Global Assessment of Hydrogen Technologies
DE-FC36-02GO12042

TASKS 3 & 4 REPORT
DOE/GO/12042-4

Economic, Energy, and Environmental Analysis of Hydrogen Production and Delivery Options in Select Alabama Markets: Preliminary Case Studies

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December 2007

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Executive Summary

This document presents an assessment of hydrogen infrastructure deployment scenarios for Alabama and the greater Southeast. The work was conducted under Tasks 3 and 4 of Cooperative Agreement Number DE-FC36-02GO12042 between the US Department of Energy and the University of Alabama at Birmingham (UAB). UAB collaborated with Argonne National Laboratory (ANL) on these tasks. Specifically, Argonne National Laboratory performed an analysis of likely scenarios for producing, storing, delivering, and dispensing hydrogen for use as a motor vehicle fuel in Alabama. This analysis assessed the costs and environmental impacts associated with a large-scale deployment of hydrogen infrastructure in the state. UAB provided a summary of current codes and standards related to producing, delivering, and dispensing hydrogen as a motor vehicle fuel and a preliminary assessment of the requirements for a demonstration hydrogen fueling station in the Birmingham area.

This report summarizes the above work. Specifically, Section I, prepared by ANL, documents a set of case studies developed to estimate the cost of producing, storing, delivering, and dispensing hydrogen for light-duty vehicles for several scenarios involving metropolitan areas in Alabama. While the majority of the scenarios focused on centralized hydrogen production and pipeline delivery, alternative delivery modes were also examined. Although Alabama was used as the case study for this analysis, the results provide insights into the unique requirements for deploying hydrogen infrastructure in smaller urban and rural environments that lie outside the DOE's high priority hydrogen deployment regions.

Hydrogen production costs were estimated for three technologies – steam-methane reforming (SMR), coal gasification, and thermochemical water-splitting using advanced nuclear reactors. In all cases examined, SMR has the lowest production cost for the demands associated with metropolitan areas in Alabama. Although other production options may be less costly for larger hydrogen markets, these were not examined within the context of the case studies.

Given the effect of economies of scale on capital-intensive production facilities, scenarios involving a single production facility supplying multiple metropolitan markets tend to produce the lowest production costs. However, such reductions should be examined on a case-by-case basis as increased transport distances (i.e. increased delivery costs) can result when production facilities serve combined markets.

In all cases considered in this analysis, hydrogen delivery via pipeline is less costly than delivery by either compressed gaseous tank truck or cryogenic liquid tank truck.

Hydrogen production at distributed locations (i.e. at refueling stations) has the potential to supply lower-cost hydrogen to relatively small markets like those associated with relatively low, early market penetration in Alabama metropolitan areas. However, distributed production is likely to have site-specific impacts on infrastructure costs (e.g., for additional pipelines to supply natural gas feedstock or for additional power lines to supply higher voltages at refueling stations). Those costs are not included in the generic models exercised for this analysis. Since infrastructure costs could significantly increase the final cost of hydrogen, they should be considered in any detailed comparison of central station versus distributed hydrogen production.

Energy efficiencies and greenhouse gas (GHG) emissions were also estimated for the scenarios considered in this analysis. Generally, for a given production or delivery technology, energy use (per kg of hydrogen) is only a weak function of market size. The same is true for GHG emissions. An exception to these generalities occurs in scenarios involving hydrogen liquefaction. In these cases, overall system efficiency is a strong function of equipment size, and larger markets (e.g., Birmingham) have a lower energy requirement (per kg of hydrogen) and lower GHG emissions than smaller markets (e.g., Montgomery).

Pipeline and gaseous truck delivery options have comparable energy efficiencies and GHG emissions. These are significantly less than those for liquid truck delivery. The liquefier itself accounts for the increased energy and GHG emissions for that delivery option.

Among centralized production options, SMR and coal gasification have high energy demands (principally due to upstream activities associated with producing the fossil fuels) and GHG emissions, while the nuclear production pathway is the most favorable from both an energy use and a GHG emissions perspective. Note that this analysis did not consider carbon capture and sequestration which would lower GHG emissions but significantly increase energy requirements and the overall cost of hydrogen for fossil fuel-based production technologies.

Section II of this report, prepared by UAB, presents a summary of current codes and standards related to the design, construction, and operation of hydrogen fueling stations. These stations will be the distribution points for the hydrogen to the hydrogen vehicle fleets. The codes and standards documented in this report summarize the current state of the practice, although many codes related to hydrogen fueling stations are still in development. This section also presents preliminary specifications for a demonstration hydrogen fueling station to be built in Birmingham, Alabama. This station will be designed to serve a fuel cell bus demonstration currently under way at UAB.

Finally, Appendix B presents an analysis prepared by Dr. Marc Melaina of data on gasoline station networks in five southeastern urban areas: Birmingham, AL (1999), Nashville, TN (1995 and 2003), Owensboro, KY (2003), Gulfport-Biloxi, MS (2003) and Hattiesburg, MS (2003). The study attempts to identify patterns within these station networks that can be generalized to urban areas in general, with the goal of providing useful inputs for models of future hydrogen fueling station networks.

SECTION I
Economic, Energy and Environmental Analysis of Hydrogen Production and Delivery Options

1. Introduction

This section summarizes work conducted by ANL in support of Cooperative Agreement Number DE-FC36-02GO12042 between the US Department of Energy (DOE) and the University of Alabama Birmingham (UAB). It addresses Tasks 3 and 4 of a separate agreement between UAB and Argonne National Laboratory. Task statements are contained in Appendix A.

In addition to the main body of this document, deliverables developed under the UAB-Argonne agreement include:

- A spatial analysis of gasoline fuel stations in Birmingham and other selected metropolitan areas in the Southeastern US. This is presented in Appendix B.
- The linked model developed for this project (consisting of H2A production and delivery models) used to conduct the case studies described below.

1.1 Background and Overview

Use of hydrogen-fueled, light-duty vehicles in the transportation sector has been suggested as a means of reducing U.S. dependence on imported oil and emissions of heat-trapping greenhouse gases. To this end, the U.S. Department of Energy (DOE) and other federal and state organizations have been supporting a variety of research and development activities. Research has been directed not only at improving the performance and reducing the cost of key technologies (e.g., fuel cells, on-board storage systems, hydrogen production, delivery infrastructure, etc.), but also toward developing analytical and assessment tools to evaluate various infrastructure and policy options. As part of this activity, DOE awarded a research contract to the University of Alabama at Birmingham (UAB) to, among other activities, conduct site-specific analyses of the costs associated with the development and utilization of hydrogen-fueled vehicles in the Southeastern U.S. with special emphasis on the State of Alabama. Since energy efficiency and environmental emissions are also of concern in the development and use of hydrogen fuels, these issues were also examined as part of the study. In order to gain access to the analytical skills and tools developed at Argonne National Laboratory, UAB entered into an agreement with Argonne to develop a set of preliminary case studies. This document summarizes results of that effort.

1.2 Objective

The basic objective of this analysis is to better understand the economics associated with the local production of hydrogen and its use as a transportation fuel. While such analysis is not sufficient to make definitive estimates of the likely price of hydrogen fuel, it provides important insights into the competing technologies that may someday produce, distribute and dispense hydrogen, and the economics of serving various markets either separately or in combination (e.g., urban and interstate as well as multiple urban areas). Efficient use of energy resources and a reduction in atmospheric emissions are also of concern in the development of large-scale hydrogen markets. Therefore, the energy requirements and greenhouse gas emissions for the various hydrogen production and delivery scenarios were estimated and compared as part of this study.

1.3 Approach

The case studies were constructed by integrating individual tools developed under the Department of Energy's (DOE's) Hydrogen Analysis program (commonly referred to as H2A), supplemented as needed by model development directed toward the specific needs of the Alabama case studies. The H2A program has focused on developing analytical tools and data to be used in evaluating and comparing hydrogen production and delivery options for different light-duty-vehicle markets. It should be noted that the H2A models, and the underlying assumptions and cost parameters used in them, are under development and thus subject to change as improved data become available.[1] DOE is supporting a number of research and development projects to improve the performance and costs of hydrogen compressors, pipelines, liquefiers, storage, and production technologies. As the knowledge base for these components increases, the H2A models will be revised to reflect the best available data and research results, thereby reducing uncertainty in hydrogen production and delivery cost estimates.

Two types of models were integrated for this effort – the H2A delivery model (known as the Hydrogen Delivery Scenario Analysis Model or HDSAM) and several of the H2A production models (referred to as the H2A production case studies). In addition to these models, several of the case studies also required off-line analysis of additional market options. Each model or type of off-line analysis is described below.

1.3.1 HDSAM

Developed by Argonne National Laboratory in collaboration with National Renewable Energy Laboratory and Pacific Northwest National Laboratory, the Hydrogen Delivery Scenario Analysis Model (HDSAM) is an Exel-based model with a user-friendly interface designed to permit rapid specification and comparison of multiple scenarios consisting of alternative markets, market penetration rates and delivery modes. Alternative markets can be urban areas, non-urban interstate-highway segments, or a combination of the two. Urban markets may be further defined as specific US urbanized areas (selected from a drop-down menu of over 450 such areas) or as generic

[1] For example, the costs of compressors capable of moving large quantities of hydrogen are highly uncertain. Since such large-capacity compressors do not currently exist, cost estimates within the H2A models are based on natural gas compressors of the same horsepower, with a 30% premium added to reflect increased material and fabricating costs. This relationship is based on engineering judgment extracted from a variety of sources.

metropolitan areas defined by population. Market penetration can vary from 1 to 100% of total light-duty vehicles in the selected market. Delivery options include pipelines, liquid-hydrogen cryogenic tank trucks or compressed, gaseous-hydrogen tank trucks. Once the analyst selects a market, penetration rate and delivery option, the model creates an appropriate pathway comprised of component equipment and facilities relevant to the selected option. For example, the pipeline delivery option to an urban area includes a transmission pipeline connecting the production facility to the outer edge of a demand center, a compressor used to overcome pressure losses and increase hydrogen transmission pressure to a level specified by the user, a geologic storage facility to store enough hydrogen to meet seasonal demand fluctuations, one or more "trunk" pipelines within the urban area to connect the transmission pipeline with lower-pressure service pipelines, service pipelines connecting the trunk lines to each individual refueling station (referred to as a "forecourt" in the H2A lexicon), and the forecourts themselves where hydrogen is further compressed, stored and dispensed to individual vehicles. Details on these markets and pathways are presented in subsequent sections of this report. Additional information on HDSAM, including a user's manual, can be found at <http://eeredev.nrel.gov/hydrogen_doe/h2a_delivery.html>.

1.3.2 H2A Production Models

As part of the H2A project, Excel-based spreadsheet models have been developed to estimate the levelized cost of hydrogen produced via a number of different processes. "Case studies" of such processes as steam-methane-reforming (SMR), coal gasification, thermochemical water-splitting using advanced high-temperature nuclear reactors, electrolysis, and various renewable technologies have been developed and made available for general use by interested analysts. Several of the case studies are posted on the DOE website, at <http://eeredev.nrel.gov/hydrogen_doe/h2a_production.html>). [2]

1.3.3 Off-Line Analyses

The current version of HDSAM, posted on the DOE website, allows only one urban and one interstate market to be considered at a time. As will be seen in later sections of this report, certain of the Alabama case studies consider markets consisting of more than one urban area. These could not be analyzed solely within the framework of HDSAM. Instead, individual market demands were estimated by separate HDSAM runs and relevant portions of the resulting HDSAM-generated delivery costs were combined offline. Costs were then allocated to individual markets to estimate overall distribution costs. Future versions of HDSAM are expected to permit multiple urban markets to be analyzed directly.

[2] Models of small-scale hydrogen production at distributed locations (i.e., at the forecourt or refueling station) have also been developed as part of the H2A project. These were not used in this effort.

As noted earlier, one of the objectives of this study was to estimate and compare the energy requirements and atmospheric emissions of various hydrogen production and delivery scenarios. These estimates were produced by using the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model developed by Argonne National Laboratory. GREET is a "well-to-wheels" fuel-cycle model that allows analysts to evaluate various vehicle and fuel combinations over the complete fuel cycle. For a given scenario, GREET estimates energy consumption, emissions of CO_2-equivalent greenhouse gases, and emissions of five criteria pollutants. Additional details on GREET, including the option of downloading the model, can be found at http://www.transportation.anl.gov/software/GREET/index.html.

2. Scenarios

In order to construct the Alabama case studies, it was necessary to combine H2A production and delivery models and off-line analyses into a set of internally consistent scenarios. This required selecting appropriate H2A model options, collecting Alabama-specific inputs and, where indicated, amending the models to add critical features/capabilities to them.

It should be noted that the H2A models were developed to represent default or "generic" conditions. Although these may be overridden by the user, they provide a useful starting point for many kinds of analysis. For example, the models are pre-loaded with nation-wide averages for pipeline costs, vehicular fuel economy, electricity rates, retail diesel fuel prices, and similar data. Although most of these defaults were retained for this study, electricity, natural gas, and coal prices were adjusted to reflect time series data from the USDOE's Energy Information Administration. Those data suggest that the cost of electricity in the study area is about 80% of the national average while natural gas and coal are each about 120% of their respective national average.[3]

Note also that the scenarios assume sufficient feedstock availability to permit hydrogen production at the production sites indicated (see below) and sufficient coverage of gasoline refueling stations to permit conversion to hydrogen dispensing.[4]

2.1 Scenarios Considered

The scenarios are intended to reflect a range of potential market sizes, production processes and delivery options that might exist within the state of Alabama. Several scenarios were defined to capture this diversity, including:

- Individual metropolitan areas of Mobile, Montgomery, Birmingham, and Huntsville;
- Individual metropolitan areas (as above) combined with demand on interstate highways connecting the metropolitan area with a specified hydrogen production location;
- Multiple metropolitan areas combined with demand on interstate highways connecting the metropolitan areas; and
- Hydrogen production using a variety of processes based on resources available within the State of Alabama.

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[3] The rationale behind not making additional changes includes the lack of definitive information on local conditions or costs, the realization that the "bottom-line" cost of hydrogen is relatively insensitive to such changes, and the recognition that some costs are likely to be incurred by non-Alabama entities (e.g., hydrogen pipeline companies). Therefore, generic costs are likely to be reasonable approximations of actual expenses.

[4] These assumptions are supported by spatial analyses of existing refueling stations and natural gas local distribution services in Alabama and neighboring states.

Three levels of hydrogen vehicle market penetration (15, 50, and 75% of all light-duty vehicles) were examined to determine whether conclusions are dependent on the percentage of hydrogen-fueled vehicles in the marketplace. While the base or reference case assumes hydrogen delivery via pipeline, additional analyses were conducted for compressed-gas truck and liquid-hydrogen truck delivery to permit comparison of costs, energy efficiencies, and atmospheric emissions for the different delivery options.

Part of the cost of hydrogen is dependent on the distance between the production site and the market. Since there are a near-infinite number of production site possibilities, several assumptions were made to limit the scope of the case studies yet still be consistent with the objectives of this study. For purposes of this analysis, it was assumed that hydrogen production occurs at one of the following Alabama locations, where large energy facilities using the same fuel already exist. These locations are:

- The Praxair Steam-Methane-Reforming (SMR) plant at McIntosh;
- The Browns Ferry nuclear power station near Athens; and
- The Ernest C. Gaston coal-fired power station near Wilsonville.

The four metropolitan areas considered in this analysis – Mobile, Montgomery, Birmingham and Huntsville – provide a representative spectrum of potential markets located at “reasonable” distances from sites that could be used to produce hydrogen at centralized facilities. Table 2.1 contains select characteristics of these four metropolitan areas. Although Montgomery has the smallest population, it also has the smallest land area and thus is the most densely populated. Huntsville and Mobile are considerably larger in area and have lower, roughly similar, population densities. Birmingham, with both the largest population and land area, has a density between that of Montgomery and Mobile. The data in this table are taken directly from the database contained within HDSAM which in turn is based on 2000 population estimates for urbanized areas, as reported by the US Census Bureau.

Table 2.1 Characteristics of Select Hydrogen Markets in Alabama

Metropolitan Area	Mobile	Montgomery	Birmingham	Huntsville
Population	317,605	196,892	663,615	231,253
Metropolitan area (square miles)	211	99	392	157
Population density (persons/sq mile)	1,507	1,994	1,692	1,357
Light-duty vehicles	241,380	149,638	504,347	162,073
Annual miles per vehicle	12,000	12,000	12,000	12,000

Other assumptions that guided these analyses are presented in Table 2.2. As noted earlier, these assumptions are the default values contained within the H2A models.

Table 2.2. General Assumptions for Cost Analyses

Daily light-duty-vehicle highway traffic	17,000 mi/mile of highway
H2-vehicle fuel economy	57.5 mi/gal of gasoline equivalent
Refueling station capacity	1500 kg of hydrogen/day
Nominal refueling station capacity factor	70%
Hydrogen production pressure	300 psi
Hydrogen pressure at pipeline inlet	1000 psi
Hydrogen pressure delivered to refueling station	300 psi
Analysis period	20 years

3. Case Study Results for "Standalone" Metropolitan Areas

The initial phase of the case study analysis focused on evaluating the four metropolitan areas as distinct or "standalone" markets, each with its own production facility. Hydrogen production was assumed to be at the closest of the three locations noted above. While other production locations and technologies are possible, these were selected as representative of Alabama facilities potentially capable of producing hydrogen in the quantities considered in these analyses. In evaluating the individual metropolitan markets, two scenarios were examined. The first assumes the market to consist solely of the metropolitan urban area. In the second, it was assumed that hydrogen refueling stations would be built along the corridor between the production facility and the urban market, and that these stations would be serviced by the same delivery system (e.g., a pipeline) and the same production facility. The objective of evaluating these two scenarios is to estimate the impact of small economies of scale in both the production and delivery systems. Larger economies of scale are examined later in this analysis when metropolitan areas are combined.

3.1 Mobile

Mobile is in close proximity to Praxair's McIntosh plant where both liquid and gaseous hydrogen are currently produced for customers throughout the southeastern US. For this analysis it was assumed that hydrogen would be produced at the McIntosh site using existing SMR technology and delivered via pipeline to the Mobile metropolitan area. McIntosh is approximately 40 miles from Mobile.

3.1.1 Mobile Metropolitan Area

Table 3.1 shows estimated costs for the production and delivery of hydrogen to the Mobile metropolitan area. Although costs are relatively high at low hydrogen vehicle penetration, they drop significantly as penetration increases.

A characteristic of increasing hydrogen vehicle penetration is that the configuration of main (or trunk) distribution pipelines shifts from a single ring to two rings. HDSAM automatically compares the costs of one-ring and two-ring distribution pipeline configurations to determine the least-cost alternative. Two rings allow shorter service lines from the rings to individual refueling stations. Typically, at higher hydrogen-vehicle penetration, the number of refueling stations increases and it becomes less costly to construct a second ring than to install a large number of longer service lines from a single ring. Note that the version of HDSAM used in these analyses is limited to a maximum of two rings; subsequent versions of the model will allow as many as four rings. However, since all the Alabama case studies are relatively compact urban areas, it is unlikely that a 3- or 4-ring configuration of distribution pipelines will reduce delivery cost.

Table 3.1 Estimated Hydrogen Costs for Mobile Metropolitan Area

Factor	15% Penetration	50% Penetration	75% Penetration
Average H2 Demand (kg/day)	20,024	66,745	100,118
No. of H2 Stations	20	64	96
Transmission pipe diameter (inch)	3 ¾	6	7
Ring 1 pipe diameter (inch)	4 ½	5	6
Ring 2 pipe diameter (inch)	NA	7	8 ¼
Delivery cost ($/kg)	$2.25	$1.19	$1.01
Forecourt cost ($/kg)	$0.89	$0.86	$0.86
Production cost ($/kg)	$2.71	$1.81	$1.68
Total cost of H2 ($/kg)	**$5.85**	**$3.86**	**$3.55**

Figure 3.1 shows breakdowns of estimated levelized hydrogen cost for the three hydrogen vehicle penetrations considered. As seen in this figure, production cost represents the largest component of the total cost of hydrogen. A significant economy of scale for the hydrogen production cost is also illustrated in this figure. A comparable economy of scale also exists for delivery cost (e.g., pipelines, compressor, and geologic storage). There is essentially no economy of scale in the forecourt (refueling station) cost.

As noted above, hydrogen production in this scenario is accomplished via the SMR technology. This technology is well established in today's hydrogen production industry, accounting for the vast majority of the hydrogen produced in the United States. The SMR process uses large quantities of natural gas and its cost represents the bulk of the ultimate cost of hydrogen production shown in Figure 3.2.

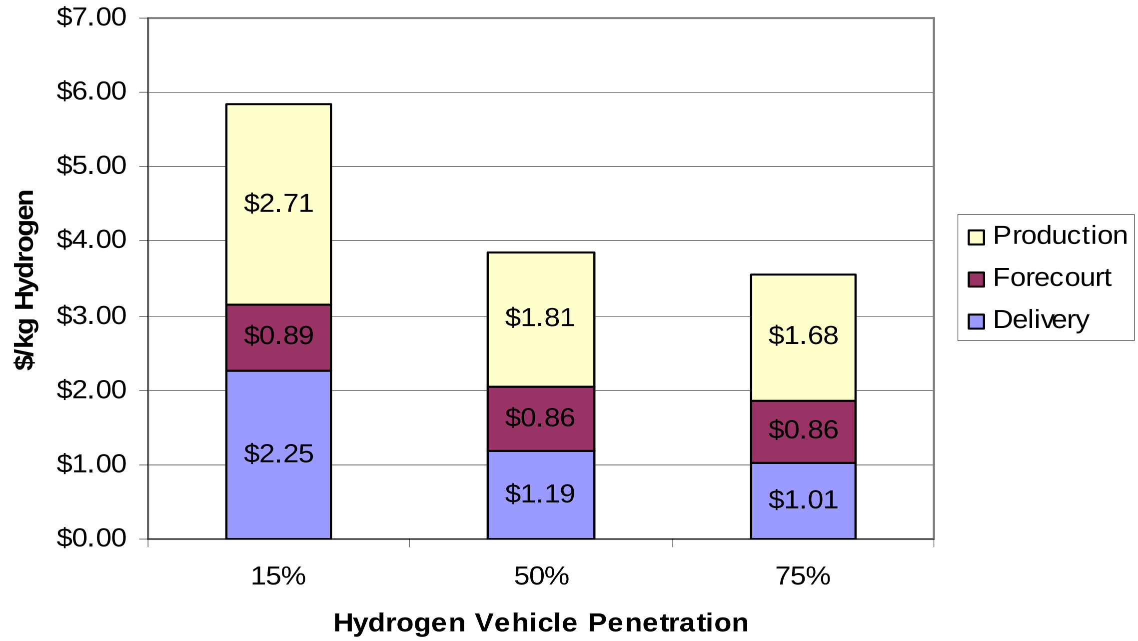

Figure 3.1 Cost Breakdown for Mobile Metropolitan Area

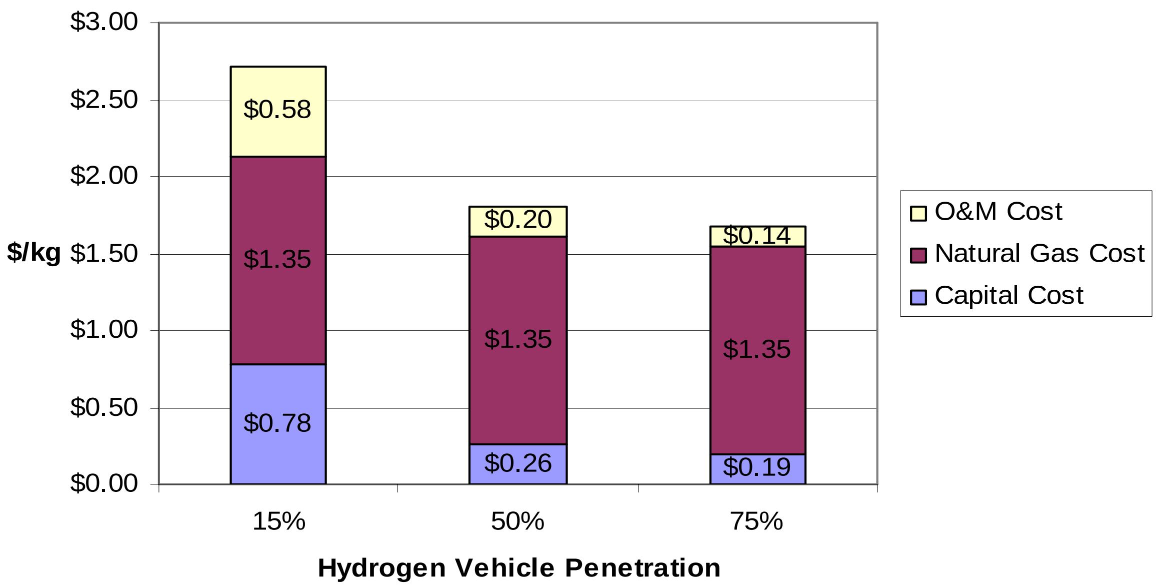

Figure 3.2 SMR Production Cost Breakdown for Mobile Metropolitan Area

As seen in Figure 3.2, natural gas feedstock cost represents the greatest percentage of the total production cost in this scenario. While feedstock cost remains constant at $1.35/kg of hydrogen sold for all vehicle penetrations, the percentage of the total production cost ranges from 52% at the lower vehicle penetration to 81% at the highest penetration.

Expressed as a percentage of the total cost of delivered hydrogen, the natural gas cost represents between 24% and 39% of that total.

3.1.2 Mobile Corridor

The next series of calculations is based on the assumption that there will be hydrogen refueling stations along a 40-mile corridor between McIntosh and Mobile. A likely location for pipeline construction along this corridor is US Highway 43. Although US 43 is not an interstate highway, much of it is grade-separated and limited access. Thus, traffic patterns are assumed to be similar to an interstate highway. Results of these analyses are shown in Table 3.2.

Table 3.2 Mobile Metropolitan Area Plus 40-Mile Interstate

Factor	15% Penetration	50% Penetration	75% Penetration
Average Metro H2 Demand (kg/day)	20,024	66,745	100,118
Average Interstate H2 Demand (kg/day)	1,711	5,707	8,560
Total average demand (kg/day)	21,735	72,452	108,678
No. of Metro H2 Stations	20	64	96
No. of Interstate H2 Stations	2	6	8
Transmission pipe diameter (inch)	4	6 ¼	7 ¼
Delivery cost ($/kg)	$2.11	$1.13	$0.96
Forecourt cost ($/kg)	$0.89	$0.86	$0.86
Production cost ($/kg)	$2.61	$1.78	$1.66
Total cost of H2 ($/kg)	**$5.61**	**$3.77**	**$3.48**

Figure 3.3 shows the cost breakdown for the combined Mobile metropolitan area and the 40-mile highway link between McIntosh and Mobile.

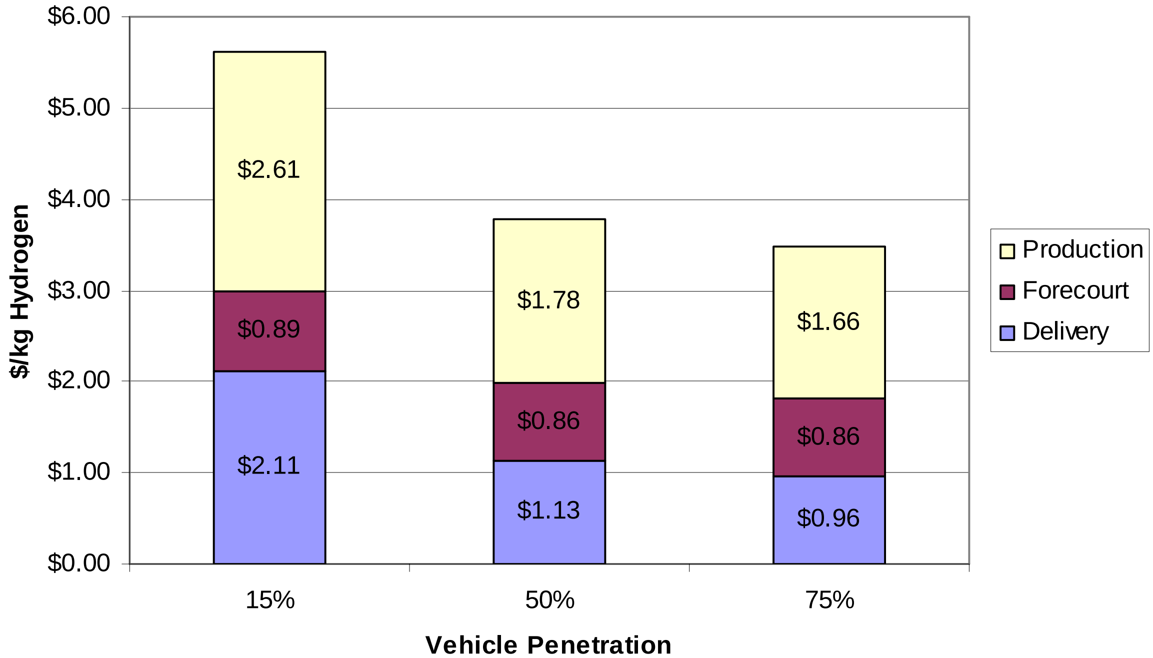

Figure 3.3 Cost Breakdown for the Combined Mobile Market

Comparison of the results in Table 3.2 and Figure 3.3 with those in Table 3.1 and Figure 3.1 shows that inclusion of a hydrogen market along the 40-mile corridor between the production facility and Mobile increases demand by about 9% over the standalone metropolitan Mobile market demand. Thus, reductions in the delivered cost of hydrogen of $0.07-$0.24/kg of hydrogen could be realized by installing hydrogen refueling stations along US 43. The majority of the cost reduction is in delivery cost; additional cost reduction comes from economies of scale in the production facility. Although the transmission pipeline would have to be somewhat larger to serve a combined market, increased hydrogen flow reduces the unit cost of hydrogen.

3.2 Montgomery

Montgomery is the smallest of the four metropolitan area markets considered in this analysis. Although a variety of hydrogen production locations may be feasible, the coal-fired facility at Wilsonville was taken as the reference case. This facility is located approximately 65 miles north of Montgomery if one follows a corridor along Interstate 65 and Alabama Highway 145.

3.2.1 Montgomery Metropolitan Area

As before, two scenarios were examined. The first assumes that only the Montgomery metropolitan area will be served while the second assumes that hydrogen refueling stations will be provided along the 65-mile corridor between the production site and

Montgomery. Results of the standalone metropolitan Montgomery scenario are summarized in Table 3.3 and displayed in Figure 3.4.

Table 3.3 Montgomery Metropolitan Area

Factor	15% Penetration	50% Penetration	75% Penetration
Average H2 Demand (kg/day)	12,413	41,377	62,066
No. of H2 Stations	12	40	60
Transmission pipe diameter (inch)	3 ½	5 ½	6 ½
Ring 1 pipe diameter (inch)	3 ½	3 ¾	4 ½
Ring 2 pipe diameter (inch)	NA	5 ¼	6 ¼
Delivery cost ($/kg)	$2.94	$1.44	$1.15
Forecourt ($/kg)	$0.86	$0.86	$0.86
Production cost ($/kg)	$3.96	$2.29	$1.97
Total cost of H2 ($/kg)	**$7.78**	**$4.59**	**$3.99**

As seen in Table 3.3 and Figure 3.4, hydrogen costs for the Montgomery standalone case are estimated to be significantly higher than for the Mobile case. Three fundamental factors contribute to this increase. First, economies of scale drive the smaller demand in Montgomery to increase both production and delivery costs. Second, the greater distance between production and market locations increase hydrogen costs in Montgomery. Third, and most importantly, coal-based hydrogen production technology significantly increases production cost (as compared to SMR technology) for the relatively small markets considered in these scenarios.

Unlike the SMR technology assumed in the Mobile scenarios, coal-based hydrogen production is heavily capital intensive. Figure 3.5 illustrates this feature for the Montgomery metropolitan area. As seen in this figure, the cost of coal feedstock is a small component of total production cost. The value of $0.32/kg of hydrogen represents only about 8% of the total production cost for a 15% hydrogen vehicle penetration and only about 16% at 75% penetration. In contrast, the capital component represents between 51% and 61% of the production cost. The actual magnitude decreases from $2.00/kg at lower penetration to $1.20/kg at higher hydrogen vehicle penetration. These strong economies of scale are typical for capital-intensive technologies in which equipment represents the major components of total facility cost.

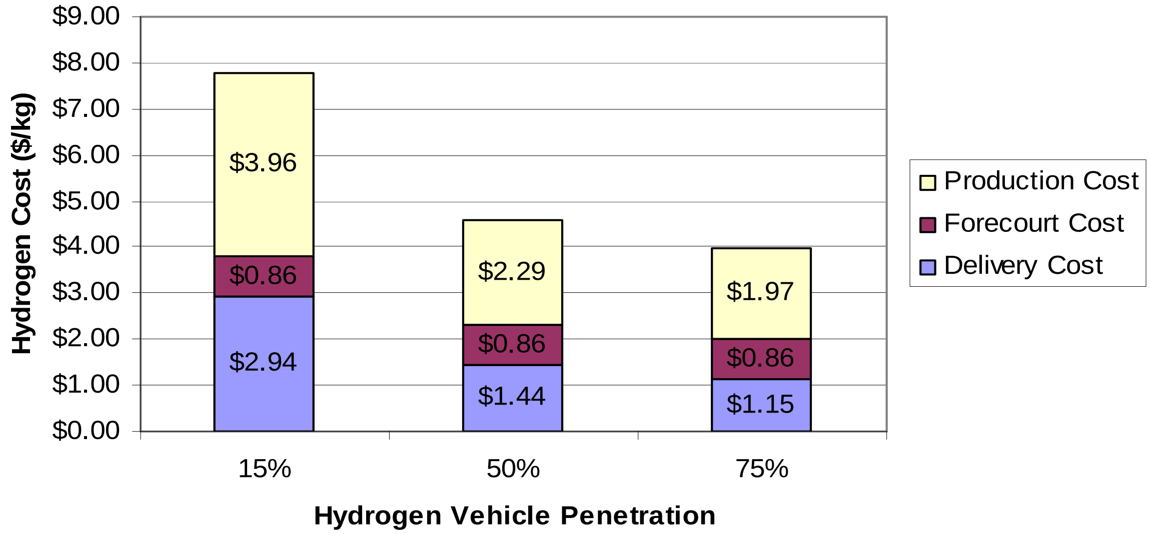

Figure 3.4 Cost Breakdown for Montgomery Metropolitan Area

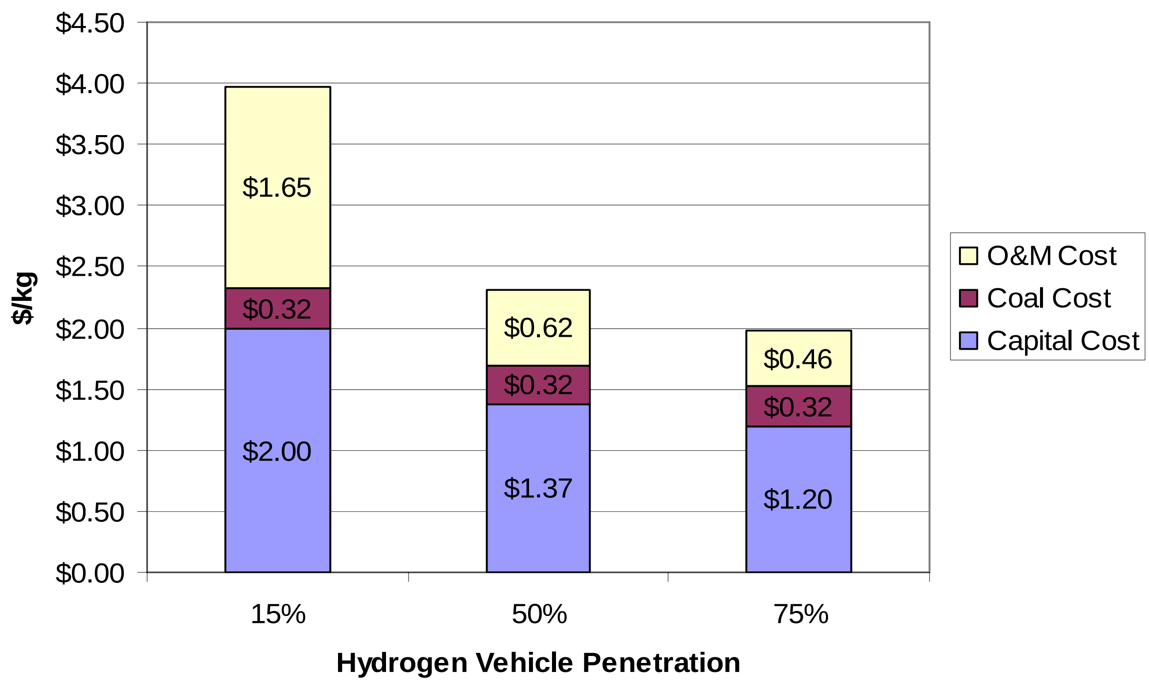

Figure 3.5 Cost Breakdown for Coal-Based Hydrogen Production

3.2.2 Montgomery Corridor

In this case, hydrogen refueling stations are assumed to be built along the 65-mile corridor between Wilsonville and Montgomery, as well as in Montgomery itself. Results of this analysis are summarized in Table 3.4. Inclusion of the 65-mile highway market increases total hydrogen demand by more than 22% above the standalone Montgomery market, as compared with a 9% increase for the similar case involving Mobile. This larger increase stems from two conditions – the 65-mile distance to Montgomery as compared to 40 miles to Mobile and the smaller population in Montgomery as compared to Mobile. As a result, hydrogen cost decreases by $0.27 to $0.84/kg due to the inclusion of the highway market, which again demonstrates the economies of scale associated with this combination of production and delivery options.

Table 3.4 Montgomery Metropolitan Area Plus 65-Mile Interstate

Factor	15% Penetration	50% Penetration	75% Penetration
Average Metro H2 Demand (kg/day)	12,413	41,377	**62,066**
Average Interstate H2 Demand (kg/day)	2,781	9,269	**13,904**
Total average demand (kg/day)	15,194	50,646	**75,970**
No. of Metro H2 Stations	12	40	**60**
No. of Interstate H2 Stations	3	9	**14**
Transmission pipe diameter (inch)	3 ¾	6	**7**
Delivery cost ($/kg)	$2.53	$1.26	**$1.04**
Forecourt cost ($/kg)	$0.86	$0.86	**$0.86**
Production cost ($/kg)	$3.55	$2.125.89	**$1.83**
Total cost of H2 ($/kg)	**$6.94**	**$4.25**	**$3.72**

3.3 Birmingham

For the Birmingham metropolitan area, hydrogen production was assumed to occur in the vicinity of the Ernest C. Gaston coal-fired facility at Wilsonville. It was further assumed that a pipeline would be constructed in a corridor extending north from Wilsonville, roughly along Alabama Highway 145 to US 280. The total distance of this route is approximately 35 miles.

3.3.1 Birmingham Metropolitan Area

Results for the Birmingham metropolitan area are summarized in Table 3.5. Birmingham is the largest individual market considered in this analysis. Comparison of the results in Table 3.5 with those in Table 3.3 shows the effects of economies of scale – both in delivery cost and in coal-based hydrogen production cost. It should be noted that the larger market and geographic size of the Birmingham metropolitan area requires that a second trunk or ring pipeline be employed even at the 15% hydrogen-vehicle penetration level. For the other case studies (with considerably smaller hydrogen demand and more compact geography) a second ring is needed only for the 50% and 75% vehicle penetrations. Figure 3.6 shows the cost breakdown for this scenario.

Table 3.5 Birmingham Metropolitan Area

Factor	15% Penetration	50% Penetration	75% Penetration
Average H2 Demand (kg/day)	41,838	139,460	209,190
No. of H2 Stations	41	134	201
Percent H2 Stations	16	53	79
Transmission pipe diameter (inch)	4 ¾	7 ¾	9
Ring 1 pipe diameter (inch)	4 ½	7 ¼	8 ½
Ring 2 pipe diameter (inch)	6	10	11 ¾
Delivery cost ($/kg)	$1.76	$1.05	$0.92
Forecourt cost ($/kg)	$0.87	$0.86	$0.86
Production cost ($/kg)	$2.28	$1.49	$1.32
Total cost of H2 ($/kg)	**$4.91**	**$3.40**	**$3.10**

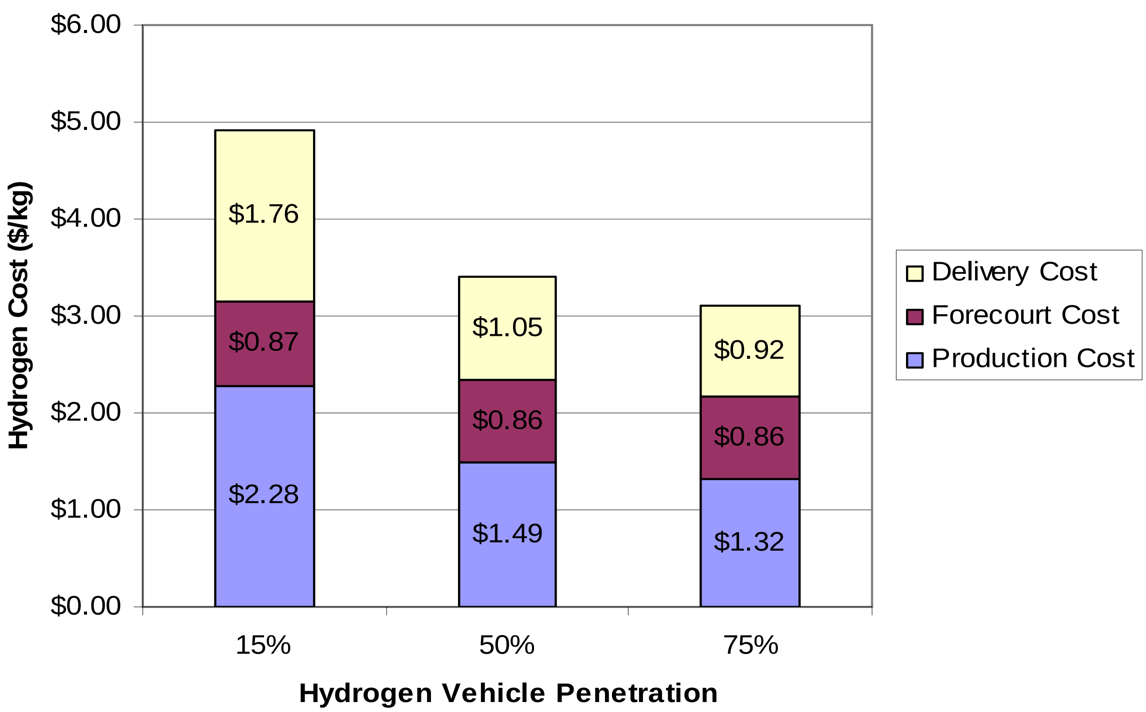

Figure 3.6 Hydrogen Cost Breakdown for Birmingham Metropolitan Area

As was the case with the coal-based hydrogen production facility assumed for Montgomery, hydrogen production cost for Birmingham is dominated by capital expenditures. This feature is illustrated in Figures 3.7 and 3.8, in which breakdowns of production cost are shown for the 15% and 75% hydrogen vehicle penetrations, respectively.

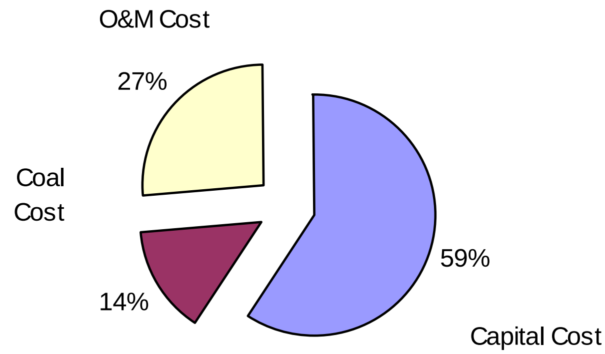

Figure 3.7 Production Cost Breakdown, Birmingham Metro Area, 15% Penetration

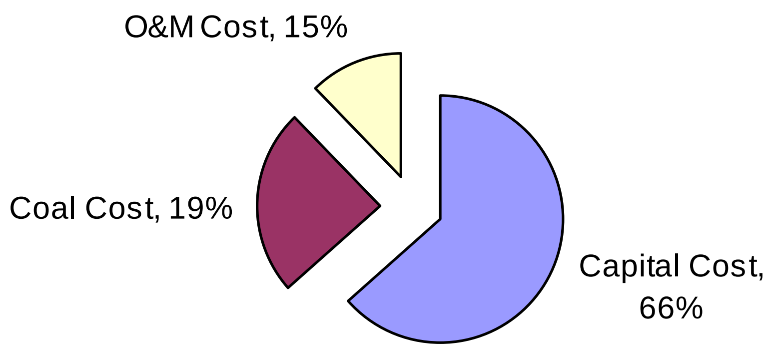

Figure 3.8 Production Cost Breakdown, Birmingham Metro Area, 75% Penetration

3.3.2 Birmingham Corridor

Hydrogen cost estimates for the combined Birmingham metropolitan area and the interstate market between the production site and Birmingham are presented in Table 3.6. Note that the inclusion of the highway market increases demand by less than 4% over the standalone metropolitan area. This small increase results from the relatively short (i.e., 35 mile) distance between the assumed production facility location and the metropolitan market, combined with the fact that the Birmingham market is the largest single market considered in this analysis.

Table 3.6 Birmingham Metropolitan Area Plus 35-Mile Interstate

Factor	15% Penetration	50% Penetration	75% Penetration
Average Metro H2 Demand (kg/day)	41,838	139,460	209,190
Average Interstate H2 Demand (kg/day)	1,497	4,991	7,487
Total average demand (kg/day)	43,335	144,451	216,677
No. of Metro H2 Stations	41	134	201
No. of Interstate H2 Stations	2	5	8
Transmission pipe diameter (inch)	5	7 ¾	9 ¼
Delivery cost ($/kg)	$1.72	$1.01	$0.90
Forecourt cost ($/kg)	$0.87	$0.86	$0.86
Production cost ($/kg)	$2.25	$1.48	$1.30
Total cost of H2 ($/kg)	**$4.85**	**$3.36**	**$3.06**

Because of the small increase in market demand, the cost of producing and delivering hydrogen is only marginally reduced by the inclusion of the highway market. Comparison of Tables 3.5 and3.6 shows decreases in total cost of only $0.04/kg and $0.06/kg of delivered hydrogen at market penetrations of 75% and 15%, respectively.

3.4 Huntsville

For the Huntsville case study, it was assumed that hydrogen would be produced at the Browns Ferry nuclear power station located on the north side of the Tennessee River, near Athens. From Browns Ferry, gaseous hydrogen would be delivered to metropolitan Huntsville via a transmission pipeline located in a corridor along US 72, a distance of approximately 30 miles.

3.4.1 Huntsville Metropolitan Area

As shown in Table 3.7, the total costs of hydrogen for the Huntsville metropolitan area are the highest of all the cases considered in this analysis. This occurs because of the high cost of producing comparatively small quantities of hydrogen via the nuclear option. As was the case with coal-based production, nuclear-based hydrogen is highly capital intensive as shown in Figures 3.9 and 3.10.

Table 3.7 Huntsville Metropolitan Area

Factor	15% Penetration	50% Penetration	75% Penetration
Average H2 Demand (kg/day)	13,445	44,816	67,223
No. of H2 Stations	13	43	65
Transmission pipe diameter (inch)	3	4 ¾	5 ¾
Ring 1 pipe diameter (inch)	3 ¾	4 ¼	5
Ring 2 pipe diameter (inch)	NA	5 ¾	6 ¾
Delivery cost ($/kg)	$2.41	$1.28	$1.06
Forecourt cost ($/kg)	$0.86	$0.86	$0.86
Production cost ($/kg)	$26.54	$9.95	$7.42
Total cost of H2 ($/kg)	**$29.82**	**$12.09**	**$9.34**

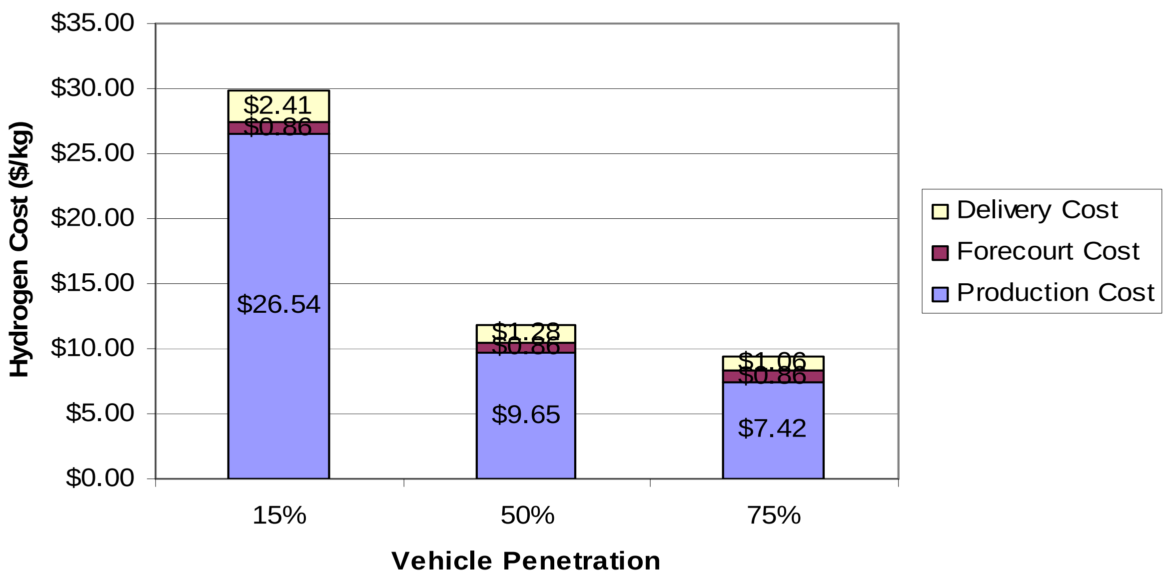

Figure 3.9 Hydrogen Cost for Huntsville Metropolitan Area

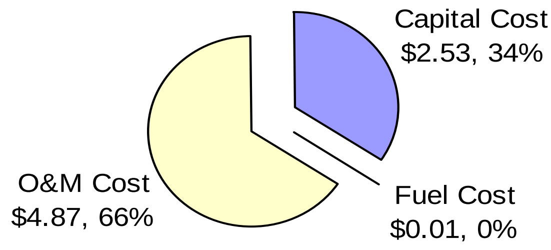

Figure 3.10 Production Cost Breakdown, Huntsville, Nuclear Hydrogen Production, 75% Penetration

Figure 3.10 shows the distribution of production cost for 75% hydrogen vehicle penetration in Huntsville. As is typical with nuclear facilities, the nuclear fuel constitutes a very small portion of total production cost. In this case, O&M cost makes a large contribution to total production cost. This results from the assumption that a relatively large O&M staff will be required for even the smallest level of hydrogen production. Although this assumption is based on the operating experience of existing nuclear power plants, it is by no means certain that hydrogen produced in advanced nuclear reactors will require comparable staffing. Thus, this O&M estimate may be considered an upper bound. It should be noted that based on the energy input required, a hydrogen production rate of 50,000 kg/day is equivalent to approximately 55 MW of electrical power, which would be of a scale unlikely to be constructed and operated as a commercial nuclear-power facility.

3.4.2 Huntsville Corridor

Table 3.8 shows the estimated cost of hydrogen for the combined Huntsville-US Hwy 72 market. The 30-mile highway market increases total demand by approximately 10% over that of the standalone metropolitan area. A comparison of the total demand in Table 3.8 with that in Table 3.4 for the combined Montgomery market shows that hydrogen demands in these two cases are similar. However, hydrogen delivery costs for the Huntsville markets are somewhat lower than those for the Montgomery markets, reflecting the 30-mile pipeline for Huntsville as compared with a 65-mile pipeline for Montgomery. However, hydrogen produced from nuclear processes is considerably more costly than hydrogen produced from coal. As noted above, a prime reason for these cost differences is believed to be the large O&M cost component associated with nuclear facilities in the H2A nuclear-production model.

Table 3.8 Huntsville Metropolitan Area Plus 30-Mile Interstate

Factor	15% Penetration	50% Penetration	75% Penetration
Average Metro H2 Demand (kg/day)	13,445	44,816	67,223
Average Interstate H2 Demand (kg/day)	1,283	4,278	6,417
Total average demand (kg/day)	14,728	49,094	73,640
No. of Metro H2 Stations	13	43	65
No. of Interstate H2 Stations	2	5	7
Transmission pipe diameter (inch)	3 ¼	5	5 ¾
Delivery cost ($/kg)	$2.25	$1.22	$1.01
Forecourt cost ($/kg)	$0.86	$0.86	$0.86
Production cost ($/kg)	$24.50	$9.30	$6.96
Total cost of H2 ($/kg)	**$27.61**	**$11.37**	**$8.83**

3.5 Observations from the Analysis of Standalone Urban Markets

The above estimates reflect conditions that might be anticipated in four different metropolitan areas in Alabama. Since each of these markets is unique, results are quite variable – ranging from a low of $3.06 to a high of $27.61 in the total cost-per-kg of delivered hydrogen. As noted in the above discussion, several factors contribute to this range, most notably market demand, the distance between the production site and the market, and the particular technology used for hydrogen production. The choice of production technology has been shown to have the greatest impact on total hydrogen cost for the scenarios examined here. While a variety of technologies and production sites could have been used for the case studies examined (with a concomitant change in results), those chosen represent the spatial arrangement of existing infrastructure and basic technologies (e.g., natural gas-based, coal-based, and nuclear-based) which are already widely used in Alabama.

Based on these results, it is clear that economies of scale (a function of market size) exert a powerful influence on hydrogen cost. While market size affects the cost of all parts of the infrastructure required to produce and distribute hydrogen, it is particularly significant on the production side. Figure 3.11 illustrates economies of scale for the centralized hydrogen-production technologies considered here. The abscissa in this figure is capacity of the production facility; the ordinate is the cost to produce a kg of hydrogen. Figure 3.11 shows that SMR production costs are relatively insensitive to capacity since the cost of natural gas dominates (see Figure 3.2). Figure 3.11 also shows the sensitivity of production cost to production rate for nuclear and coal-based technologies. Although the effect is somewhat dampened by the way it is displayed in the figure (i.e., a lack of granularity in the ordinate and limiting the abscissa to 300 tonnes per day or less), both coal and (especially) nuclear technologies show scale effects. For nuclear-based technology, production cost decreases by a factor of approximately six over the range considered in this analysis. As noted in earlier figures, the fuel component of hydrogen production is extremely small for the nuclear-based option. Scale effects are particularly significant at production rates below 100 tonnes of hydrogen per day. Note that a 100 tonne per day hydrogen production rate is approximately equivalent (on a heat input basis) to a 110 MW-electric power generating plant.

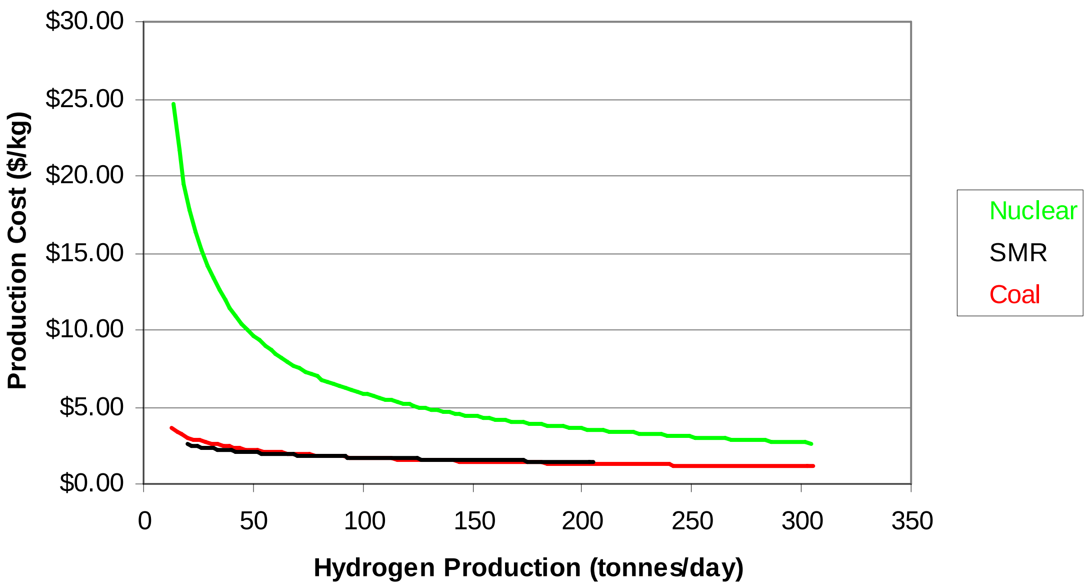

Figure 3.11 Production Costs vs. Hydrogen Production Capacity

Of particular interest in this study is the relationship between the population of a metropolitan area (or areas) and the required hydrogen production rate. This relationship depends on vehicle ownership, miles driven, fuel economy, and the number of hydrogen-fueled vehicles in the market. Figure 3.12 shows this relationship for the three hydrogen penetration rates examined in this study under typical rates of vehicle ownership, miles driven, and fuel economy (see Tables 2.1 and 2.2). As shown in Figure 3.12, average hydrogen demand does not exceed 200 tonnes/day until population exceeds 500,000, even at high hydrogen vehicle penetration. Considering the comparatively small metropolitan areas in Alabama, it is likely that hydrogen costs will be on the high side when compared to those for larger metropolitan areas in other states.

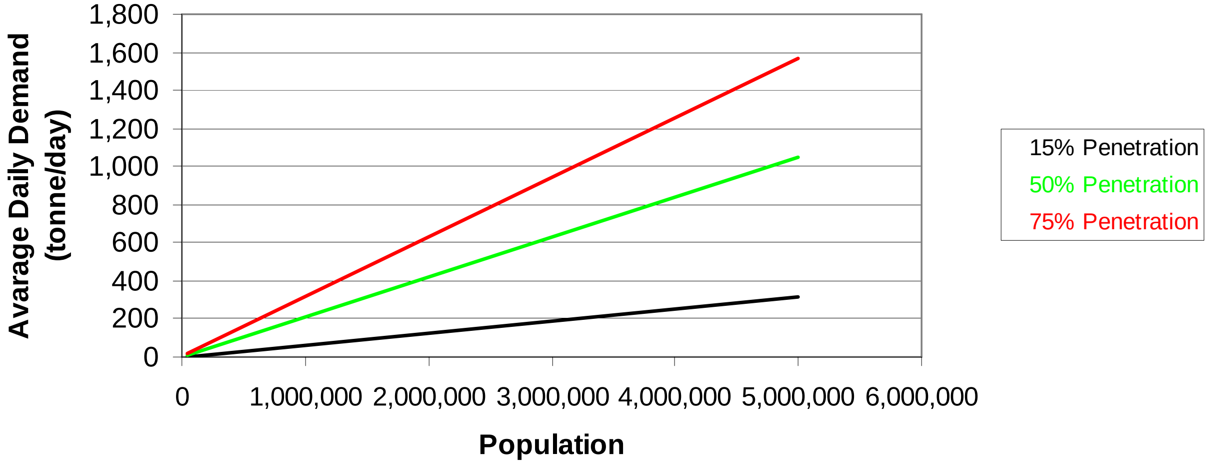

Figure 3.12 Influence of Population on Hydrogen Demand

4. Case Study Results for Combined Metropolitan Markets

As discussed above and illustrated in Figure 3.11, production rate (i.e., the quantity needed to satisfy average daily market demand) has a significant effect on the cost of hydrogen production. Since relatively small markets cannot achieve the demand needed to move down the cost curve, the second phase of the case study analysis focused on exploring the economics of combining metropolitan markets in such a way that more than one market could be supplied by a single production facility. Clearly, economies of scale from larger-volume production can lower production cost; however, some of the savings may be offset by increased pipeline lengths and diameters, larger compressors, and increases in other delivery-system capacities that tend to raise delivery cost. Thus, the analyses reported here summarize the net effects of various market combinations. The intent is to provide insights into the relative importance of these factors as applied to the Alabama case studies. In conducting these analyses, it was assumed that both urban markets and interstate markets would be served.

4.1 Combined Mobile-Montgomery Market

For the Mobile-Montgomery combined market case, it was assumed that a centralized SMR at McIntosh would supply 100% of the hydrogen for both markets. It was further assumed that a pipeline would extend south in the vicinity of US Hwy 43 to serve the Mobile portion (just as for the separate Mobile market). Approximately 10 miles north of Mobile, the hydrogen needed to supply the Montgomery market would be compressed up to transmission pipeline pressure and transported to Montgomery along a corridor following Interstate 65. This distance is approximately 160 miles.

For purposes of this analysis, it was assumed that the cost of hydrogen would be the same in all markets, i.e., the cost of hydrogen at interstate stations, at refueling stations in Mobile, and at refueling stations in Montgomery would be equivalent.

Summary results for this combined market case are shown in Table 4.1.

Table 4.1 Combined Mobile-Montgomery Market

Parameter	15% Penetration	50% Penetration	75% Penetration
Combined hydrogen demand (kg/day)	40,993	136,643	204,966
Pipe diameter along US 43 (inch)	5	8	9 ¼
Pipe diameter along US 65 (inch)	4 ¾	7 ¾	9
Delivery Cost ($/kg)	$3.92	$2.48	$2.28
Forecourt Cost ($/kg)	$0.86	$0.86	$0.86
Production Cost ($/kg)	$2.05	$1.61	$1.55
Total Cost of H2 ($/kg)	**$6.83**	**$4.95**	**$4.69**

Comparison of the estimates in Table 4.1 with those for the standalone Mobile case in Table 3.2 shows that the combined Mobile-Montgomery market results in an increase in the cost of hydrogen in Mobile. Two factors combine to produce this result. First, even though the addition of the Montgomery market almost doubles the hydrogen production rate over that of the standalone Mobile market, economies of scale for SMR technology are relatively weak and there is little reduction in production cost. When combined with the significantly longer pipeline required to connect the McIntosh site with Montgomery, the total cost of hydrogen increases.

Comparison of the estimates in Table 4.1 with those for Montgomery in Table 3.4 suggests that the production cost savings from SMR technology (as compared with coal-based technology) more than compensates for the increased delivery cost associated with the longer pipeline from McIntosh to Montgomery. Thus, total hydrogen cost declines for Montgomery.

4.2 Combined Birmingham-Montgomery Market

Results for the Birmingham and Montgomery standalone markets were summarized in Tables 3.3-3.6. In considering these areas as individual markets, it was assumed (in both cases) that hydrogen would be produced at the Ernest C. Gaston coal-fired facility at Wilsonville. For the combined market case, a single coal-based hydrogen production plant at Wilsonville was assumed to serve both cities. Capital cost for this much larger plant, as well as for larger-capacity geologic storage and compressors to bring plant-gate hydrogen to transmission pipeline pressures, are spread over a much greater delivery volume, thereby reducing delivered cost.[5]

Results for the combined Birmingham-Montgomery market are summarized in Table 4.2. As can be seen in the table, transmission pipelines and additional distribution systems offset some of the economies of scale. Comparison these results with those for the respective individual markets shows that while hydrogen delivery costs increase, hydrogen production costs decrease more -- due to economies of scale for the coal-based production technology. At the two lower vehicle penetrations (15% and 50%), the total cost of hydrogen for the combined markets is lower than for Montgomery alone because of the high production costs in the Montgomery standalone scenario. For Birmingham, economies of scale are not as dominant and higher delivery costs result in a higher total cost of hydrogen in the combined market than for the Birmingham standalone case.

[5] Larger-capacity, “shared” equipment and facilities may be infeasible for high levels of hydrogen demand. However, given the moderate levels of hydrogen demand examined in this report, shared facilities were assumed for all combined market cases.

Table 4.2 Combined Birmingham and Montgomery Market

Parameter	15% Penetration	50% Penetration	75% Penetration
Combined hydrogen demand (kg/day)	58,529	195,097	292,647
Pipe diameter along US 65/AL 145 to Montgomery (inch)	3 ¾	6	7
Pipe diameter along AL 145/US 280 to Birmingham (inch)	5	7 ¾	9 ¼
Delivery Cost ($/kg)	$2.70	$1.88	$1.75
Forecourt Cost ($/kg)	$0.86	$0.86	$0.86
Production Cost ($/kg)	$2.01	$1.34	$1.19
Total Cost of H2 ($/kg)	**$5.57**	**$4.08**	**$3.80**

4.3 Combined Birmingham-Huntsville Market

Two production scenarios were considered for the Birmingham-Huntsville combined market. In the first, the Ernest C. Gaston coal-fired facility at Wilsonville was assumed to supply all the hydrogen. In this case, hydrogen was assumed to be piped to Birmingham along a corridor from Alabama Hwy 145 to US 280. This is the same route assumed in the analysis of the Birmingham standalone market. However, in the combined market case, hydrogen for the Huntsville market is assumed to be piped north from Birmingham, in a corridor following US 65. Upon reaching Mooresville, the pipeline is assumed to turn north-east along Alabama Alternate 72 into Huntsville. The total route, from Birmingham to Huntsville, is approximately 100 miles.

The second production option considered for the Birmingham-Huntsville combined market is the Browns Ferry nuclear facility at Athens. In examining this option, it was assumed that two pipelines would be built. The first would extend from Athens directly to Huntsville. That line would be similar to the 30-mile pipeline assumed for the standalone Huntsville case. The second pipeline would extend south from Athens along US 65 to Birmingham – a distance of approximately 100 miles. A single compressor would be used to increase hydrogen pressure from its production level of 300 psi to the assumed pipeline inlet pressure of 1000 psi.

As mentioned above, pipeline costs for this study (as well as for the DOE H2A program) are generic with respect to geographic and topographic conditions. For both of the options considered above, the Tennessee River would have to be crossed. Obstacles of this magnitude are not reflected in the cost estimates generated by the model used in this analysis. Several alternatives for crossing a barrier such as the Tennessee River are available including bridges, trenching, and tunneling. Any decisions regarding which alternatives would be used must be based on regulatory, environmental, safety, and economic factors that are beyond the scope of the current analysis.

Results for the combined Birmingham-Huntsville market are shown in Tables 4.3 and 4.4 for the coal-based and nuclear-based cases, respectively.

Table 4.3 Combined Birmingham-Huntsville Market: Coal-Based Production

Parameter	15% Penetration	50% Penetration	75% Penetration
Combined hydrogen demand (kg/day)	61,058	203,528	305,291
Pipe diameter to Birmingham (inch)	5 ½	9	10 ½
Pipe diameter to Huntsville (inch)	4 ¼	6 ¾	8
Delivery Cost ($/kg)	$2.87	$0.93	$0.81
Forecourt Cost ($/kg)	$0.86	$0.86	$0.86
Production Cost ($/kg)	$1.98	$1.33	$1.18
Total Cost of H2 ($/kg)	**$5.71**	**$3.12**	**$2.85**

Table 4.4 Combined Birmingham-Huntsville Market: Nuclear-Based Production

Parameter	15% Penetration	50% Penetration	75% Penetration
Combined hydrogen demand (kg/day)	60,844	202,815	304,221
Pipe diameter to Birmingham (inch)	6 ¼	10	11 ½
Pipe diameter to Huntsville (inch)	3 ¼	5	5 ¾
Delivery Cost ($/kg)	$2.88	$0.95	$0.82
Forecourt Cost ($/kg)	$0.86	$0.86	$0.86
Production Cost ($/kg)	$7.96	$3.66	$2.92
Total Cost of H2 ($/kg)	**$11.70**	**$5.47**	**$4.60**

Examination of the cost estimates in these tables and with those presented earlier for the separate Birmingham and Huntsville metropolitan areas suggests the following:

- For the combined Birmingham-Huntsville market, hydrogen produced from coal is less costly than production from nuclear power, after accounting for the corresponding increases in delivery costs;
- For Huntsville, hydrogen costs are lower in the combined market case for either coal- or nuclear-based production as compared with nuclear-based production for the separate Huntsville market; and
- At 15% vehicle penetration, hydrogen costs in Birmingham are higher in the combined market case if production were via coal-based technologies. However,

at 50% or 75% penetration, the higher level of demand for the combined markets results in lower hydrogen cost in Birmingham. On the other hand, if the hydrogen for the combined markets were produced via nuclear power, the cost of hydrogen in Birmingham would increase over the cost for the sseparate Birmingham market fed by coal-based hydrogen production.

4.4 Observations from Analyses of Combined Markets

The combined market analysis examined potential cost reductions that might be realized by using a single production facility to supply hydrogen to multiple markets in Alabama. In essence, the analysis compared the cost reductions due to the economies of scale of production facilities with the increased costs due to larger and longer delivery pipelines.

While one must be cautious in generalizing from a limited number of case studies, some observations are apparent from these analyses.

- Combining markets supplied by SMR production technology is likely to lower the cost of delivered hydrogen in those cases where the markets are relatively nearby. SMR technology offers little economy of scale and small production cost reductions are quickly negated by increased delivery costs from longer, larger-diameter pipelines;
- The economy of scale for coal-based hydrogen production has the potential to lower hydrogen costs in combined markets. Cost reductions realized from larger facilities can be significant enough to overcome increased delivery costs, even if comparatively small markets are combined; and
- Nuclear-based hydrogen production offers potential savings in combined markets. Since current H2A modeling efforts suggest that economies of scale are significantly greater than for the coal-based option (see Figure 3.11), cost reductions due to combined markets can be realized at large production volumes.

5. Alternative Scenarios

Basic assumptions for defining the hydrogen demand and supply scenarios considered thus far are that hydrogen would be produced at a single large facility for each market and delivered to individual refueling stations via a pipeline distribution system. It was presumed that these assumptions would lead to the lowest hydrogen costs. Analyses of other options for production and delivery have also been conducted and the results are compared to those for the reference case analyses reported thus far.

5.1 Alternate Delivery Options

In addition to a pipeline distribution system, HDSAM also allows consideration of hydrogen delivery via truck. Truck delivery may be of two types – as a compressed gas in pressurized cylinders manifolded together into a "tube trailer", or as a cryogenic liquid in a tanker truck. For either option, a truck terminal is assumed to be co-located at the production facility. In addition to building, parking and maneuvering areas, the terminal includes a compressor (or liquefier, as appropriate) to condition the hydrogen, storage facilities, and a sufficient number of bays for truck loading. For gaseous hydrogen delivery, the pressurized cylinders are left at the refueling station as part of the station storage/refueling system. For this analysis, it was assumed that the gaseous hydrogen would be compressed to approximately 7000 psi at the terminal and that each tube trailer would hold approximately 700 kg of hydrogen. Although these conditions are beyond current (2007) capabilities, it is anticipated that continued advances in pressure tubes will enable this capability to be achieved in the near future.

By contrast, no increases in the carrying capacity of tanker trucks were assumed for this analysis.[6] For this option, it was further assumed that liquid hydrogen would be offloaded to a liquid hydrogen storage facility at the refueling station and that the delivery truck itself would make multiple deliveries from a single load, depending on demand at individual refueling stations.

Estimates were developed for each of the four metropolitan areas and for each of the three delivery options considered in HDSAM. In each scenario, it was assumed that refueling stations would be located along the pipeline and/or highway connecting the production facility with the specific metropolitan area under consideration. Results for each of the three hydrogen-fuel-vehicle penetrations considered are shown in Figures 5.1-5.3. The cost estimates presented in these figures represent the sum of delivery cost and forecourt (refueling station) cost. This sum was used to compare delivery options because the station design and cost for a gaseous-fuel station differs from that of a liquid-fuel station.

[6] Each truckload of liquid hydrogen was assumed to contain approximately 4100 kg of hydrogen.

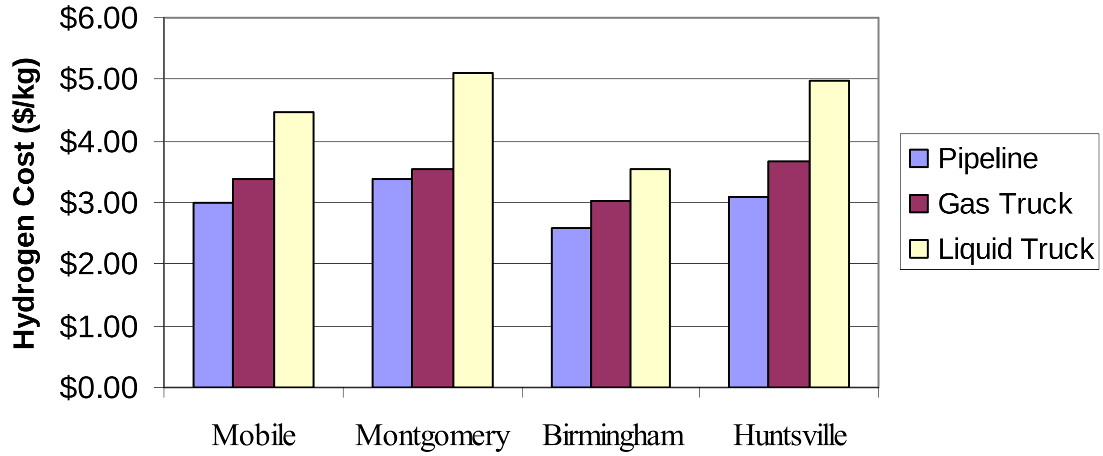

Figure 5.1 Alternative Delivery Options at 15% Penetration

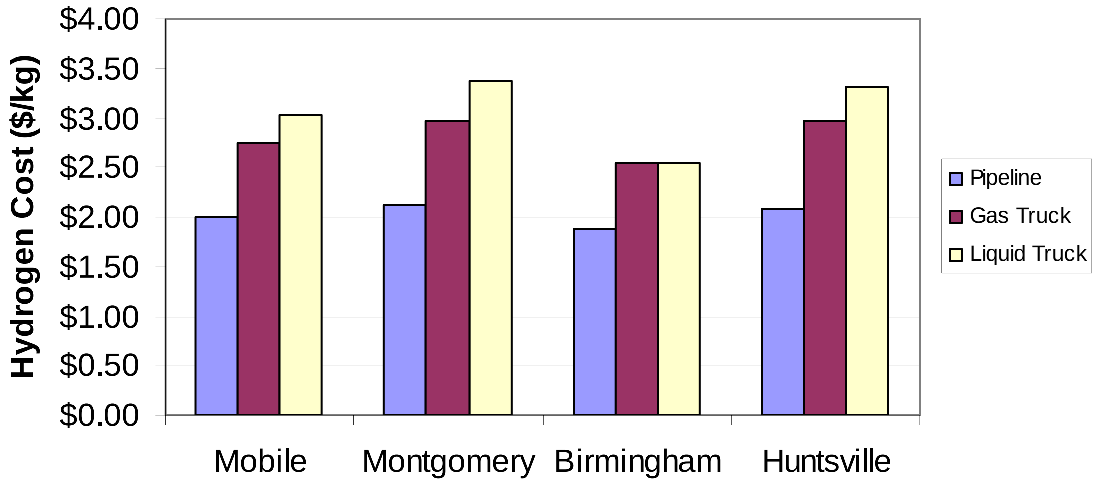

Figure 5.2 Alternative Delivery Options at 50% Penetration

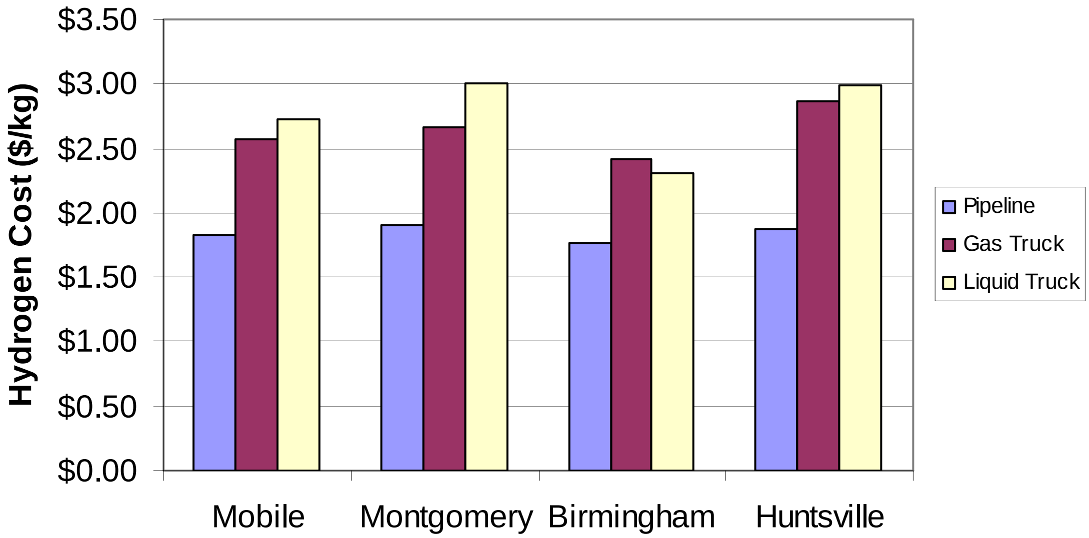

Figure 5.3 Alternative Delivery Options at 75% Penetration

As shown in these figures, for all metropolitan areas considered in this study pipeline delivery is the lowest cost delivery option. At the lowest market penetration level, gaseous truck is only slightly higher while liquid truck delivery is considerably more expensive. One of the factors contributing to the high cost of liquid hydrogen delivery is the cost of the liquefier itself. As can be seen in Figure 5.1, this cost is especially high for smaller markets like Montgomery and Huntsville. As market size increases, the differential between gaseous truck and liquid truck delivery becomes smaller as evidenced by comparing the small metropolitan areas and increasing the vehicle penetration. The economies of scale for the liquefier reduce the cost of liquid delivery while the number of gaseous trucks (which exhibit no economy of scale) becomes of greater influence as the market (e.g., number of deliveries) increases. At 50% vehicle penetration, the estimated costs in the Birmingham area are essentially identical for the gaseous and liquid truck delivery options. At 75% penetration, the liquid delivery option for Birmingham is lower in cost than gaseous truck delivery. The cost differential between the two truck options also decreases with an increase in vehicle penetration for the other three metropolitan areas as well.

5.2 Alternate Production Options

For the case studies discussed above, it was assumed that hydrogen would be produced at a centralized facility using natural gas, coal or nuclear technologies and that the product hydrogen would be delivered to individual refueling stations for dispensing into light-duty vehicles. The concept of distributed hydrogen production, i.e., production at the refueling station or forecourt, is an important alternative to this concept (i.e., centralized production). Two technologies for localized production have been considered in DOE's H2A program. These are: 1) steam methane reforming (SMR) but at a much smaller scale than in centralized production, and 2) electrolysis to split water into hydrogen and oxygen. The cost tradeoff between distributed and centralized production alternatives is increased production cost (due to smaller scale) versus zero delivery cost by the elimination of compressors, pipelines, terminals, trucks, etc.

The distributed production cost models developed within the H2A program were used to examine distributed production in the context of this study.[7] Results are described below.

Based on current versions of the distributed hydrogen production models, the estimated cost of hydrogen for distributed SMR production is $3.30/kg while that for distributed electrolysis is $4.60/kg. Comparison of these values with the hydrogen costs presented in the earlier tables suggests that distributed production may be cost-competitive with centralized production for several of the markets considered in this study. While it is risky to extend this observation to other scenarios that have not been examined, some additional insight can be obtained by looking at Figures 3.11 and 3.12. If one assumes that forecourt and delivery costs total $1.50/kg (a value lower than any estimated in this study), centralized production costs must be less than about $1.80/kg and $3.10/kg to compete with distributed SMR and distributed electrolysis, respectively. With these criteria, examination of Figure 3.11 suggests that a centralized demand greater than approximately 20 tonnes/day would allow the coal-based technology to potentially compete with de-centralized production via electrolysis. At demand greater than 150 tonnes/day coal-based production could compete with de-centralized SMR production. At 50% hydrogen vehicle market penetration, these hydrogen demands correspond to populations of approximately 100,000 and 750,000, respectively. For nuclear-based hydrogen production, a demand of 300 tonnes of hydrogen per day would be needed to be cost competitive with de-centralized electrolysis and a significantly greater demand would be required to compete with de-centralized SMR. A 300 tonnes/day hydrogen demand corresponds to a population of approximately 1.5 million if 50% of the light-duty vehicles are hydrogen-fueled. Centralized SMR production appears to be competitive with distributed production as long as the delivery and forecourt costs do not become excessive.

5.3 Other Markets in the Southeast United States

In addition to the above-described case studies for Alabama metropolitan areas, there is interest in hydrogen markets in other areas of the southeastern U.S., most notably Atlanta. Representing the largest single market in the region, the Atlanta metropolitan area has a population of approximately 3.5 million, a light-duty-vehicle ownership rate of 0.68 vehicles per person, and an annual average driving rate of 13,866 miles per vehicle. Although Atlanta could be served by a variety of potential production sites, this analysis assumed that hydrogen would be produced at the US Department of Energy's Savannah

[7] H2A production cost models may be downloaded at the US Department of Energy's Energy Efficiency and Renewable Energy website, http://www.hydrogen.energy.gov/h2a_prod_studies.html. It should be noted that the distributed production models have not received the benefit of peer review to the same extent as has HDSAM, the delivery model. Further, the production cost models do not include all of the infrastructure improvements that might be needed to bring raw materials (or energy) to each individual forecourt. These might include additional pipelines and utility connections to deliver large quantities of natural gas, water and electric power.

River Site, located near Aiken, SC, approximately 175 miles from Atlanta. One reason for selecting this production location is that it permits comparison with results from another study conducted under a DOE contract with the Savannah River National Laboratory.

At 15% hydrogen vehicle penetration and with hydrogen refueling stations along US Highway 20 between Aiken and Atlanta, hydrogen demand is estimated to be approximately 237,000 kg/day. Pipeline delivery of this quantity of hydrogen (including dispensing at each refueling station) is estimated to cost $2.70/kg. This cost, along with estimated costs for the three principal production technologies, is shown in Figure 5.4.

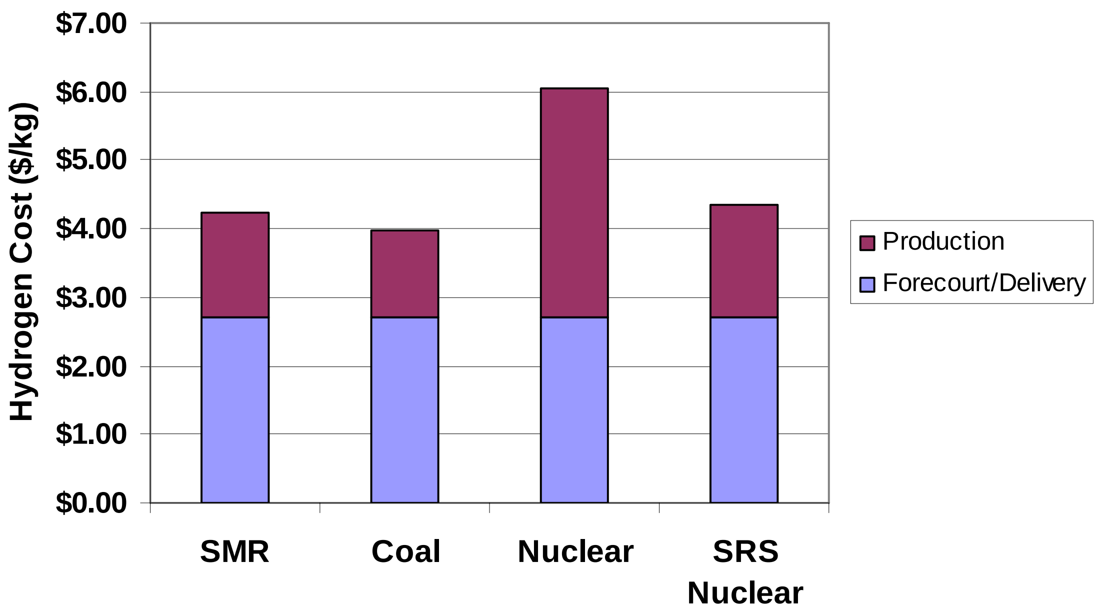

Figure 5.4 Hydrogen Cost in Atlanta for Various Production Technologies

The bar on the far right in Figure 5.4 is another estimate of the cost of producing and delivering hydrogen, generated by a team representing DOE National Laboratories and private companies in the energy production and delivery businesses.[8] Labeled "SRS Nuclear" this team looked specifically at the feasibility of installing a nuclear-based hydrogen production facility on the Savannah River Site (SRS). The forecourt and delivery costs for the SRS study were estimated with HDSAM; production costs were estimated from a detailed nuclear hydrogen design study. The facility size in the SRS study is 270 tonnes/day, which is somewhat larger than required to meet a 15% vehicle penetration in Atlanta. Nonetheless, the estimate serves as a point of comparison for the estimates in the H2A production models.

The coal and nuclear costs shown in Figure 5.4 suggest that the larger markets in the Southeastern US provide significant economies of scale which can allow these

[8] Summers, W.A., *Centralized Hydrogen Production from Nuclear Power: Infrastructure Analysis and Test-Case Design Study* (WSRC-TR-2004-00318) July 2004.

technologies to be cost competitive with SMR. Figure 5.4 also shows that the hydrogen production cost estimated in the SRS study is considerably less than that estimated in the H2A production model. One reason for this difference is that the operations and maintenance staff is considerably larger in the H2A model. This issue will be investigated as the H2A program continues.

The SMR and coal-based hydrogen production costs displayed in Figure 5.4 do not include any cost for carbon-dioxide capture and sequestration. Should sequestration be required, the cost of these carbon-based hydrogen production technologies would be increased considerably.

5.4 Alternative Economic Metrics

All of the hydrogen cost estimates in this report are presented in terms of dollars per kilogram of hydrogen delivered to the consumer ($/kg). This is the metric used throughout the H2A program, as well as in many other studies investigating the use of hydrogen as a transportation fuel. There are a number of reasons for using this metric, including the fact that the energy content of a kilogram of hydrogen is very nearly the same as the energy content of a gallon of gasoline. Thus, the $/kg metric offers a near-equivalent to the familiar metric of $/gallon of gasoline.

One of the underlying assumptions in promoting the use of hydrogen as a transportation fuel is that miles traveled per kilogram of hydrogen will be considerably greater than miles traveled per gallon of gasoline by light-duty vehicles. The corresponding fuel economy assumption in the reference-case H2A studies (as well as in this study) is that hydrogen vehicles achieve a fuel efficiency of 59.6 miles/kg of hydrogen (the energy equivalent of 57.5 miles per gallon) as compared to an average of 19.7 miles per gallon of gasoline for current light-duty vehicles.[9] Because the purpose of any fuel is to move a vehicle a certain distance, another metric that could be used is $/mile driven. The dollars in this metric should include capital, operating, and maintenance, as well as fuel cost. Vehicle capital, operating, and maintenance costs are outside the scope of this study; however, it is still informative to compare the $/mile cost of gasoline and hydrogen vehicles solely as a function of fuel cost. This comparison is shown in Figure 5.5 for the reference case conditions of fuel economy noted above.

Figure 5.5 shows that, based on fuel economy alone, the cost of hydrogen ($/kg) can be almost three times the cost of gasoline ($/gallon) to achieve an equivalent cost per mile driven. For example, a gasoline cost of $2.50/gallon might be equivalent to a hydrogen cost of about $7.48/kg. Note that the hydrogen costs reported here do not include state and local gasoline or sales tax, whereas gasoline costs at the pump do include these costs.

[9] *Highway Statistics 2005*, US Department of Transportation, Federal Highway Administration, FHWA-PL-06-009, Dec. 2006.

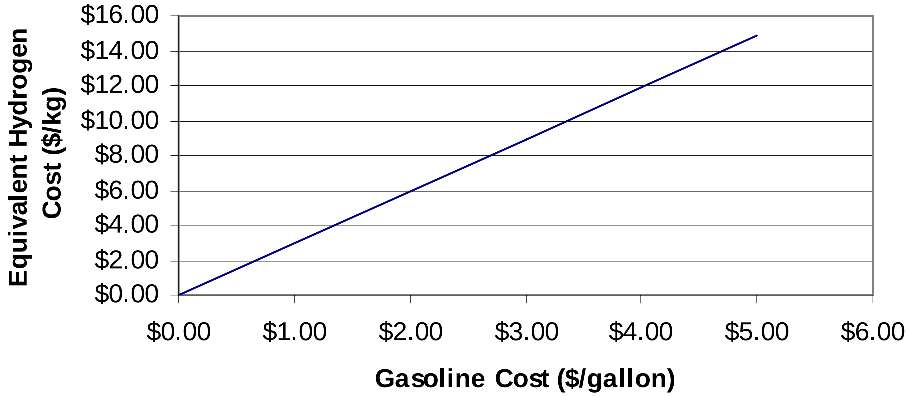

Figure 5.5 Equivalent Fuel Costs

6. Energy Efficiency and Emissions

As discussed above, hydrogen production and delivery models developed under the US Department of Energy's H2A program were used to estimate the delivered cost of hydrogen to select Alabama markets. Expressed in terms of $/kg levelized over an investment lifetime, these estimates provide important insights into the total cost of different production and delivery alternatives across a range of market types and sizes. However, cost is not the full story. Although critical to program development and infrastructure planning and a potential barrier to market success, cost estimates still must be supplemented with other key measures. The following discussion summarizes two such measures – energy efficiency and greenhouse gas (GHG) emissions – estimated using common metrics and standardized tools for many of the case studies reported above.[10] Together with cost estimates, the resulting characterizations provide a more broad-based comparison of hydrogen production and delivery alternatives available to urban areas in Alabama and elsewhere.

6.1 Methodology

Energy efficiency and GHG emissions can vary substantially across different hydrogen production and delivery alternatives, including those considered in the Alabama case studies. Some processes (e.g., hydrogen production from nuclear power) use virtually no fossil fuel and produce few GHGs, while others (e.g., hydrogen liquefaction) are very energy intensive and produce considerable upstream GHG emissions (either from the process itself or from generating the electricity required). These parameters are not calculated within the H2A suite of models currently available on the DOE website. Thus, in order to complete the case study analyses, it was necessary to turn to other analytical tools – the GREET 1.7 model and the second generation HDSAM (currently being developed by staff of Argonne National Laboratory, National Renewable Energy Laboratory and Pacific Northwest National Laboratory). These models provided energy and GHG estimates for specific portions of the hydrogen production-delivery pathways constructed for the Alabama case studies.

GREET 1.7 is a nationally recognized tool for lifecycle analysis of alternative transportation fuels and vehicles. Developed over the past 15 years by staff of Argonne National Laboratory, GREET 1.7 estimates energy and GHG emissions associated with several hydrogen fuel pathways, both upstream (to produce hydrogen feedstock and fuel) and downstream (to distribute hydrogen fuel).[11] Since GREET does not explicitly account for all of the components required to deliver and dispense hydrogen to the consumer, the downstream energy and emissions estimates within GREET are far less detailed than

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[10] Water use, criteria pollutant emissions and land use impacts are additional factors that should be considered in a broad-based comparison. However, these are beyond the scope of the current study.

[11] For further information on key assumptions, methodologies and results, or to download a copy of GREET 1.7 and the GREET Users' Manual, readers should visit the GREET website (http://www.transportation.anl.gov/software/GREET).

those within HDSAM. Thus, they were supplemented with the more detailed component-based estimates of energy use and GHG emissions from HDSAM 2.0.

As part of model development and expansion, HDSAM 1.0 is being modified to incorporate a number of refinements and new features. One of these is the ability to estimate energy use and greenhouse gas emissions for the many components involved in a delivery pathway. Some of the energy efficiency and greenhouse gas emission rates being added to HDSAM are being obtained from GREET; others are being estimated independently. HDSAM 2.0 is scheduled to be released in late 2007 and to be posted on the US Department of Energy's EERE website by year end.

Both GREET and HDSAM were configured to represent conditions applicable to the Alabama case studies. The following discussion highlights the effects of market size, production technology, and delivery option on energy use and GHG emissions as estimated by these HDASM and GREET model runs.

6.2 Market Size

To examine the effect of market size on energy use and GHG emissions, Montgomery and Birmingham were selected to represent small and large market sizes, respectively. Figure 6.1 shows upstream and onsite energy estimates for these markets at 50% vehicle market penetration. Note that "upstream" energy use includes consumption for all activities involved in hydrogen production and transport, feedstock production and transport, and central station power generation and transmission (for purchased electricity), while "onsite" energy use refers to consumption at the forecourt or refueling station. It is clear from Figure 6.1 that energy use and GHG emissions are weak functions of market demand, for both hydrogen production and delivery. This is attributed to the fact that for most delivery components, energy efficiency is relatively insensitive to equipment size (and therefore to market demand). In other words, within the range of commercial-scale equipment, most delivery components (e.g., storage tanks, compressors pipelines) have comparable energy efficiencies. Although the energy efficiency of production technologies may be more variable, it was assumed to be constant due to the absence of reliable information on the relationship between the size (or capacity) of production equipment and their energy efficiencies. This resulted in near-constant energy use per kg of hydrogen produced and delivered to specific markets.

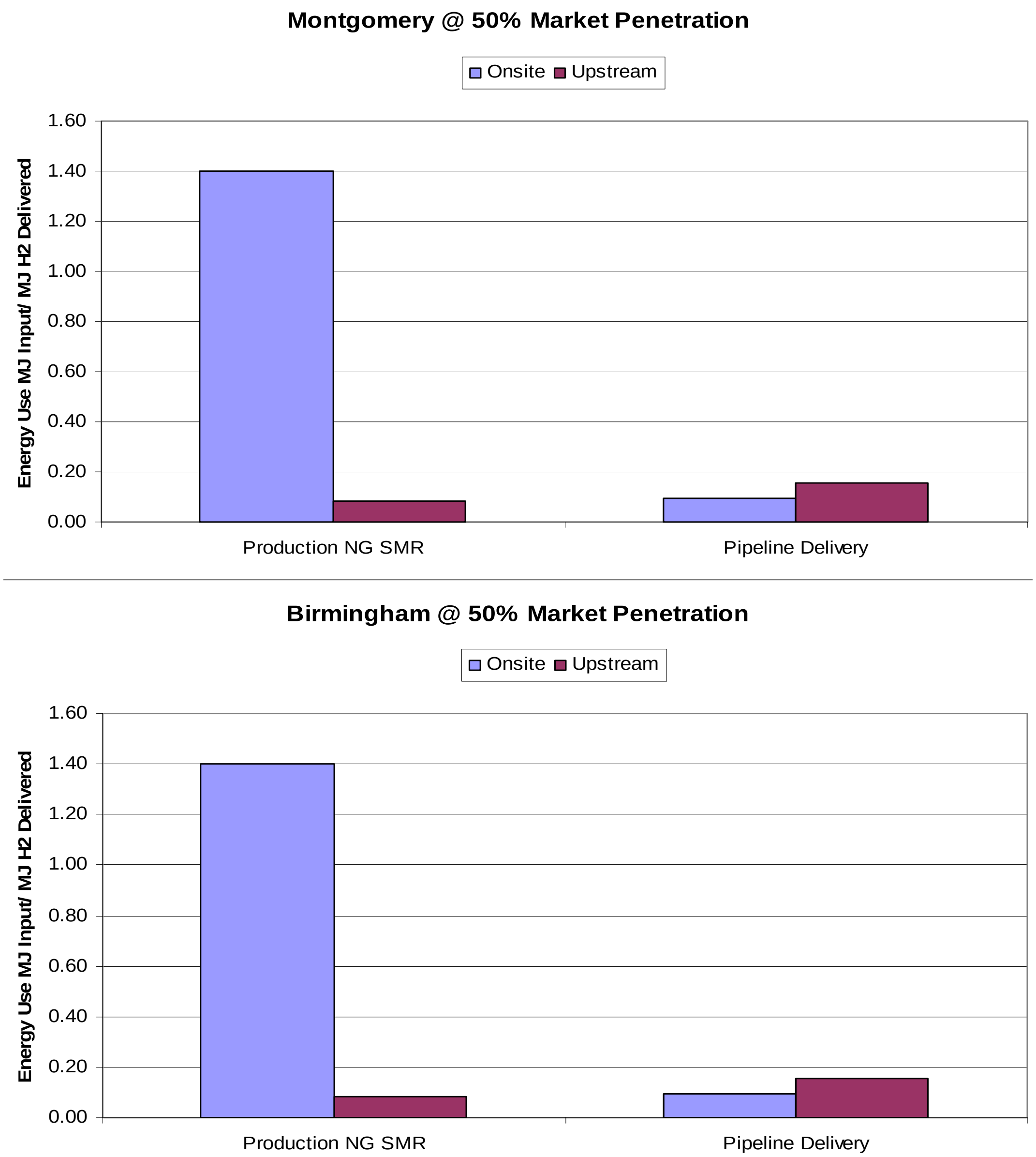

Figure 6.1 Effect of Market Size on Energy Use

Liquid truck delivery is a key exception to this conclusion. Liquefier energy efficiency is strongly dependent on equipment capacity, resulting in significantly lower energy use per kg of hydrogen produced and delivered. This is shown in Figure 6.2. Greenhouse gas emissions per MJ of hydrogen delivered drop by approximately 20% for liquefiers sized to meet Birmingham demand, as compared with those sized for comparable market penetrations in Montgomery. Other portions of the pathway – SMR production, liquid hydrogen trucking and the refueling station – vary little between the two metropolitan areas.

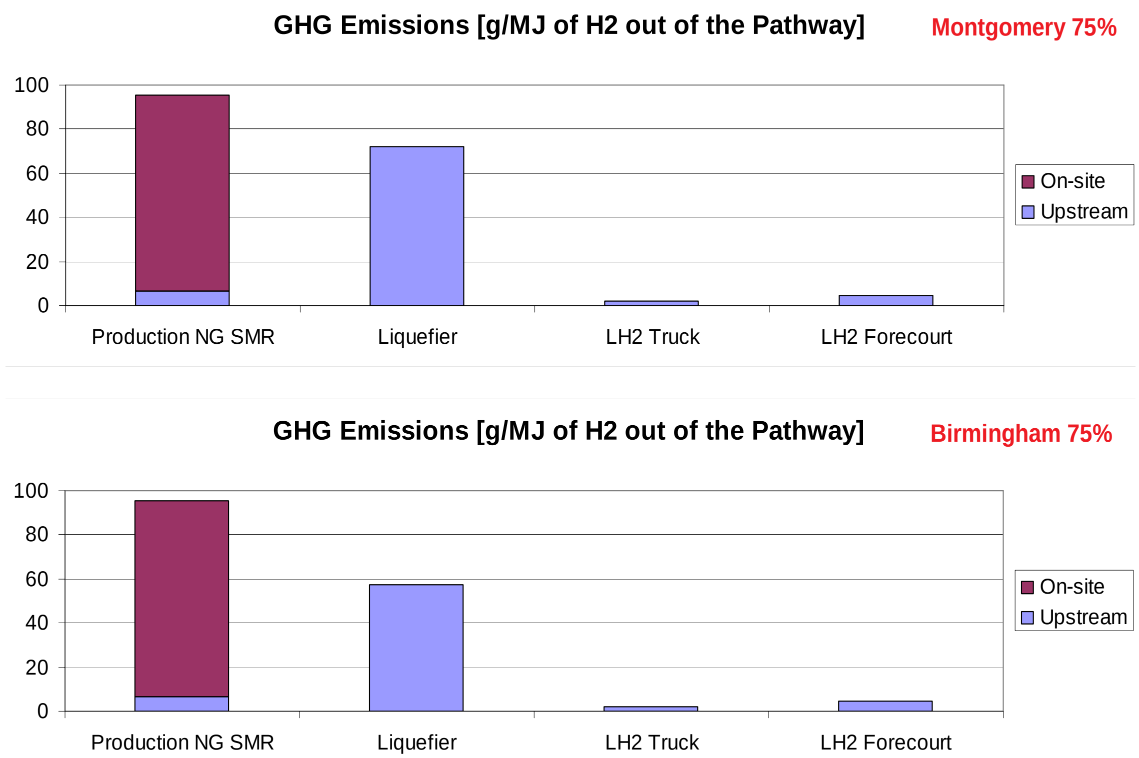

Figure 6.2 Liquefier GHG Emissions Scales with Demand

6.3 Production Technologies

As noted above, three centralized hydrogen production technologies were considered for the Alabama case studies – steam methane reforming (SMR) using natural gas feedstock, coal gasification, and nuclear thermo-chemical water cracking (TCWC). Figure 6.3 shows estimated energy use per quantity of hydrogen produced for each of these options in the Birmingham market at 50% vehicle penetration. It is clear from the figure that production of hydrogen via coal gasification is the most energy-intensive, followed by production via SMR, while production via nuclear TCWC demands significantly less energy per unit of hydrogen provided to the Birmingham market. This is because onsite energy consumption at the nuclear plant is considered renewable, and a relatively small amount of energy is required upstream to mine and enrich the uranium fuel. Figure 6.4 shows much larger GHG emissions from coal gasification as compared with a natural gas SMR plant. This is directly attributable to the larger carbon percentage per unit energy in coal as compared to natural gas. In all of the above production cases, no electricity co-production or carbon capture and sequestration were assumed.

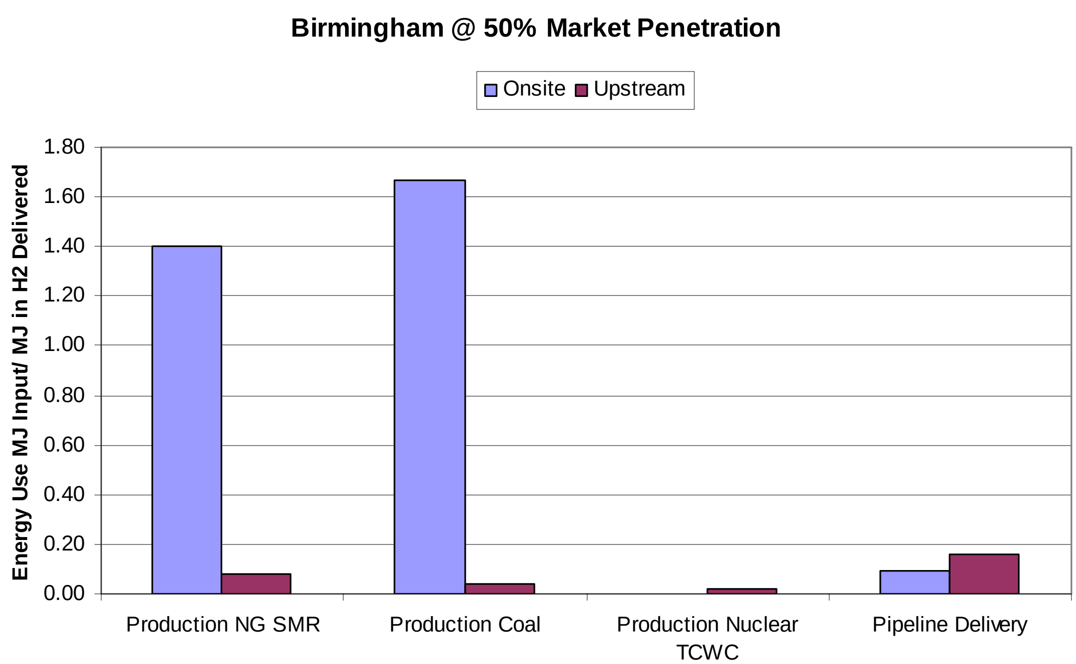

Figure 6.3 Energy Use for Different Production Technologies

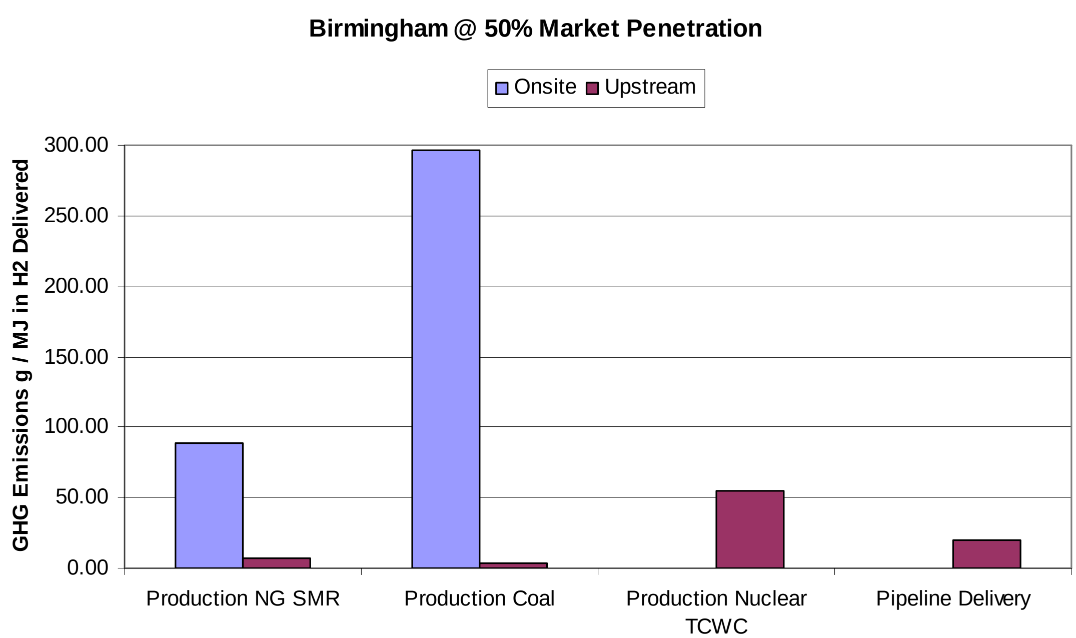

Figure 6.4 GHG Emissions for Different Production Technologies

6.4 Delivery Options

As stated earlier, three delivery options were considered in this analysis – compressed gas truck delivery, liquid truck delivery, and pipeline delivery. Theoretically, hydrogen produced in a centralized plant via SMR, coal gasification or nuclear TCWC could be delivered to market by any one of these delivery modes. In practice, however, large markets are unlikely to be served by small-scale delivery options. Thus, although compressed gas truck delivery was included in this analysis, it is not likely to be a viable option for many of the case studies considered here.

Figure 6.5 compares the energy intensity associated with producing hydrogen at a central SMR plant and delivering it via these three options to refueling stations in Birmingham, Alabama. (The comparable figure for Montgomery is virtually identical.) As the figure clearly indicates, production is far more energy intensive than any of the delivery options. For delivery alone, compressed gas truck delivery and pipeline delivery are less energy intensive than liquid truck delivery. Similar conclusions can be drawn with respect to GHG emissions, as shown in Figure 6.6.

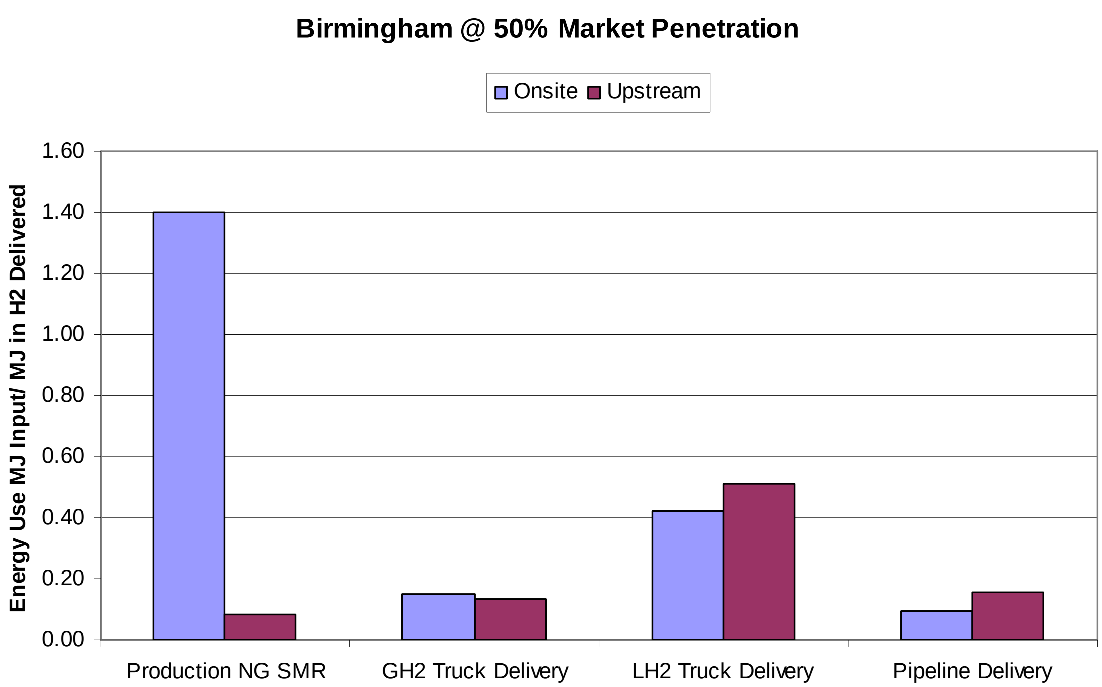

Figure 6.5 Energy Intensities of SMR Production and Delivery Options

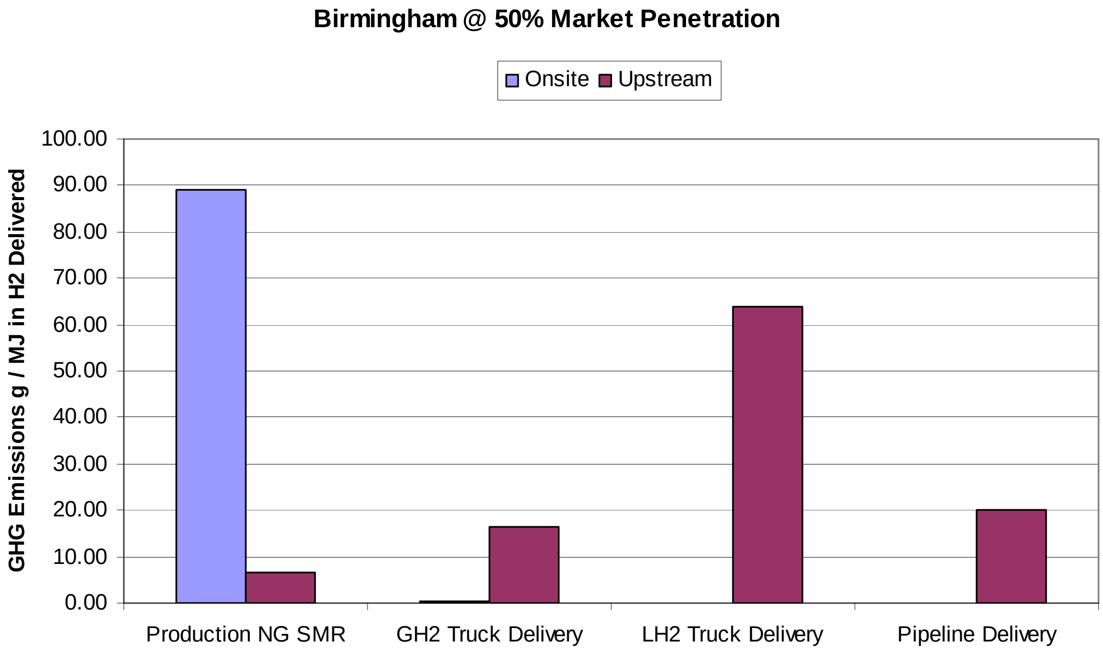

Figure 6.6 GHG Emission Rates of SMR Production and Delivery Options

1. Conclusions and Future Directions

Levelized costs for producing and delivering hydrogen to several transportation markets in Alabama have been estimated. These estimates assume that hydrogen infrastructure will build upon current indigenous resources (e.g., facilities, transportation and handling infrastructure, and feedstocks within Alabama) and that distribution distances will be comparable to those from existing, large energy facilities to their respective markets.

7.1 Conclusions

Markets consisting of individual metropolitan areas in Alabama tend to be smaller than those in many other metropolitan areas in the US. Thus, unless relatively high hydrogen vehicle penetration is assumed, production facilities fail to achieve significant economies of scale. This results in SMR technology typically being less costly (on a $/kg of hydrogen produced basis) than either coal- or nuclear-based production technologies. This situation is particularly dominant for low hydrogen vehicle penetration cases, which might be expected during early phases of the “hydrogen economy.”

Using a single production facility to supply hydrogen to multiple metropolitan areas may be expected to reduce production cost per kilogram of hydrogen, but this cost reduction may be offset by increased delivery costs resulting from greater distances to market.

While pipeline delivery was taken as the reference case option for this study, truck deliveries of compressed gaseous hydrogen and of cryogenic liquid hydrogen were also examined. For each scenario considered in this study, pipeline delivery was found to have the lowest unit cost.

Distributed hydrogen production, i.e., production at individual refueling stations, was also considered as an alternative to centralized production. Based on the current suite of H2A production models, costs for distributed production via either SMR or electrolysis technologies were very competitive with costs for producing hydrogen at centralized facilities and delivering it via pipeline. However, the estimates presented here do not account for additional infrastructure enhancements that might be required to deliver large quantities of natural gas, water, or electricity to individual refueling stations. Utility upgrades would be needed not only for operating production equipment, but also for compressing hydrogen to storage and dispensing pressures.

Energy efficiency and greenhouse gas (GHG) emissions were estimated for several of the case studies considered in this analysis. It was concluded that energy intensity (expressed as energy input per unit of energy output) decreases slightly with increasing market size for most production and delivery components. The notable exception to this finding is the case where hydrogen is liquefied as part of the delivery pathway. In this case, energy efficiency is directly related to market size, with a strong decrease in energy use as market size increases. The SMR and coal-based production technologies require high energy inputs per unit of energy output. These carbon-based technologies also produce high GHG emissions. The nuclear-based production option has the highest energy efficiency and produces the lowest rate of GHG emissions of the options considered in this analysis

Pipeline and truck delivery of gaseous hydrogen have much lower energy use and GHG emissions per unit of hydrogen delivered than does truck delivery of liquefied hydrogen. For this latter option, the liquefier accounts for most of the energy use and GHG emissions produced.

7.2 Path Forward

The results presented in this report represent a set of "snapshots" or case studies of how hydrogen might serve as a transportation fuel in Alabama. Transitions from the gasoline-fueled present to a hydrogen-fueled future are not considered. While the models used in these analyses represent the state-of-the-art of H2A modeling, there are continuing efforts to improve both the models and the corresponding input data to better represent expected conditions. Specific areas of on-going investigation include hydrogen storage, compression, liquefaction, and refueling station capacity and design. Assumptions regarding pipeline pressures, construction techniques, and operating requirements are also being examined. Models for additional production technologies are being developed, as are models for alternative delivery options. As noted previously in this report, enhancements to the pipeline model to include additional distribution trunk lines within a metropolitan area could lower hydrogen delivery cost.

To continue to provide a representative picture of the economics of hydrogen use in Alabama, it would be advantageous to reproduce the analyses for a number of the scenarios considered in this study. In this way, an understanding of "if", or "in what way", the basic conclusions of this study might be impacted by improved and extended modeling capabilities could be gained. Additional parametric studies could also be conducted to examine the effect of such variables as population density, fuel efficiency, and annual miles driven. These analyses, and others, could provide additional insight and understanding regarding the use of hydrogen as a transportation fuel in Alabama and other areas in the southeastern United States.

SECTION 2
CODES AND STANDARDS FOR HYDROGEN FUELING STATIONS

8 Codes and Standards

This section presents a summary of current codes and standards related to the design and operation of hydrogen fueling stations. The scope of this subtask was to document the development of codes and standards related to hydrogen fueling stations, since this is an emerging field that up until recently had few codes and standards to guide station design, inspection, or approval.

8.1 Background

Any large scale deployment of hydrogen fueled vehicles will require a network of hydrogen fueling stations in order to make market acceptance possible. These hydrogen fueling stations will need to be sited in the same types of locations that conventional gas and diesel fueling stations are found, including urban areas, commercial areas, and adjacent to residential communities. Comprehensive codes and standards guiding their design and operation will be critical for several reasons:

1. Hydrogen fueling technology is new and therefore unfamiliar to traditional design engineers. Engineers, and in particular those municipal engineers and fire officials who will be tasked with reviewing and approving designs, will need clear codes and standards to follow. These codes will also be critical for subsequent inspections and testing.

2. Few states or municipalities currently have any codes or standards in place for hydrogen fueling stations. These will become necessary as hydrogen vehicles become a reality. It is likely that these initial national codes will serve as the basis for subsequent local codes.

3. The risks of fire or explosion at a hydrogen fueling station result from different mechanisms than those at traditional gasoline or diesel fuel. Hydrogen fueling stations will require new types of operating procedures as well as monitoring and safety equipment.

4. As an unfamiliar fuel, stringent codes and standards will be necessary to ensure public confidence in and ultimate acceptance of hydrogen fueling technology. National standards with a proven record of safety will help to encourage public acceptance of these technologies.

5. Unlike traditional gasoline and diesel fueling stations, there will likely be several types of hydrogen fueling stations that will receive and store their hydrogen supplies in different ways. Many hydrogen fueling stations will likely produce and compress hydrogen on-site. Others may receive compressed or liquefied hydrogen via tanker or pipeline. Comprehensive codes will be required to ensure that all of these design options are adequately covered.

The initial deployments of prototype hydrogen fueling stations have faced a distinct lack of codes and standards to guide design and construction. When hydrogen vehicle technologies first began to emerge within the last decade, existing codes and standards for the production and handling of hydrogen were geared largely toward industrial production and applications. Codes related to hydrogen production were aimed primarily at high-volume industrial facilities; consequently the design parameters related clearances and setbacks were often impractical for small-scale hydrogen facilities like fueling stations which are typically located high density areas. The development of small on-site hydrogen generators created another design parameter not covered under the industrial codes.

Birmingham, Alabama, like many cities, has no specific codes related to hydrogen production or fueling stations. It has relied primarily on the NFPA Uniform Fire Code and specific codes for compressed gases and cryogenic fluids (NFPA 55) for the instances when hydrogen storage has been required within the city. Cities that have installed prototype stations have often had to create their own standards or rely on exhaustive engineering study to determine appropriate levels of safety. In may instances it has resulted in very costly design processes, and even more importantly, very long plan review and approval times.

Led by the Department of Energy and standard making organizations including ISO, the Compressed Gas Association (CGA), the National Fire Prevention Association (NFPA), the International Code Council (ICC), and others, codes and standards for hydrogen infrastructure and fueling stations are emerging. This section documents available codes and standards related to hydrogen fueling stations. These codes and standards relate to station siting, hydrogen delivery, on-site production, compression and storage, and dispensing.

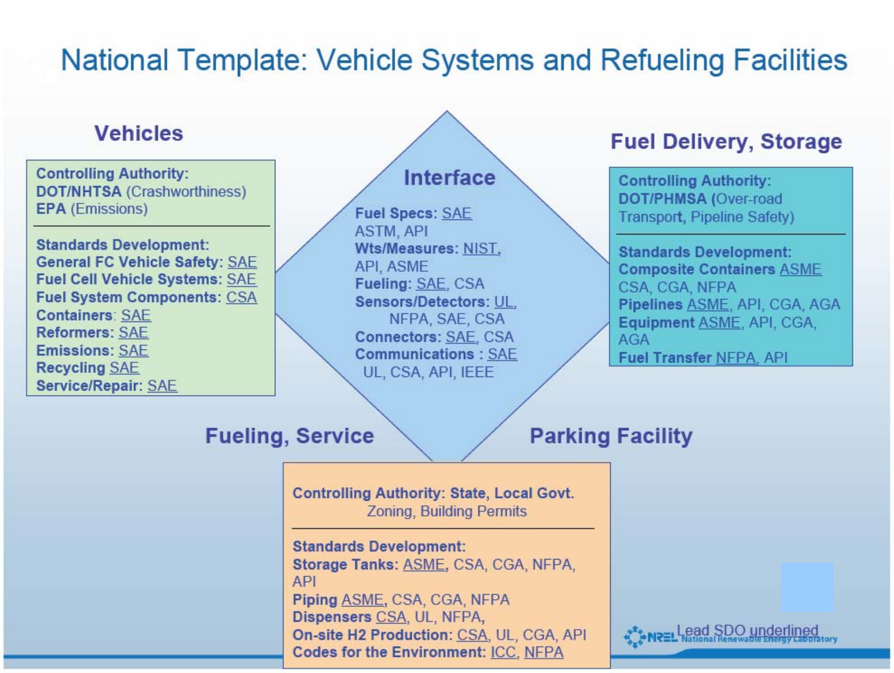

Figure 8.1 DOE national template for hydrogen vehicle systems and refueling facilities
(Source: National Renewable Energy Laboratory)

8.2 Hydrogen Fueling Station Types

Unlike typical gasoline and diesel fueling stations, there are several options for the delivery and or production of hydrogen at hydrogen fueling stations. They include the following:

1. Gaseous hydrogen delivered via pipeline, compressed and stored on-site;
2. Liquid hydrogen delivered by truck or rail and stored on-site;
3. Gaseous hydrogen delivered by tube trailer and stored on-site;
4. Hydrogen generated, compressed, and stored on-site.

Which design is used in a given location is likely to depend on factors such as market demand, availability and proximity of industrial hydrogen sources, proximity of hydrogen pipelines, and local utility rates for electricity and natural gas. On-site hydrogen production may be more cost effective for initial deployments and low-demand scenarios, whereas centralized hydrogen production will become more cost effective as market penetration of hydrogen vehicles increases. Under many deployment scenarios there will likely be several fueling station types in operation in a given area, so the available codes and standards must adequately cover all the technologies available.

8.2.1 Hydrogen Delivered by Pipeline

Under this scenario, hydrogen would be produced at a central production facility and distributed to fueling stations via pipeline. This hydrogen production and distribution scenario has the advantages of economies of scale and reduced emissions, but is likely to be attractive only once the market penetration of hydrogen vehicles has reached certain thresholds. Once at the fueling station, the hydrogen gas would be further compressed and stored in high pressure tanks. A typical scenario is illustrated in Figure 8.2 below.

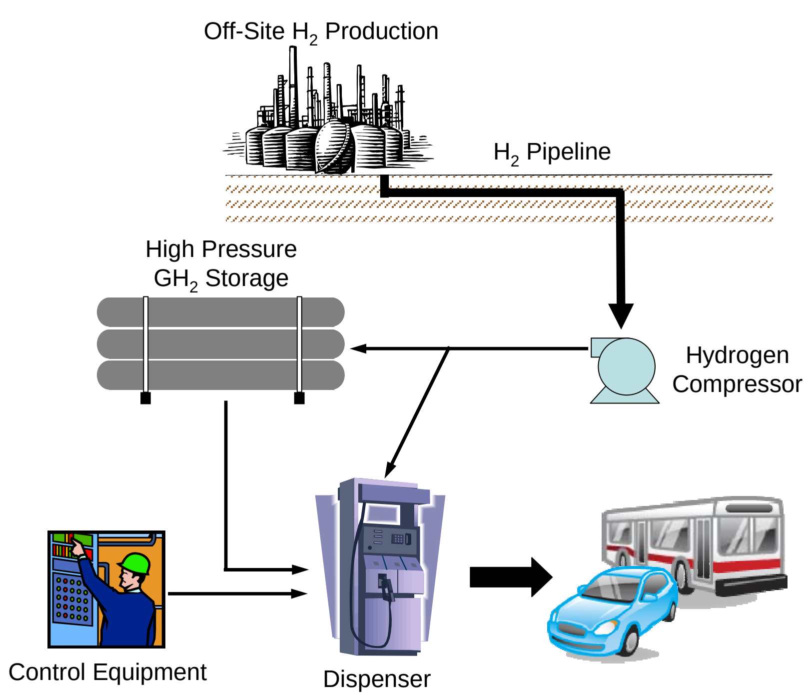

Figure 8.2 Typical fueling station with H_2 delivered by pipeline

Under this scenario, the applicable codes and standards would be related to hydrogen pipelines, on-site compression and high pressure storage, control systems, and dispensing. It is assumed that the centralized hydrogen production would be already covered under existing industrial codes and standards.

8.2.2 Liquid Hydrogen Delivered by Truck or Rail and Stored On-Site

Under this scenario, hydrogen would be delivered in liquid form by truck or rail and stored in on-site storage tanks for dispensing. Cryogenic compression would be required to maintain the liquid hydrogen storage as well as for conversion of the liquid hydrogen to high pressure gaseous hydrogen in vaporizers. From there the gaseous hydrogen could be stored in high pressure tanks or dispensed to vehicles. This scenario is illustrated in Figure 8.3 below.

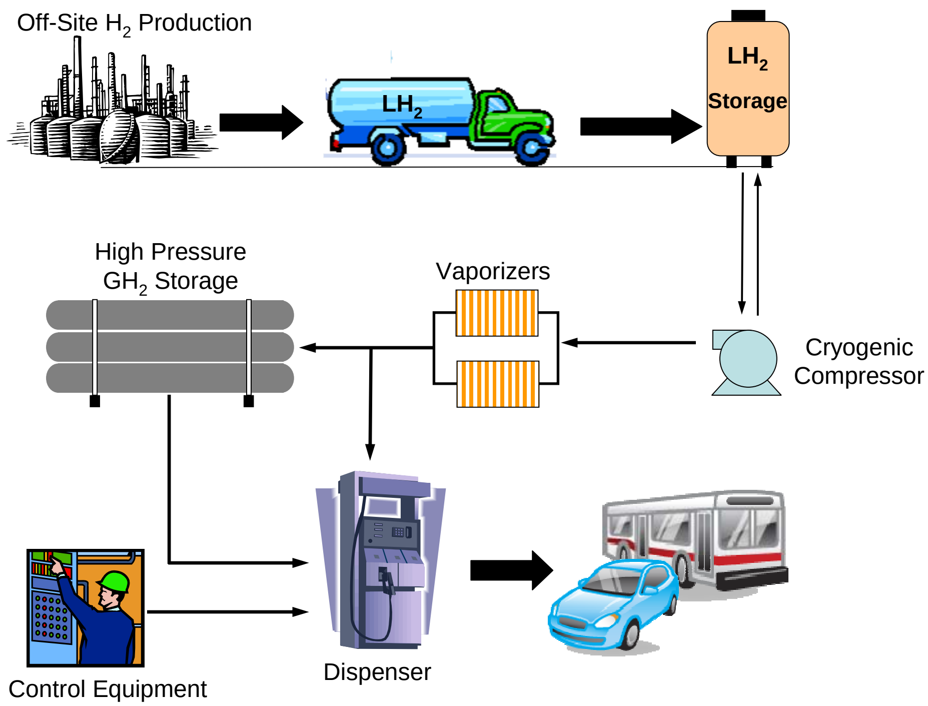

Figure 8.3 Typical fueling station with LH_2 delivered by truck or rail and stored on-site

The applicable codes and standards under this scenario would be related to transfer of liquid hydrogen from tanker to on-site storage, storage tanks for liquid hydrogen, cryogenic compression, vaporizers, high pressure storage of gaseous hydrogen, control equipment, and dispensing.

8.2.3 Gaseous Hydrogen Delivered and Stored in Tube Trailer

Under this scenario, hydrogen would be delivered as a high pressure compressed gas in a tube trailer. Upon arrival at the fueling station, the tube trailer would be detached from the tractor and remain at the station to serve as storage. Depending on the pressure of the hydrogen stored in the tubes, additional compression and storage in a dispensing tank may be required. This scenario is illustrated in Figure 8.4 below.

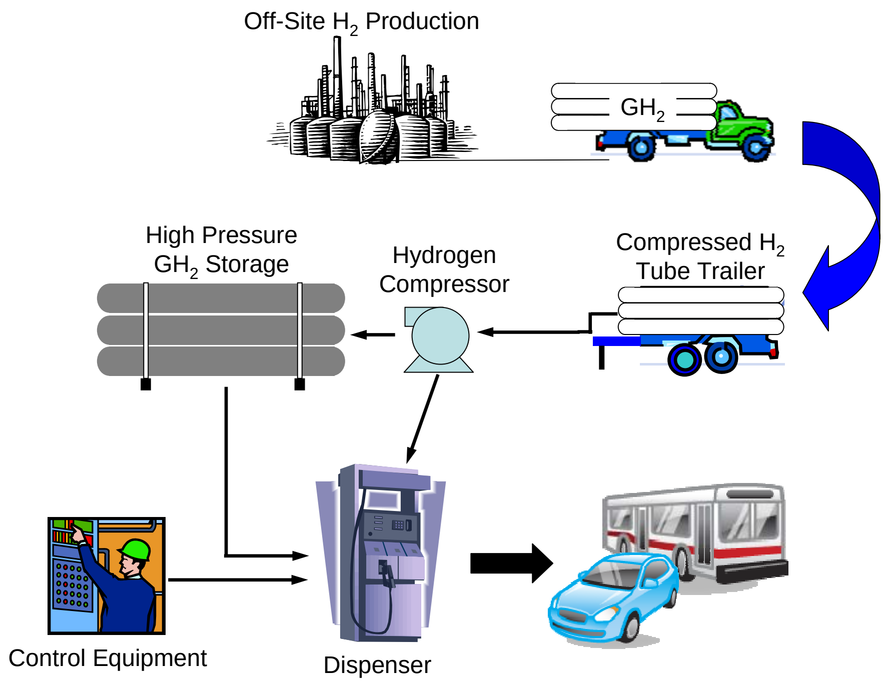

Figure 8.4 Typical fueling station with GH_2 delivered and stored in tube trailer

The applicable codes and standards for this scenario would be related to hydrogen transport in tube tanks, on-site storage in tube tanks, compression, high pressure storage, control systems, and dispensing.

8.2.4 Hydrogen Generated, Compressed, and Stored On-Site

Under this scenario, hydrogen would be produced on-site using either an electrolyzer or a small natural gas reformer, compressed and stored at high pressure, and then dispensed. Production could vary from 1 kg per day to 20 or more kg per day depending on demand. This type of operation may prove economical for demonstration sites and low-demand scenarios. The feasibility of on-site reforming would depend on the availability and cost of feed stock (natural gas, LPG, or other hydrogen rich sources) and electricity. The cost effectiveness of an electrolyzer will likely depend on local electricity prices. A typical scenario is illustrated in Figure 8.5.

The applicable codes and standards under this type of operation would be related to on-site production, fuel purification, compression, high pressure storage, control systems, and dispensing.

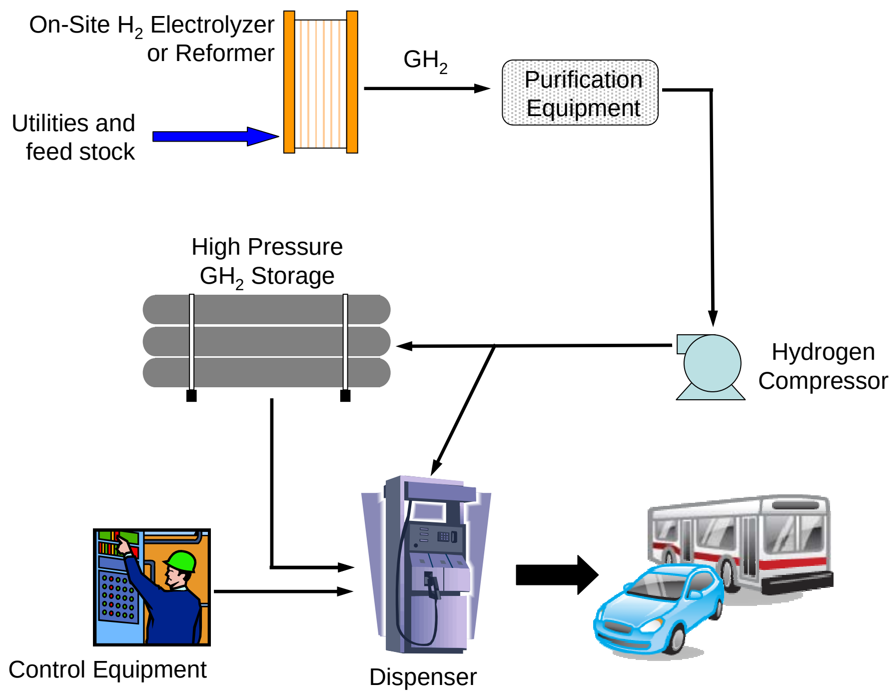

Figure 8.5 Typical fueling station using GH_2 generated, compressed, and stored on-site

8.2.5 Typical Components of Hydrogen Fueling Stations

The different fueling station designs described previously contain many common elements. All types of hydrogen fueling stations will require dispensing equipment and control systems. Most will require some type of compression equipment and high pressure gaseous H_2 storage. All will require a set of operating procedures and emergency response plans. These common elements as well as those unique to each type of design are described in the following subsections along with applicable codes and standards.

Applicable codes and standards are drawn from organizations which have produced or are in the process of producing standards for hydrogen fueling stations. In cases where a proposed standard is in development but not yet published, it has been noted as pending.

8.3 Applicable Codes and Standards

A number of standards organizations have developed, or are currently developing codes and standards for each of the typical components of a hydrogen fueling station. Table 8.1 presents a list of the major standards organizations and their areas of focus in the hydrogen arena:

Table 8.1 Leading Standards Organizations for H_2 Fueling Stations

Organization	Abbr.	Areas of Focus
American National Standards Institute	**ANSI**	Hydrogen gas detectors
American Society of Mechanical Engineers	**ASME**	Pressure vessels, storage tanks, pipelines, piping
British Standards Institute	**BSI**	Combustible gas detection and monitoring
Compressed Gas Association, Inc.	**CGA**	Safety, handling of compressed gases, piping, venting systems, pressure relief devices
CSA America, Inc.	**CSA**	LPG and H_2 appliances
International Code Council	**ICC**	Publish a variety of codes including: • International Building Code (IBC) • International Fire Code (IFC) • International Fuel Gas Code (IFGC) • Electric Code (EC) • International Mechanical Code (IMC) While none of these codes are hydrogen specific, they each contain sections relevant to hydrogen fueling station design and operation.
International Electrotechnical Commission	**IEC**	H_2 control systems
International Society of Automation	**ISA**	Hydrogen gas detectors and monitors.
International Organization for Standardization	**ISO**	Gaseous and liquid H_2 facility design.
National Fire Protection Association	**NFPA**	Hydrogen safety, non-H_2 fuel dispensing systems, H_2 vehicle fueling systems, storage tanks, electrical equipment, and building codes.
National Institute of Standards and Technology	**NIST**	Fuel dispensing measurement devices
Occupational Safety and Health Administration	**OSHA**	Safety, training, reporting requirements.
Society of Automotive Engineers	**SAE**	Vehicle fueling connections, vehicle – infrastructure communications, hydrogen fuel standards
Underwriters Laboratory	**UL**	Fueling appliance safety specifications

Standards documents reviewed and cited in the preparation of this report include the following:

Code/Standard	Title
AIAA G-095	***Guide to Safety of Hydrogen and Hydrogen Systems***
ASME B31	***Standards of Pressure Piping*** *(for hydrogen and non-hydrogen applications)*
BSI BS EN 50073	***Guide for Selection, Installation, Use and Maintenance of Apparatus for the Detection and Measurement of Combustible Gases or Oxygen***
BSR/UL2075-200x	***Gas and Vapor Detectors and Sensors***
CGA G-5	***Hydrogen*** *(safe handling of hydrogen)*
CGA G-5.4	***Standards for Hydrogen Piping Systems at Consumer Sites***
CGA G-5.5	***Hydrogen Vent Systems***
CGA G-5.6	***Hydrogen Pipeline Systems***
CGA G-5.8	***High Pressure H_2 Piping Systems at Consumer Sites***
CGA H3	***Cryogenic Hydrogen Storage***
CGA H5	***Installation Standard for Bulk Hydrogen Supply Systems*** *(pending)*
CGA P-12	***Safe Handling of Cryogenic Liquids***
CGA PS-17	***Underground Installation of Liquid H_2 Storage Tanks*** *(position statement)*
CGA PS-20	***Direct Burial of Gaseous H_2 Storage Tanks*** *(position statement)*
CGA PS-21	***Adjacent Storage of Compressed H_2 and other Flammable Gases*** *(position statement)*
CGA PS-25	***Aerial Storage of Compressed Hydrogen*** *(position statement)*
CGA PS-26	***Use of Carbon Fiber Composite Storage Vessels*** *(position statement)*
CSA HGV4.x	***Standards for H_2 Fuel Dispensing Equipment and Components***
ICC IBC	***International Building Code***
ICC IFC	***International Fire Code***
IEC 60079-29-1	***Performance Requirements for Gas Detectors***
ISA 12.13.01	***Performance Requirements for Combustible Gas Detectors***
ISO 14687	***Hydrogen Fuel – Product Specification***
ISO 16110-1	***Hydrogen Generators Using Fuel Processing Technologies - Safety*** *(pending)*
ISO 16110-2	***Hydrogen Generators Using Fuel Processing Technologies – Procedures to Determine Efficiency*** *(pending)*
ISO/CD TS 20012	***Gaseous Hydrogen – Fueling Stations (Under Development)***

Code/Standard	Title
ISO/CD 2274-1	***Hydrogen Generators Using Water Electrolysis Process***
ISO/TC 197	*Technical Committee Developing Standards for Hydrogen Technologies*
ISO/TR 15916	***Basic Considerations for the Safety of Hydrogen Systems***
NFPA 1	***Uniform Fire Code***
NFPA 2	*Pending document combining hydrogen standards from various NFPA documents*
NFPA 30A	***Motor Fuel Dispensing Facilities and Repair Garages*** *(covers largely non-hydrogen fueling stations but parts have been adapted for hydrogen)*
NFPA 52	***Vehicular Fuel Systems Code***
NFPA 55	***Standards for Use, Storage, and Handling of Compressed and Cryogenic Gases*** *(formerly NFPA 50A and 50B)*
NFPA 70	***National Electrical Code***
NFPA 497	***Classification of Flammable Liquids, Gases, and Vapors***
NFPA 5000	***Building, Construction, and Safety Code***
OSHA 1910.103	***Occupational Safety & Health Standards - Hydrogen***
SAE J2578	***General Fuel Cell Vehicle Safety***
SAE J2600	***Compressed Hydrogen Vehicle Fueling Connection Devices***
SAE J2601	*Pending document on vehicle fueling connection and communication devices*
SAE J2719	***Hydrogen Specification Guideline for Fuel Cell Vehicles***
SAE J2799	***70 MPa Compressed Hydrogen Surface Vehicle Fueling Nozzle***
UL 2075	***Standard for Gas a Vapor Detectors and Sensors***
UL 2264	***Gaseous Hydrogen Generating Appliances***

Standards for each major fueling station component are described in the following sections. An excellent reference for codes and standards related to hydrogen fueling facilities is the Department of Energy document, "*Permitting Hydrogen Motor Fuel Dispensing Facilities*", first published in 2004. Now over 3 years old, some of the code references are dated, and have therefore been updated in the following sections.

8.3.1 Station Siting

Station siting describes the process of determining where a hydrogen fueling station can or should be located. Ideally, a hydrogen fueling station could be located in any place that could be occupied by a conventional gasoline fueling station. As discussed previously, early standards were geared more toward industrial facilities and therefore specified large spacing and setback distances that were impractical for smaller fueling station applications. Newer standards are addressing these concerns and attempting to provide more realistic guidance for fueling station applications. Factors which can influence station siting include:

- Local zoning regulations
- Proximity of utilities (electric, natural gas, hydrogen pipelines)
- Proximity of other structures or sensitive receptors
- Fueling capacity/space requirements
- Roadway access
- Market characteristics (private, fleets, transit) and potential demand
- Environmental justice issues

The factors covered by technical codes and standards are typically related to fueling capacity and building size, indoor vs. outdoor fueling requirements, and proximities to other structures and utilities. Primary codes related to station siting are summarized below.

Table 8.2 Codes and Standards Related to Station Siting

Application	Description	Applicable Codes	
		Published	Pending
General building codes for fueling stations	Codes related to location of fueling stations (conventional as well as CNG and H_2)	NFPA 30A NFPA 1 ICC IFC ICC IBC (§106)	
Facility setbacks	Provides setback distances and clearances to adjacent properties and buildings, streets, sidewalks, rail lines, storage tanks, and potential ignition sources.	NFPA 52 (§9.3) Local zoning regs	
Required clearances to utilities, combustible materials, and other systems.	Setbacks and clearances to overhead utilities, trolley power lines, combustible materials, and adjacent storage facilities. Also guidelines for elevation of H_2 storage relative to combustible liquid storage on adjacent properties. Minimum clearances to ventilation systems on adjacent properties.	NFPA 55 (§10.3, 11.3) ICC IFC (§2209)	

8.3.2 Station Design and Layout

These codes and standards relate to the actual design and layout of the hydrogen fueling facility. They include guidance on the types and sizes of structures allowed according to system fueling capacity, the locations of key components, and minimum spacing requirements between system components. They also provide setback distances for key system components relative to adjacent properties and structures. It should be noted that the requirements for liquid hydrogen systems differ from those for gaseous hydrogen systems in many cases. Applicable codes and standards for station design and layout are summarized in Table 8.3.

Table 8.3 Codes and Standards Related to Station Design and Layout

Application	Description	Applicable Codes	
		Published	Pending
General layout requirements for fueling stations	General guidelines for fueling station design, especially where H_2 fueling may be co-located with conventional gas/diesel fueling infrastructure.	NFPA 1 NFPA 30A (§12.2-12.4) NFPA 55 NFPA 70 NFPA 5000 ICC IBC ICC IFC (§2209)	
Criteria for indoor vs. outdoor fueling facilities	Limitations on indoor facility size based maximum fuel capacities. Higher capacity fueling stations must be located in outdoor structures. Also provides minimum standards for a building to be considered "outdoor".	NFPA 55 ICC IBC (§302.1.1) ICC IFC (§2209.3.1)	
Gaseous H_2 (GH_2) facility layout	Requirements specific to gaseous H_2 fueling station design. Includes above ground storage clearances, minimum spacing requirements between system components, limits for indoor/outdoor buildings, clearances to walls, wall openings, other equipment, and adjacent storage tanks.	NFPA 55 (§10.2-10.4) OSHA 1910.103 NFPA 55 (§10) ICC IFC (§3202.6.1)	NFPA 2 ISO/TS 20012 ISO TC 197
Liquid H_2 (LH_2) facility layout	Requirements specific to liquid H_2 fueling station design. Location of tanks relative to electric utilities, limits for indoor/outdoor buildings, clearances to walls, wall openings, other equipment, and adjacent storage tanks. Also clearance criteria for locating storage tanks underground.	NFPA 52 (§14.2) NFPA 55 (§11.2-11.3) ICC IFC (§3504.2.1)	NFPA 2 ISO/TS 20012
Clearances to other equipment or exposures	Minimum clearance requirements between common equipment and/or exposures at H_2 fueling facilities (see also above).	NFPA 52 (§9, 14) NFPA 55 (§10,11) ICC IBC (§302.1.1) ICC IFC (§2209.3)	
Clearances to other flammables	Minimum clearances to storage, piping, or equipment handling other flammable liquids or gases, with and without separation walls.	NFPA 55 (§10,11) ICC IFC (§2209.3)	
General codes for electrical equipment	Codes pertaining to the location, setback, and clearances required for electrical equipment located in proximity to hydrogen fueling systems	ICC IFC (§3203, 2209.2) NFPA 70 (§501.4-501.16) NFPA 55 (§6.6,10,11)	

Table 8.3 (continued) – Codes and Standards Related to Station Design and Layout

Application	Description	Applicable Codes	
		Published	Pending
Building construction requirements	Materials, designs, and construction methods for indoor and outdoor buildings, separation walls, floors, ceilings, and other non-combustible materials. Building heating and ventilation.	NFPA 30A (§7.1-7.7) NFPA 55 (§6) IBC (§414.6, T302.1.1) ICC IFC (§2209.3) CGA G-5 (§8)	
Canopy specifications	Specifications for design of canopies over dispensing equipment.	NFPA 30A (§12.4) NFPA 55 (§6) ICC IBC (§414.6) ICC IFC (§2209.3.3)	

8.3.3 Hydrogen Delivery and Offloading

In cases where hydrogen will be delivered to a fueling station from an off-site industrial hydrogen production facility, systems and standards are needed to govern the transfer of hydrogen fuel to the site storage units. Hydrogen can be delivered by truck or rail as either a cryogenic liquid or compressed gas. Transport and transfer standards are dependent on whether the hydrogen is in liquid or gas form. The location of offloading areas, transfer connections, and procedures for transferring hydrogen to on-site storage units is covered under the following codes and standards.

Table 8.4 – Codes and Standards Related to Hydrogen Delivery and Offloading

Application	Description	Applicable Codes	
		Published	Pending
General H_2 transport and transfer	General guidelines for fuel transfer, including CNG, LPG, and H_2.	ICC IBC (§506.2) NFPA 30A	CGA H5
Location of transfer area and connections	Locations of offloading areas, equipment, and connections and minimum offsets to other system components, and offloading procedures.	NFPA 52 (§14.3) NFPA 55 (§10,11)	
GH_2 transport	Standards for tank cars and tube trailers designed to carry compressed gaseous hydrogen.	CGA G-5 (§4.3-4.4)	
LH_2 transport	Standards mobile cargo tanks designed to carry liquefied hydrogen.	CGA G-5 (§4.5, 8.0)	

8.3.4 Hydrogen Pipelines

Hydrogen may be supplied directly to a fueling facility via pipeline. While there are currently few such pipelines in the U.S., this supply method may become more common as the number of hydrogen fueling stations increases and production moves to centralized industrial facilities. Hydrogen can cause embrittlement in traditional pipelines and fittings and therefore codes for their design and construction are critical. The following codes provide standards for the manufacture, design, installation, and maintenance of pipeline systems.

Table 8.5 – Codes and Standards Related to Hydrogen Pipelines

Application	Description	Applicable Codes	
		Published	Pending
H_2 pipeline guidelines	General guidance on the design, construction, testing, and operation of pipelines carry hydrogen and hydrogen blends. Includes metallurgic standards, location guidelines, cleaning, and maintenance. Also cover associated valves, pressure relief devices, piping, and control systems.	CGA G-5.6 ASME B31.12	

8.3.5 On-Site Production

It is likely that many hydrogen fueling stations will produce hydrogen on-site. This offers many cost advantages, especially for demonstration sites where demand may be low and distances to industrial hydrogen production facilities may make delivery impractical. The most likely on-site production methods are natural gas reformers and electrolyzers. Standards are needed for the design, installation, location, and operation of these generators. Standards will also be needed to ensure the hydrogen gas produced meets minimum fuel quality standards. Applicable codes are summarized in Table 8.6.

Table 8.6 – Codes and Standards Related to On-Site Hydrogen Production

Application	Description	Applicable Codes	
		Published	Pending
General guidelines for H_2 generators	Standards for hydrogen generators which produce less than 400 m^3/hour. Intended primarily for pre-packaged appliances to be used at fueling facilities.	ISO/CD 16110-1 ICC IFC 2000	ISO 16110-2
Safety of H_2 generators	General guidelines for safe operation of hydrogen generators. Includes training and hazards identification.	OSHA 1910.103	UL 2264
H_2 reformers	Standards for stationary hydrogen generators which use as an input stream hydrogen rich fuels such as natural gas, LPG, or other organic compounds. Covers location, operation, safety, and potential hazards.	ISO/CD 16110-1 UL STP 2264	

Table 8.6 (continued) – Codes and Standards Related to On-Site Hydrogen Production

Application	Description	Applicable Codes	
		Published	Pending
H_2 electrolyzers	Standards for stationary hydrogen generators which is water and an electrolysis process to produce hydrogen. Covers location, operation, safety, and potential hazards.	ISO/CD 22734-1 UL STP 2264	
Fuel quality	Standards for purity and allowable contaminants in H_2 fuel produced on- or off-site for fuel cell or ICE use.	ISO 14687 CGA G-5.3	SAE J2719

8.3.6 Hydrogen Compression and Storage

For all hydrogen production and delivery methods, the hydrogen will ultimately need to be compressed and stored as a high pressure gas prior to dispensing. Codes and standards related to compression and storage cover compressor equipment, type of storage (liquid or compressed gas), location of storage tanks (above or below ground), and vaporizers are summarized in Table 8.7.

Table 8.7 – Codes and Standards Related to Hydrogen Compression and Storage

Application	Description	Applicable Codes	
		Published	Pending
Pressure relief devices, regulators, and gauges	Specifications for pressure relief devices, regulators, and gauges including design and installation.	NFPA 52 (§5.4-5.9, 9.5-9.7)	
Pumps and compressors (LH_2)	Design, manufacture, and testing of packaged H_2 compressor equipment for fueling facilities. Installation of compressors and associated piping and control valves. Compressor safety and emergency shutdown procedures.	NFPA 52 (§14.8) CSA HGV 4.8	
Vaporizers	Design, installation, and operation of vaporizers used to convert liquid hydrogen to gaseous form. Includes safety procedures and design safeguards.	NFPA 52 (§14.9-14.10) ICC IFC (§3203)	
H_2 storage - general	General guidelines for storage and safe handling of hydrogen fuel. Includes tanks, setbacks and clearances to other system components, setbacks from ignition sources, and clearances to other combustible materials.	NFPA 55 (§10.4, 11.2) CGA P-12 (§7.0-7.6, 8.4) ICC IFC (§30,32,35) OSHA 1910.103 CGA PS-21	

Table 8.7 (continued) – Codes and Standards Related to Hydrogen Compression and Storage

Application	Description	Applicable Codes	
		Published	Pending
H_2 storage (above ground)	Standards for above ground storage tanks for GH_2 and LH_2. Includes piping, associated electrical systems, testing, and maintenance. Also includes position statements from the Compressed Gas Association on above ground storage methods.	CGA H3 CGA PS-25* CGA PS-26* CGA G-5.4 (§5.1)	
H_2 storage (below ground)	Standards for below ground storage tanks (LH_2). Includes piping, associated electrical systems, testing, and maintenance. Also includes position statements from the Compressed Gas Association on below ground storage methods.	CGA PS-17* CGA PS-20* CGA G-5.4 (§5.2)	
Testing	Standards for testing compressor and storage systems.	NFPA 52 (§9.9)	

* Position statement.

8.3.7 Piping and Control Equipment (Gaseous H_2)

Regardless of generation or delivery method, hydrogen fueling stations will require significant amounts of piping and associated valves, pressure relief devices, and gauges. They will also require electronic control systems to monitor and regulate operation as well as venting systems to ensure that no hydrogen released either through pressure relief devices or unintended leaks can accumulate and develop an explosion risk. Table 8.8 summarizes applicable codes and standards for gaseous H_2 systems, which differ slightly from those designed for liquid H_2 systems.

Table 8.8 – Codes and Standards Related to Piping and Control Equipment (GH_2)

Application	Description	Applicable Codes	
		Published	Pending
General system piping	Covers material specifications, pipe sizes and pressures, connection and brazing methods, and specifications for insulation and clearances between pipes and other system components.	NFPA 52 (§5,9,14) CGA G-5.4 OSHA 29CFR 1910 H ICC IFC (§2209,3003, 3203) AMSE B31.3	CGA G5.8
Pressure relief devices (PRD)	Requirements for PRD's, specified uses, design, maintenance, and replacement.	NFPA 52 (§5.4)	

Table 8.8 (continued) – Codes and Standards Related to Piping and Control Equipment (GH_2)

Application	Description	Applicable Codes	
		Published	Pending
Vent systems	Requirements for venting systems to prevent accumulation of hydrogen gas in fueling station structures. Covers sizing, design, materials, and components.	NFPA 52 (§5.5,6.4, 9.5,12.6) CGA G-5.5 (§6.1-6.5) ICC IFC (§2209.5.4) NFPA 5000 ASME B31.3	
Pressure gauges, regulators, valves	Specifications for size and design of gauges, regulators, and valves designed for use with gaseous hydrogen. Also specifications for materials.	NFPA 52 (§5.6-5.9)	
Hoses and connections	Guidelines for materials, design, and testing of hoses and connections designed for use with gaseous hydrogen.	NFPA 52 (§5.10-5.11, §9.8)	
Electrical equipment	Specifications for installation of electrical equipment in proximity to hydrogen systems, including minimum clearances and definitions of electrical zones.	NFPA 52 (§9.11) CGA G-5.4 (§5.3-5.4) CGA G-5.5 (§6) NFPA 70 (§250)	
Testing	Guidelines for testing, startup, and monitoring of piping for gaseous hydrogen systems.	ASME B31.3 CGA G-5.4 (§7.2) CGA G-5.5 (§6.13-6.14) NFPA 52 (§9.9-9.15) NFPA 55 (§3)	

8.3.8 Piping and Control Equipment (Liquid H_2)

Table 8.9 summarizes applicable codes and standards for piping and associated valves, gauges, and pressure relief devices designed for use specifically with liquid hydrogen systems.

Table 8.9 – Codes and Standards Related to Piping and Control Equipment (LH_2)

Application	Description	Applicable Codes	
		Published	Pending
System piping	Covers material specifications, pipe sizes and pressures, connection and brazing methods, and specifications for insulation and clearances between pipes and other system components.	NFPA 52 (§5,9,14)	
Pressure relief devices (PRD)	Requirements for PRD's, specified uses, design, maintenance, and replacement.	NFPA 52 (§14.6)	

Table 8.9 (continued) – Codes and Standards Related to Piping and Control Equipment (LH_2)

Application	Description	Applicable Codes	
		Published	Pending
Vent systems	Requirements for venting systems to prevent accumulation of hydrogen gas in fueling station structures. Covers sizing, design, materials, and components.	NFPA 52 (§5.5,6.4, 9.5,12.6) CGA G-5.5 (§6.1-6.5) ICC IFC (§2209.5.4) NFPA 5000 ASME B31.3	
Electrical equipment	Location, installation, and safety specifications for electronic control equipment.	NFPA 52 (§14.11-14.12)	

8.3.9 Fuel Dispensing Equipment

Fuel dispensing equipment transfers hydrogen from the facility storage tanks to the vehicle tank. It includes the dispensing appliances, which are generally assumed to be packaged equipment, and the connection devices which link the hydrogen dispenser and the vehicle fuel storage system. Future codes will also address communications between vehicle and the fueling equipment. Applicable codes are summarized in Table 8.10.

Table 8.10 – Codes and Standards Related to Dispensing Hydrogen Fuel

Application	Description	Applicable Codes	
		Published	Pending
Vehicle fueling connection (GH_2)	Specifications for the materials, design, design pressures, and operation of gaseous hydrogen fueling connections. Includes fueling nozzle and vehicle receptacles.	NFPA 52 (§5.11) SAE J2600	
Vehicle fueling connection (LH_2)	Specifications for the materials, design, design pressures, and operation of liquid hydrogen fueling connections. Includes fueling nozzle and vehicle receptacles.	NFPA 52 (§14.4) ISO 17268 SAE J2783	
Fuel dispensing equipment	Codes cover dispensing equipment, hoses, valves, breakaway devices, temperature compensation devices, control equipment, and ancillary piping, compressors, and storage tanks.	NFPA 52 (§9.16) NIST H_2 meter code CSA HGV 4 (§4.1 -4.8) ICC IFC (§2203, 2205,2209)	
Communication devices	Communication interface between the fueling facility and vehicle.		SAE J2601 SAE J2799

8.3.10 Operations and Maintenance

Codes and standards related to fueling station operation cover operating guidelines, system inspections, training for personnel, and system maintenance. Applicable codes and standards are summarized in Table 8.11.

Table 8.11 – Codes and Standards Related to Station Maintenance and Safety

Application	Description	Applicable Codes	
		Published	Pending
System inspection	Codes cover inspections during installation and system startup. Also periodic inspections conducted during system operation and record keeping.	CGA G-5.4 (§6.1-6.4) CGA G-5.5 (§7, 8) NFPA 52 CGA S-1.1 – 1.3 ICC IFC (§3203.2)	
General fueling system operations	Requirements for fueling operations, including maximum allowable fill pressures, fueling protocols, signage, operator qualifications, and safety requirements.	NFPA 52 (§9.13) NFPA 30A (§9.2-9.6) ICC IFC (§2204.3.4) CGA G-5.4 CGA G-5.5	
Operator training	General guidelines for operator training.	ICC IFC (§2209.4) NFPA 5000	
GH_2 operations	Specific requirements for operations of gaseous hydrogen systems. Include operator training and safety inspection.	NFPA 55 (§10.5)	
LH_2 operations	Specific requirements for operations of liquid hydrogen systems.	NFPA 55 (§11.5)	
System maintenance	Requirements for written maintenance programs, procedures for servicing system components, maintenance of grounds, and intervals for maintenance of safety equipment.	NFPA 52 (§9.15, 14.13) CGA G-5.4 (§7.1-7.4) CGA G-5.5 (§9.1-9.3)	

8.3.11 Safety and Training

This category includes codes and standards related to the safe handling of hydrogen fuel. To ensure safety, all hydrogen fueling stations will have to meet the following requirements:

- Preparation of an approved safety and emergency response plan
- Appropriate safety training for employees
- Minimizing safety hazards
- Install hydrogen gas and fire detection devices
- Provide fire suppression devices
- Develop emergency shutdown protocols

Applicable codes related to these are summarized in Table 8.12.

Table 8.12 – Codes and Standards Related to Station Safety and Training

Application	Description	Applicable Codes	
		Published	Pending
Safety and emergency planning	Requirements for safety and emergency response plans.	NFPA 55(§4.2-4.5) OSHA 29CFR 1910H AIAA G-095 ISO TR 15916 SAE J2578	
Safety training	Requirements for the training of employees and operators for the safe handling of hydrogen fuel.	NFPA 55 (§4.6-4.7, 7.6) CGA P-12 (§5.0)	
Ignition source controls	Minimum safe distances to open flame, ignition sources, or smoking areas.	NFPA 55 (§4.8, 6.7-6.10) CGA G-5.5 (§8.4)	
Fire protection, detectors, and alarms	Standards for combustible gas and fire detection devices. Also specify minimum hydrogen concentration levels that should be detectable and automated responses.	NFPA 52 (§9.14) NFPA 55 (§6.7, 6.10, 10.6) ANSI/UL 2075 ISA 12.13.01 IEC 60079-29-1 BSI BS EN 50073 BSR/UL2075-200x CGA G-5.5 (§5.1-5.4) ICC IFC (§2211.7)	IEC 60079-29-2 ISO TC 197
Fire suppression	Fire prevention and fire suppression procedures for hydrogen and other types of fuel fires.	CGA P-12 (§6.4)	
Emergency shutdown	Conditions and protocols for initiating emergency shutdown procedures.	NFPA 52 (§9.10) CGA G-5.4 (§4.3.3) ICC IFC (§2209)	
Signs	Required signing at hydrogen fueling facilities for safety .	NFPA 55(§4.9)	

8.3.12 Summary of Codes and Standards

The previous sections summarize codes and standards applicable to hydrogen fueling station design. These codes and standards should be used in conjunction with local zoning regulations, building codes, and fire codes to ensure a design that conforms to local standards. Furthermore, the above codes and standards provide a useful starting point for station design and, more importantly, local review since most municipalities do not have existing codes and standards for these types of facilities.

8.4 Conceptual Requirements for a Birmingham Hydrogen Fueling Station

As part of this task, conceptual requirements were developed for a demonstration hydrogen fueling station in the Birmingham area. There are many technical factors that will determine the design of this type of station:

- Types of vehicles to be served (auto, fleet vehicles, bus)
- Number of vehicles per day to be served
- Amount of fuel required (kg/day)
- Peak fueling demand (kg/hr)
- Desired fueling time (fast or slow fill)
- Fueling pressure (psi)
- Storage pressure (main and secondary, psi)
- Storage capacity (kg)
- Hydrogen source (delivery or on-site generation)
- H_2 generator capacity (if on-site generation, kg/day)
- Compressor capacity (kg/hr)
- Expandability
- Location
- Availability of utilities

8.4.1 Design Scenario Assumptions

There are many possible demonstration scenarios, however it was felt that a demonstration hydrogen fueling station designed for use by private automobiles or fleet vehicles would be impractical at this time since there has been little investment in hydrogen vehicle technologies in Alabama. It was decided to base the conceptual design on a scenario involving the demonstration of a fuel cell powered transit bus within the Birmingham City limits. UAB currently has a grant from the Federal Transit Administration to build and demonstrate a hydrogen fuel cell powered bus in Birmingham. The project is underway but the proposed bus is still in the preliminary design stages. It is anticipated that the bus will begin revenue service for the Birmingham-Jefferson County Transit Authority (BJCTA) in 2010.

The design specifications for the proposed bus have not yet been finalized, however based on discussions with team members we have been able to arrive at reasonable estimates for bus design and performance. The proposed vehicle will be a 35 foot low-floor transit bus equipped with a hybrid fuel cell/electric propulsion system. The proposed propulsion system will be a "battery dominant" design, meaning the bus will operate primarily on battery power with the fuel cell serving as a range extender. The bus will be able to operate without the fuel cell if needed.

The proposed fuel cell for the bus will be an off-the-shelf product with a rated power less than 20 kW. The bus will be operated by BJCTA in full revenue service on a yet to be determined route. The design team estimates that in the course of a typical operating day the fuel cell will require a maximum of 5 kg of hydrogen. It will likely be the only hydrogen vehicle using the fueling facility during the demonstration period. The on-board hydrogen storage capacity has not yet been determined but will likely be in excess of 5 kg so the bus will not require midday refueling and most likely will be refueled at night. Nonetheless, it was decided that the proposed fueling station should be capable of fast fill fueling. This will allow the station to be used for future demonstrations of buses with larger fuel cells and larger on board storage capacities.

8.4.2 Conceptual Design Parameters

A summary of conceptual design parameters based on the assumed demonstration scenario is presented in Table 8.13.

Table 8.13 – Summary of Conceptual Design Parameters

Parameter	Discussion
Type of vehicle(s) to be served	35-foot fuel cell /electric hybrid transit bus in revenue service for BJCTA in the City of Birmingham. Fuel cell will have a maximum rating of 20 kW and will serve as a range extender for a "battery dominant" propulsion system.
Number of vehicle fuelings per day	For design purposes, it is assumed that the bus will require one night refueling and one "fast fill" refueling during the day. It is anticipated that the bus will be the only vehicle fueled at the station during the demonstration period.
Amount of fuel required per day	Estimated $\leq$ 5 kg/day
Peak fueling demand	Actual demand will likely be no more than 5 kg/hr but station should be designed for 10 kg/hr
Desired fueling time	Maximum fast fill time of 15 minutes
Fueling pressure	The storage pressure for the vehicle fuel cylinders is not yet known, but an upper limit of $\approx$ 6500 psi (450 bar) was chosen.
Storage pressure	6500 psi (450 bar)
Storage capacity	15 kg
Hydrogen source	On-site generation, either natural gas reformer or electrolysis. Required hydrogen supplies will be small enough to be easily handled by an on-site generator. Tube trailers would not be economically feasible due to the distances to hydrogen production facilities and the small quantities required.
Hydrogen generator capacity	$\geq$ 2 kg/hr
Compressor capacity	2 kg/hr
Expandability	Facility should be upgradable to total fueling capacity of 20 kg/day

Table 8.13 (continued) – Summary of Conceptual Design Parameters

Parameter	Discussion
Location	Must be located within City of Birmingham and near BJCTA bus depot. In vicinity of existing BJCTA fueling station desirable.
Availability of utilities	On-site hydrogen generation will require electric and possibly natural gas availability. Both Alabama Gas Company and Alabama Power have expressed interest in cooperating in developing a fueling station. Both utilities are readily available.

The location of the fueling station has not been determined, but since it will serve a BJCTA bus demonstration it should be located within the City of Birmingham and in proximity to the BJCTA bus depot or existing CNG fueling station. Co-location at BJCTA's CNG fueling station would be ideal, but BJCTA has expressed concerns about space limitations at this site. Meetings have been held with Alabama Power Company and Alabama Gas Company to discuss their interest in partnering on a demonstration fueling station. Both companies have expressed an interest in participating and Alabama Power has expressed the possibility of locating a fueling station on existing sub-station property. These possibilities will be explored further as the project progresses.

In our preliminary discussions with BJCTA and the City of Birmingham Fire Marshall, it is apparent that permitting such a station would be a time consuming process. It would be the first hydrogen station of its kind in Alabama and the City of Birmingham does not have prior experience dealing with hydrogen installations. The codes and standards outlined in Section 6.3 would serve as the basis for design and permitting.

Appendix A

Task Statements

Task 3

Expertise in engineering cost estimation, hydrogen production and delivery analysis and transportation infrastructure systems will be used to develop regional estimates of resource requirements and costs for the infrastructure needed to deliver hydrogen fuels to advanced-technology vehicles. Data on applicable resources, cost structures and infrastructure in the region will be compiled and used to characterize the existing Southeastern US transportation energy infrastructure. These characterizations will then be input to DOE's H2A models to develop case studies of select Alabama metropolitan areas. The case studies will estimate the delivered cost of hydrogen fuel to select markets under alternative assumptions about production and delivery technologies. Several H2A models will be utilized to complete the case studies. These include centralized production via steam methane reforming (SMR), advanced thermo-chemical water splitting or coal gasification; distributed production via SMR or electrolysis; and delivery via liquid truck, gaseous tube trailer or pipeline. Depending on time and resources, the models may be run separately with manual linkages and integration of results, or combined into an automated system.

Task 4

In Task 4, the case studies of delivered hydrogen cost via alternative production and delivery options will be expanded. In Task 3 direct, indirect and total capital and operating costs associated with hydrogen production and delivery are being estimated using H2A cost models calibrated to Alabama conditions. In Task 4, these estimates will be expanded to include energy and greenhouse gas emissions associated with the specific production and delivery options being modeled in the case studies. Energy estimates will be broken down into fossil and non-fossil fuels. Emissions will include CO2, N2O and CH4. The methodology and results will be presented at the UAB-sponsored conference, *Generation FC2006: Shaping the Southern Fuel Cell Economy*, as well as in a final report. Deliverables will include the presentation and report, and transfer of the models themselves to UAB.

Appendix B

Analysis of Gasoline Station Networks in Five Southeastern Urban Areas

Prepared by Dr. Marc Melaina

Analysis of Gasoline Station Networks in Five Southeastern Urban Areas
With a focus on Birmingham, Alabama

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Prepared for Argonne National Laboratory
April 7, 2006

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1 Introduction and Summary Results

This study presents an analysis of data on gasoline station networks in five southeastern urban areas: Birmingham, AL (1999), Nashville, TN (1995 and 2003), Owensboro, KY (2003), Gulfport-Biloxi, MS (2003) and Hattiesburg, MS (2003). The original data include the geographic coordinates of each station and the average station outputs (1000s of gallons per month) of each station during each of the years indicated. The data sets include all public gasoline service stations within a defined survey area, which typically encompasses at least some of the rural areas surrounding each urban area. The present study attempts to identify patterns within these station networks that can be generalized to urban areas in general, with the goal of providing useful inputs for models of future hydrogen station networks.

General characteristics of the station networks are discussed in the next section (Section 2). To allow for consistent comparisons between urban area networks, local service areas have been identified that correspond to the predefined survey areas (Section 2.1). Using these uniquely defined service areas as a common basis, gasoline station networks are compared with reference to urban population demographics using tract-level data from the U.S. census (Section 3). The networks are also analyzed in terms of station numbers, average station outputs, and total city-wide outputs (Section 4).

Additional analysis focuses on Birmingham, Alabama (Section 5). The gasoline station networks serving this urban area have been assessed using a *ring analysis method* (which identifies variations in station characteristics by proximity to the city center) and a *station clustering method* (which characterizes the degree to which stations tend to be clustered near to one another). Ring analysis provides a perspective on how stations are distributed within cities, while cluster analysis is a method of simulating a reduced network of refueling stations.

This study extends the previous analysis of four U.S. urban areas (Atlanta, GA, Phoenix, AZ, Hartford, CT, and Salt Lake City, UT), as described in a report prepared for Oak Ridge National Laboratory (Melaina 2004). Some of the results from this previous report have been included in this study for reference. Five major trends were identified in the previous ORNL report. They are listed below, followed by corresponding findings from the present study.

1. *High population density cities tend to have relatively larger stations and more stations per square mile than do cities with lower population densities.*

This appears to be less of a trend when taking into account the five southeastern cities. Several low population density cities have average station sizes as large or larger than the average station size in the highest population density city (Salt Lake City), and Hattiesburg, Owensboro and Birmingham each have station densities as high or higher than the second highest population density city (Phoenix).

2. *Stations of different sizes are fairly evenly distributed across urban areas, though there is a slight tendency for larger stations to be located further from city centers.*

This appears to also be the case for Birmingham, though no tendency for larger stations to be located near or far from the city center was seen.

3. *Approximately 45-65 percent of total urban fuel use is dispensed within the most central 30 percent of urban land area.*

Approximately 60 percent of the total fuel use is dispensed within the most central 30 percent of the Birmingham urban land area.

4. *Between 35 and 43 percent of urban stations are located within 0.1 miles of another station.*

In Birmingham, 38 percent of urban stations are located within 0.1 miles of another station.

5. *Clustering stations within 1 mile of one another into single stations reduces the number of stations in a network by approximately 70 to 76 percent.*

In Birmingham, clustering within 1 mile reduces the number of stations by 76 percent.

The results of this study offer further evidence that at least the last four of the above five trends appear to be common to a wide range of urban areas, and may therefore provide guidance for general models of alternative refueling infrastructures (e.g., hydrogen) within U.S. cities.

2 Characteristics of the MPSI Gasoline and Diesel Station Data

Data on gasoline station networks was acquired from MPSI, a commercial provider of data on retail marketing trends. MPSI maintains a large database of gasoline station data for numerous U.S. cities. In response to requests from gasoline and diesel fuel marketers, MPSI conducts surveys of particular urban areas, and offers the resulting data to companies attempting to identify profitable locations for new service stations and c-stores. With over 30 years of experience, MPSI has developed an elaborate process of surveying and modeling to characterize gasoline retail markets. Referring to the thoroughness of their surveying methods, MPSI representative have expressed confidence in the accuracy of their station output estimates, and assert that their inventories include all public gasoline stations within the defined survey areas. This cannot be claimed for other sources of gasoline station data, such as U.S. census data or survey results from National Petroleum News. Although diesel fuel outputs are also included in the data sets, these data are not analyzed in the present study.

The following were acquired from MPSI:

1. Station locations (street addresses and latitude and longitude coordinates).
2. Average monthly outputs of gasoline fuel (and diesel, if applicable) for each station (in 1000s of gallons per month).
3. Hard copies of maps representing the geographic boundaries of each survey area.

The first two types of data are straightforward, while the survey boundaries have been used to estimate the total land area and total population contained within the MPSI survey area. This has been done using year 2000 U.S. Census population data on a tract level. Details of this analysis are discussed in Section 2.1.

Correlations between population density and station networks characteristics are central to the present analysis. To provide context, the land area and population density of each of the cities analyzed are depicted in Figure 1, which includes all major urban areas in the U.S. (The population densities and land areas indicated are from U.S. census data on *urban areas*, and do not necessarily correspond to the demographics determined for urban areas in the present study.) Each data point is distinguished by color and shape as falling within one of three population ranges, with the smallest urban areas including between 50,000 and 25,000 persons, and the largest urban areas including more than 1,000,000 persons. Note that land area on the horizontal axis is log scale. The figure indicates each of the southeastern cities analyzed in the present study, as well as the cities analyzed in the previous ORNL report, in bold lettering. It should be noted that 6 of the 8 cities have relatively similar population densities, and the other two cities (Salt Lake City and Phoenix) also have similar population densities. This selection of cities limits, to some degree, the correlations drawn between station network characteristics and population density of cities. Future analyses will draw upon a set of urban areas that includes a broader range of population densities.

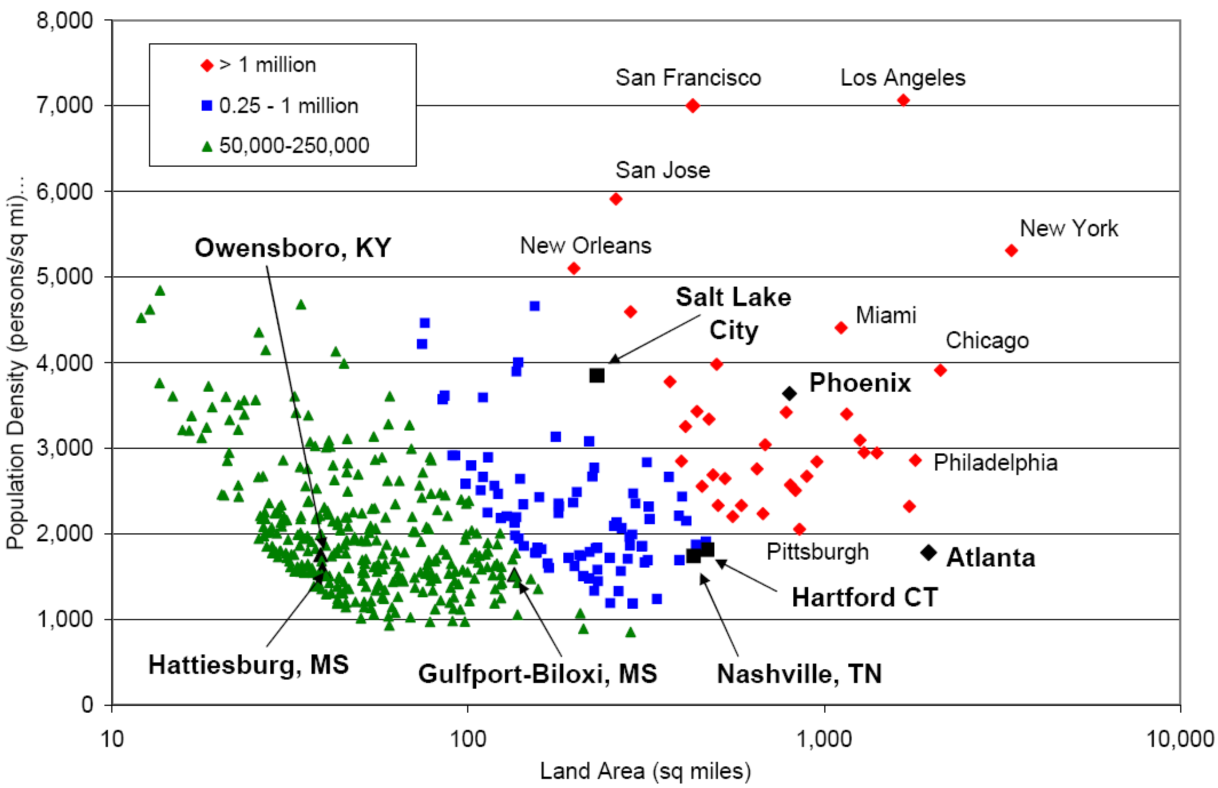

Figure 1. Urban area population density and land areas for three population sizes (year 2000 census urban areas).

2.1 Identifying Local Service Areas

A consistent demographic basis is required in order to compare the station networks serving different cities. Boundaries for *local service areas* have been determined for each city to provide a consistent demographic basis. In general, these local service areas adhere closely to the survey boundaries provided by MPSI. Where discrepancies exist, a general rule is applied: local service areas do not extend beyond the MPSI survey boundaries, and they do not extend beyond census tracts having population densities less than 250 persons per square mile. As a result, some service stations included in the MPSI data sets, but located in low population density areas, have been excluded from the analysis. The rationale is that these stations primarily serve rural markets, or pass-through traffic along interstates.

Because census tract boundaries often follow major roads, some exceptions are made for stations located nearby census tracts with greater than 250 persons per square mile. “Nearby” is defined as a distance roughly equal to 5% of the diameter of the urban area. In these cases, the service stations are included as part of the local service area network, but the populations and land area of the census tracts they are located within are not included as part of the local service area.

Figure 3 through Figure 13 indicate the MPSI survey maps and defined local service areas for each of the five southeastern urban areas. As indicated in Figure 5, Gulfport-Biloxi and Hattiesburg were included within a single survey boundary. In each figure, the boundaries shown as red solid or dotted lines indicated the MSPI survey area. For the figures indicating local service area boundaries, the boundaries are indicated with solid black lines. The service area maps (Figure 4, Figure 6,Figure 7,Figure 9Figure 11Figure 13) also indicated population density by tract (green shaded regions) and service station locations. The dots representing service stations are color-coded to indicate ranges of station sizes. Stations included in the original MPSI data but excluded from the local service areas are indicated with black shaded squares. These figures were generated using MapPoint™ software, with year 2000 census population densities.

2.2 Local Service Area for Birmingham, Alabama

Figure 2 is included as a reference to orient the city of Birmingham with the surrounding region. The inset in this figure indicates the map area with reference to nearby states and major cities (Nashville, TN, to the north, Atlanta, GA, to the east, Montgomery, AL, to the south, and Jackson, MS, to the west). Nearby urban areas (with populations indicating census tracts with population densities greater than 250 persons per square mile) include Jasper (13,271), Gadsden (53,638), Anniston (73,743), Talladega (14,181), Sylacauga (12,104) and Tuscaloosa (108,380). As indicated in Figure 3 and Figure 4, Alabaster to the south is included as part of the Birmingham urban area. For the entire region indicated in Figure 2, the urban areas include some 0.95 million persons, and the rural areas include 0.7 million (rural areas include all white tracts with population densities less than 250 persons per square mile). The scale in Figure 2 shows that the Birmingham local service area (the boundaries of which are shown in Figure 4) is roughly 25 miles across and 30 miles North to South.

As indicated in Figure 4, the majority of Birmingham’s gasoline stations tend to be clustered within two broad corridors crisscrossing the city: the first running North-South along I65, and the second running Southwest-Northeast along I59 and I20.[1] Furthermore, as indicated by the color-coded representation of average station outputs, it appears that the North-South corridor has a relatively larger fraction of high output stations than the Southwest-Northeast corridor. Nearly all of the Birmingham stations with average outputs greater than 200,000 gallons per month are contained within the North-South corridor. In contrast, a large number of stations with average outputs less than 50,000 gallons per month are located nearby 3rd Avenue and the Bessemer Super Highway, both running parallel to I59 and I20 south of the city center. Additional details of station numbers and sizes in Birmingham are presented in Section 4.

[1] Interstates I59 and I20 are separate in the Northeastern part of the region, but combine near Fairfield and remain combined as they pass through the remainder of the greater Birmingham urban area.

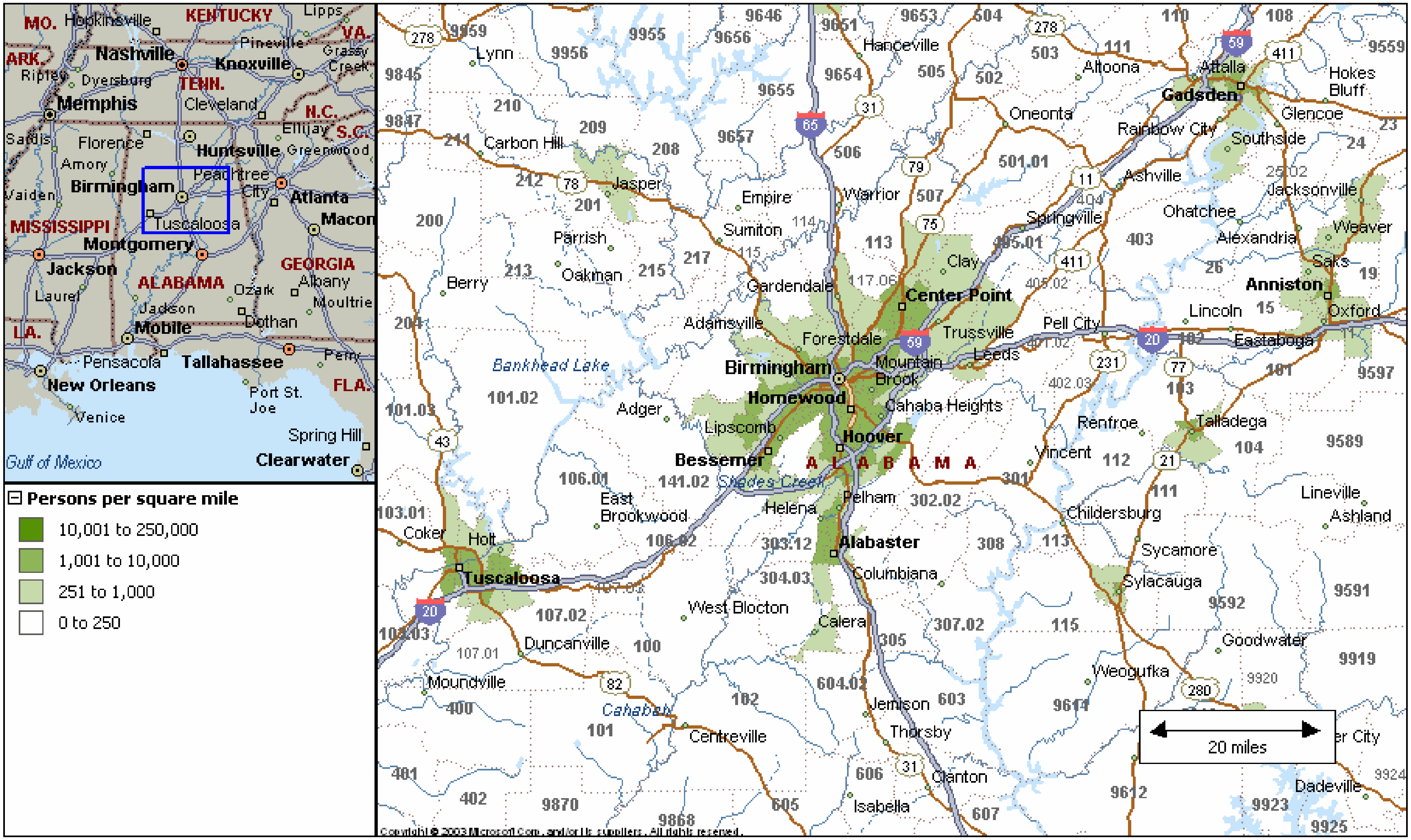

Figure 2. Birmingham region, with population density on a tract level from year 2000 census data.

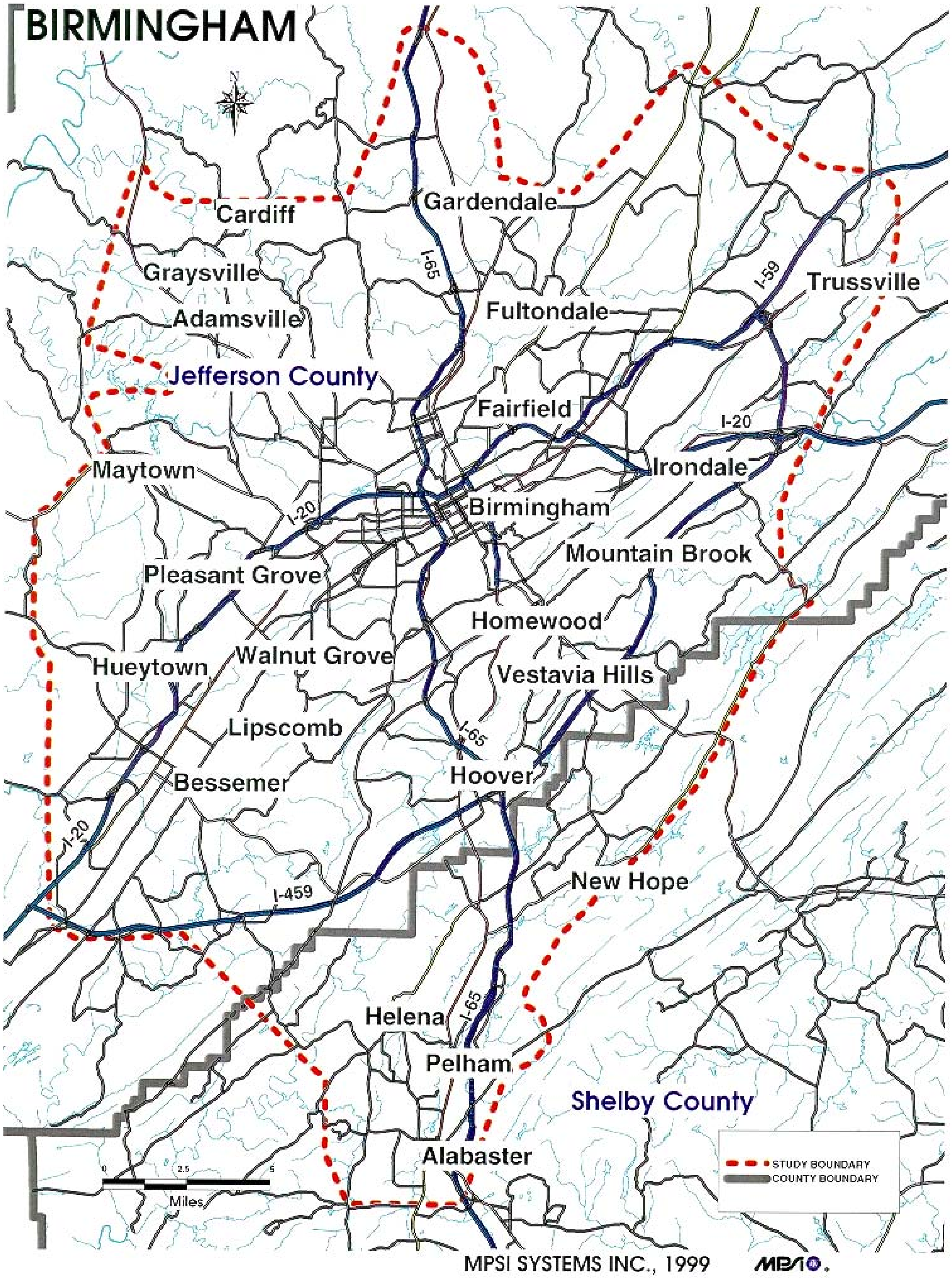

Figure 3. MPSI survey area for Birmingham, Alabama (1999).

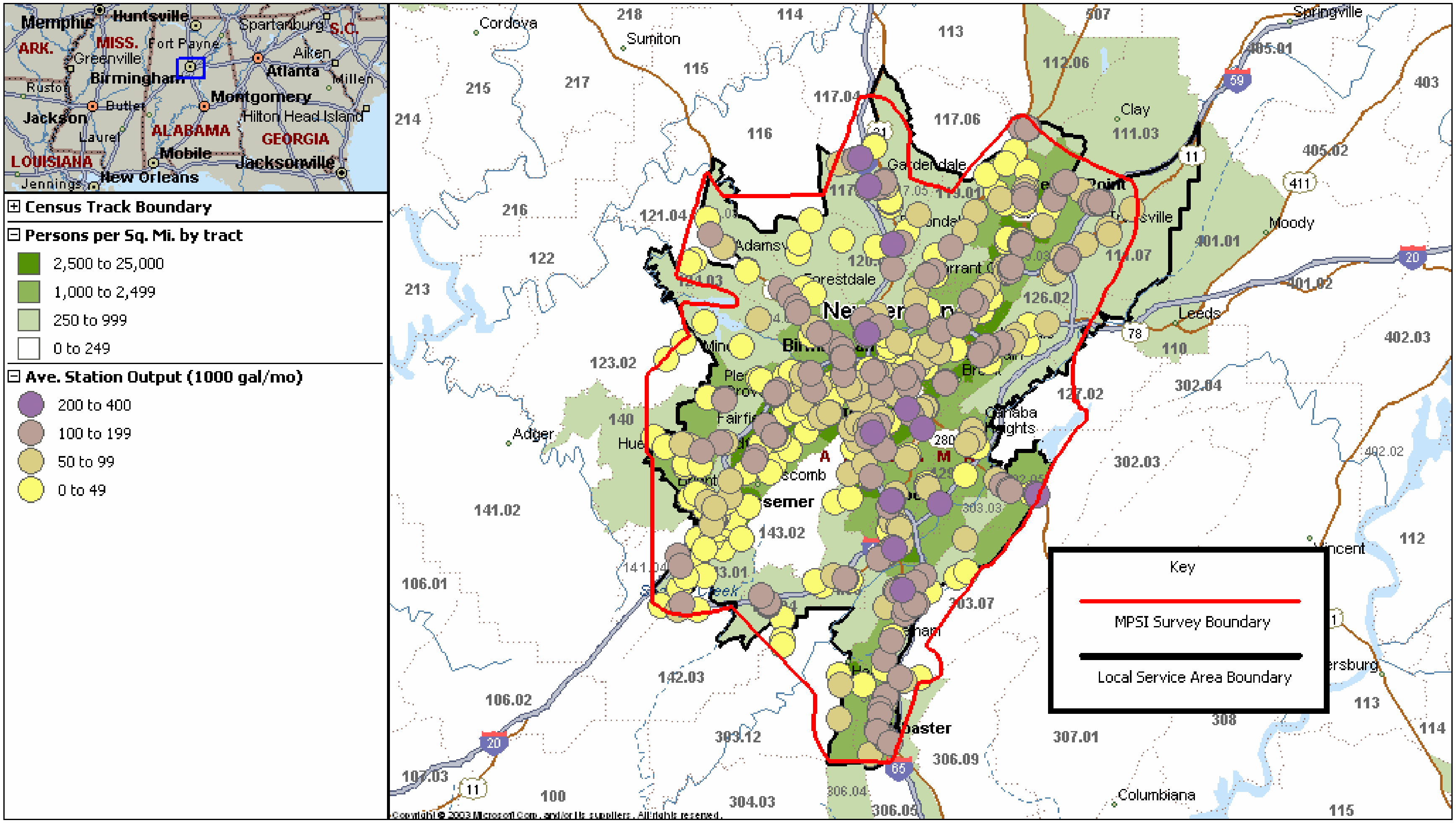

Figure 4. MPSI survey boundary and local service area boundary for Birmingham, Alabama (1999).

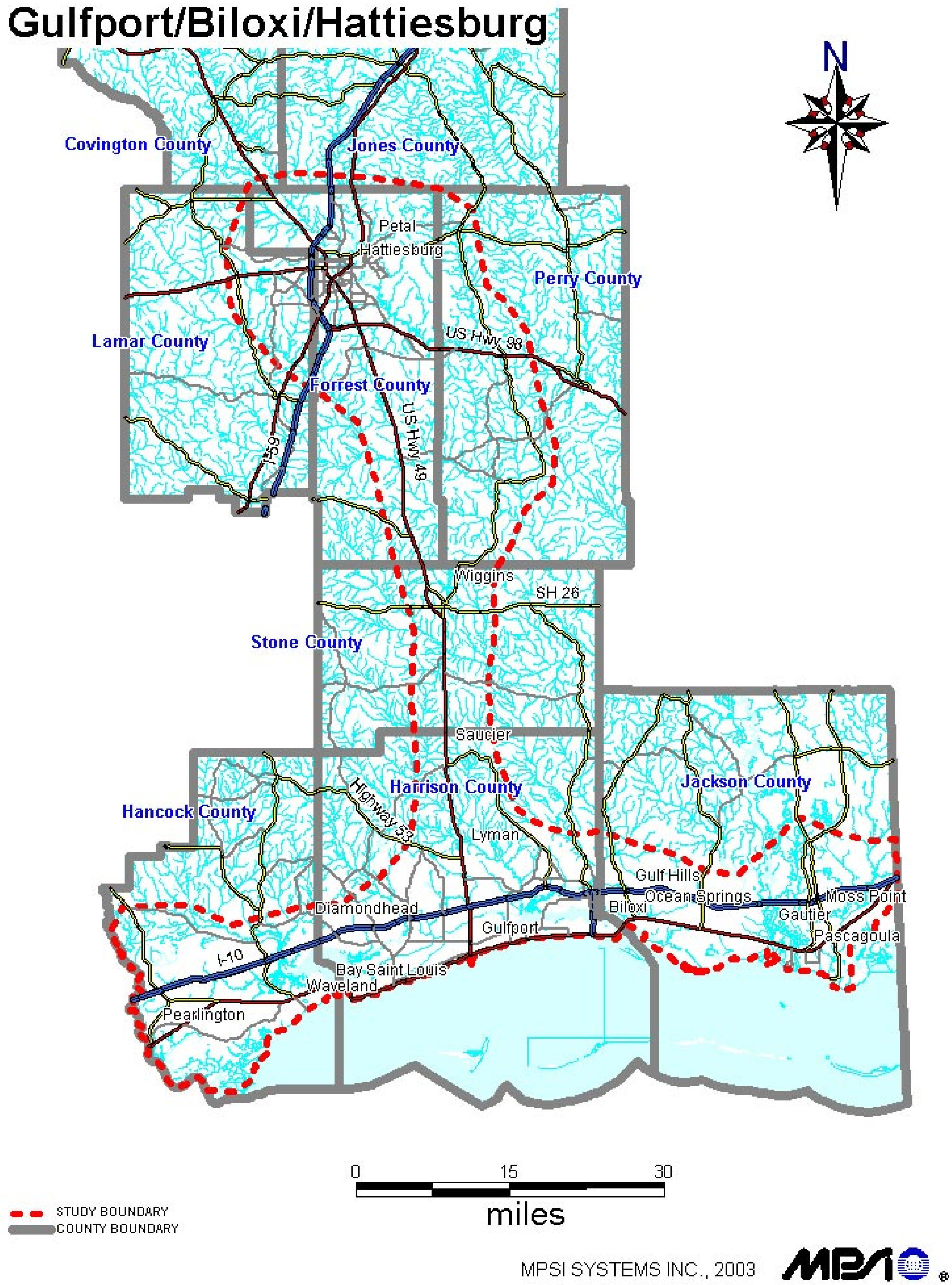

Figure 5. MPSI survey area for Gulfport-Biloxi and Hattiesburg (2003).

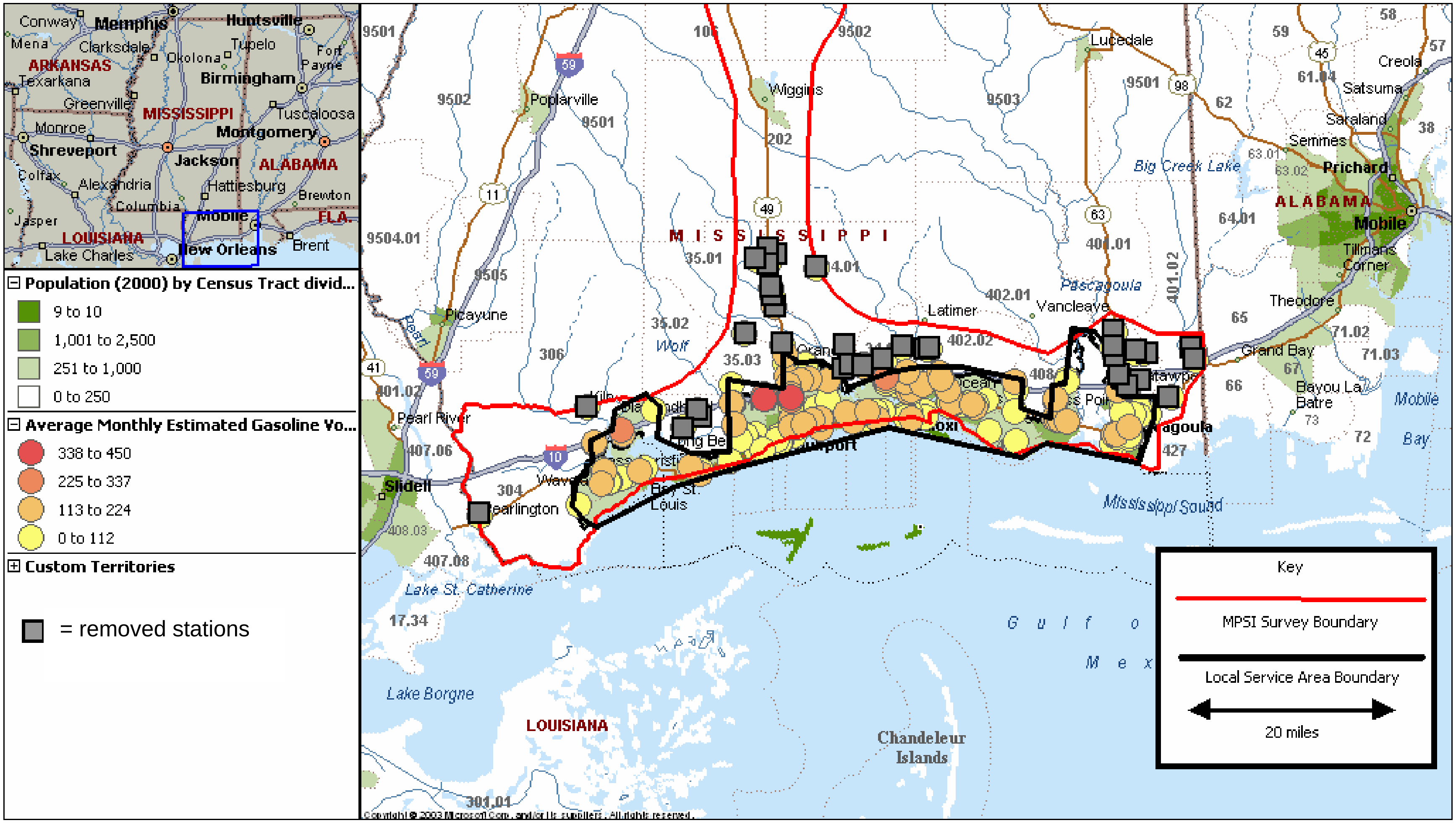

Figure 6. MPSI survey boundary and local service area boundary for Gulfport-Biloxi, Mississippi (2003).

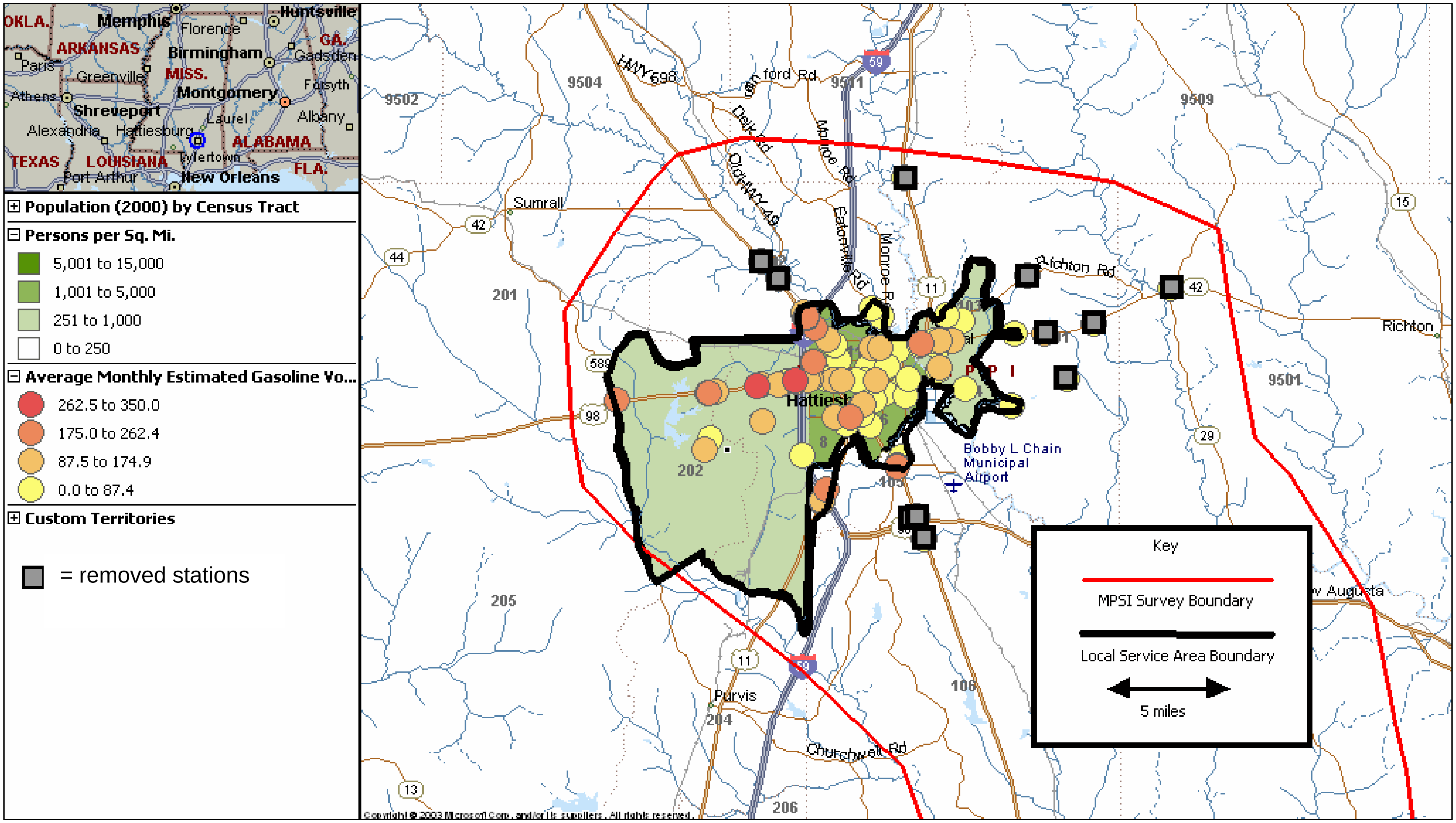

Figure 7. MPSI survey boundary and local service area boundary for Hattiesburg, Mississippi (2003).

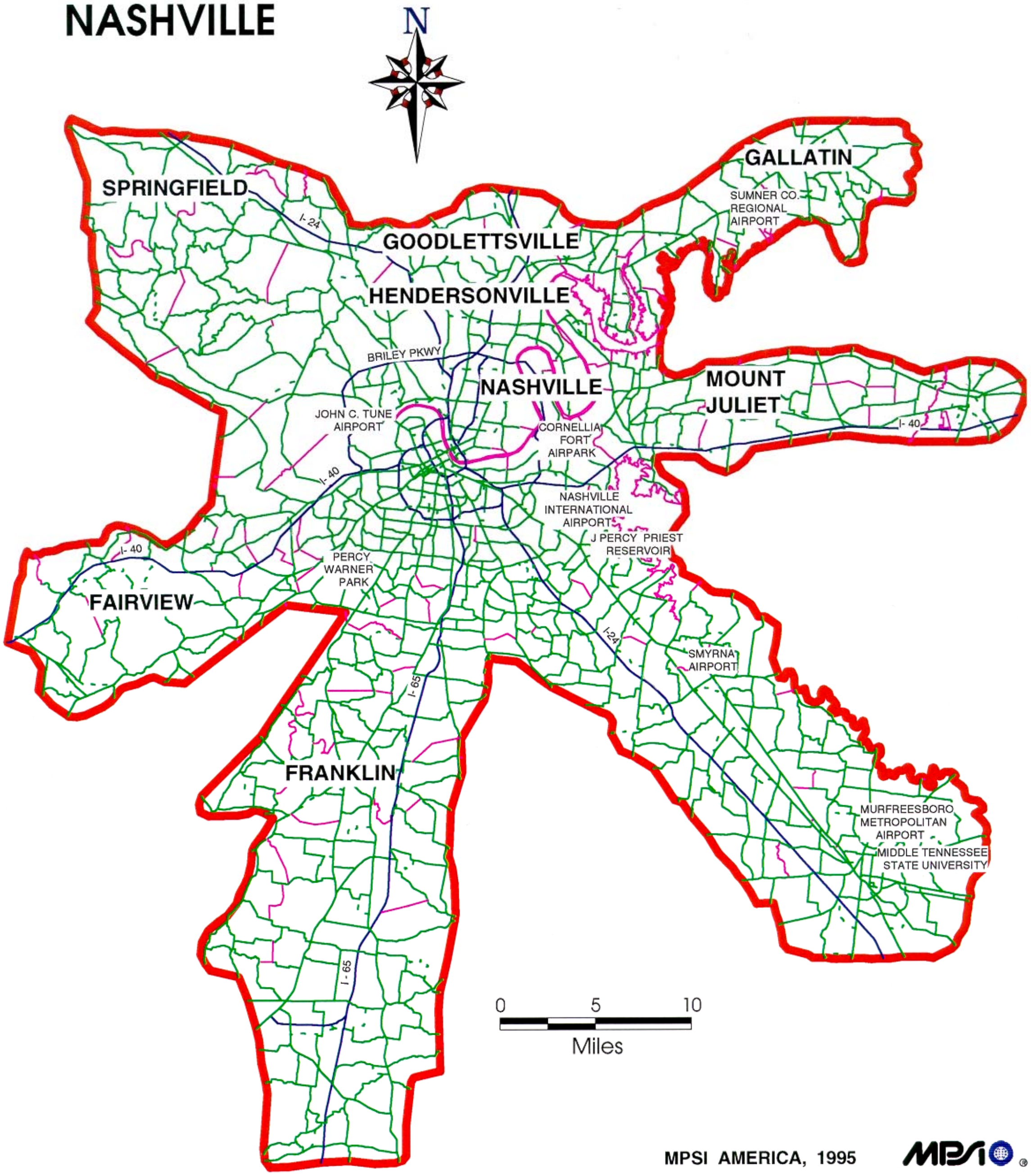

Figure 8. MPSI survey map for Nashville, Tennessee (2003).

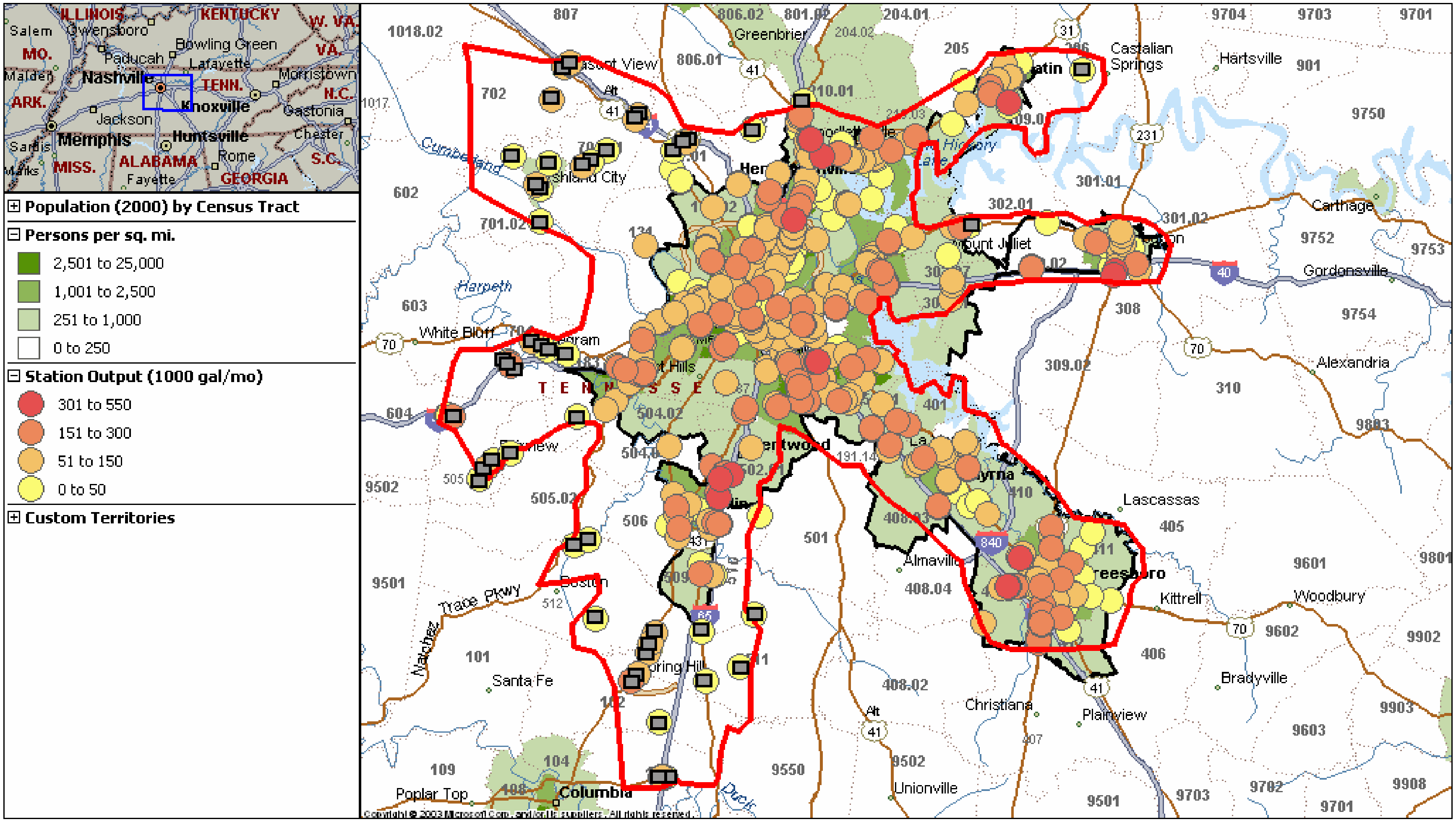

Figure 9. MPSI survey boundary and local service area boundary for Nashville, Tennessee (2003).

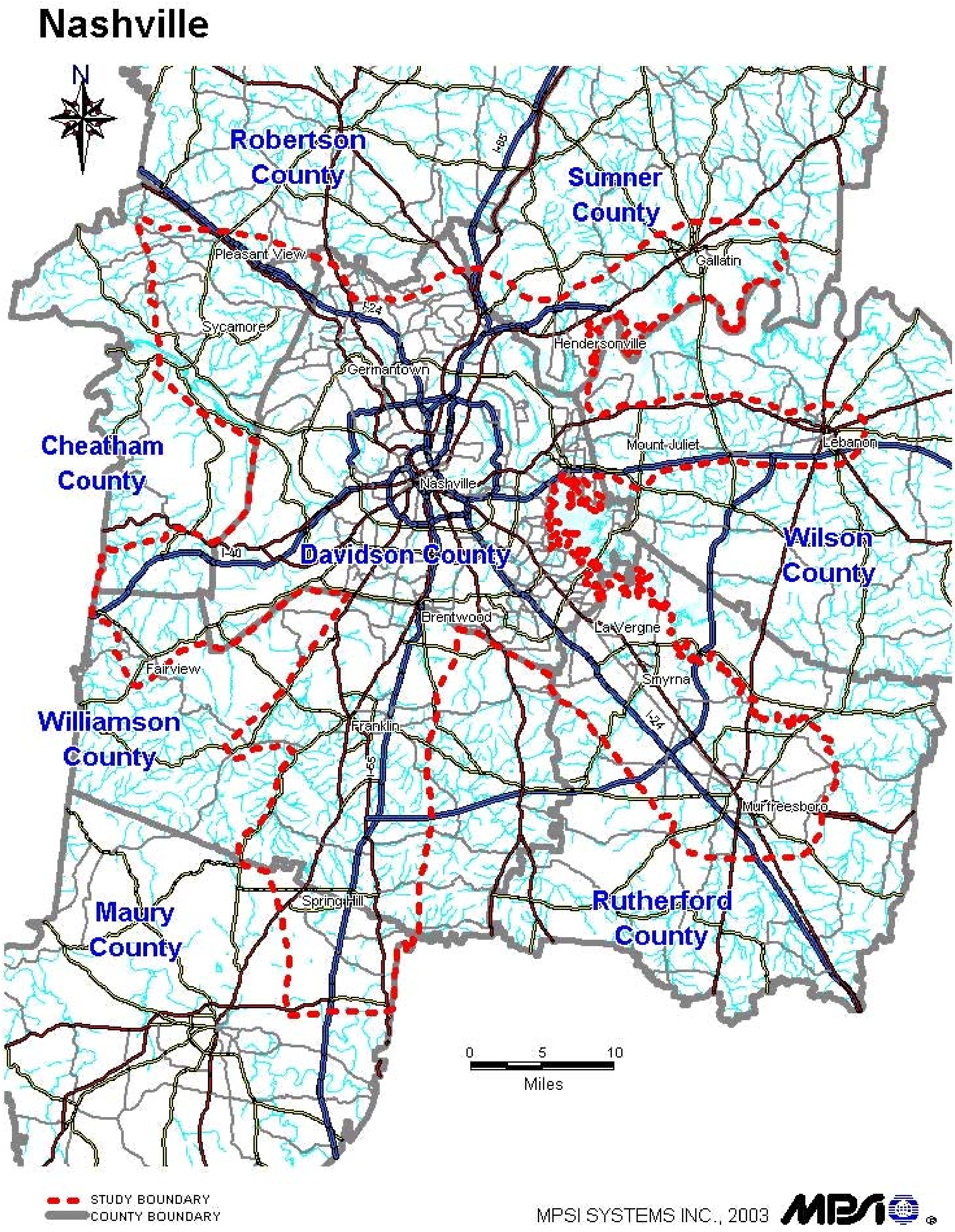

Figure 10. MPSI survey map for Nashville, Tennessee (1995).

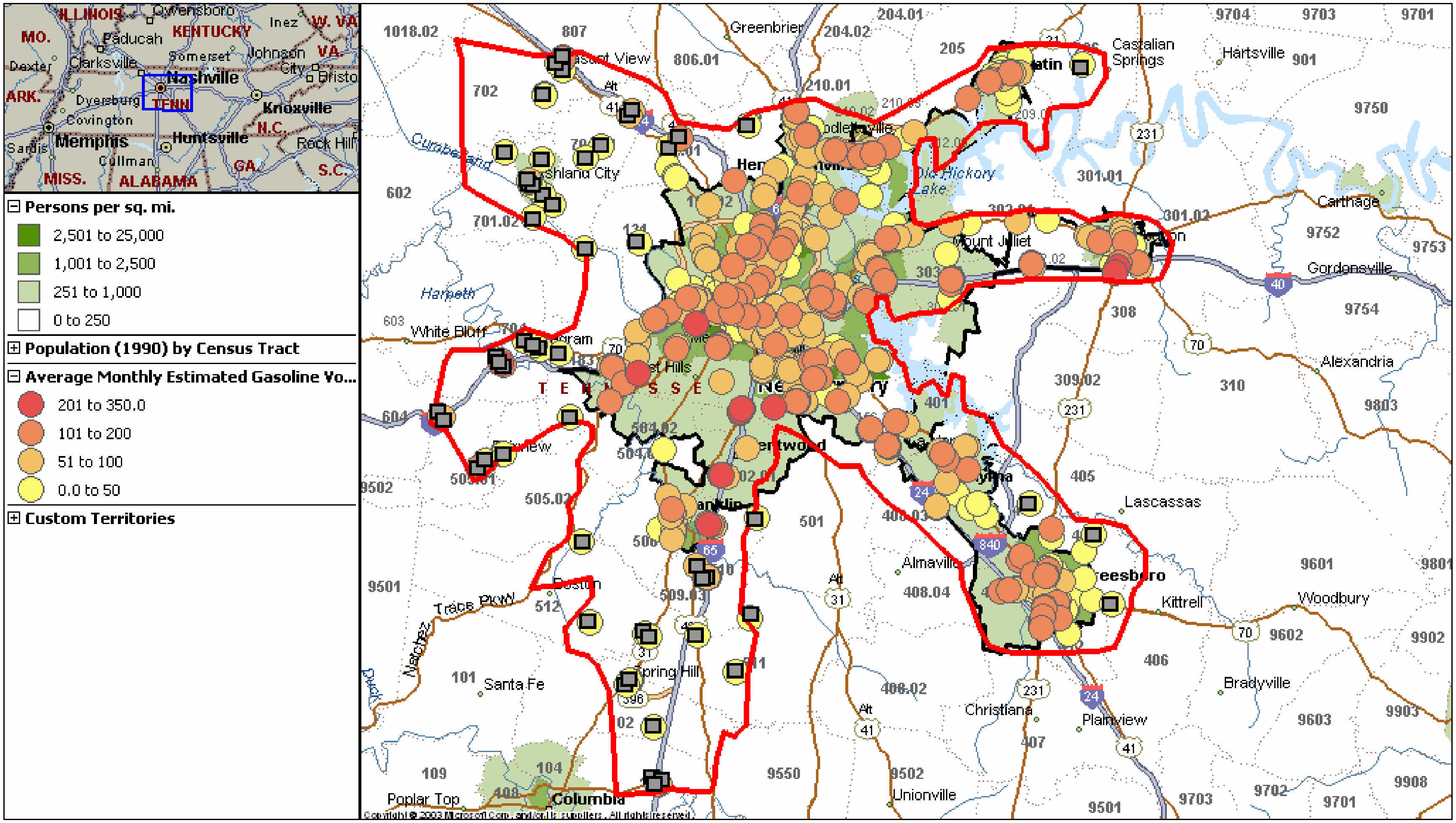

Figure 11. MPSI survey boundary and local service boundary for Nashville, Tennessee (1995).

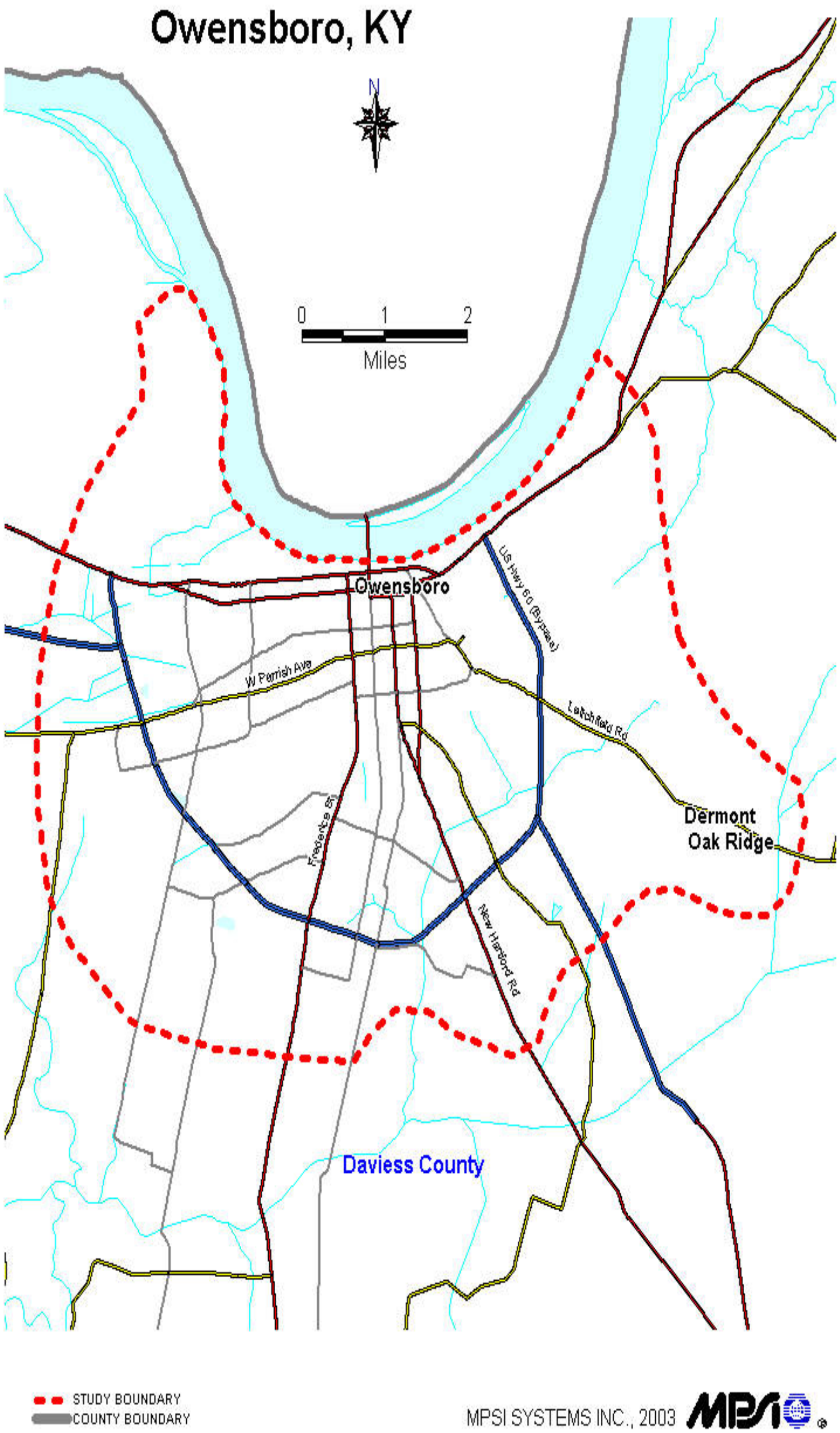

Figure 12. MPSI survey area for Owensboro, Kentucky (2003).

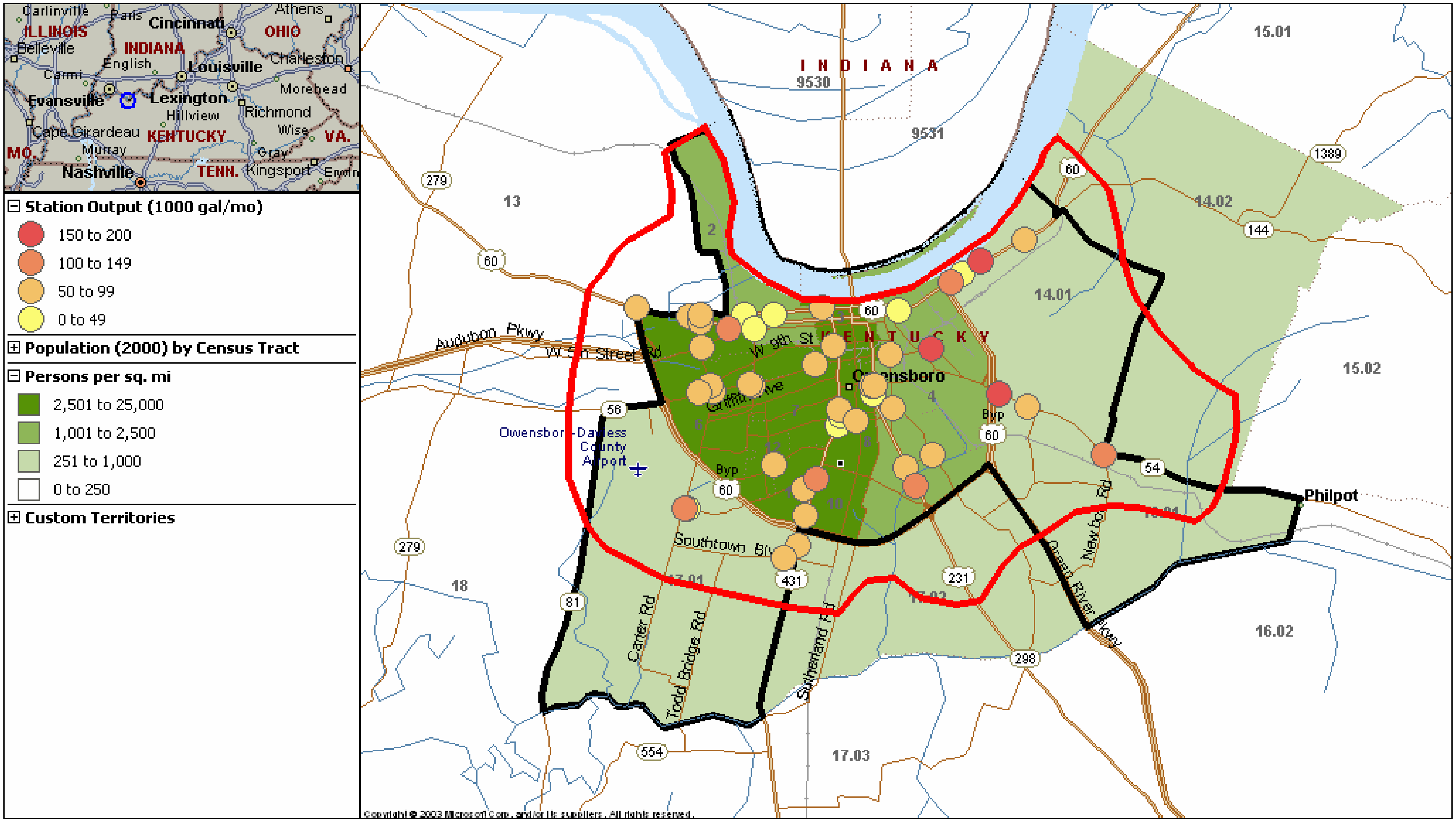

Figure 13. MPSI survey boundary and local service boundary for Owensboro, Kentucky (2003)

3 Correlations with City Demographics

Having defined local service areas for each urban area, populations, land areas and population densities can be determined. These are indicated in Table 1. The major differences between the urban areas are that Atlanta and Phoenix have much larger populations than the other cities, while Owensboro and Hattiesburg have much smaller populations. In addition, the population densities of Phoenix and Salt Lake City are 2-3 times those of the other cities. The table also lists the number of stations, the station density and the number of persons per station for each urban area. The last four rows of the table contain data on average outputs, including the total gasoline output, average station output, gasoline output density and gallons of gasoline consumed per person.

Relevant (but somewhat inconclusive) trends associated with these demographics are indicated in Figure 14 through Figure 17. Figure 14 indicates station density (stations per square mile) in relation to population density. A clear trend is not identifiable, but it is conceivable that station density increases with population density, while some cities, such as Hattiesburg, Owensboro and Birmingham, contain an excessive number of gasoline stations. Additional research is required to determine if such as trend exists and why networks in some cities have a relatively high station density. The persons per station ratios in Figure 16 are essentially an inverse of the trends shown in Figure 15. As might be expected, for urban areas with similar population densities, those with higher station densities have lower person-to-station ratios.

Figure 16 suggests that there is no correlation between average station size and population density. This somewhat counter-intuitive result may be a result of a small sample population. For example, Salt Lake City has a very high station density, and may therefore prove to be an exception to this trend.

Figure 17 is suggestive of a significant trend, though a large sample will still be required to prove a statistical correlation. It appears that higher population density does correlate with lower per person gasoline consumption, with Hattiesburg and Hartford being significant outliers. Of each of the cities, Hartford is the only city that borders upon several dense urban areas, which may allow residents opportunities to refuel outside the city, while pass-through traffic is less likely to refuel within the city. By comparison, Hattiesburg is a small town, surrounded by rural area, that is located at the intersection of an interstate (59) and two highways (98 and 49). Moreover, Hattiesburg is approximately 90 miles from three major cities, New Orleans, Jackson and Mobile. It is therefore likely that pass-through traffic makes a major contribution to the high per person gasoline consumption in Hattiesburg.

Table 1. City demographics and gasoline station network characteristics.

City Characteristic	Units	Atlanta	Phoenix	Nashville	Salt Lake City	Hartford
Population	persons	3,602,689	2,943,029	882,764	842,349	823,960
Area	sq. mi.	2,886	981	793	219	600
Population Density	persons/sq. mi.	1,248	3,001	1,114	3,847	1,374
Stations	#	1,698	845	538	310	336
Station Density	Stns/mi^2	0.59	0.86	0.68	1.42	0.56
Persons per Station	persons/station	2,122	3,483	1,641	2,717	2,452
Total Gasoline Output	1000 gal/mo	175,547	114,937	56,534	30,039	25,853
Average Station Output	1000 gal/mo	103	136	105	97	77
Gasoline Output Density	1000 gal/mi^2/mo	61	117	71	137	43
Gallons per Person	gal/person/mo	49	39	64	36	31

City Characteristic	Units	Birmingham	Gulfport	Owensboro	Hattiesburg
Population	persons	637,344	264,067	56,270	66,824
Area	sq. mi.	498	276	44	94
Population Density	persons/sq. mi.	1,280	956	1,293	712
Stations	#	461	168	47	79
Station Density	Stns/mi^2	0.93	0.61	1.08	0.84
Persons per Station	persons/station	1,383	1,572	1,197	846
Total Gasoline Output	1000 gal/mo	35,685	17,194	3,427	8,072
Average Station Output	1000 gal/mo	77	101	73	102
Gasoline Output Density	1000 gal/mi^2/mo	72	62	79	86
Gallons per Person	gal/person/mo	56	65	61	121

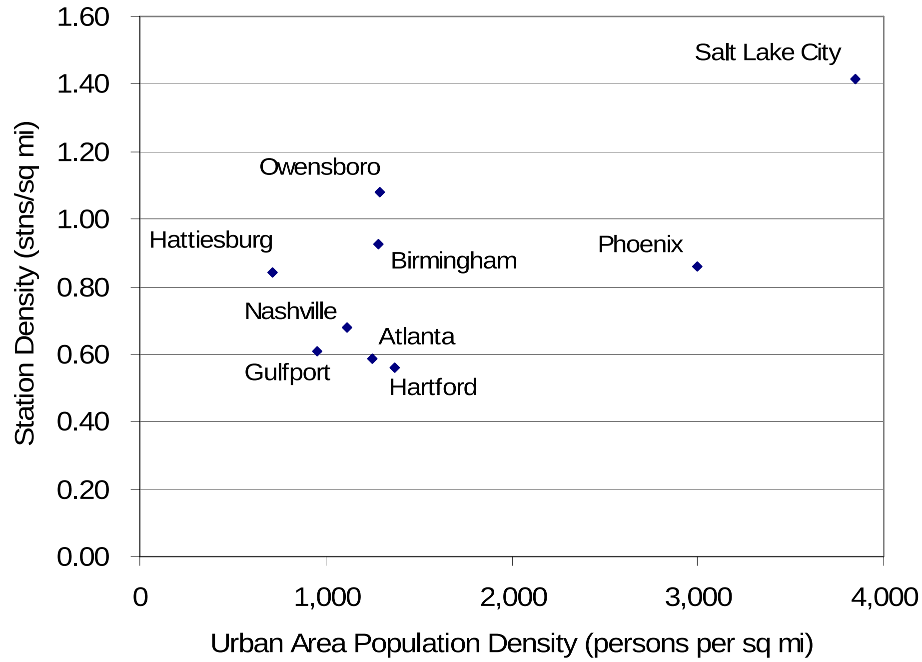

Figure 14. Station density vs. urban area population density.

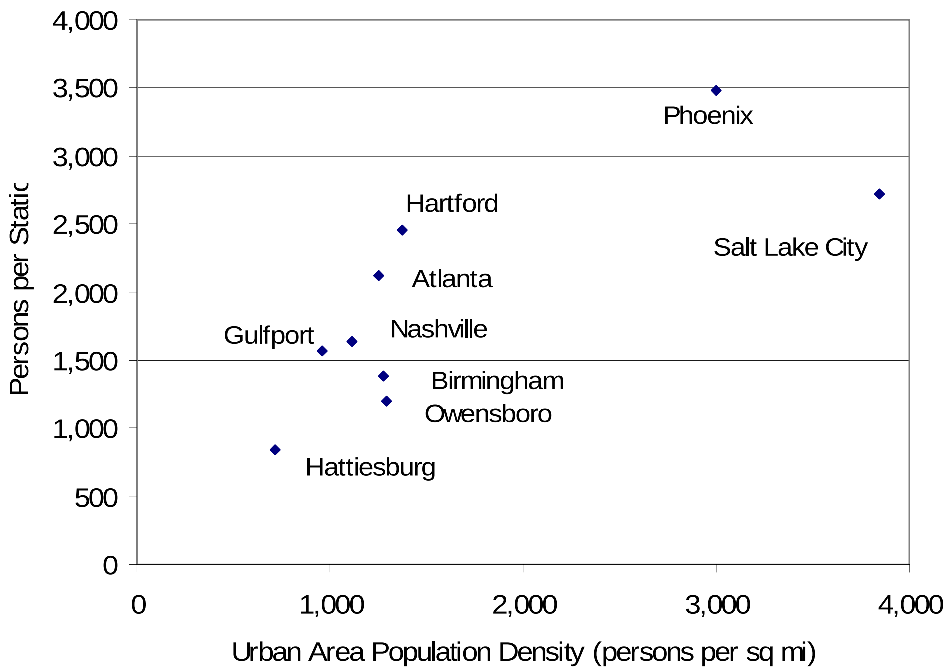

Figure 15. Persons per station vs. urban area population density.

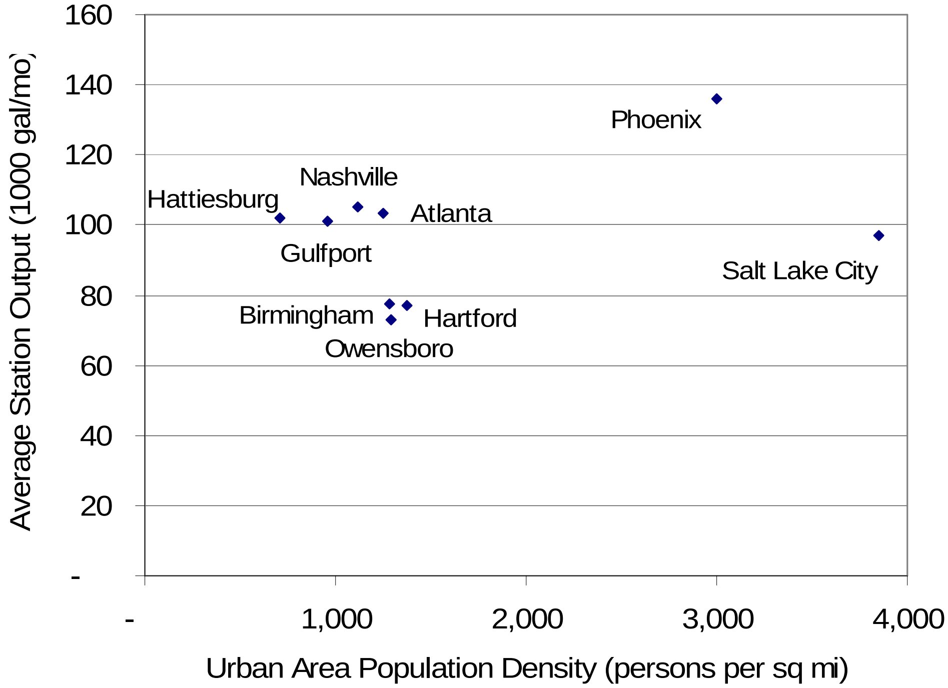

Figure 16. Average station output vs. urban area population density.

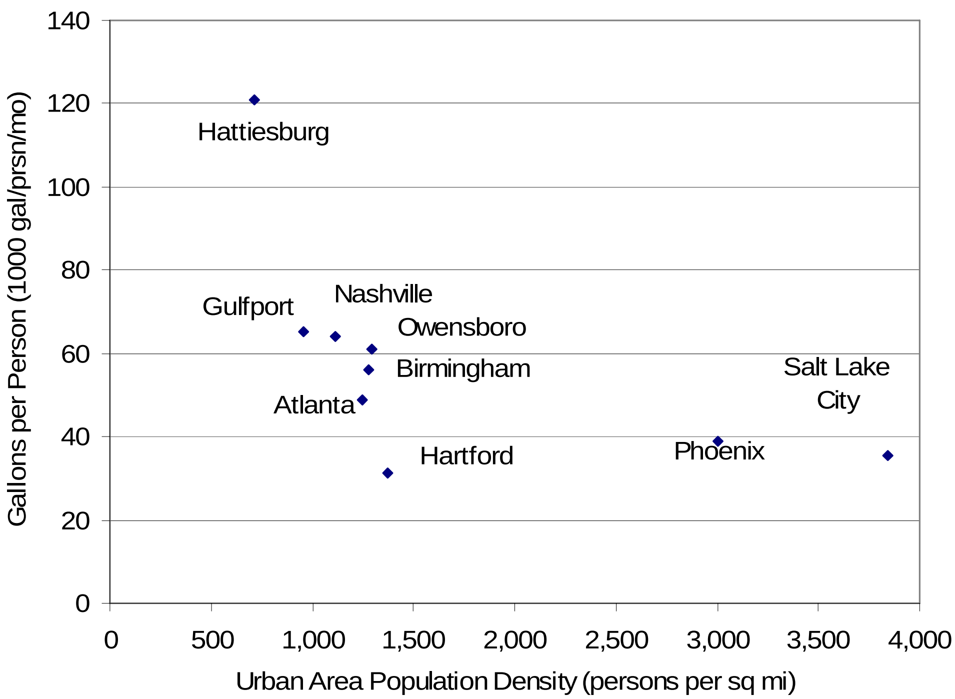

Figure 17. Average gallons per person per month vs. population density.

4 Station Numbers, Sizes, and Outputs

Gasoline station networks serving different urban areas can be compared in terms of the total number of stations, the distribution of station sizes within each network and the total output dispensed by stations of different sizes. These characteristics are described below, but in many cases additional research will be required to fully explain the patterns observed in the data.

Figure 18 summarizes the gasoline station networks serving each city by indicating the number of stations (horizontal axis) and the size of each station (vertical axis), where the stations have been ranked left to right by size. The area under each distribution is proportional to the average output of each city. The distribution of station sizes for each city includes a small number of large stations and a relatively large number of small stations. A few stations have average monthly outputs greater than 400,000 gallons per month, the upper range indicated in the figure. In comparing cities, the largest 300 or so stations in Atlanta and Phoenix have a very similar distribution of sizes, but Atlanta is served by a much greater number of smaller stations. Similarly, the largest 60 or so stations in Birmingham, Hartford and Gulfport-Biloxi have a similar size distribution, though the total number of stations service each city varies considerably.

Figure 19 shows the same data contained in Figure 18, but the horizontal axis has been normalized to a percentage of the total number of stations in each urban area. In general, most of the station size distributions cluster towards a common distribution curve, which is perhaps best represented by the distribution for Atlanta. Four exceptions include Phoenix, which has mostly large stations, and Birmingham, Hattiesburg and Owensboro, which have much smaller stations. Birmingham and Hartford are exceptional in this case in that, unlike Owensboro, they are relatively large cities that are being served by a large number of small stations. As indicated in Figure 16, the average station size is similar in each of these three cities.

The vertical axis in Figure 19 can be normalized by the average station size in each city to develop a normalized relative station size distribution, as shown in Figure 20. Each of the distributions now adheres to a common distribution curve, with major deviations seen only for the three smallest cities, Owensboro, Hattiesburg and Gulfport-Biloxi.

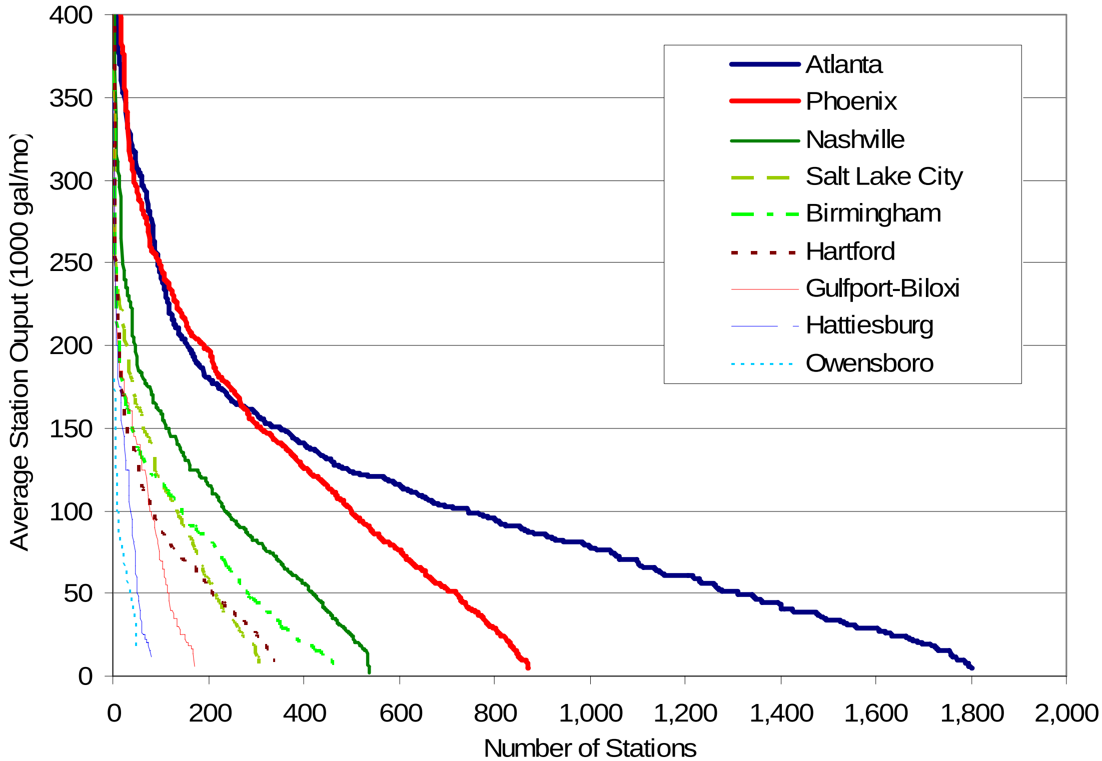

Figure 18. Stations from all urban areas ranked by average monthly output.

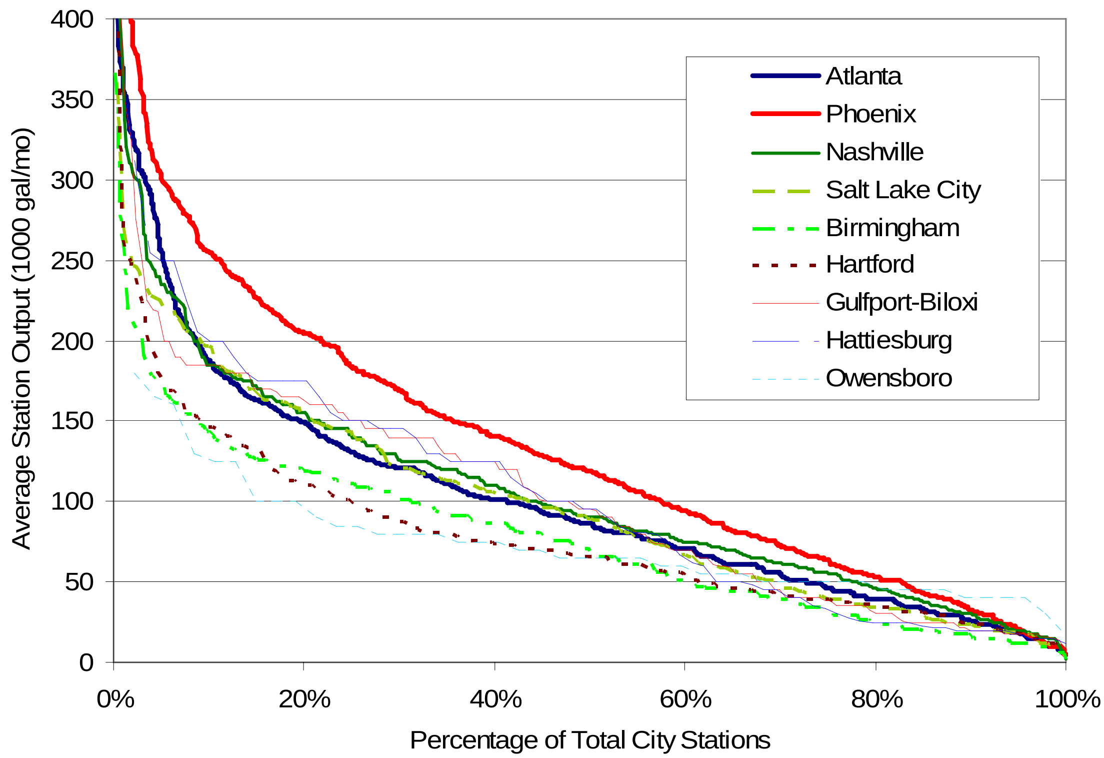

Figure 19. Average station output as a function of the percent of stations in each urban area.

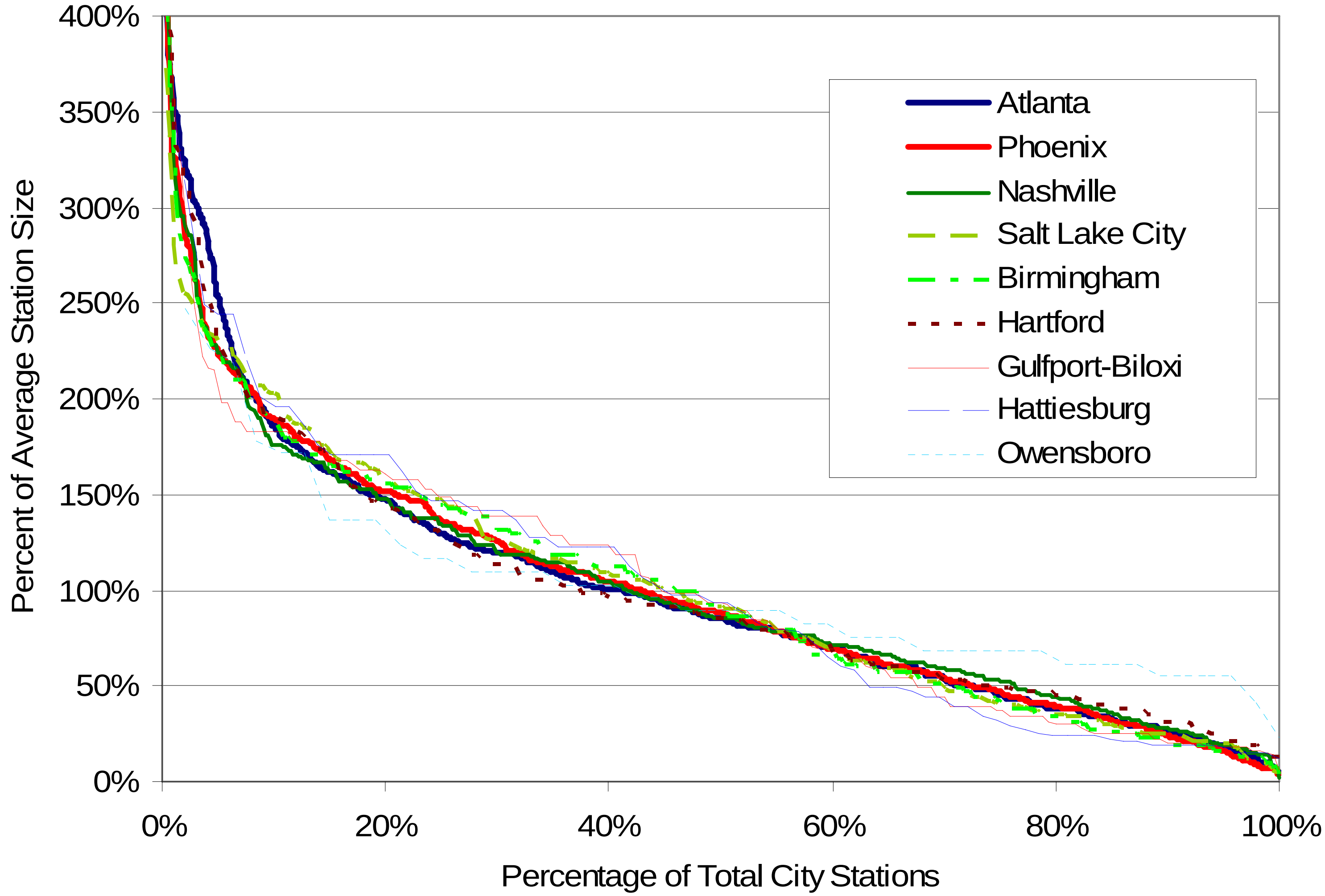

Figure 20. Normalized relative station size distribution: percent of the average station size as a function of the percent of stations in each urban area.

The same data presented in Figure 18,Figure 19 and Figure 20 are shown in Figure 21 with the number of stations in each city separated into bins spanning the range of station sizes. This distribution highlights some of the similarities and differences between each city. (Note that this figure does not include the three smallest urban areas, each having less than 0.5 million persons: Gulfport-Biloxi, Owensboro and Hattiesburg. As suggested in Figure 20, the distribution of stations sizes in these three cities is more erratic than in the larger cities.) For example, Phoenix has a relatively small percentage of stations dispensing less than 50,000 gallons per month, while Birmingham and Hartford have a large percentage within this range. For each city, some 40-55 percent of all stations dispense an average of 50,000 to 150,000 gallons per month. Above this range, the fraction of stations diminishes steadily with increased station output. Birmingham and Hartford have a relatively small fraction of stations dispensing between 150,000 and 200,000 gallons per month, while Salt Lake City and Phoenix have a relatively large fraction dispensing between 200,000 and 250,000 gallons per month. Phoenix also has a large fraction of stations in the 250,000 to 300,000 gallons per month range.

The relative differences between cities are similar in Figure 22, which indicates the percentage of the total city output from stations contained in each bin. The figure shows that roughly 60 to 75 percent of all gasoline is dispensed from gasoline station with average outputs ranging from 50,000 to 150,000 gallons per month.

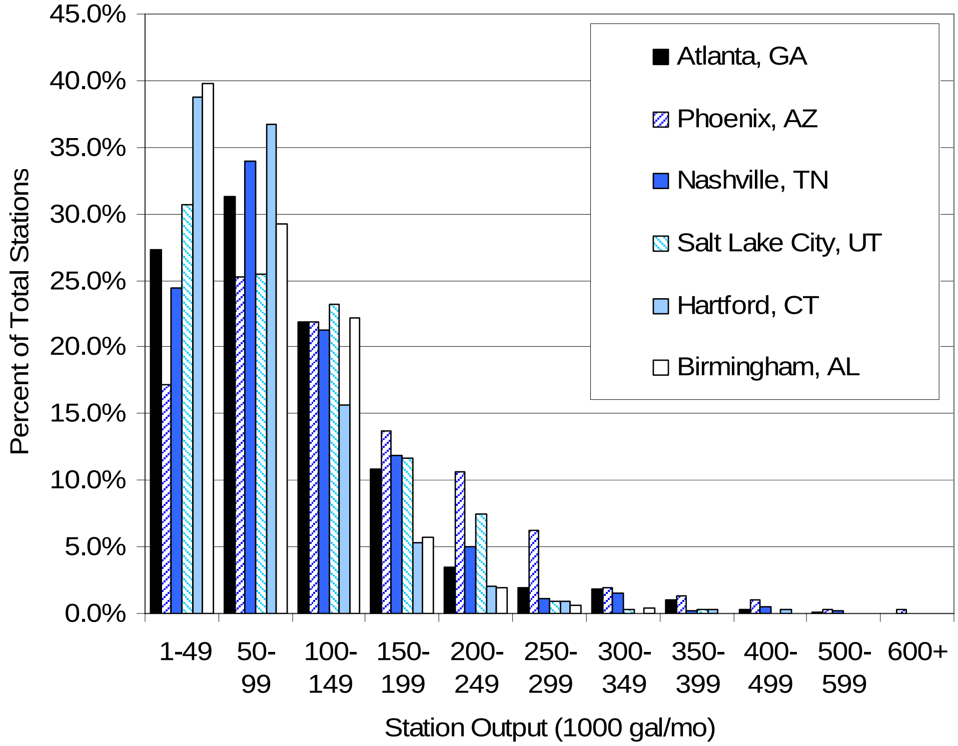

Figure 21. Percent of total stations by station size.

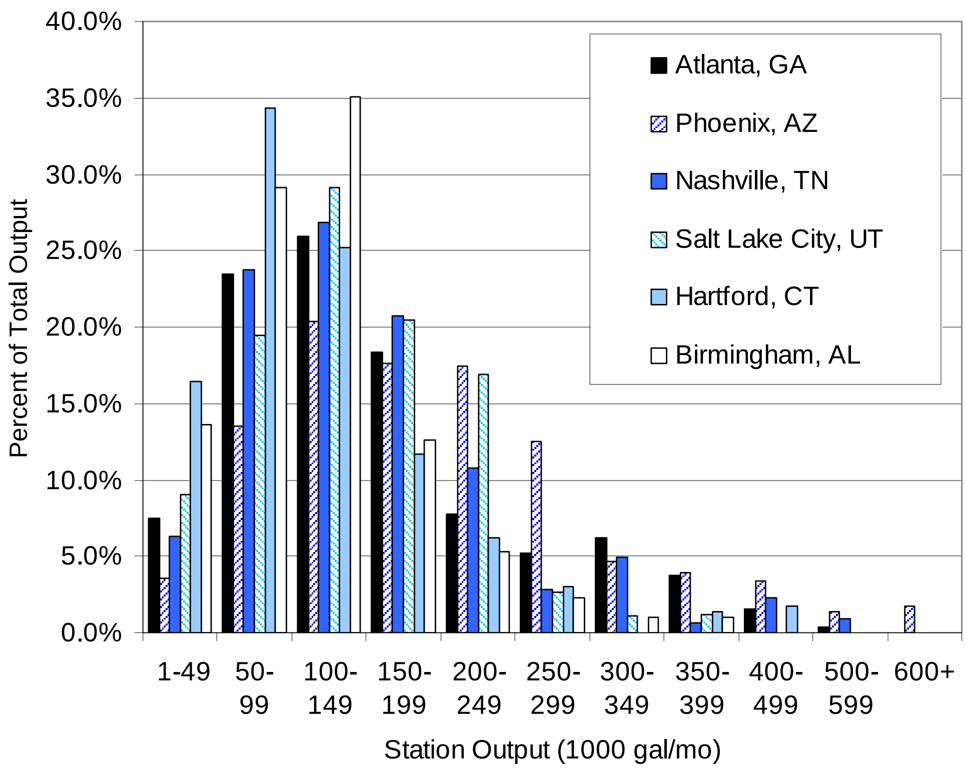

Figure 22. Percent of total output by station size.

5 Focus on Birmingham, Alabama

5.1 Birmingham, Alabama: Analysis by Concentric Rings

This method of analyzing gasoline station data involves dividing the city of Birmingham into a series of geographic regions bounded by concentric rings. The rings are uniformly spaced and have a common center located close to downtown Birmingham. The upper portion of Figure 23 shows the outermost ring encompassing all gasoline stations within the MPSI survey area. This ring has a radius of 18 miles, and has a center located some 3 miles directly south of downtown Birmingham.

The 18 ring areas are used to characterize station and population densities (stations per square mile or persons per square mile). Figure 23 indicates that the outermost rings are mostly composed of areas with population densities less than 500 persons per square mile. This must be kept in mind when interpreting station and population densities defined by ring regions.

The equation for the land area contained by ring *n* is:

$$A_n = 2\pi R_n - \sum_{n=1}^{n-1} 2\pi R_n$$

Where R_n is the distance from the common ring center to the outermost edge of ring *n*. For the present analysis, the 18 rings dividing Birmingham are each separated by an interval of one mile (i.e., $R_n - R_{n-1} = 1$ *mile*).

Figure 24 indicates the density of gasoline stations per ring and the moving average station density for groups of three rings. Figure 25 indicates the total gasoline output per ring. Apart from the peaks in ring densities within rings 4-6 and 9-10, stations per ring and total output per ring values are relatively consistent: both fall off relatively steadily moving away from the city center.

Figure 26 indicates the number of stations per ring by station size. A close examination reveals that stations of different sizes are distributed more or less uniformly throughout the urban area. Figure 27 shows the percentage of gasoline output increasing as a function of the percentage of land area, moving outwards from the city center. Approximately 50 percent of the total gasoline output occurs within the innermost 22 percent of the city, and 72 percent occurs within the innermost 45 percent of the city. (It should be noted, however, that this definition of land area is based upon the outermost ring indicated in Figure 23, and does not correspond to the land area shown in Table 1.)

Despite this concentration of fuel use near the city center, Figure 23 indicates that a ring-shaped pipeline system with a 6 mile radius would pass through at least two areas with low population and fuel use densities. This suggests that a branched distribution system may be more suitable for the city of Birmingham than a single ring-shaped distribution system.

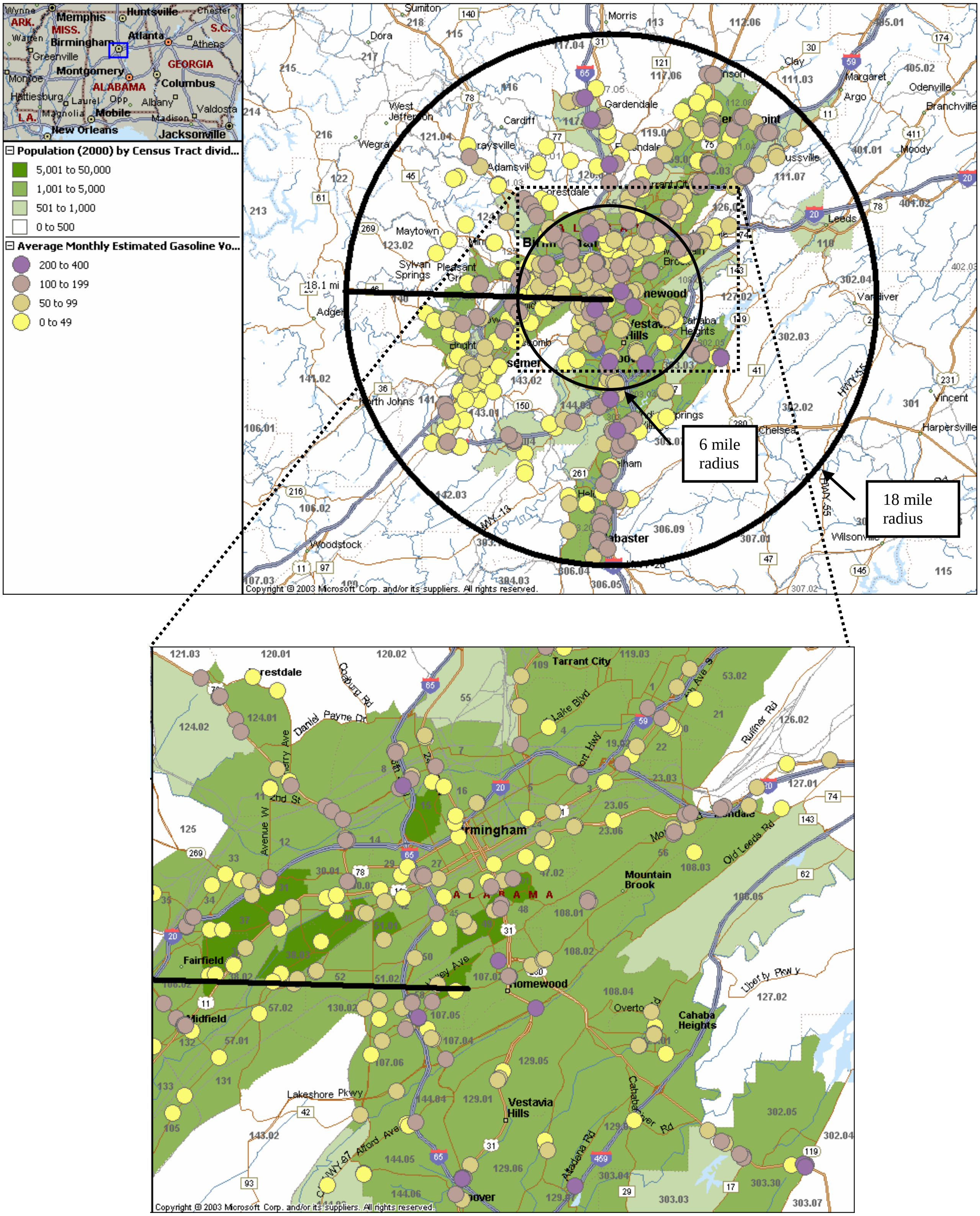

Figure 23. Outermost ring and proximity of its center to downtown Birmingham. Green shades indicated population densities, and station colors indicate average monthly output.

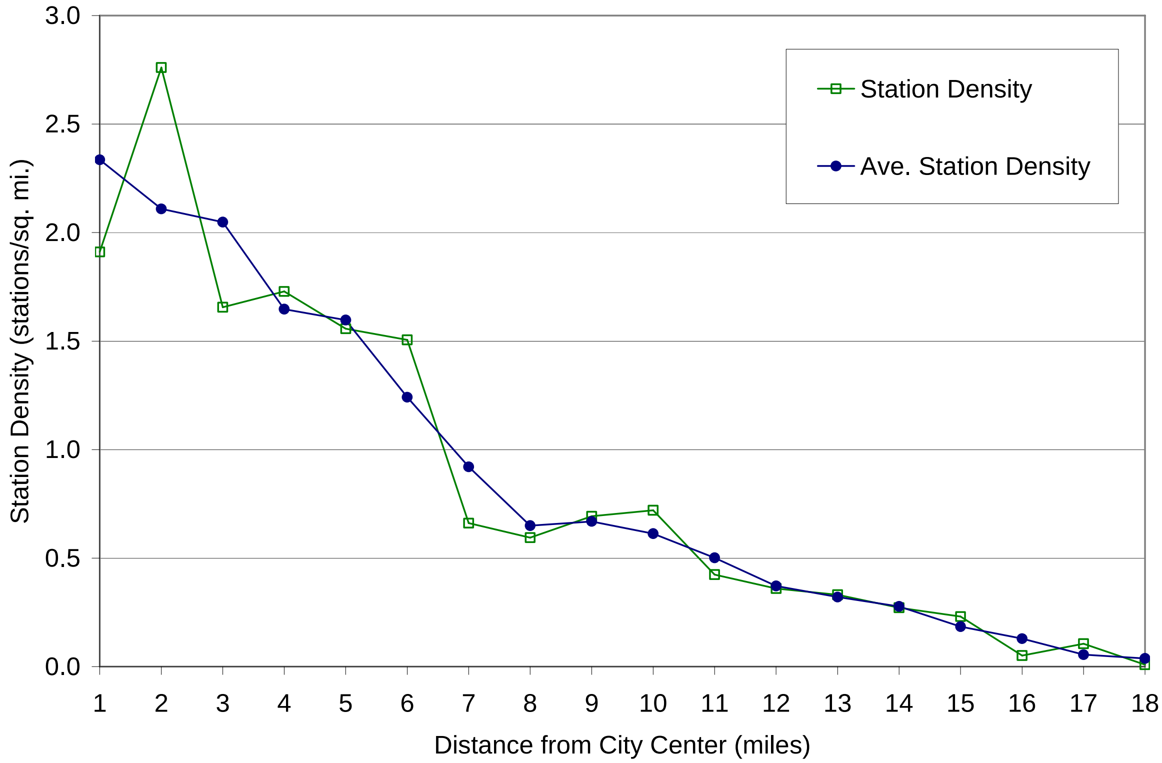

Figure 24. Single ring and three-ring average stations densities (Birmingham, AL).

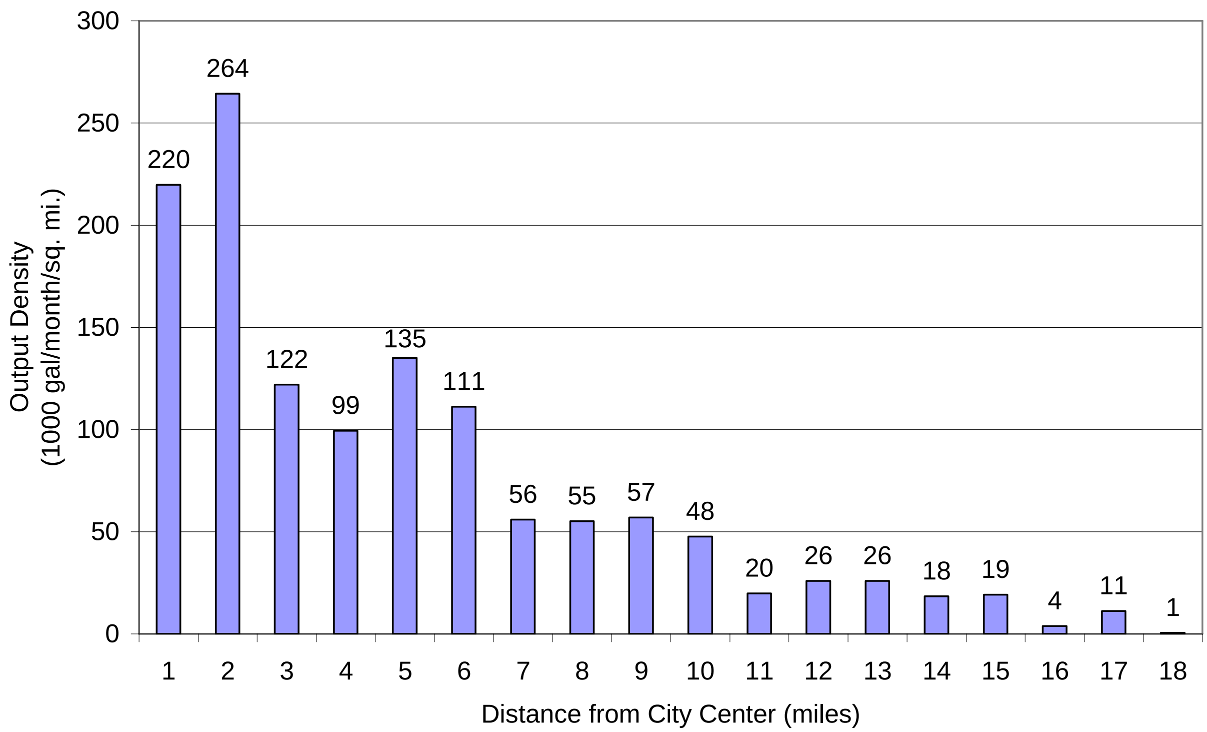

Figure 25. Output density per ring (Birmingham, AL).

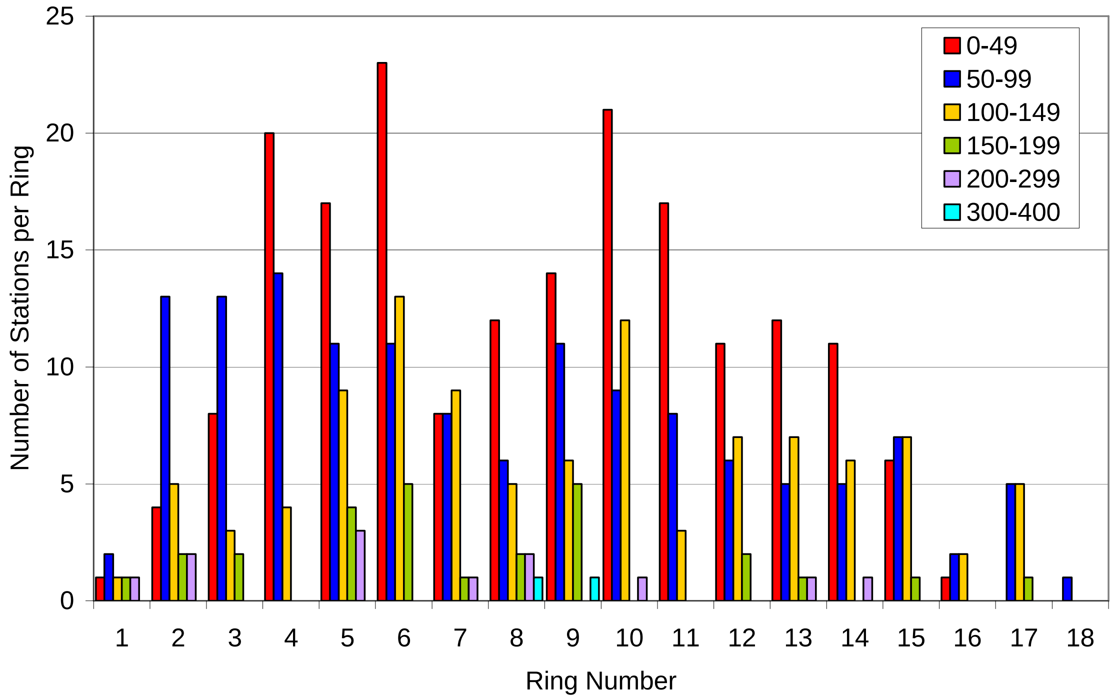

Figure 26. Stations per ring by station size (1000s gal/month; Birmingham, AL).

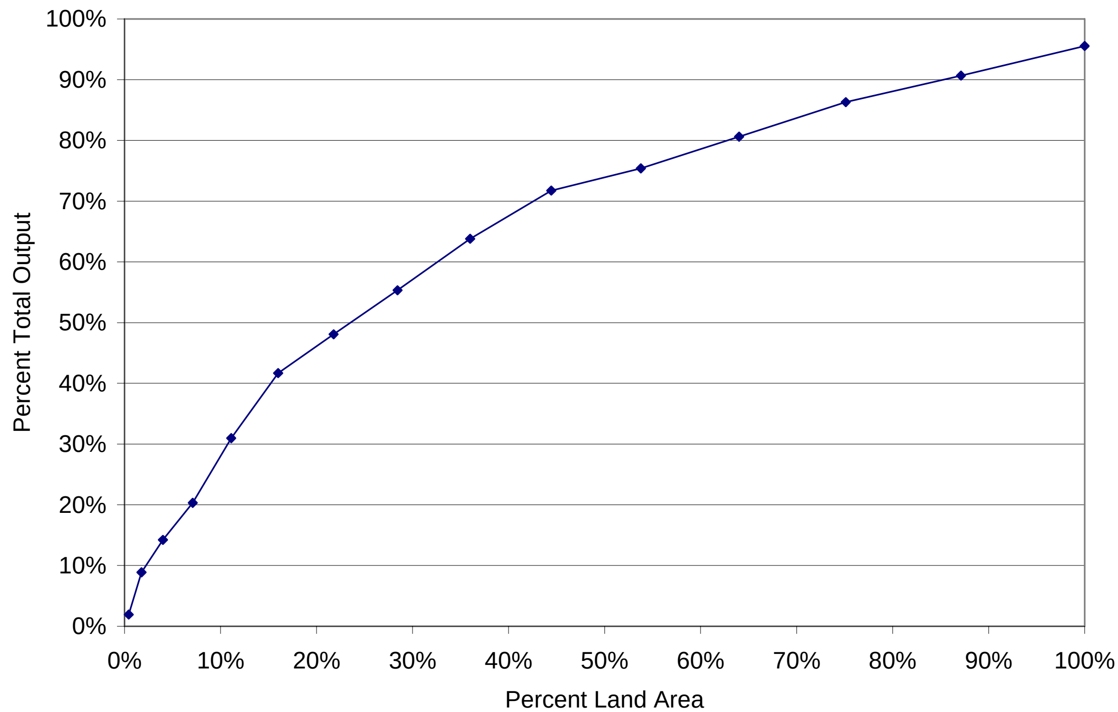

Figure 27. Percent of total output by percent of land area, with land area percentage increasing outwards from the city center (Birmingham, AL).

5.2 Birmingham, Alabama: Cluster Analysis

A consistent clustering routine is applied to combine groups of stations in close proximity to one another into single stations, resulting in a reduced network with fewer but generally larger stations. At each clustering step, stations within a defined distance from one another are combined into a single station. The output of the remaining station is set equal to the total of all stations clustered, while other stations within each cluster are eliminated from the network. The total output of the network therefore remains constant while the number of stations is reduced.

The clustering routine begins by identifying a clustering distance measured in miles. Clustering distances used in the present analysis increase in 0.1 mile increments between 0.1 and 1.0 miles, and also include 1.3, 1.6, 2, 3, 4 and 5 miles. Potential stations clusters include any groups of stations enclosed by a circle centered on an individual station with a radius equal to the cluster distance. Once potential station clusters have been identified, subsets of all potential clusters are combined into single stations. The criteria used to identify this subset are the following:

1. Potential clusters with the greatest number of stations are combined. If two or more overlapping potential clusters enclose an equal number of stations, the cluster that would result in the largest single station is combined.
2. Among potential clusters enclosing the same subset of stations, the cluster centered on the largest station determines the location of the single combined station.

These two criteria are applied iteratively, and in order, until all stations within the clustering distance from one another have been combined into single stations. Note that for potential clusters enclosing the same subset of stations (e.g. pairs of stations, trios of stations all within the cluster distance from one another, etc.), the first criteria is not sufficient because each of the possible combined stations would have the same output.

This methodology is demonstrated by examining the hypothetical station network shown in Figure 28. Large circles indicate the cluster distance from a set of five stations. Of all the stations shown in this network (each indicated by a small circle), only Station A is not within the clustering distance from any other station, and therefore will not be combined into a larger station at this clustering distance. In addition to the circle centered on Station A, circles have been drawn around stations, C, F, G and H. Each of these stations is at the center of a potential cluster containing three to four stations. Furthermore, these four potential clusters overlap one another, and because two of them contain fours stations (C and H) applying only Criteria 1 will not be sufficient to determine which potential clusters should be combined. The location and size of the resulting combined stations will therefore depend upon both the total number of stations within each potential cluster and the relative sizes of each station.

Applying Criteria 1, one of the two potential clusters centered on stations C and H will be combined first. Each of these two potential clusters encloses four stations, so the cluster to be combined will depend upon the sum of the station capacities enclosed by each cluster. Assume that the four stations within the cluster centered on Station C have a greater combined output than the four stations within the cluster centered on Station H. In this case, Stations B, D, and I are eliminated from the network, and a larger combined station located at the coordinates of Station C will be included in the reduced network. Notice that because Station I has been eliminated, the potential clusters centered on Stations F, G and H now each enclose three stations. Applying Criteria 1 again, assume that combining Stations G and J into station H would result in the largest station. In this case, only Stations E and F remain, and they would be combined into a single station located at the position held by the larger of the two stations. In an alternate case, assume that the potential cluster centered on Station G has a larger combined output than the potential clusters centered on Stations F or H. In this case, Stations F and H are combined into Station G and Stations E and J remain as unclustered stations in the resulting reduced network.

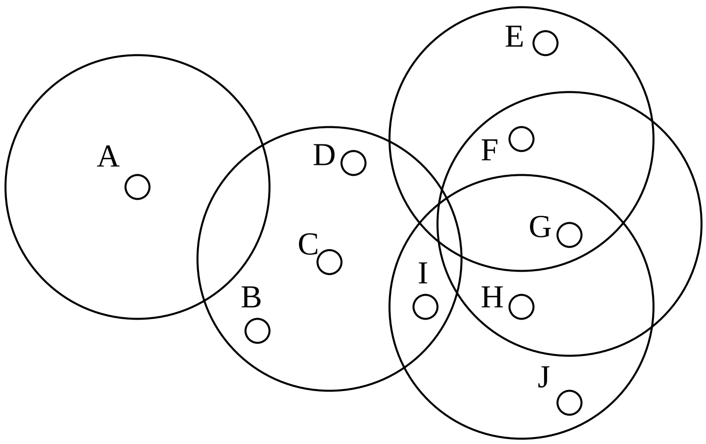

Figure 28. Network Clustering Example.

The results of applying this clustering methodology to the network of stations serving Birmingham are summarized in Figure 29, which also shows clustering results for the cities of Hartford and Salt Lake City. In general, the results of this analysis are similar to those from the other two cities: between 35 and 43 percent of stations are located within 0.1 miles of another station (38 percent in the case of Birmingham), and 70 to 76 percent of the total number of stations are eliminated when a clustering distance of 1.0 miles is applied (76 percent in the case of Birmingham).

It is not clear why Birmingham and Salt Lake City have such similar clustering patterns, or why they cluster more densely than Hartford. Station density certainly plays a role, but does not provide a complete explanation because the density in Salt Lake City is much higher than in Birmingham (1.42 vs 0.93 vs. stations per square mile, compared to Hartford at 0.56 stations per square mile). Additional stations must be analyzed using this clustering analysis to provide a general description of trends in station clustering.

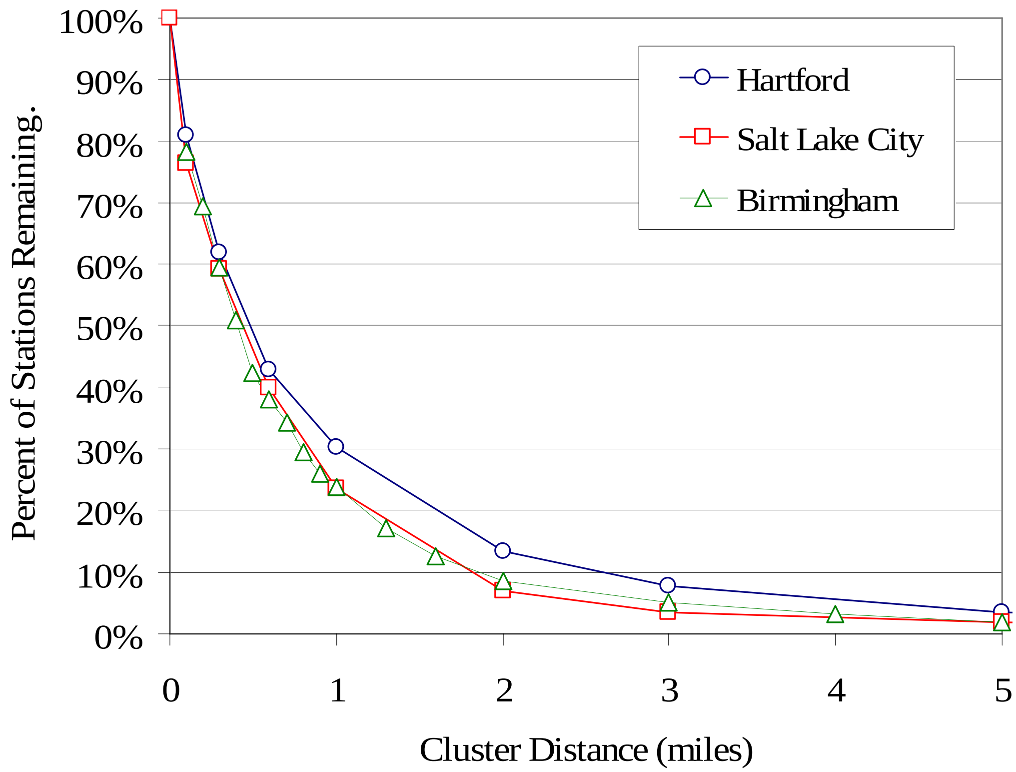

Figure 29. Percent of stations remaining at various cluster distances.

6 References

Melaina, 2004. Analysis of MPSI Gasoline Station Data for: Hartford, Salt Lake City, Phoenix and Atlanta. Prepared for the HyTrans model. November 18.