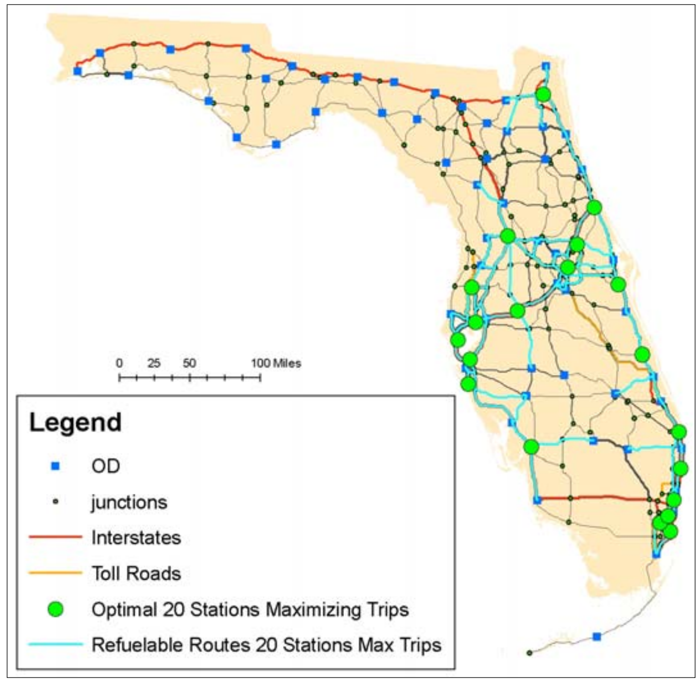

Figure 4.12 Optimal 20 stations maximizing trips with 100-mile working range

A new strategy emerges when expanding the network to 20 stations (Figure 4.12). The model begins adding some connecting or bridging stations. Stations are added 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 and further down the west coast, these five stations only increase the percentage of refuelable intercity trips from 84% to 89%, because Florida residents make far fewer long-distance trips than short-distance trips.

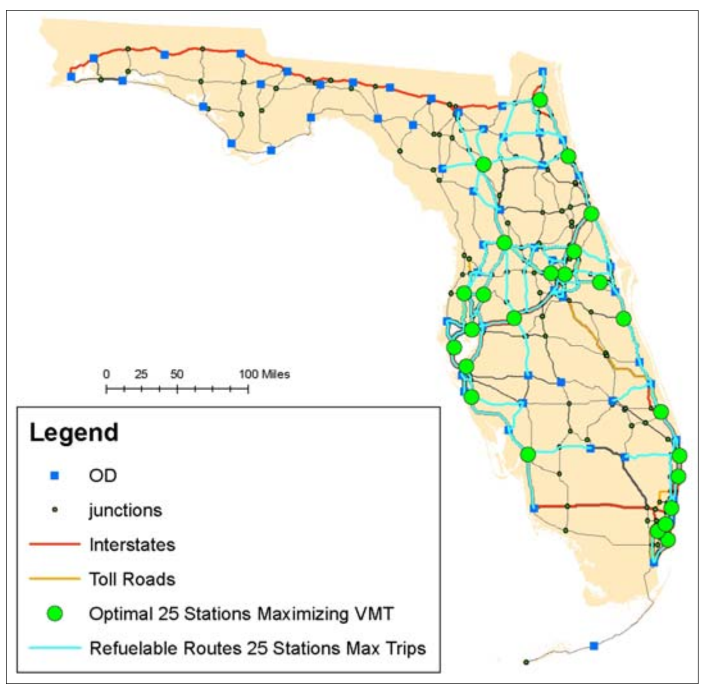

Figure 4.13 Optimal 25 stations maximizing trips with 100-mile working range

With 25 stations, the model adds stations as far north as Gainesville, home to the University of Florida, and adds to the clusters in the Orlando, Tampa, and Miami areas (Figure 4.13). One noteworthy aspect of this solution is that it serves neither the Florida Panhandle nor trips from Miami to Tampa or Orlando. Despite ignoring these trips, these five stations serve almost 93% of estimated intercity trips. Strictly from the point of view of maximizing the number of intercity trips that can be served with 25 stations, locating stations in the Panhandle or the Everglades simply does not pay off. It is worth pointing out, however, that other factors may justify stations there.

Note also that some stations that were optimal with 20 stations are no longer optimal with 25. For instance, the station that was near Cocoa Beach east of Orlando shifts off of I-95 to the junction point in the "Y" shape. This station is now able to serve trips from Orlando to both Cocoa Beach and Cape Kennedy. This shift is made possible by the addition of a station on I-95 south of Cocoa Beach near Melbourne. From Melbourne it is less than a 100-mile trip north to Daytona, so the ability to drive from one end of Florida to the other on I-95 is not compromised.

The base case scenario has been presented in some detail above to demonstrate how the model locates stations. Next, scenarios based on other assumptions are summarized in less detail.

Maximizing VMT

In this scenario, the model maximizes vehicle-miles traveled (VMT) instead of the number of trips. This VMT objective multiplies the number of trips on each shortest path by its distance in order to maximize the gasoline consumption potentially replaced by hydrogen. The results are surprisingly similar (Figure 4.14). Twelve of the locations that were optimal for maximizing trips remain optimal for maximizing VMT, and numerous 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. The Orlando station enables ODs within 50 miles of Orlando to complete trips, and also makes the 85-mile Orlando-Tampa trip possible. Despite the increased emphasis on serving longer trips, there would still not enough VMT served in the Panhandle to justify placement of scarce refueling resources in that region.

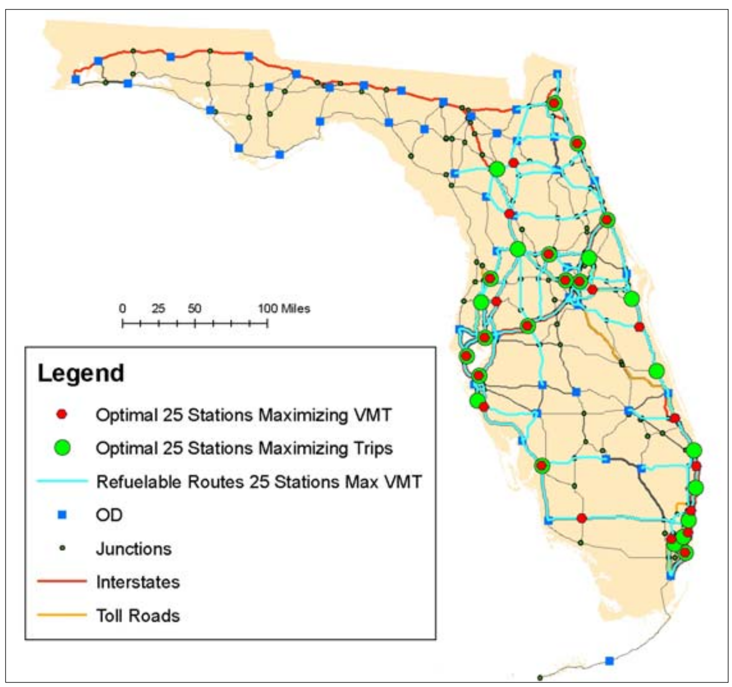

Figure 4.14 Comparison of optimal networks of 25 stations maximizing VMT and trips, for a 100-mile working range

Two examples highlight the differences in the max-trips and max-VMT solutions.

When maximizing VMT, the model locates a station on I-75 crossing the Everglades, because of the higher weight placed on the 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 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 trips, whereas the station on US-301 facilitates fewer but longer trips.

Shorter Vehicle Range

Figure 4.15 presents results for 25 stations maximizing trips, but assuming working ranges of 50 miles and 75 miles instead of 100 miles. The shorter range provides a larger margin for error in case of stations being inoperative, drivers refueling improperly, or drivers taking side trips. With a range of 75 miles, more stations are needed to link Miami with Jacksonville via I-95 because of the closer spacing required. The first ten stations continue to be placed in the Miami-Palm Beach region and the Tampa-Orlando I-4 corridor, and the network does not reach as far north as Gainesville. With a 50-mile range, the optimal network of 25 stations breaks up into 3 independent clusters. Stations are clustered even closer together because of the shorter range, and as a result, there are not enough stations to provide the linkages between the Miami-Palm Beach cluster, the Tampa-Orlando cluster, and the solo station in Jacksonville.

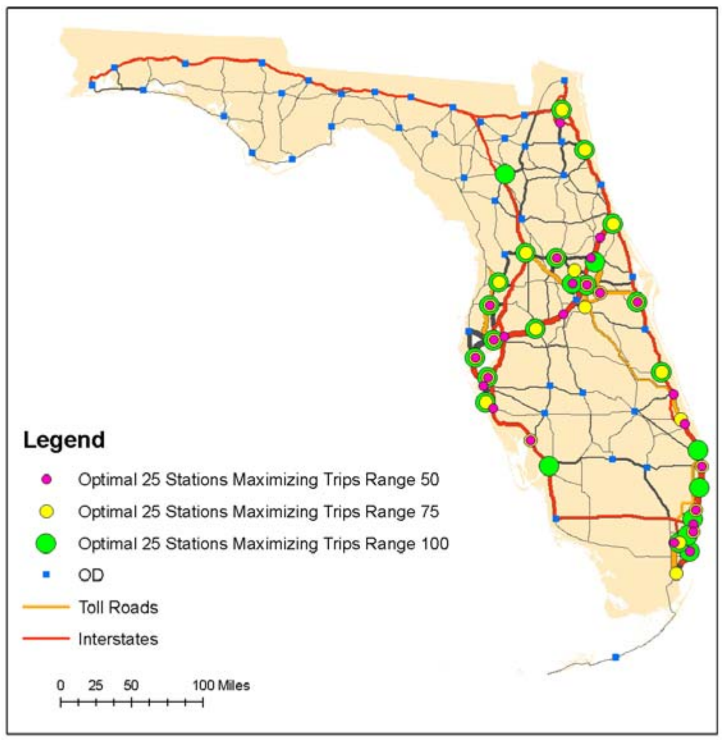

Figure 4.15 Comparison of optimal networks of 25 stations for different vehicle ranges

Tradeoff Curves

Figure 4.16 provides tradeoff curves for both the max-trips and max-VMT objectives for assumed safe driving ranges of 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 [25, 43] has shown, however, that returns are not strictly diminishing, because sometimes it takes two additional stations to be able to refuel a well-traveled but longer trip. Second, the curves for a 75-mile range are lower than the curves for a 100-mile range. This is simply the result of the need for more stations spaced closer together to serve the same long-distance round trips. Third, a given number of stations can generally refuel a higher percentage of trips than VMT. A greater percentage of the total VMT consists of very long trips between smaller origins and destinations, which require more stations to serve.

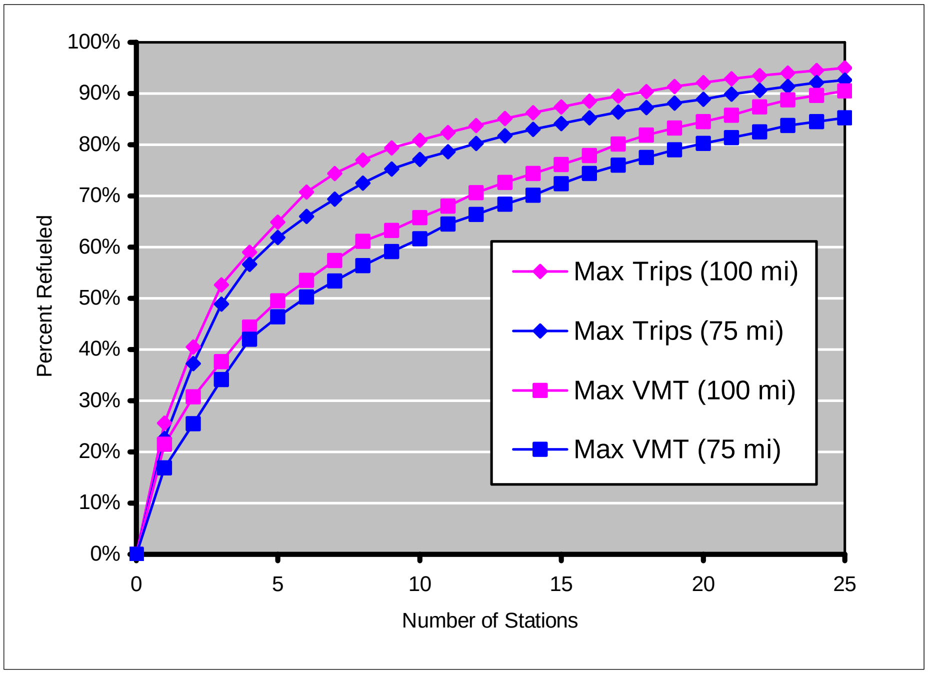

Figure 4.16 Tradeoff between number of stations and percent of demand able to be refueled for the statewide network

Other Factors: Rental-cars, State Government, and Scientific Research

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 be certain locations that should be included for tourism, political, or scientific reasons even though the model, based on intercity estimated trip demand, does not select them. To begin with, we found in the rental-car section of this study that the bundles of trips made by approximately 80% of car renters at the Orlando International Airport could be serviced by three hydrogen stations: at OIA, 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 are intra-city trips that are not modeled in the statewide network. In addition, OIA was not modeled as a destination for intercity trips based on the gravity model. Yet these stations play a key role in the rental-car business model.

Likewise, no scenarios with 25 or fewer stations ever chose Tallahassee based on the *intercity* trips to, from, or through it. A station in Tallahassee, however, may be justified on other legitimate grounds. As the home of Florida State University, a station in Tallahassee may be important for scientific research and environmental education. Similarly, as the state capital, a station 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 near I-75. For this reason, we ran some scenarios in which these five stations are forced into the solution, and the rest of the station network was optimized around these five fixed points.

Forcing in 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. As Figure 4.17 shows, the three rental-car stations in the Orlando area and the Gainesville/Tallahassee stations can serve only 7% of intercity trips estimated by the gravity model for our Florida statewide trip table, versus 65% for the first five stations optimally located in southeast Florida and Tampa. While this appears at first to be a costly tradeoff, it is important to keep several things in mind. First, one must consider the difference between potential trips and actual trips. A small network of stations in southeast Florida can potentially refuel a large number of intercity trips, but until consumers start buying hydrogen cars, the potential will remain unrealized. In contrast, the stations situated to serve a hydrogen rental-car fleet have a built-in source of demand. Likewise, the Tallahassee and Gainesville stations may serve very little intercity demand but might be heavily used by early adopters such as professors and scientists as well as university and government fleets making local trips not included in this intercity model. Second, none of these five required stations are in the Miami area, where the number of intercity trips is highest.

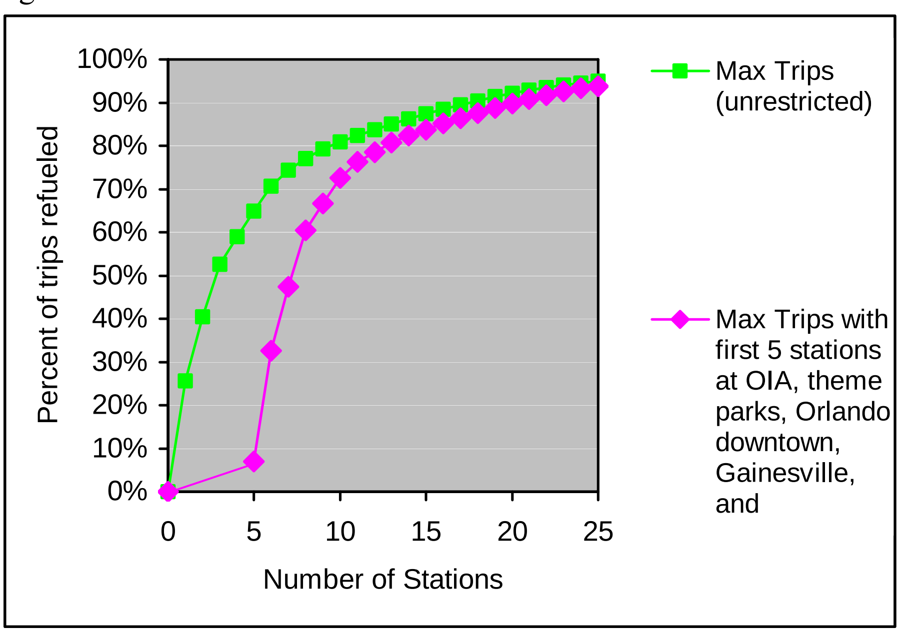

Figure 4.17 Tradeoff curves for max trips, 100-mile range scenarios.

When we run the model to locate five optimal stations in addition to the five required stations, the model chooses the same four stations in SE Florida and one in Tampa to increase the percentage of refuelable trips to 73%, compared with 81% for the unrestricted model. As we continue to add stations in both model runs, the gap continues to close between the two scenarios. With 15 stations the difference is 87% v. 84%; closing to 92% vs. 90% for 20 stations; and 95% vs 94% for 25 stations. Thus, as the network grows, the sacrifice of locating stations specifically for the rental-cars and universities becomes negligible.

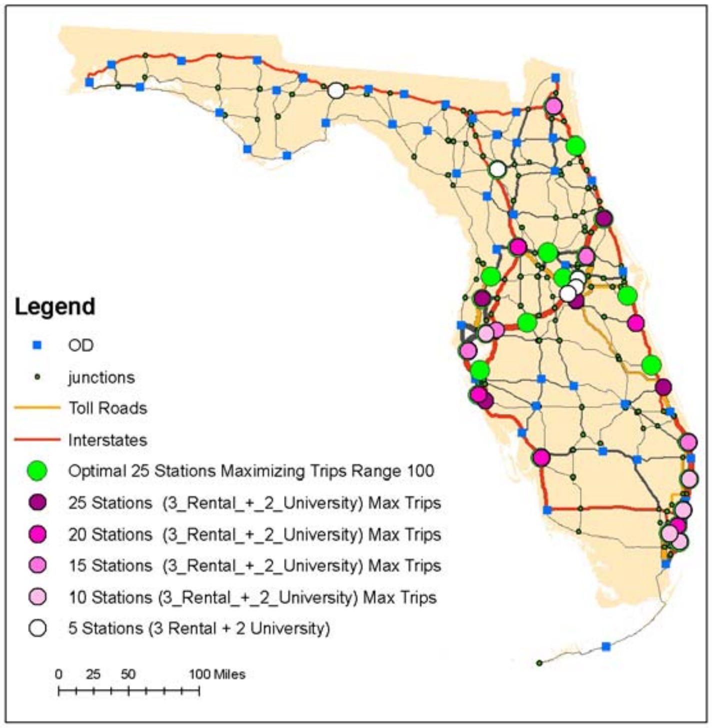

Figure 4.18 Optimal 25 stations for maximizing trips refueled, assuming 3 rental-related stations are built in Orlando and 2 university stations are built, color-coded by priority, and compared with optimal network without rental and university stations (green circles)

The downtown Orlando and Gainesville stations would be optimal in any case in the unrestricted network, entering in the top 10 and top 25 respectively. The question, then, is how does forcing in the stations at the theme parks, the Orlando airport, and Tallahassee change the optimal location of the other stations? The main change is that these three stations replace some of the stations from the Orlando-Tampa-Ocala triangular cluster (in Figure 4.18, green circles show former optimal 25 stations without these required stations). Intermediate size cities in the less urbanized parts of the cluster—such as Ocala, Tavares, Brooksville, and Lakeland—drop out of the Top 25, as does the connecting station on I-75 across the Everglades in the max VMT scenario. Another important finding is that it is still not worthwhile to connect the Tallahassee station to Gainesville or Jacksonville by locating other stations on I-10—at least not with the first 25 stations. There are simply not enough intercity trips along this corridor by Florida residents to justify putting other connecting stations on I-10. More trips or VMT could be served by locating those stations elsewhere.

Finally, many stations remain where they would otherwise have been placed. There are 17 stations in the maximizing trips scenario and 10 stations in the maximizing VMT scenarios that remain exactly the same, showing that these are good locations regardless of whether the rental-car stations and university stations are included in the top 25.

Weighted Hydrogen Consumer Demand

We ran a number of infrastructure scenarios using the weighted hydrogen consumer demand factors based on NREL's GIS-based model [52]. Using multipliers based on demographic and policy variables, we weighted the number of trips and the VMT by the likelihood of consumers at the origins and destinations to adopt hydrogen technology. We then ran a number of different scenarios for the statewide network, 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 safe vehicle driving range.

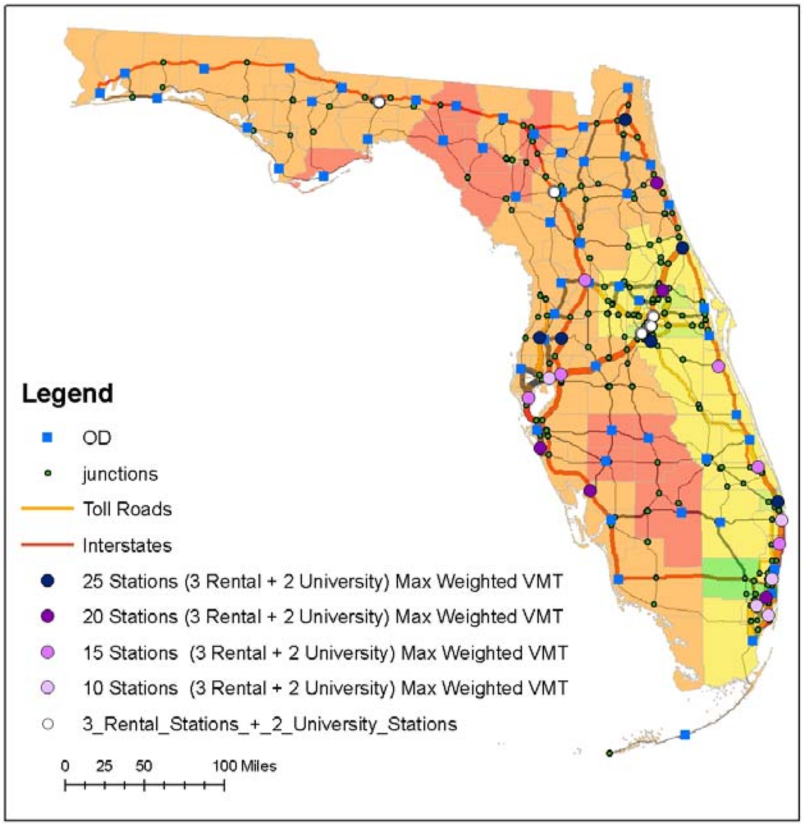

Figure 4.19 Optimal 25 stations maximizing VMT weighted by hydrogen consumer demand scores, assuming 3 rental-related stations in Orlando and 2 university stations

In the weighted demand scenarios, the Miami-Palm Beach and Orlando metropolitan area are predicted to have higher consumer demand than the Tampa and Jacksonville areas mainly because of their Clean Cities coalitions, 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 to maximize the demand that can be served with the same number of stations. In the max trips scenario with five rental-car/university stations, a station in Tavares in the medium-demand area northeast of Orlando replaces a station in medium-low demand Sarasota. In the max VMT scenario with five rental-car/university stations (Figure 4.19), 24 of 25 stations remain the same, but a station in Palm Beach Gardens replaces one on I-95 near St. Augustine. Stations between Palm Beach and the Space Coast become a higher priority, moving up into the Top 15. Overall, however, many locations continue to be optimal both with and without geographically varying weighted consumer demand, which helps lead us to a robust final set of recommendations for the initial hydrogen refueling infrastructure in Florida.

General Conclusions

A number of general policy conclusions can be drawn from these analyses regarding the development of a statewide network of stations for the early stages of the transition to hydrogen vehicles:

1. Although the model does not assume either a clustering or bridging strategy, the preliminary results appear to suggest a strategy somewhat similar to that being developed in California, beginning with clusters in the major cities and later building bridging stations between them to facilitate trips between urban regions.
2. In order to maximize both VMT and trips, the initial set of stations should be clustered in and around the largest metropolitan areas, where they 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.
3. The Miami-West Palm Beach region is ideal for the first cluster because of its high population, short distance among cities, and its linear arrangement.
4. The I-4 corridor consisting of Tampa and Orlando and the rapidly urbanizing area between them is the second-best cluster.
5. There is no consistent formula or guideline to determine when bridging stations should be introduced to connect the clusters. Given the high expense of hydrogen refueling stations, it does not make sense in Florida to roll out bridging stations on all interstate highways at once—something California has gradually come to realize. Connecting Tampa and Orlando along I-4 is the first priority, followed by connecting West Palm Beach to Daytona to Jacksonville on I-95. The I-75 route across the Everglades connecting Miami to Tampa-St. Petersburg-Fort Myers is less important, as is the Florida Turnpike connecting Miami to Orlando and Gainesville. The I-10 corridor connecting Jacksonville to Tallahassee might be justified by out-of-state traffic, but not by in-state, intercity traffic.
6. 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 endanger lives and generate bad publicity. On the other hand, spacing stations too closely sacrifices coverage of more trips and could lead to duplication and underutilization. Our choice of a 100-mile safe driving range is consistent with NREL's assumptions, and should be adequate for dealing with detours, getting lost, and incomplete refueling, and station closures. Assuming maximum spacing of 50 or 75 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 well-populated parts of Florida.
7. Whatever the recommended station spacing, it should be enforced as a maximum spacing only. Strict regular spacing will waste scarce resources. It is important to place bridging stations where they can also serve crossing traffic flows and local traffic flows.

8. Not all Florida residents are equally likely to purchase hydrogen vehicles when they become available. While difficult to estimate, NREL has provided a solid basis for estimating geographic differences in consumer demand [52], which we have adapted to weight our estimated trips between places. While use of this data introduces additional uncertainty, we think it provides a more reasonable estimate of early consumer demand than the raw trip estimates, and we place greater emphasis on these scenarios accordingly. That being said, the weighted consumer demand multipliers do not have a large effect on the optimal facility locations, inducing only minor shifts towards the Orlando and the southeastern counties.
9. Factors not included in the model's data must be taken into consideration. Unique synergistic opportunities with a possible OIA rental-car business, with Florida's flagship universities, Kennedy Space Center and Disney, and the state capital should be considered when locating stations.
10. Tradeoff curves are helpful for thinking about how many stations should be built. The results clearly show that while the greatest demand can be served by the first 10-15 stations, the potential demand continues to grow steadily through 25 stations.

4.5 Orlando Metropolitan Station Location Analysis

The Orlando area was chosen as the study area for analysis at the metropolitan scale. Orlando is the focus of our feasibility study on a hydrogen rental-car business, and it is also the site of Florida's first two hydrogen stations. One station is located at the Orlando International Airport to refuel airport shuttle vans. Although it is not officially a permanent station, we treat it as existing and permanent in these model runs, and it is therefore always the first station sited by the model. The second existing station is a mobile refueling unit currently located at 2801 State Road 426 in Oveido. This station is not open to the public and is scheduled for decommissioning in 2008, and we do not treat it as existing in any scenarios.

The most important difference between analysis at the state scale and at the local scale 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 O-D pair.[2]

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[2] 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.

Base Case

The base case for the Orlando network is maximizing trips based on the FDOT trip table, with only the airport location required. Figure 4.20 shows the optimal locations for 25 stations, color-coded by priority. We generated these priorities by first solving the model for 5 stations, then 10 stations, and so on up to 25 stations. The color shown for each location is the highest order in which it was first chosen. If a location was chosen for a small number of stations but was then replaced by a different location for a larger number of stations, the swap is shown by an arrow. The stability of this sequence of solutions is a positive outcome for planning stations in Orlando. It means that if stations are developed in this order, future stations are not likely to cannibalize the demand of the earlier stations substantially enough to make them suboptimal.

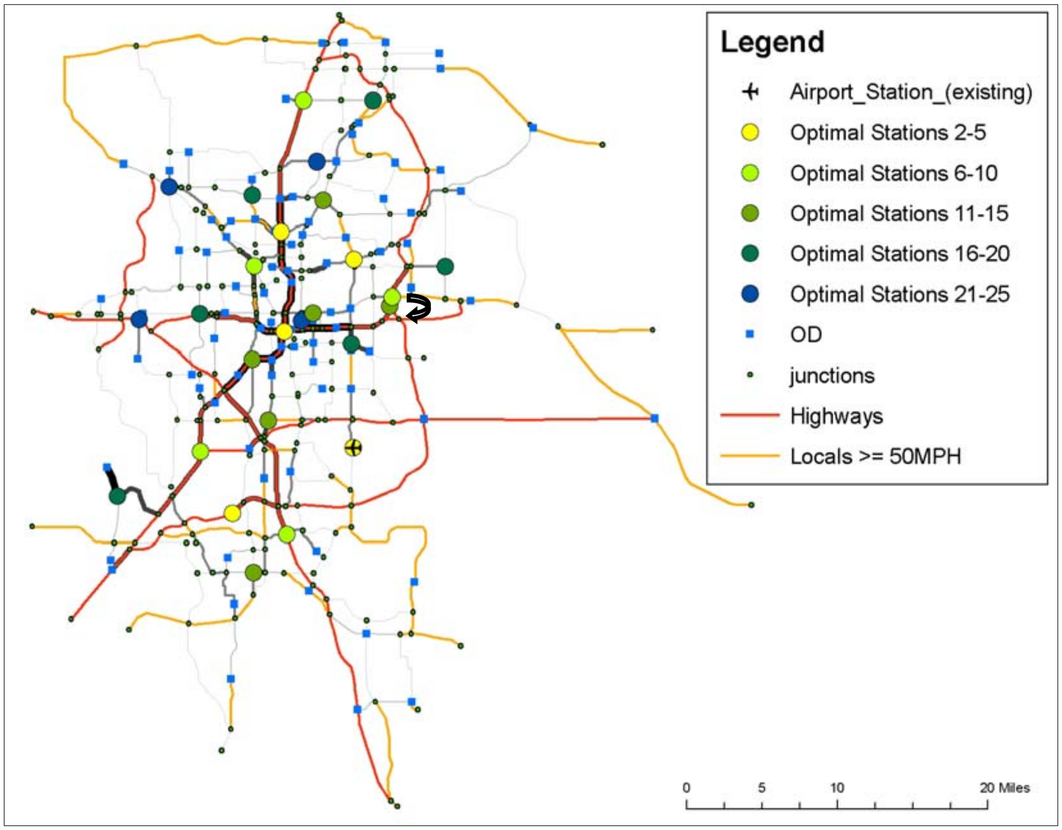

Figure 4.20 Optimal 25 stations in the Orlando area, maximizing trips with 100-mile working range

After the existing station at Orlando International Airport, the best location is in downtown Orlando, near the intersection of I-4 and the East-West Expressway. As can be seen in the tradeoff curve of Figure 4.21, this 2nd station intercepts and can potentially refuel 14% of the daily trips in Orlando. It is assumed that a suitable site could be found near this freeway intersection. The possibility of a feasible downtown site is not unrealistic, as evidenced by the hydrogen station in downtown Phoenix, Arizona operated by Arizona Public Service, which is used by APS vehicles and by taxis that run on CNG-H_2 blends.

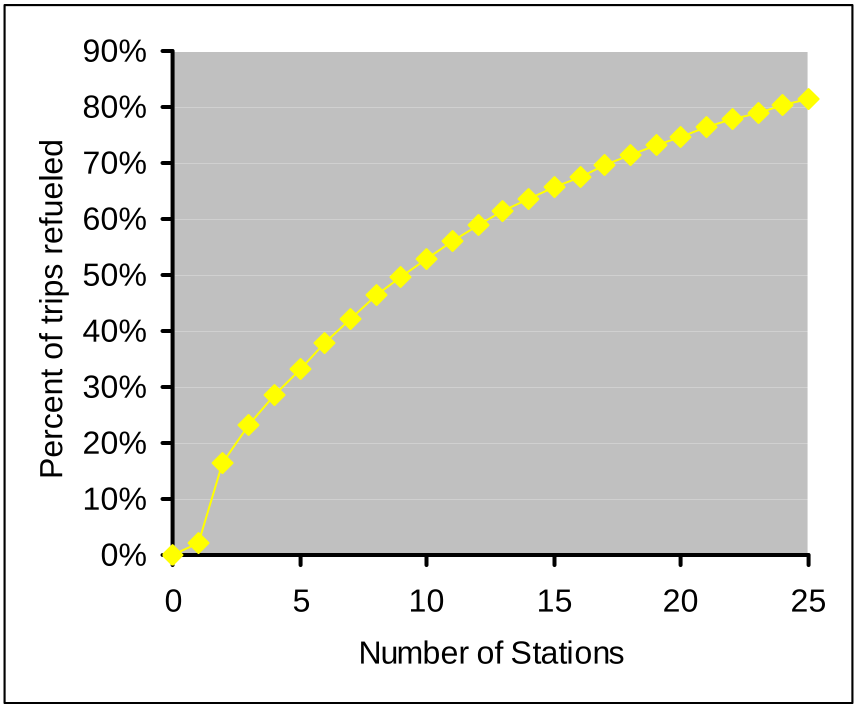

Figure 4.21 Tradeoff between number of stations and percent of inter-zonal trips refueled for Orlando

Of the eight next best station locations (Figure 4.20), six are on major freeways. These sites are located on 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 are not captured by the other stations.* Notice that the freeway stations in the top ten are located a substantial distance away from each other and from the downtown station. They each capture substantial flow volumes that are not otherwise captured by the other stations. A certain amount of cannibalization of demand is inevitable, but our modeling approach tries to maximize the unique flow volume that can be refueled with each additional station. The model also places two of the top ten stations at heavily trafficked intersections of major arterial streets: Aloma Ave. (SR 426) and Semoran Blvd. (SR 436) northeast of downtown, and John Young Parkway (SR 423) and US Highway 441 northwest of downtown.

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 around to minimize the average distance from residential zones to their nearest stations. The top ten station sites are not spread evenly around metropolitan Orlando. Many O-D centroids remain far from any of the top ten sites, and large areas *appear* to be under-served. Appearances, however, can be deceiving. Many trips from these residential areas do in fact pass through at least one of the top ten station sites. In all, the top ten sites intercept 53% of daily inter-zonal Orlando trips.

As seen in the statewide results, the tradeoff curve indicates diminishing marginal returns for additional locations. While the first five stations capture 33% of trips, the subsequent sets of five add 20%, 13%, 9%, and 7% respectively. Not surprisingly, as we move up the curve, fewer and 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 (Figure 4.20). Even so, the overall spatial pattern of 25 stations selected by the FRLM is more concentrated than would be expected with a distance-minimizing, p-median approach.

There is some empirical evidence that consumers prefer to refuel near their homes [32,53]. 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 offer the opportunity to refuel when one is in less of a rush. Locating stations in each and every neighborhood, however, is a luxury that we cannot afford when building the first set of hydrogen stations at roughly $1 million apiece. We would argue that when locating the initial refueling infrastructure, the rules must be different. It is most important in the early stages of the infrastructure rollout 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. With only a handful of stations, a station that is far from home but on their route may in fact be more convenient than a station that is within a few miles of their home but requires a special trip to go there.

Rental-oriented Stations and Weighted Demand Scenarios

To optimize the refueling network around the three targeted rental-car stations, only one change is needed. Because we already treat the airport station as fixed, and the downtown station is always the first station added, only the station at the epicenter of the theme parks needs to be required. We designated the area near Epcot Center Drive and World Drive as the location.

The weighted demand scenarios account for the difference in the likelihood of consumers in different census tracts to purchase hydrogen vehicles. We ran two scenarios based on weighted trips and weighted VMT. Both assumed the airport station exists and the theme park station would be built, and both added 5 stations at a time from p=5 to p=25. The optimal stations for maximizing weighted trips is shown in Figure 4.22.

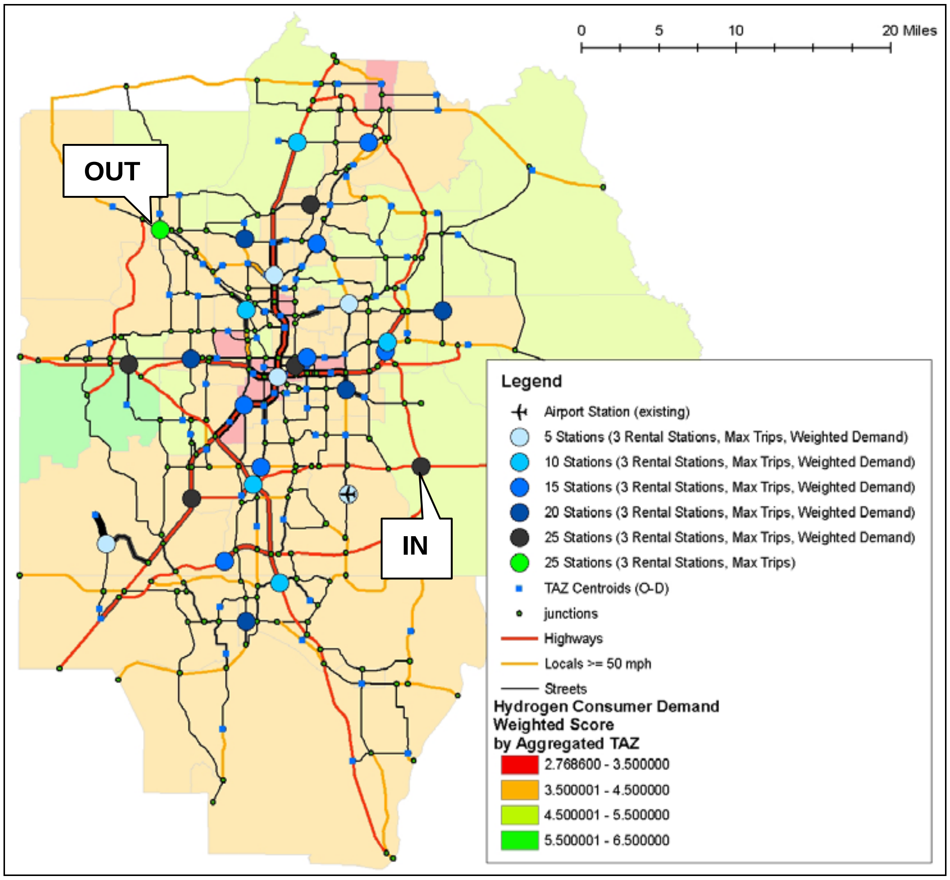

Figure 4.22 Optimal 25 stations maximizing trips refueled weighted by hydrogen consumer demand, assuming airport and theme park stations are built, compared with similar unweighted scenario (green circles)

Geographic differences in adoption rates had only a minor effect on the optimal station locations. Of the 25 optimal stations in the unweighted scenario, only one in northwest Orlando in an area with a demand score of around 4 drops out of the solution. It is replaced by a station in southeast Orlando in an area with a demand score of around 5.

General Conclusions of the Orlando-Scale Analysis

Several general conclusions emerge from this analysis:

1. To get the most benefit out of the initial refueling 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. In Orlando, this is best achieved by locating most of the first ten stations on major freeways with high volumes of passing traffic, where they intersect with other freeways or with major arterials and high volumes of crossing traffic, and where many trips start and end.
2. It is equally important that these funnel points duplicate or cannibalize each other as little as possible. Thus, the major freeway locations within the first ten locations are spaced far apart on the network where they can capture different sets of freeway flows and different sets of crossing/starting/ending trips.

3. The highest priority locations, and the first to be built, should not necessarily be spread evenly across the landscape to minimize average distance from where people live to their nearest stations. As more stations are added beyond the first ten, 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 even distribution that would minimize average distance to stations.
4. While other empirical research has shown that consumers tend to refuel their conventional vehicles near their homes, we would caution against concluding that the initial set of 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 stations can only truly be near a small fraction of Orlando residents' homes, but can be right on the route of over half of their trips.
5. Diminishing marginal returns are less pronounced at the Orlando metropolitan scale, as can be seen in Figure 4.23. While each additional station serves less new demand, there is no particular number of stations at which the demand served begins to noticeably level off. Any of the optimal networks of 10 stations can refuel over 52% of the daily trips in the network. The next 10 stations add about 22% more weighted trips or 19% more weighted VMT. Beginning with a rollout of approximately 10 stations in the Orlando area would place stations on convenient routes for a large number of consumers with demographic profiles reflecting a greater likelihood of adopting hydrogen vehicles in the future.

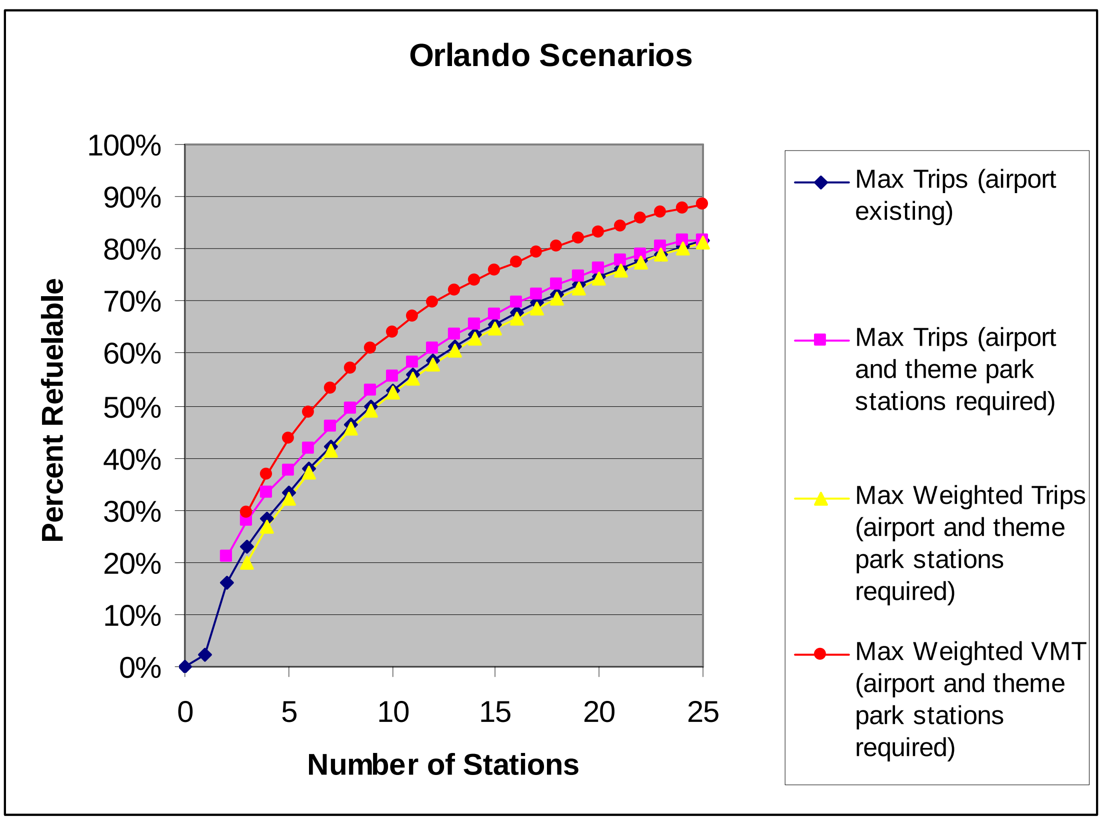

Figure 4.23 Tradeoff curves for the Orlando scenarios

5. RECOMMENDATIONS FOR THE HYDROGEN REFUELING STATION INFRASTRUCTURE IN FLORIDA AND ORLANDO

In planning an initial hydrogen-refueling infrastructure in Florida, our team of researchers considered the results of a large number of model scenarios for both the statewide and Orlando networks, but ultimately employed our expert judgment and local knowledge to interpret the model results and arrive at our best recommendations. This approach recognizes that the Flow-Refueling Location Model for Florida 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 operations research 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 model scenario can determine the best hydrogen station network for refueling.

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 that require multiple refuelings, regardless of vehicle range, demand weighting, and whether we are maximizing trips or VMT. For the Orlando area, we also analyzed which locations would perform well for intercity, intra-city, and rental-car trips. 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 propose the station locations presented below.

Recommended Statewide Network of Hydrogen Refueling Stations

Table 5.1 lists all stations that were chosen as optimal in any scenario, and their highest rank in each scenario. Rows represent stations, and columns represent model scenarios, and the cells relate whether the station was optimal in the scenario. 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. Other scenarios were solved only for 10 or 25 stations. Based on all the model results and the expert judgment of the research team, we then sorted the stations (and the rows of the table) into tiers of Top 5, Top 10, and so on through Top 25. In ranking them, we considered synergies, spacing, timing, and local intra-city consumer demand. We do not attempt to rank stations within each tier of five.

In ranking the stations, we did not consider all scenarios equally. 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 trip 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 trips *long-distance* trips, we placed slightly more emphasis on maximizing VMT. Our final recommendations for 25 stations are quite close to the Max VMT-Range 100-Weighted Demand-Five Required Sites scenario in the last column of Table 5.1, with the substitution of Kennedy Space Center for the Shady Hills station, substitution of Fort Pierce for Palm City, some minor relocation of locations within towns, and some shuffling of stations among the tiers. As can be seen in Table 5.1, these 25 recommended stations generally perform very well across the board. However, through the modeling we are confident that this set of stations will coordinate well with each other for serving longer distance trips and cannibalize each other's demand as little as possible.

The locations are mapped in Figure 5.1, and it can be seen that the connecting stations outside of the clusters are nicely spaced. The spacing of stations along I-95 never exceeds 100 miles. The spacing on I-4 between the I-75 station at Mango and any of the Orlando area stations is also less than 100 miles, as is the distance from the Ft. Pierce station to the southernmost Orlando station at Osceola Parkway.

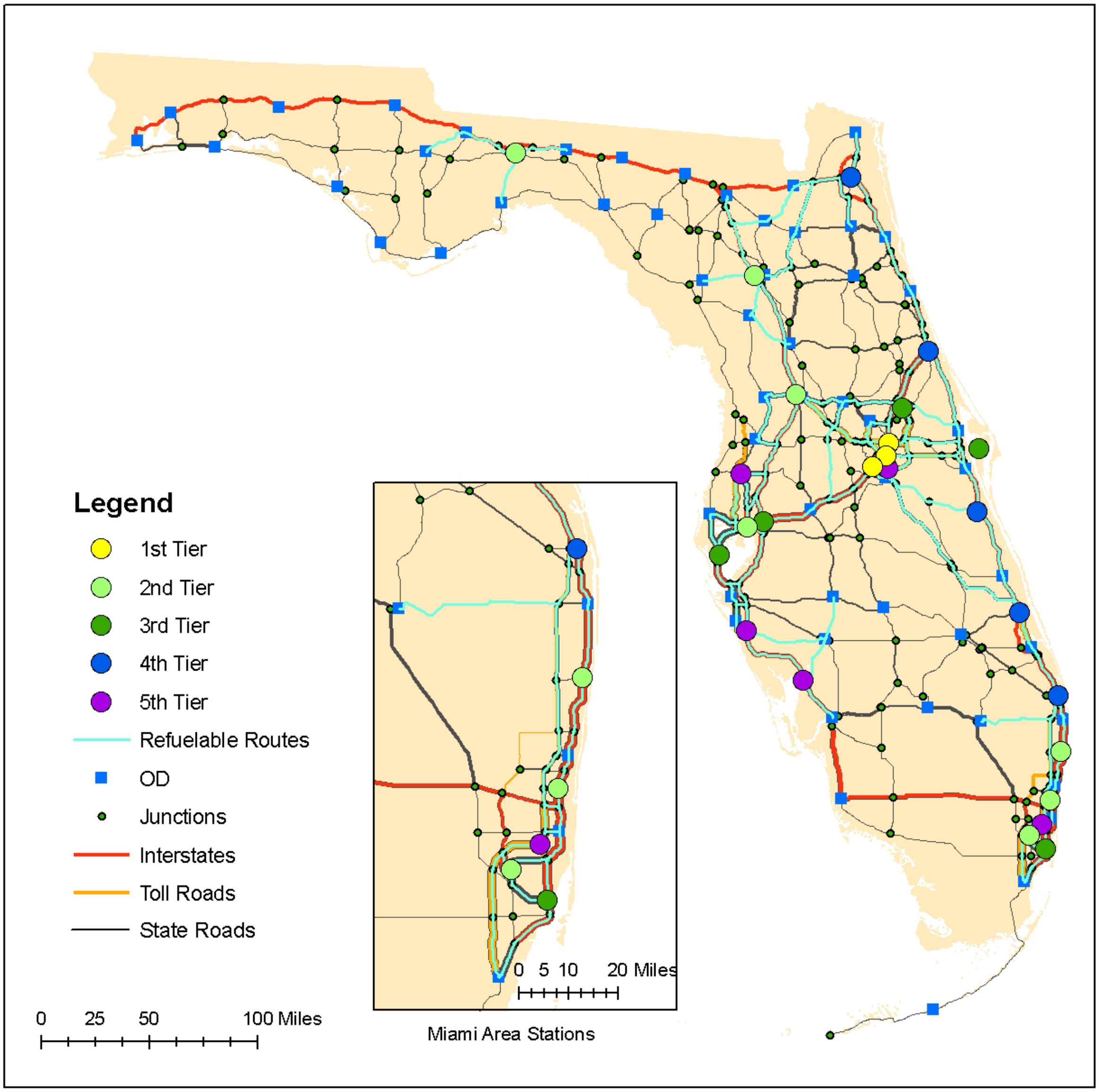

Figure 5.1 Recommended hydrogen stations for the statewide network

As can be seen in Figure 5.1, 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.

Discussion

We included the Orlando airport, downtown, and theme park stations in the Top 5 because the hydrogen rental-car business would be impossible without them. There are several factors that recommend them above the two university stations. First, 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), but the hydrogen rental-car company at the Orlando airport could be the first in the US. Second, these Orlando stations have more potential to do triple duty for intra-city trips, intercity trips, and rental-car trips than the university stations. Third, the rental-car business can provide guaranteed customers for these stations, unlike the university stations.

We ranked the two university stations in the second set of five stations. 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 an even higher priority considering the already thriving scientific research program at the University of Florida, as well as university vehicle fleets and the greater likelihood of professors and administrators to be early adopters. These same 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.

Table 5.1 Recommended Statewide Station Network[*]

Jct	City	Intersection	Max Trips Range 100	Max VMT Range 100	Max Trips Range 50[+]	Max Trips Range 75[#]	Max VMT Range 75[+]	Max Trips Range 100 Five Required Sites	Max Trips Range 100 Weighted Demand	Max Trips Range 100 Weighted Demand Five Required Sites[+]	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

[*] 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.
[+] Stations in these columns are not ranked. Only one scenario (for p=5) was analyzed.
[#] Stations in this column are either Top 10 or Top 25. Other p values were not analyzed.

Jct	City	Intersection	Max Trips Range 100	Max VMT Range 100	Max Trips Range 50[+]	Max Trips Range 75[#]	Max VMT Range 75[+]	Max Trips Range 100 Five Required Sites	Max Trips Range 100 Weighted Demand	Max Trips Range 100 Weighted Demand Five Required Sites[+]	Max VMT Range 100 Weighted Demand Five Required Sites
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 Forida'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

[+] Stations in these columns are not ranked. Only one scenario (for p=5) was analyzed.
[#] Stations in this column are either Top 10 or Top 25. Other p values were not analyzed.

Jct	City	Intersection	Max Trips Range 100	Max VMT Range 100	Max Trips Range 50[+]	Max Trips Range 75[#]	Max VMT Range 75[+]	Max Trips Range 100 Five Required Sites	Max Trips Range 100 Weighted Demand	Max Trips Range 100 Weighted Demand Five Required Sites[+]	Max VMT Range 100 Weighted Demand Five Required Sites
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
Never Chosen by Model, but Could be Important for Connecting Tallahassee to Jacksonville, Gainesville, and Points South, and for Interstate Traffic											
176	Lake City	I-75 & I-10									
Other Frequently Optimal Locations											
176	Brooksville	US Hwy 41 & St Hwy 50	Top 25	Top 25		Top 25	Top 25		Top 25		
203	Cocoa West	I-95 & King St	Top 20		Top 25	Top 25	Top 25				
240	Fort Myers	I-75 & Palm Beach Blvd	Top 20	Top 15				Top 20	Top 20	Top 25	
257	Hollywood	I-95 & Hollywood Blvd		Top 25	Top 25	Top 10	Top 25		Top 5	Top 25	
88	Lakeland	I-4 & US Hwy 98	Top 10	Top 10		Top 10			Top 10		
213	Manatee	I-75 & I-275	Top 20	Top 15	Top 25	Top 25	Top 25		Top 20		
202	Orlando	Central Florida Greenway & Bee Line Expwy		Top 25	Top 25	Top 25	Top 25				
223	Palm City	Floridas Tpke & SW Martin Downs Blvd		Top 15		Top 25					Top 15
225	Palm City	I-95 & Kanner Hwy			Top 25						
226	Palm City	I-95 & Floridas Tpke					Top 25				

[+] Stations in these columns are not ranked. Only one scenario (for p=5) was analyzed.
[#] Stations in this column are either Top 10 or Top 25. Other p values were not analyzed.

Jct	City	Intersection	Max Trips Range 100	Max VMT Range 100	Max Trips Range 50[+]	Max Trips Range 75[#]	Max VMT Range 75[+]	Max Trips Range 100 Five Required Sites	Max Trips Range 100 Weighted Demand	Max Trips Range 100 Weighted Demand Five Required Sites[+]	Max VMT Range 100 Weighted Demand Five Required Sites
92	Pasco	I-75 & St Hwy 52		Top 10							Top 25
98	Pasco	US Hwy 41 & St Hwy 52	Top 15		Top 25	Top 25	Top 25	Top 25	Top 15	Top 25	
248	Pompano Beach	I-95 & Atlantic Blvd		Top 25	Top 25	Top 10			Top 5	Top 25	
301	Sarasota	US Hwy 301 & US Hwy 41	Top 20			Top 25	Top 25	Top 20	Top 20	Top 25	Top 20
273	South Miami Heights	Dixie Hwy & W Dade Expwy				Top 10			Top 10	Top 25	
124	St. Johns	I-95 & St Hwy 16	Top 25	Top 25		Top 25	Top 25			Top 25	
144	St. Johns	I-95 & St Hwy 206									Top 20
37	Tavares	US Hwy 441 & St Hwy 19	Top 25	Top 25	Top 25	Top 25				Top 25	
241	West Palm Beach	I-95 & Southern Blvd		Top 5	Top 25	Top 10			Top 10	Top 25	Top 10 (but replaced in Top 25)
Occasionally in Top 25--Not Recommended											
4	Alachua	St Hwy 26 & US Hwy 301		Top 25							
145	Apopka	Orange Blossom Trl & Western Expwy				Top 25			Top 20		
79	Bradenton	St Hwy 64 & US Hwy 41			Top 25						
58	Celebration	I-4 & Irlo Bronson Mem. Hwy					Top 25				
67	Citrus Ridge	I-4 & US Hwy 27			Top 25						
249	Collier	I-75 & St Hwy 29		Top 25							
139	De Land	I-4 & St Hwy 44			Top 25						

[+] Stations in these columns are not ranked. Only one scenario (for p=5) was analyzed.
[#] Stations in this column are either Top 10 or Top 25. Other p values were not analyzed.

Jct	City	Intersection	Max Trips Range 100	Max VMT Range 100	Max Trips Range 50[+]	Max Trips Range 75[#]	Max VMT Range 75[+]	Max Trips Range 100 Five Required Sites	Max Trips Range 100 Weighted Demand	Max Trips Range 100 Weighted Demand Five Required Sites[+]	Max VMT Range 100 Weighted Demand Five Required Sites
258	Fort Lauderdale	I-95 & SW 34th St			Top 25						
268	Hialeah Gardens	Okeechobee Rd & W Dade Expwy			Top 25						
43	Jacksonville	US Hwy 17 & I-295			Top 25						
78	Manatee	US Hwy 301 & St Hwy 70	Top 15						Top 15		
267	Miramar	I-75 & Dade Expwy		Top 25			Top 25				
181	Oakland	W Colonial Dr & Floridas Tpke					Top 25				
160	Ocala	I-75 & US Hwy 27		Top 25							
182	Ocoee	Floridas Tpke & Maguire Rd	Top 25	Top 25	Top 25						
201	Orlando	Floridas Tpke & Central Florida Greeneway							Top 25		
244	Palm Beach	Floridas Tpke & Southern Blvd					Top 25				
299	Palm Coast	I-95 & Palm Coast Pky							Top 20		
166	Sanford	St Hwy 46 & I-4			Top 25		Top 25				
81	Sarasota	I-75 & St Hwy 72		Top 25	Top 25			Top 25			
164	Seminole	I-4 & Seminole Blvd				Top 10					
100	Shady Hills	St Hwy 52 & Suncoast Pky									Top 25
300	Titusville	I-95 & Garden St							Top 25		

[+] Stations in these columns are not ranked. Only one scenario (for p=5) was analyzed.
[#] Stations in this column are either Top 10 or Top 25. Other p values were not analyzed.

Jct	City	Intersection	Max Trips Range 100	Max VMT Range 100	Max Trips Range 50+	Max Trips Range 75#	Max VMT Range 75+	Max Trips Range 100 Five Required Sites	Max Trips Range 100 Weighted Demand	Max Trips Range 100 Weighted Demand Five Required Sites+	Max VMT Range 100 Weighted Demand Five Required Sites
102	Town 'n' Country	W Hillsborough Ave & Veterans Expwy					Top 25				
153	West Vero Corridor	I-95 & St Hwy 60	Top 20			Top 25	Top 25				

+ Stations in these columns are not ranked. Only one scenario (for p=5) was analyzed.
# Stations in this column are either Top 10 or Top 25. Other p values were not analyzed.

Stations on the southeastern coast provide the most bang for the buck because of the large populations with favorable demographics and the linear arrangement of cities. Compared with some other areas of Florida, however, there is less consistency across scenarios regarding *which* particular stations are optimal. The combination recommended here, consisting of Miami Lakes, Delray Beach, Ft. Lauderdale, Miami (I-95 & I-195), Miramar, and Palm Beach Gardens, were grouped together in several scenarios, including the max VMT weighted demand scenario. Miami Lakes in particular entered every scenario with a 100-mile vehicle range, and was usually one of the first sites chosen.

In the Orlando area, we recommend two stations in addition to the downtown, theme park, and airport stations needed for hydrogen car rentals. In the 3rd tier we propose a station near Sanford and Lake Mary that would capture long-distance trips that skirt around the beltway in northeast Orlando away from the three rental stations. The final Orlando station in the Top 25 would be located somewhere around Osceola Parkway between Orange Blossom Trail and Florida's Turnpike. This station would serve the Kissimmee area and daily commutes on the Turnpike, as well as enable drivers to connect to a station in Fort Pierce without exceeding the 100-mile safe driving range.

While there is no station on I-4 midway between Tampa and Orlando, long-distance commuting from the Lakeland area could conceivably be possible if the family had a hydrogen car for long-distance commuting and a second conventional car for local trips. Lakeland commuters could refuel near their jobs in Tampa or Orlando and be able to complete several long-distance commutes before refueling again near work. A similar logic applies to intercity commutes from West Palm Beach.

Daytona is another location of particular interest, which we place in the 4th tier. It was rarely chosen in the Top 20 in the model, but it consistently appeared in the Top 25 as a key connecting station between I-4 and I-95. About 5% of car renters included it in their bundle of trips with the Orlando theme parks and/or downtown Orlando. Like KSC, it may attract technology enthusiasts who are more likely adopters. Daytona is also a popular weekend destination from Orlando and the terminal point of the I-4 corridor.

Seven of these 25 stations are in towns where a publicly accessible CNG station exists (Appendix 5). These include Tampa, Fort Lauderdale, Delray Beach, Palm Beach Gardens, Fort Pierce, Kennedy Space Center, and Daytona Beach. Five of the other cities have privately owned CNG stations not open to the public, including Orlando, St. Petersburg, Miami, Jacksonville, and one at the Disney theme parks. While co-locating a hydrogen station with these CNG stations may save on investment and permitting costs, the CNG stations may not be located in high-traffic and high-visibility locations ideal for a consumer-oriented station. Most CNG stations were originally sited for serving industrial or governmental fleets.

Although not justified by any of our model runs, a station at the junction of I-10 and I-75 near Lake City should be considered at some point. This station will eventually be needed to connect Tallahassee with Jacksonville, Gainesville, and points south. It would also be important for out-of-state traffic coming from the north at some future time.

Recommended Orlando Area Network of Hydrogen Refueling Stations

Because of the finer scale of the OD zones in the Orlando network, we feel that the consumer hydrogen demand multipliers are likely to be more reliable for the Orlando network than the statewide network. Therefore, we considered those scenarios 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. The emphasis, therefore, should be on refueling as many trips as possible, both short and long. The more trips that can be refueled, the more convenient it will be for consumers, more of whom will be able to purchase hydrogen vehicles. Compared with the statewide network, there is more consistency across scenarios in the Orlando network, leading to a robust plan with reduced uncertainty.

We recommend an initial network of 11 hydrogen-refueling stations that together can refuel about 54% of weighted trips (Figure 5.2). 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.

Discussion

Eight of the 11 recommended stations were consistently in the Top 10 in every scenario. They are easy, robust recommendations. The three stations needed for the rental business are joined in the Top 5 by stations at I-4 and Maitland Blvd. and at Aloma Ave. and Semoran Blvd. These stations at funnel points of the network consistently maximize the number of trips that could not otherwise be 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. Alternatively, Disney might be interested in having a station at EPCOT or Magic Kingdom, or it could be placed on International Drive.

The second tier includes stations in Northwest Orlando at Orange Blossom Trail & N John Young Parkway, in Heathrow at I-4 & W Lake Mary Blvd, and in Union Park at Central Florida Greenway & E Colonial Dr. (Hwy 50) that consistently place in the Top 10. A few points about these and the remaining stations are worth mentioning:

- The Union Park station trades in and out of optimal solutions with a site just to its south at the Greenway (SR 417) and Valencia College Lane. The site we recommend on Colonial Drive is more frequently optimal in networks of more than 15 stations, meaning it is likely to remain a good location as the network develops further. The Valencia College Lane site, in contrast, has complicated access problems if coming from the south on the Greenway.
- The Florida Mall station would be somewhere near Orange Blossom Trail and Sand Lake Rd. This location trades in and out of solution with a station just to its south at the intersection of Florida's Turnpike and the Bee Line Expressway. A station anywhere in this vicinity, with high visibility and easy access to the freeways, would be ideal.

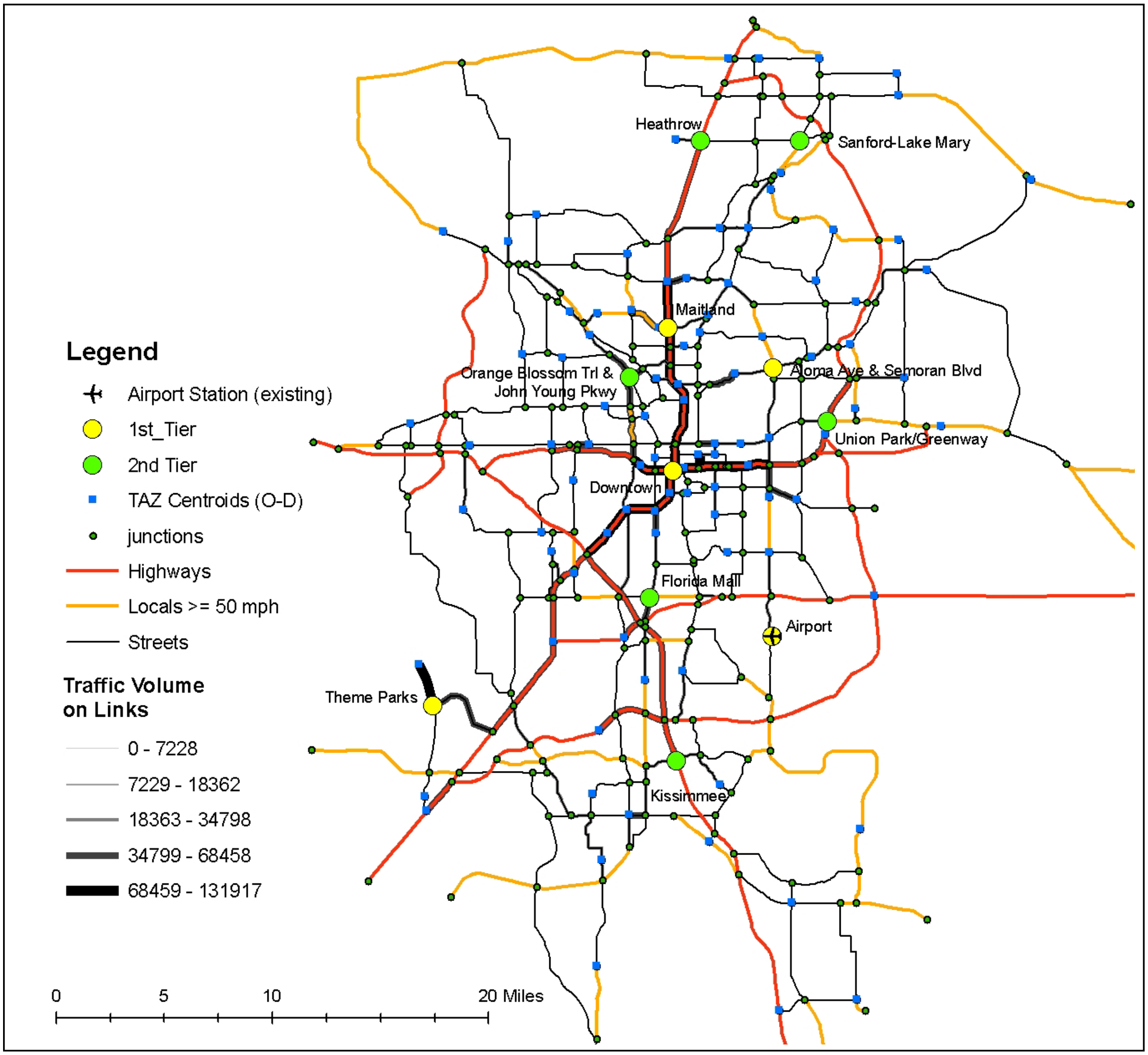

Figure 5.2 Recommended stations for the Orlando area

Table 5.2 Recommended Orlando Station Network

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
Top 15 Stations						
71	US Hwy 17/92 & St Hwy 436	Casselberry	Top 15	Top 15	Top 15	Top 15/25
101	E Colonial Dr & N Bumby Ave	Fashion Square Mall	Top 15	Top 15	Top 15	Top 20
179	Cent Florida Greenway & Valencia College Ln	Valencia East	Top 15	Top 15	Top 15	
252	I-4 & S John Young Pky	Southwest Orlando	Top 15	Top 15	Top 15	
Top 20 Stations						
269	Town Loop Blvd & Town Center Blvd	Seminole Towne Center Mall	Top 5	Top 15	Top 15	
44	South Sermoran Blvd & Curry Ford Rd	East Orlando	Top 20	Top 20	Top 20	
57	St Hwy 434 & St Hwy 438a	Northwest Orlando	Top 20	Top 20	Top 20	
81	N Alafaya Trl & University Blvd	University of Central Florida	Top 20	Top 20	Top 20	Top 20
88	W Colonial Dr & N Hiawassee Rd	Pine Hills	Top 20	Top 20	Top 20	

Jct	Intersection	Place	Max Trips Airport	Max Trips Airport + Disney	Max Trips Airport + Disney Weighted Demand	Max VMT Airport + Disney Weighted Demand
Top 25 Stations						
132	W Vine St & S John Young Pky	Kissimmee	Top 15	Top 15	Top 20	Top 15
102	E Robinson St & N Mills Ave	Downtown Orlando	Top 25	Top 25	Top 25	
185	Florida's Tpke & Maguire Rd	Ocoee	Top 25	Top 25	Top 25	
219	I-4 & Bee Line Expwy	Orange County Convention Center	Top 10	Top 25	Top 25	Top 25
272	St Hwy 434 & Wilma St	Longwood	Top 25	Top 25	Top 25	
Optimal in Some Scenarios but not Consistently – Not Recommended						
207	Cent Florida Greenway & Bee Line Expwy	Innovation Place			Top 25	Top 15
218	Florida's Tpke & Bee Line Expwy	Near Florida Mall		Top 10	Top 10 but not Top 15-25	
63	E Main St & Sand Lake Rd	Apopka	Top 25	Top 25		Top 20
54	S Park Ave & St Hwy 435	Lockheed-Martin				Top 25
62	N Apopka Vineland Rd & Clarcona Ocoee Rd.	Clarcona				Top 25
78	US Hwy 17-92 & St Hwy 434	Longwood				Top 20 not 25
138	N Hoagland Blvd & W Vine St	Osceola Square Mall				Top 25
172	Red Bug Lake Rd & Cent Florida Greenway	Oviedo				Top 20
186	East-West Expwy & Hiawasee Rd.	Pine Hills				Top 15
215	I-4 & Florida's Tpke	Universal Studios				Top 10
222	Florida's Tpke & Cen Florida Greenway	South Orange County				Top 5 not 20 not 25
231	I-4 & World Dr	Disney's Wide World of Sports				Top 15 but not in Top 25
241	South Sermoran Blvd & East-West Expwy	Azalea Park				Top 20
248	University Blvd & Cen Florida Greenway	University of Central Florida				Top 15 but not in Top 20 or 25

- The station near Kissimmee is an important station in the fifth tier for the statewide network. This station needs to be close to a Turnpike exit for drivers coming from the southeast part of the state. Otherwise it is over 100 miles from Fort Pierce. This station also needs to be close to the heavy traffic on South Orange Blossom Trail. A location on the newly developing Osceloa Parkway between the two highways would fit the bill.
- We include an 11^{th} station in the second tier on South Orlando Drive between the Eastern Beltway and Lake Mary Blvd in Sanford. This station usually becomes optimal in the range of 15-25 stations, but being an important component of the statewide network, we moved it up for consistency between the state and metro networks.

Future Research

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 points, while the Tampa area stretching from Sarasota to Pasco County to Lakeland is represented by eight points, compared with over 100 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. While adequate for modeling longer-distance intercity trips, the level of geographic detail used for Miami and Tampa should be improved for modeling their intra-city trips.

Future research could also incorporate out-of-state trips, which were omitted from these data, limiting the traffic in the Panhandle. Also, detouring from shortest paths is not considered in the model, although we have sometimes adjusted our recommendations based on the potential for minor detouring to move a site up in the rankings. Recent developments in flow-capturing research may make it feasible to incorporate detouring behavior [54].

The model and Florida data sets could be applied to other policy questions. Decision-makers may want to test other assumptions and strategies. In addition, the model could be applied to other alternative fuels. A denser network of CNG stations would have to take into account the locations of existing CNG stations. There is little in the model that is specific to hydrogen. Demand patterns for other alternative-fuel vehicles might be similar to those for hydrogen.

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Appendix 1: Car Renter Survey Instrument

Florida Hydrogen Initiative Car Rental Study
Rollins College/Florida Atlantic University/Arizona State University/ US Dept. of Energy

This survey will help us understand what is needed to develop a hydrogen rental-car option for the Orlando International Airport. Hydrogen, the most common and lightest element in the universe, is produced from water or natural gas. Hydrogen cars either use an internal combustion engine to burn hydrogen or a fuel cell to generate electricity for a quiet but powerful electric motor. The only emission from either process is water vapor. Hydrogen rental-cars would be refueled by trained professionals at a limited number of convenient locations.

Please circle the appropriate items or fill in the blanks. Please write any answer that cannot be adequately expressed by checking or filling in a blank.

1. Which of the following destinations did (will) you visit on your trip to Orlando?

[1] Disney World	[2] Universal Studios	[3] Sea World	[4] EPCOT
[5] Other theme park	[6] Downtown Orlando	[7] Kennedy Space Ctr.	[8] Daytona Beach
[9] Tampa-St. Petersburg	[10] Miami-Palm Beach	[11] Everglades	[12] Port Canaveral (cruises)

2. How long was your stay in the Orlando area? _____ days

3. Rank the importance of the following features in convincing you to rent a hydrogen car on a future trip to Orlando, on a scale from 1 (not important) to 5 (very important)?

	Scale is: 1 (not important) to 5 (very important)				
a. Map of refueling stations in Florida and Orlando	[1]	[2]	[3]	[4]	[5]
b. Able to exchange for a gasoline car at no extra cost	[1]	[2]	[3]	[4]	[5]
c. Priority parking at theme parks	[1]	[2]	[3]	[4]	[5]
d. Using a pollution-free vehicle	[1]	[2]	[3]	[4]	[5]
e. Fuel cost per mile comparable to gasoline	[1]	[2]	[3]	[4]	[5]
f. Opportunity to test-drive first	[1]	[2]	[3]	[4]	[5]
g. Driving range of vehicle (miles between refuelings)	[1]	[2]	[3]	[4]	[5]
h. Vehicle performance (acceleration, noise)	[1]	[2]	[3]	[4]	[5]
i. Opportunity to experience a new technology	[1]	[2]	[3]	[4]	[5]
j. Availability of insurance	[1]	[2]	[3]	[4]	[5]
k. Full-service refueling by a trained attendant	[1]	[2]	[3]	[4]	[5]
l. On-call, roadside repair/refueling service	[1]	[2]	[3]	[4]	[5]

4. How far out of your way would you be willing to drive for a hydrogen refueling station, without you considering it a hassle?
[1] up to 1 mile   [2] up to 3 miles   [3] up to 5 miles   [4] more than 5 miles

5. Would you be willing to pay more money to rent a hydrogen vehicle? [1] Yes [2] No

If yes, how many more dollars per day? [1] $0-$5   [2] $5-$10   [3] $10-$15   [4] $15-$20
If no, would you be willing to rent a hydrogen car at a lower price? [1] Yes   [2] No

6. Please rate your understanding of hydrogen vehicle and fuel-cell technology prior to completing this survey:
[1] Never heard of it   [2] Vague awareness   [3] Some knowledge of how it works
[4] Clear understanding of how it works

7. Please tell us a little about yourself:

Age: [1] 20-29   [2] 30-39   [3] 40-49   [5] 50-59   [6] 60-69   [7] 70 and above

Education: [1] less than high school   [2] high school [3] college graduate
[4] post-graduate degree

Marital Status: [1] Single   [2] Married

Number of children: [0]   [1]   [2]   [3]   [4]   [5]   [6 and above]

Occupation: [1] student [2] private industry/business [3] military
[4] government/education [5] retired   [6] other

Origin: (What state or country do you consider home?) __________________________

Household income: [1] under $30K [2] $30K-49K [3] $50K-99K   [4] over $100K

Thank you very much for your cooperation.

Appendix 2

Statistical Relationships Between Demographic Characteristics and Responses

We analyzed the survey results statistically to determine if the demographic characteristics of the renter significantly influenced their responses. We used analysis of variance (ANOVA) to search for relationships between the opinion variables and gender, marital status, education, and income. Our tests were done at the 95% confidence level or as alternatively stated, the 5% significance level (also known as the alpha level).

There are no statistically significant variations in survey response on all opinion questions BY **Marital Status**.

For **Gender**, there are seven (7) questions that have significant differences (M vs F). They are:

	Male Mean	**Female Mean**	**F-TestValue**	**Significance**
Ability to Exchange	3.68	4.10	12.98	.000
Cost Per Mile	4.21	4.52	11.73	.001
Vehicle Performance	3.85	4.22	14.69	.000
Road Service	4.18	4.53	14.50	.000
How Often do You Rent Cars	1.57	1.37	6.96	.009
How Far to Station	2.52	2.33	4.28	.039
Understanding of Technology	2.72	2.13	37.92	.000

Conclusions: on first 4 opinion questions above females are **more concerned** than males. On frequency of rental, distance to station, and understanding of technology males indicate higher use, more concern with distance to station, and they say they understand the technology at a higher level.

For **Education,** there are four (4) significantly different responses.

	High School Mean	**College Mean**	**Grad School Mean**	**F-Test Value**	**Significance**
Pollution Free	4.52	4.41	4.19	3.20	.042
Refueling by trained agent	4.28	3.88	3.99	4.69	.010
How Often do You Rent Cars	1.28	1.45	1.60	4.18	.016
Lower Price	1.10	1.02	1.00	5.13	.007

Conclusions: people with higher education levels are **less concerned** with renting a pollution-free car, refueling by trained agent, and lower price. Higher education persons rent cars more frequently.

For **Income** there are two (2) significantly different responses.

	Less than $30K	**$30K - $49K**	**$50K - $99K**	**$100K +**	**F-Test Value**	**Significance**
Understanding of Technology	2.00	2.22	2.30	2.61	4.89	.002
How Often do You Rent Cars	1.00	1.41	1.32	1.65	7.31	.000

Conclusions: Higher income persons believe they understand the technology better, and in general higher-income persons rent cars more often.

Appendix 3

Spatial Decision Support System for Locating Hydrogen-Refueling Stations

This appendix is based on a draft chapter from the future dissertation of Seow Lim

Software Architecture of the FRLM-SDSS

We implement the FRLM-SDSS 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.

Workflow

Figure 1 shows the workflow normally performed when working with the FRLM-SDSS. Detailed information about each step is discussed in the next sections.

- Work with the input data using ESRI ArcGIS Desktop products, such as ArcMap and ArcCatalog to create GIS data in the ArcGIS personal geodatabase format. This includes generating the shortest path between origin and destination using ArcGIS Network Analysis tool.
- Run the ConvertData custom .NET ArcGIS command implemented as part of the SDSS to convert the input GIS data in the personal geodatabase to the FRLM native network data format in a Microsoft Access database.
- Invoke the greedy or genetic algorithms implemented as custom .NET ArcGIS commands. User can specify parameter values, such as number of facilities, fixed facilities, objective type, and vehicle range, before running the algorithm. The algorithm read in the data from the FRLM native network data in the Access database.
- After completing the run, the algorithm outputs the results to the ArcMap window, text file and the Access database. Results include the selected facilities, covered routes, time taken to solve the problem, and percentage of flow covered.

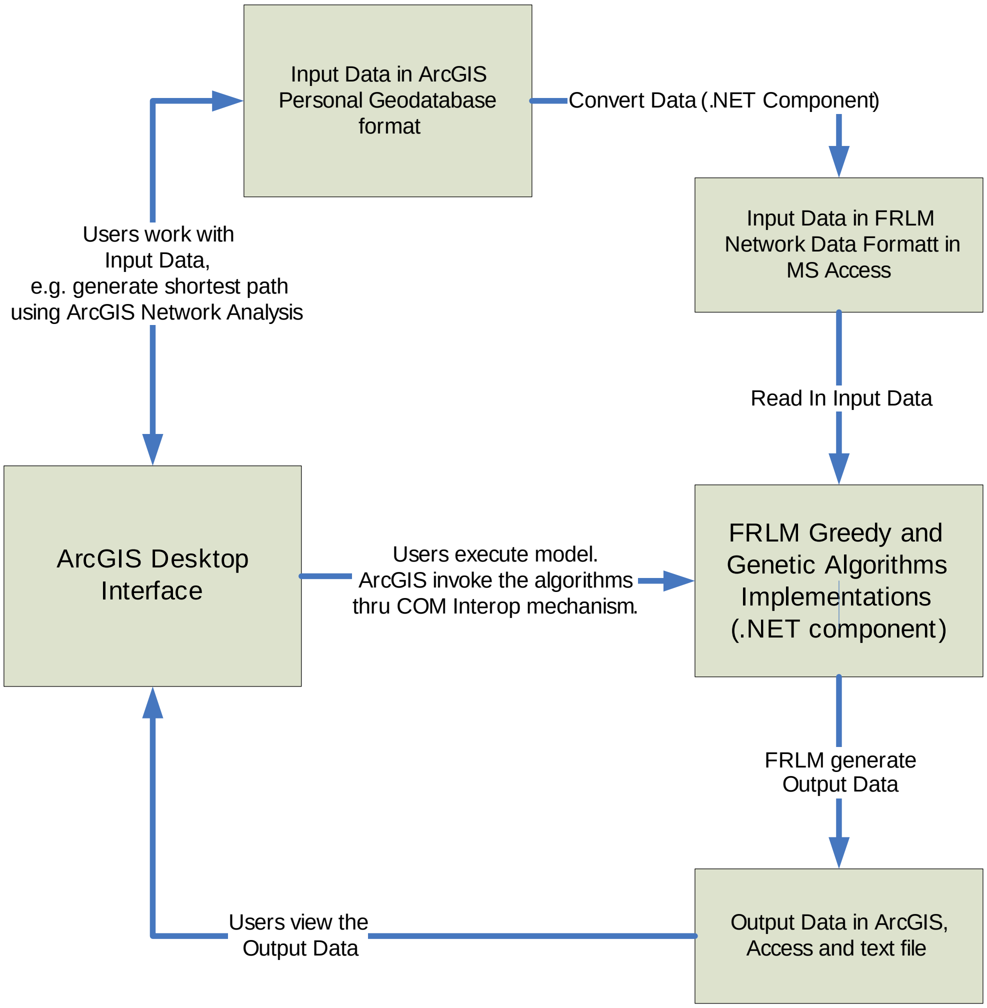

Figure 1: Workflow for the SDSS

Input

The inputs to the SDSS include spatial and non-spatial data. The spatial inputs to the SDSS are in the form of ESRI ArcGIS feature data class. Users build the input data by manipulating spatial data using ArcGIS Desktop. The five input layers for the SDSS are:

1. Population centers point layer. This layer can be derived from spatial manipulation of an underlying population data set. For instance, the user can define zones, and then the SDSS would find the centroids, automatically move them to the nearest road, and compute the populations within the zone. This layer forms the origin and destination (OD) pairs of the network.
2. Junctions point layer. This layer is derived from the junctions of the road network. Junctions are also important for turns in the shortest path algorithm.
3. Candidate facilities point layer. This layer defines the candidate facilities for hydrogen-refueling stations. The population centers and junctions layers form the basis of this layer.

4. Road network line layer. This layer defines the road network of the region where hydrogen-refueling stations are to be allocated. All the population centers and candidate facilities must be connected to a line in the road network. We also use the length and road type (e.g. Interstate, tool road, us highway, local street) of the road segments to determine the shortest paths based on travel time. Travel time for every road segment is estimated using length divided by the driving speed corresponded to the road type.
5. Shortest path routes layer. This layer is obtained by using the closest facility feature of ArcGIS network analysis tool. By using the origin-destination pairs in the population centers layer, ArcGIS network analysis calculates the shortest path for every origin-destination pair using the shortest path algorithm. We use travel time as the impedance of each road segment for calculating the path with the shortest travel time.

The non-spatial input data to the SDSS includes vehicle range, number of facilities to be built, and trip table for all origin and destination pairs.

Data Conversion

We implement a data conversion tool using .NET and ArcObject to convert data in ArcGIS format into tables in Microsoft Access. These tables in Access form the input data for the heuristic algorithms. The tables in Access are simplified representations of the data in ArcGIS format, as they only contain the connectivity information for the origin-destination, candidate facilities, road network segments, and shortest path routes. The real-world locations and shapes of the objects are not preserved when converting from ArcGIS format to Access format, because such information is not needed by the algorithms.

In the GIS, a road segment that connects two nodes can comprise of multiple lines to represent the real location and shape of the road in the real-world. The real-world location of the nodes, such as origins, destination, and candidate facilities, are also preserved. Such information is important in the GIS because both input and output data can be displayed on a map with a realistic looking road network.

The data conversion algorithm produces the simplified network model by performing spatial analysis on the GIS road network to determine the connectivity of the network. In the simplified network model, the link between two nodes is represented by a line associated with the corresponding impedance value, such as length or traveling time. The SDSS loads the simplified network from the database and initialize the network on the computer’s memory before performing the computational search. Without the one-time data conversion, the SDSS would have to perform spatial analysis on the GIS network every time before executing the search algorithms. This would have introduced redundant computational time to the SDSS.

Algorithms Execution

After the input data layers are converted, the user can execute the algorithms. The user has the choices of selecting different algorithms to the problem. The algorithms include greedy, greedy substitution and genetic algorithms. These algorithms are implemented using the Microsoft .NET programming framework. The SDSS extends ArcGIS Desktop interface by allowing users to invoke the algorithms using customized buttons and dialogs from ESRI ArcMap application. Figure 2 shows the custom buttons on ArcMap that can be clicked by user to invoke the greedy and genetic algorithms, in addition to the data conversion tool.

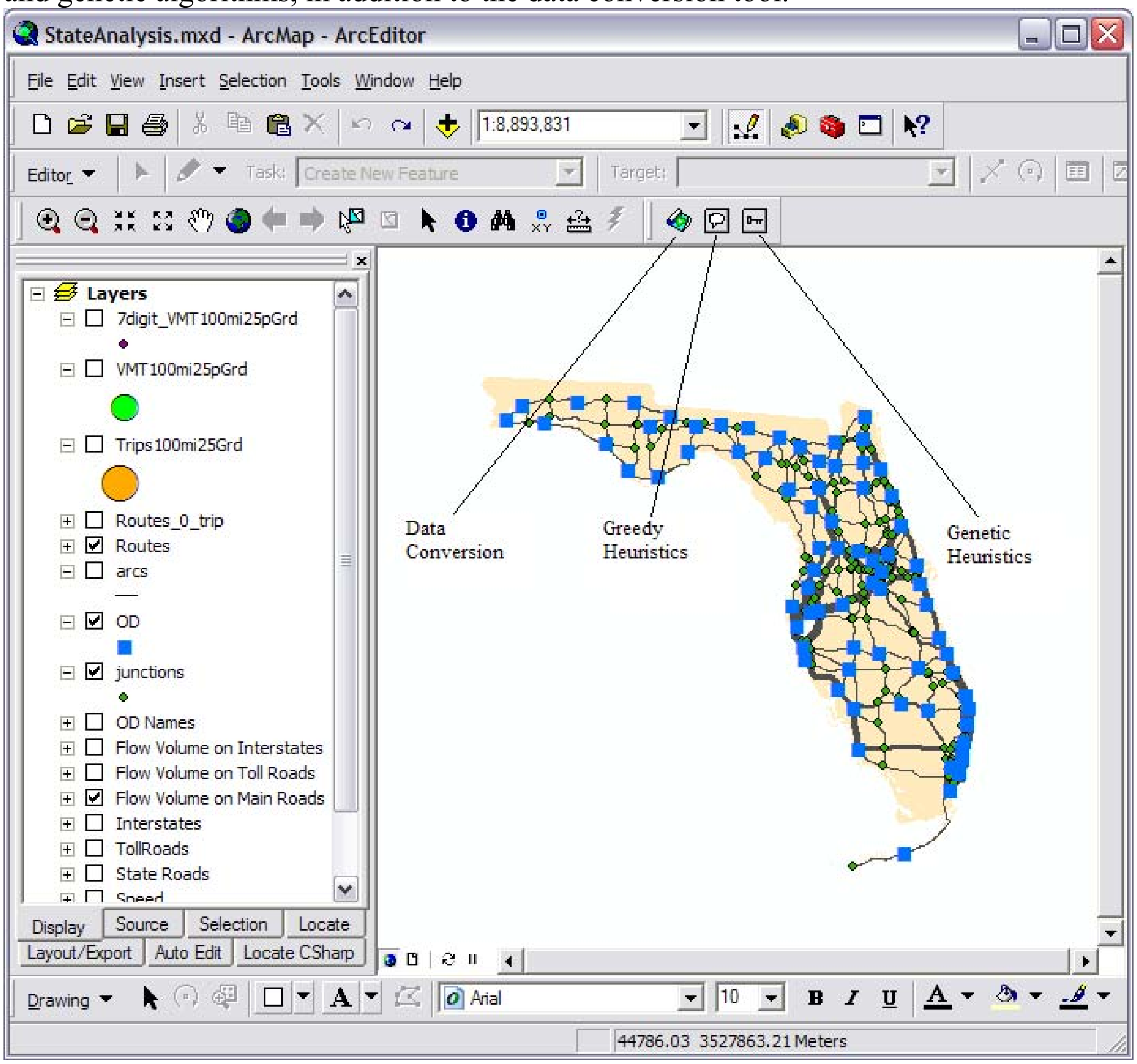

Figure 2: Custom FRLM-SDSS ArcMap buttons

For each algorithm, users have the options to specify different parameters for the algorithms. For instance, users can specify the vehicle range, the number of facilities, and the objective to be maximized. Users can also specify refueling stations that already exist on the network. In this case, the algorithm will always include the specified facilities in the final selection of optimal refueling stations. This is useful in cases where existing hydrogen-refueling stations are already built within the network. These execution options enable the users to perform scenario analysis and study the results of different scenarios. Figure 3 and 4 show the execution options for running the greedy and genetic algorithms.

The parameters that are common for both the greedy and genetic algorithms are as follow:

- Vehicle Range: The vehicle range of the hydrogen vehicle. The unit is based on the unit of the GIS road layers, usually in meter.
- Number of facilities: The total number of hydrogen-refueling facilities to be built, including the fixed facilities.
- Objective Type: The objective to maximize. For "Number of Trips", the model maximizes the total number of trips covered by refueling facilities. The number of trips for every route is stored in the trip table. For "Unweighted Routes", every route is considered to have the weight of one. This objective is useful for validating the model and data. For "Vehicle Mile Trip", the model maximizes the total number of vehicle miles times the number of trips for all the paths that are covered by the refueling stations. For example, if shortest path route A has 100 trips with length of 10000 meters, and shortest path route B has 100 trips with length of 5000 meters, the model will attempt to cover route A first since it has double the number of "Vehicle Mile Trip" of route B. "Unit Length Per Mile" is the number of length unit in a mile. For example, if the unit is meter, then "Unit Length Per Mile" is 1609.3. This value is used by the model to calculate the "Vehicle Mile Trip" for every path.
- Fixed Facilities: These are the existing hydrogen refueling stations in the network. User specifies the facility ID of these facilities ID from the network model. For example, the input parameter of "10 23 154" specifies that facility 10, 23 and 154 as fixed facilities. The "Number of Facilities" includes the facilities specified in this field. If the "Number of Facilities" is five, and three fixed facilities are specified in this field, the model will search for two more facilities to maximize the objective.
- Show selected facilities: Determine whether selected facilities will be output on the GIS after the execution of the algorithm.
- Show covered routes: Determine whether routes covered by the selected facilities will be output on the GIS after the execution of the algorithm.

Algorithm-specified parameters, such as iterations, number of generations, are covered in the later chapter specified to the algorithms.

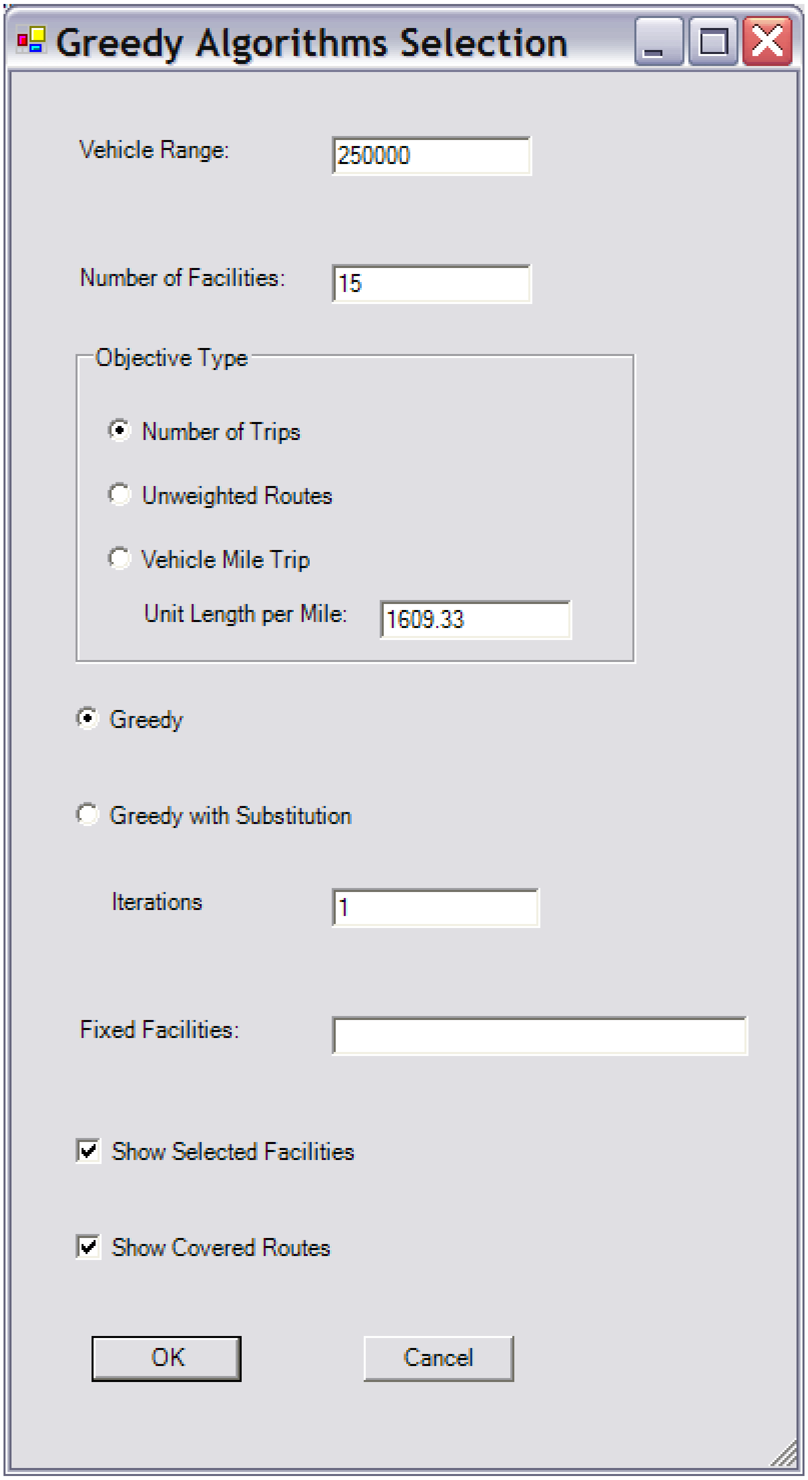

Figure 3: Execution Options for Greedy and Greedy Substitution Algorithm

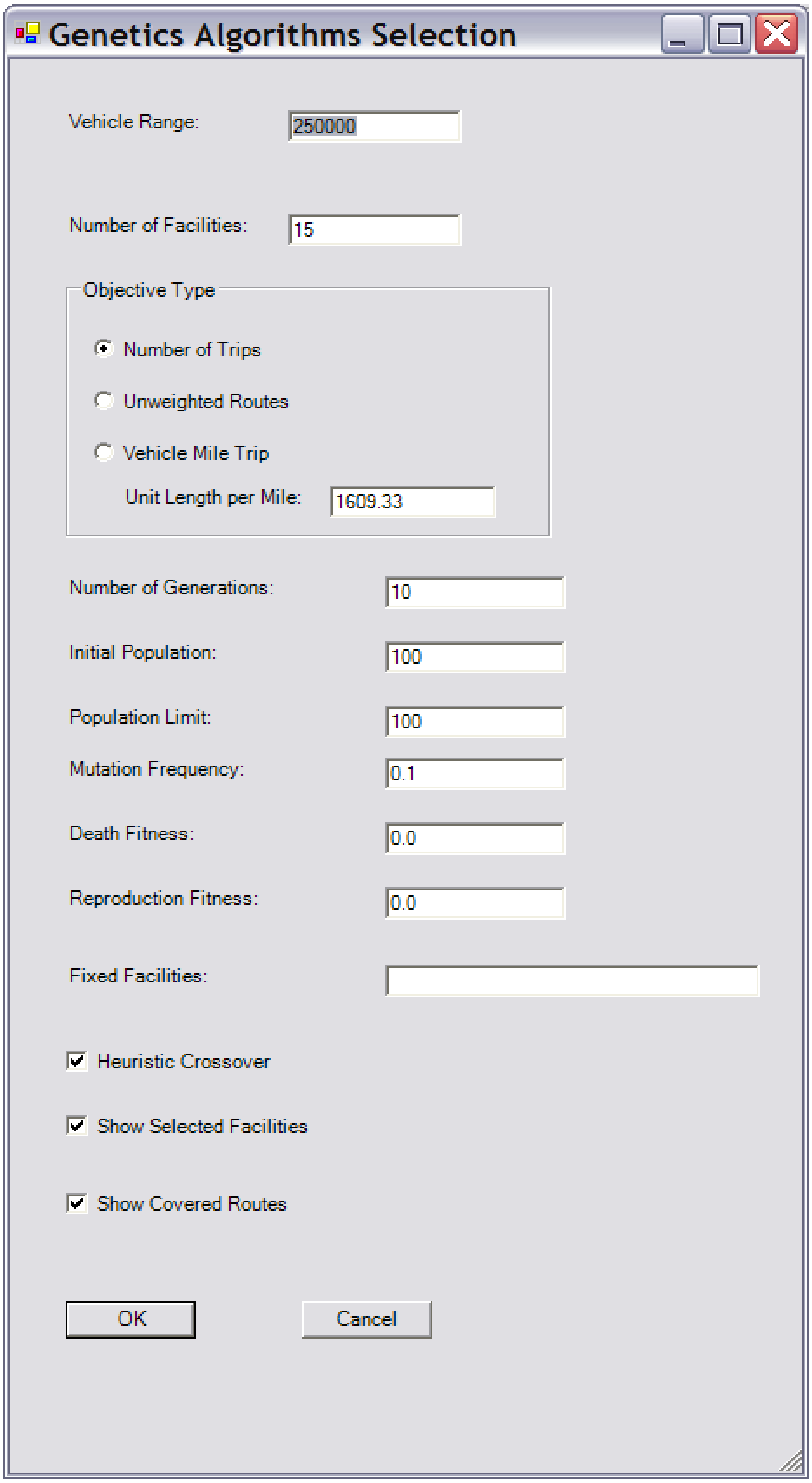

Figure 4: Execution Options for Genetic Algorithm

Output

Once the algorithm completes its execution, it output the results to the map and a text file. The map output of the model consists of the following:

- Selected refueling stations are output as selected features in the junction layer.
- Covered routes are output as selected features in the shortest path route layer.

The user can easily export the selected features to separate feature data class using ArcGIS data export tool. The SDSS also output detailed results, such as percentage covered, paths refueled information, into a text file. Figure 5 shows the map output of an algorithm run. The gas stations represent the selected facilities, while highlighted routes represent covered routes. Note that the routes displayed on the map are different from road segments. Every route is comprised of one or more road segments. From the output map, what we see are essentially road segments that are part of at least one covered route.

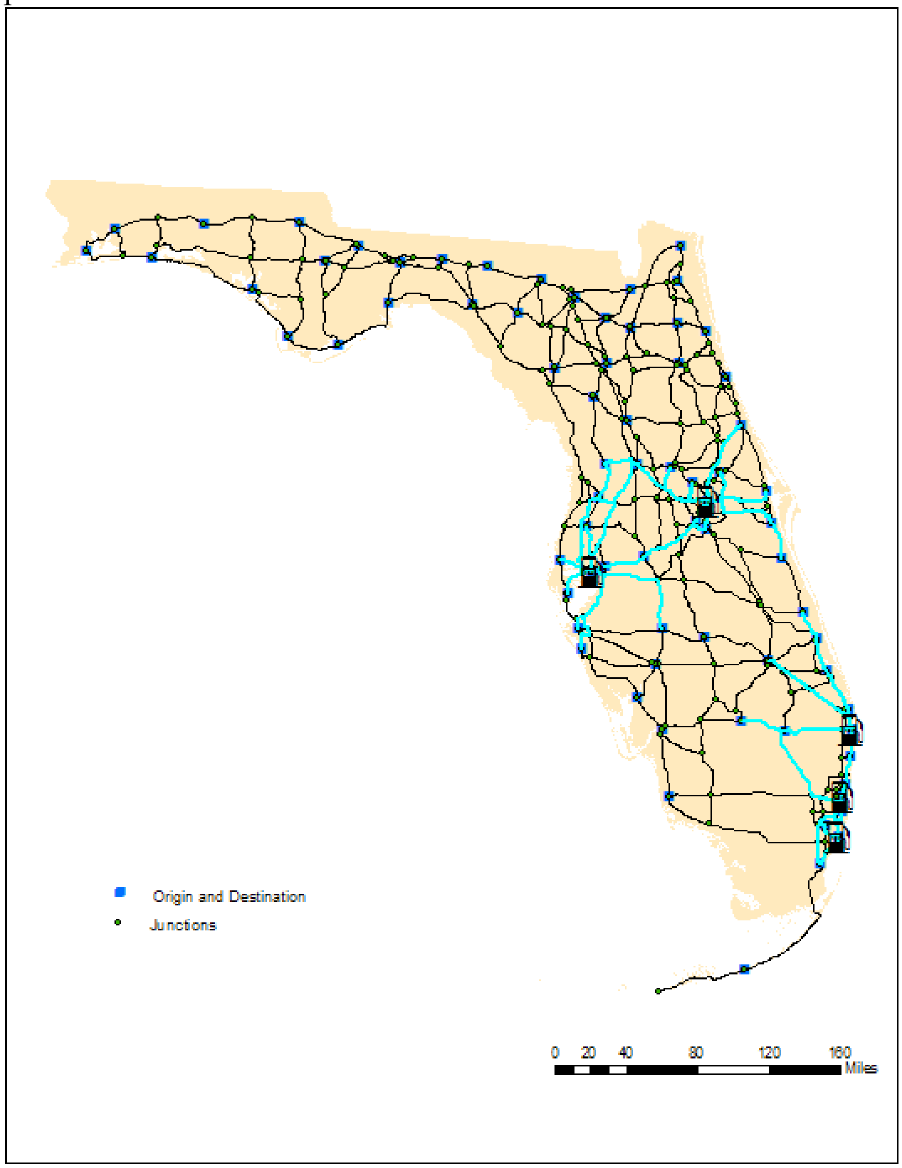

Figure 5: Sample output of an algorithm run

Solving the Flow Refueling Location Model

Kuby and Lim (2005) originally solved the FRLM problem by using branch-and-bound algorithm. While branch-and-bound algorithm is able to obtain optimal solution for the problem, it would usually take too long to solve for a complex real-world complex problem. Thus, we implement heuristic algorithms, such as greedy and genetic, within the SDSS to help obtain solutions within a more reasonable timeframe.

To solve the FRLM using brand-and-bound, we develop a program to generate all the possible facility combinations for every path. These combinations are determined exogenous to the FRLM, and form the input to the model. The generation of these combinations can be very computational intensive, if the network has long paths with large number of facilities. With heuristic algorithms, we evaluate facility combination (i.e. solution to the problem) as part of the search algorithm, and thus we do not need to pre-generate the combinations of facilities for every path.

Greedy and Greedy with Substitution Algorithms

The greedy algorithm selects one facility at a time to maximize the additional flow covered. The selected facility is then fixed in the selected set. The algorithm repeats the selection of one facility at each iteration until it selects the total number of facilities it needs (Daskin 1995).

The greedy-with-substitution algorithm is based on the greedy algorithm. However, after each new facility is added, other facilities in the selected set are substituted with facilities in the non-selected set. If the substitution increase the total flow covered, the substitution that yields the most improved solution are preserved. The user can specify the number of iterations of substitution from one to four. The algorithm attempts to substitute one facility in the selected set with facilities from the non-selected set one at a time. If the substitution improves the solution, the algorithm will attempt to substitute one additional facility in the selected set with facilities from the non-selected set until the number of iterations is reached. If no substitution improves the solution, no additional substitution will be performed for that particular solution set. Refer to chapter three for more information regarding greedy and greedy substitution algorithms.

Genetic Algorithms

Genetic algorithms are heuristic search algorithms that iteratively evolve into better solutions, similar to the process of biological evolution (Alp, Erku and Drezner 2003). In genetic algorithms, solutions randomly interact with each other to produce new solutions. Just like the process of evolution, where the fittest survive, genetic algorithms tend to keep the good solutions while eliminating the poor solutions. One of the common applications of genetic algorithms is to perform combinatorial search. The FRLM is a combinatorial search problem, where we select p facilities out of n candidate facilities to maximize the flow covered. Thus, it would be valuable to investigate the performance and effectiveness of genetic algorithms in solving the FRLM.

The implementation of genetic algorithms is unique in every problem. The encoding, fitness function, population size, new member generation, mutation frequency, replacement and termination need to be designed and fine-tuned for every problem.

Encoding is the strategy of representing the solutions of a search problem in terms of chromosomes. For location-allocation problem, a set of p number of candidate facilities can form a chromosome in the implementation of genetic algorithms.

The fitness function is generally the same as the objective function, which determines how fit a particular chromosome or solution is. For maximization problem, such as the FRLM, the higher the value of the objective function or fitness function, the better the solution is.

Population size determines the number of solutions or chromosomes the genetic pool has at one time. Large population size provides higher solutions diversity, but also increases the computation time, as the genetic algorithms need to perform more operations and calculations.

New member generation is the crossover algorithm that determines how new solutions are produced from two old solutions. Mutation is the mechanism of introducing noise into the solutions set to help the algorithms escape from local optima situations. Replacement and termination determines how one generation of solutions is replaced by the next generation.

In this SDSS, we implement genetic algorithm to search for optimal solutions for the FRLM. The genetic algorithm is a lot more computing extensive than the greedy and greedy substitution algorithms. However, depending on the problem and conditions, the genetic algorithm may have a better chance to obtain better solution than the greedy algorithm. Refer to chapter four for more information about solving the FRLM using genetic algorithm.

Application of the SDSS: The Florida Hydrogen Initiative

The goal of the Florida Hydrogen Initiative (FHI) is to "move Florida to the forefront of the nation's hydrogen economy" (Florida Hydrogen Initiative 2007). Funded by the FHI, the FRLM-SDSS is applied to the Orlando and Florida statewide road network to locate hydrogen-refueling stations. We collect and build the input spatial data for both case studies. Table 1 shows the spatial input layers for both the Orlando and Florida case studies.

	Orlando	**Florida**
OD Centers	Aggregated from TAZs defined by FDOT.	County Centroids. Some large urban counties are disaggregated, while some small rural counties are aggregated.
Junctions	Defined by analysts at all intersections of arcs.	Defined by analysts at all intersections of arcs.
Candidate Facilities	Combines the OD and junctions layer.	Combines the OD and junctions layer.
Road Network	FDOT and ESRI layers	FDOT layers

Shortest Path Routes	Generated using ArcGIS Network Analysis Closest Facilities, and specified the population centers layer as the facilities.	Generated using ArcGIS Network Analysis Closest Facilities, and specified the population centers layer as the facilities.

Table 1: Input Spatial Layers to FHI

The trip table for Orlando is derived from the aggregation of Florida Department of Transportation (FDOT) TAZ-TAZ weekday flows. The trip table for Florida statewide is generated from a modified gravity model formulation. We could not obtain the estimated statewide long-distance trip tables from Florida as it appears very few states collect those kind of information anymore.

We use the SDSS to locate hydrogen-refueling stations using different input parameters, such as the number of facilities. With the output capability of the SDSS, we can easily compare the results and visualize the locations of refueling stations generated by the algorithms.

User's Comments

We solicited some comments from the users of the SDSS regarding the system to help us determine what are the things that we did right, as well as the areas for improvements. Below are excerpts from some of the users.

Zhixiao Xie – GIS Expert

GIS was useful in several aspects for the FHI-SDSS: data preparation (network, nodes), network analysis (shortest distance, for example), visualization of model results. The visualization function is especially indispensable. It helped us effectively combine general transportation infrastructure, census data and local knowledge when simplifying network and determining appropriate nodes. Visualization was also essential for presenting and evaluating model results. To general users, it is the first impression of the model. For me, it was based on the location maps of the proposed stations that we were able to examine the differences between model results and intuition and identify some possible model issues for improvement. So GIS-based visualization is possibly one of components I like more and it was implemented very nicely. Some more details on model parameters and methods in the form of help file may be useful to end users, since it is the key for successfully utilizing the model, but not absolutely necessary if it is only intended for research purpose.

Conclusions

In order to transition to a hydrogen-based transportation infrastructure, one of the steps is to build a hydrogen-refueling infrastructure so that hydrogen fuel is easily accessible to consumers. The FRLM-SDSS is a powerful tool to help decision makers locate hydrogen-refueling stations in regions of different scales during the initial built-up of hydrogen-refueling infrastructure. By integrating GIS with the FRLM, the SDSS combines the mapping and spatial analysis of a GIS with the optimization capability of an operations research model. In the SDSS, we implement the greedy, greedy substitution, and genetic algorithms to solve the FLRM problem. This provides the users more options to solve the problem during the decision making process. It also allows us to study the effectiveness of these different heuristic algorithms in solving the FRLM problem. The SDSS has been utilized by the Florida Hydrogen Initiative to determine the optimal locations for hydrogen-refueling stations in the Orlando metropolitan and the state of Florida.

For future research, the FRLM-SDSS can be applied to larger scale areas, such as the U.S. or the continental Europe, for locating hydrogen or other alternative-fuel refueling stations. The SDSS can also be utilized to locate refueling stations used for different transportation modes, such as the railroad system. For theoretical type of research, different heuristic algorithms, such as tabu search and simulated annealing, can be implemented to solve the problem. This will allow us to compare the effectiveness of these algorithms with the greedy and genetic algorithms. The FRLM can also be extended to consider traffic flows that can detour from the shortest path to refuel.

Appendix 4
Data Processing Steps

1. Florida Atlantic University (FAU) obtains a database for a GIS road network.
2. FAU—consulting with Rollins College (RC)—combines FDOT traffic analysis zones (TAZs) into a set of aggregated TAZs that are the origins and destinations of trips in the model. These typically number over 100.
3. FAU—consulting with RC—selects a single point, known as a centroid, to represent each aggregated set of TAZs. These centroids serve as the origin and destination points (ODs) of all trips in the model, as in most transport models.
4. FAU—consulting with RC—selects a subset of more important roads to include in the model network for serving these origin and destination points.
5. FAU and ASU obtain speed data for all road segments.
6. The teams obtain or generate a table of traffic volumes among TAZs.
7. The FAU team combines the traffic flows from the FDOT TAZ level to the aggregated ODs.
8. The FAU team sends these GIS databases to ASU for further processing.
9. ASU classifies OD nodes and junction nodes within the network.
10. Using SDSS software developed for this project, ASU combines smaller segments of roads into single arcs connecting nodes. These arcs are geographically accurate, not stylized straight lines as in many networks. Distances and travel times (based on speed data) of all subsegments of an arc are totaled.
11. ASU generates shortest travel-time paths for every OD pair. Paths for ij are considered identical to ji. With 100+ OD nodes, this is typically 5000+ paths (100x100/2).
12. ASU chooses a sample of OD pairs and makes maps of their shortest travel time paths. ASU sends these maps to FAU and RC to spot-check the realism of routes generated by the model.
13. Based on their local knowledge, FAU and RC check whether these paths follow a route likely to be used by real drivers. For unlikely paths, we determine the cause of the poor routing, such as missing roads, and unrealistic road speeds. After some experimentation, we lowered posted speed limits by 15% to estimate the actual average speed on all roads that are not limited-access highways. Steps 12 and 13 are repeated until satisfactory paths are generated. This is the first step of model calibration to reality.
14. Using all the inputs generated thus far, ASU solves the Flow-Refueling Location Model (FRLM) to optimally choose the 10 best refueling locations.
15. ASU maps the optimal locations, superimposed on maps of the traffic flow on each arc (created by our SDSS software by summing traffic over all paths using each arc).
16. ASU sends these maps and other outputs to FAU and RC to check whether the locations and traffic flows are realistic, and compare with known traffic flows. For unlikely locations and flow volumes, we study the network for causes, such as missing roads, missing access points, overaggregation of TAZs, and poor choice of centroids. Local knowledge of the main traffic generator points and the road usage is invaluable in this process. We then make changes to the network as far back as Step 9, and repeat Steps 9-16 until satisfactory results are achieved.
17. We then solve the model for 1-25 optimal new facilities to generate a base case.
18. Finally, we define and solve a variety of scenarios, such as:

- Maximizing the number of trips that can be refueled
- Maximizing the VMT of trips that can be refueled
- Maximizing trips and VMT weighted by the NREL hydrogen demand model
- Experimenting with different vehicle ranges

Appendix 5
CNG Stations in Florida

Station Name	Address	City	Access
Energy Services Center/ Fort Pierce Utilities Authority	1701 S 37th St	Fort Pierce	Public - call ahead
City Gas Company of Florida	955 E. 25th St.	Hialeah	Public - call ahead
NASA - Kennedy Space Center	Bldg. M6-688	Kennedy Space Ctr	Public - call ahead
City Gas Company of Florida	8150 N.W. 90th St.	Medley	Public - call ahead
Okaloosa Gas District #1	136 Lewis St.	Niceville	Public - call ahead
City of North Miami	776 N.E. 125th St.	North Miami	Public - call ahead
TECO Peoples Gas	301 Maple Avenue	Panama City	Public - call ahead
Teco/Peoples Gas	301 Maple Ave	Panama City	Public - call ahead
City of Sunrise Mobile Station	4747 N. Nob Hill Rd.	Sunrise	Public - call ahead
Peoples Gas System, Inc.	1400 Channelside Dr.	Tampa	Public - call ahead
Central Florida Gas Company	1015 6th St SW	Winter Haven	Public - call ahead
Shalimar	1250 Eglin Pkwy.	Shalimar	Public - card key after hours
Palm Beach County Fleet Mgmt.	345 S Congress Ave	Delray Beach	Public - card key at all times
Natural Gas of Milton	6869 Municipal Dr	Milton	Public - card key at all times
City of North Miami	1855 N.E. 142nd St.	North Miami	Public - card key at all times
City of North Miami Police Station	700 NE 124th St	North Miami	Public - card key at all times
City of Sunrise NGV Station 1	8300 NW 44th Street	Sunrise	Public - card key at all times
City of Sunrise NGV Station 2	14150 NW 8th Street	Sunrise	Public - card key at all times
City of Sunrise NGV Station 3	4401 NW 103rd Avenue	Sunrise	Public - card key at all times
Palm Beach County	3700 Belvedere Rd	West Palm Beach	Public - card key at all times
Space Coast Coalition - Titusville CNG Station	4235 Capron Road N	Titusville	Public - credit card at all times
Motorfuelers, Inc.	13790-B 49th St N	Clearwater	Public - see hours
TECO Peoples Gas	618 W Internat'l Speedway Blvd.	Daytona Beach	Public - see hours
Cash's Amoco	345 S.W. 24th St.	Fort Lauderdale	Public - see hours
Donnini Enterprises - Light House Shell	9730 Hwy. A-1-A	Palm Beach Gardens	Public - see hours

Source: National Renewable Energy Laboratory, Alternative Fuels Data Center (April 12, 2007).