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Refueling availability for alternative fuel vehicle markets: Sufficient urban station coverage

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A R T I C L E I N F O

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A B S T R A C T

Alternative fuel vehicles can play an important role in addressing the challenges of climate change, energy security, urban air pollution and the continued growth in demand for transportation services. The successful commercialization of alternative fuels for vehicles is contingent upon a number of factors, including vehicle cost and performance. Among fuel infrastructure issues, adequate refueling availability is one of the most fundamental to successful commercialization. A commonly cited source reports 164,300 refueling stations in operation nationwide. However, from the perspective of refueling availability, this nationwide count tends to overstate the number of stations required to support the widespread deployment of alternative fuel vehicles. In terms of spatial distribution, the existing gasoline station networks in many urban areas are more than sufficient. We characterize a sufficient level of urban coverage based upon a subset of cities served by relatively low-density station networks, and estimate that some 51,000 urban stations would be required to provide this sufficient level of coverage to all major urban areas, 33 percent less than our estimate of total urban stations. This improved characterization will be useful for engineering, economic and policy analyses.

1. Introduction

Transportation energy systems face a number of long-term challenges, including climate change, urban air pollution, energy security, limited inexpensive oil resources and continued growth in demand for transportation services. In the light-duty vehicle sector, vehicle fuel economy improvements are an effective means of addressing each of these challenges (DeCicco et al., 2001; Greene et al., 2005; NAS, 2002). However, the benefits of efficiency improvements will prove limited in the long term if future demand projections are realized (EIA, 2006). Mode shifting and smart growth can reduce automobile dependency, but may have limited potential in countries such as the United States where personal vehicles are strongly entrenched. Given these limitations and future demand projections, alternative fuels such as liquid biofuels, synfuels, hydrogen and electricity must play a fundamental role in achieving future social, environmental and economic goals (Birky et al., 2001; Greene and Schafer, 2003; WBCSD, 2001). The lack of retail stations is one of the major barriers to the adoption of alternative fuel vehicles (AFVs), especially dedicated AFVs that operate on a single fuel. The present analysis improves our understanding of this barrier by estimating how many alternative fuel stations would be needed to satisfy the refueling needs of the general population living in urban areas. Analysis of sufficient rural coverage is more challenging, and is not addressed directly in this study.

Adequate refueling availability is fundamental to the commercialization of AFVs. Owners of flex-fuel or bi-fuel vehicles are more likely to use alternative fuels if retail stations are prevalent.[1] And the adoption of dedicated AFVs, which rely exclusively on an alternative fuel, is wholly contingent on refueling availability—-consumers will not purchase vehicles that they cannot refuel, regardless of the cost or performance of vehicle technology. Moreover, refueling availability may be an important cost factor for some fuels. For liquid fuels with energy densities similar to gasoline, retail costs will likely comprise a relatively small fraction of the total fuel cost. For lower energy density fuels, and for hydrogen in particular, retail costs may be a significant fraction of total fuel costs due to the higher capital costs of storage and handling equipment, as well as production costs for stations that produce hydrogen onsite (H2A, 2005; NAS, 2004). An improved characterization of refueling availability can contribute to ongoing and future efforts to commercialize AFVs.

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[1] Flex-fuel vehicles can be powered by blends of fuels contained in a single tank, such as gasoline/ethanol blends, while bi-fuel vehicles can be powered by two fuels contained in separate tanks, such as gasoline/CNG vehicles.

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The existing network of gasoline stations may offer some insights into the refueling availability requirements of future AFVs. Unfortunately, reliable, detailed and consistent nationwide data on the coverage provided by this network does not exist. National and regional perspectives on the issue of refueling availability therefore remain obscure, though some micro-scale studies have offered important insights (Greene, 1998; Nicholas et al., 2004). Comprehensive nationwide data are reported on a state basis through the annual survey conducted by National Petroleum News (NPN) (NPN, 2006). However, as discussed in Section 3, these data are inconsistent among states, do not distinguish between urban and rural stations, and are best interpreted as an overestimate of the actual number of public gasoline stations.

The present analysis makes two contributions to our understanding of refueling availability. First, we build on existing data sources to estimate how many gasoline stations serve urban areas and how many serve rural areas. Second, we demonstrate that the existing station network provides more than adequate coverage in many urban areas, and we propose a *sufficient* level of coverage that meets the refueling needs of the general population living in urban areas. This sufficient level of station coverage is based upon a subset of cities served by relatively low density station networks, and is expressed as a function of urban area population density, with higher density cities requiring a higher density of alternative fuel stations. Moreover, this characterization provides a context for interpreting previous studies that estimate a *necessary* level of coverage to support early AFV markets—the relatively sparse coverage that would satisfy the refueling needs of AFV early adopters. Of the approximately 175,000 gasoline stations reported by NPN in 2000, we estimate that some 75,800 were located in urban areas, and that 51,000 of these stations (67 percent) would provide a sufficient level of urban refueling availability while maintaining some degree of retail competition. This characterization of urban and rural refueling station networks will prove useful for engineering, economic and policy analyses of future efforts to introduce AFVs.

This paper is presented in six sections. Following this introduction, Section 2 reviews the issue of refueling availability with respect to AFVs. Section 3 reviews the 100-year history of gasoline retailing and offers a perspective on future trends. Section 4 describes our estimate of the total number of urban and rural refueling stations, and presents various comparisons to verify that our parametric representations of stations are consistent with related transportation and demographic trends. Section 5 expands on this analysis by proposing a sufficient level of refueling availability in urban areas, and Section 6 provides a brief summary.

2. Refueling availability

Many attempts have been made to promote alternative fuels, but success stories, such as Brazil and Argentina (Fracchia, 2000; Goldemberg et al., 2004), tend to be exceptions among a longer list of failures. Public support for refueling stations alone does not assure success, as has been demonstrated with compressed natural gas vehicles in New Zealand and Canada, and methanol vehicles in California (Flynn, 2002; MacDonald, 2005; Yeh, 2007). Several studies (Leiby and Rubin, 2004; Melaina, 2002; Sperling, 1988) have discussed the chicken-and-egg problem associated with dedicated AFVs, which involves a bind between three major stakeholders: consumers reluctant to purchase vehicles that cannot be refueled, vehicle manufacturers reluctant to produce vehicles that will not be purchased, and fuel providers reluctant to provide fuels for vehicles that do not exist. Given the stasis and market failures reinforced by this three-way bind, and considering the public benefits of many alternative fuels, government agencies have a justifiable role as a fourth critical stakeholder. Government support for the adoption of alternative fuels may involve a wide range of options, including financial incentives, mandates, information dissemination, development of codes and standards, labeling and certification, and stakeholder coordination.

Support for early alternative fuel stations is often discussed in terms of strategic niche management, in which AFVs are first introduced into controlled and centrally refueled fleets, such as government, utility or commercial fleets (Kemp et al., 1998). This strategy is a component of AFV support provided through the 1992 Energy Policy Act and the 1990 Clean Air Act, and it underlies the structure of the Clean Cities program (DOE, 2007). Though these efforts are ongoing, the fleet approach has met with limited success with light-duty vehicles in the United States, and the strategy may prove to be limited due to a variety of factors (GAO, 2000; McNutt and Rogers, 2004; Nesbitt and Sperling, 1998). For example, refueling facilities serving centrally fueled fleets are often not available to the public and many centrally refueled fleet vehicles also rely on public refueling stations. Though niche market programs can result in technological learning and improved stakeholder communication and coordination, they are not sufficient to bring about the widespread commercialization of AFVs.

A more ambitious strategy will be required to move beyond niche markets and overcome the chicken-and-egg challenge. At some point in time, a *necessary* level of station coverage must be established to satisfy the refueling needs of a large fraction of potential AFV early adopters. As a response to the chicken-and-egg problem, this strategy is ambitious due to the timing and scale of the endeavor: a large number of stations will be needed, they must be dispersed across relatively large geographic regions and they must be operational before AFVs are successfully mass-produced and sold. The coupled relationship between the automobile manufacturing and transportation fuels industries is explicitly recognized by this strategy: the extent of the refueling coverage achieved must enable demand for vehicles proportional to the economies of scale needed to reduce AFV production costs. In the case of hydrogen vehicles and infrastructure, this "initiation" strategy has been examined by researchers (Melaina, 2005; Melaina and Ross, 2000; Wurster, 2002), advocated by industry (Gross et al., 2007; McCormick, 2003), and adopted (at least in part, and conceptually) by government agencies (CEPA, 2005; FDEP, 2007; HyNor, 2007). The capital costs and investment risks associated with this strategy would be large. However, the risks faced by fuel providers would be smaller in scale than the financial and technological risks faced by auto makers in deploying large volumes and multiple models of advanced AFVs, such as hydrogen fuel cell vehicles. As discussed elsewhere, fuel costs are a relatively small component of total vehicle lifecycle costs (Ogden et al., 2004). Establishing a necessary level of refueling availability is one of the many inputs required to support the AFV technology innovation process (Norberg-Bohm, 2002; PCAST, 1999; Popper and Wagner, 2002).

The financial risks associated with installing early alternative fuel station networks will be proportional to the level of refueling availability needed to support early AFV markets. This necessary level of availability cannot be quantified precisely, but it can be estimated. Some studies have characterized a necessary level of refueling availability in terms of the percentage of existing gasoline stations in a given area. In a study of consumer behavior and expectations, Kurani surveyed vehicle owners during the introduction of diesel vehicles in California and natural gas vehicles in New Zealand (Kurani, 1992; Sperling and Kurani, 1987). Analysis of initial survey results suggested that concerns over refueling availability diminished rapidly after approximately

15 percent of existing stations provided the alternative fuel, and subsequent analysis suggested that the level was closer to 10 percent (Nicholas et al., 2004). A consumer survey by Greene (1998) was relatively consistent with this result, concluding that the cost of inconvenience to consumers would decrease rapidly if approximately 10–25 percent of existing stations provided an alternative fuel. An inherent shortcoming of these types of percentage estimates is that the total number of gasoline stations varies between cities and regions. As discussed in Section 4, station densities (i.e., stations per square mile) may vary by a factor of two between urban areas of similar size and population density. Due to the risks of stranding capital in early refueling station networks, a more robust methodology for estimating necessary coverage levels is desirable.

Estimates of a necessary level of refueling availability have also been made on an absolute basis. Melaina (2003) developed two simple estimation approaches for urban areas based on land area and miles of major roads, concluding that coverage at 18–25 square miles per station would require approximately 1600–4500 stations, and major urban road lengths of 10–20 miles per station would require approximately 3100–6200 stations. The first land area approach treats all urban areas similarly, while the second approach accounts for road network structure and may therefore provide a better representation of required coverage. A more recent and detailed study by Melendez and Milbrandt (2006) found similar results. Nicholas et al. (2004) employed a traffic model to optimize station locations by minimizing the average consumer travel time to the nearest station. Their analysis suggests that an average driving time of 3 min would be achieved if 48 stations in the Sacramento region (roughly 16 percent of existing stations) provided an alternative fuel. In subsequent analyses of multiple urban areas, equivalent levels of convenience were achieved at different percentages of stations: higher population density cities required a lower percentage of stations to ensure the same average driving time (Nicholas and Ogden, 2006). Reports from E4Tech and LBST estimate that less than 5000 stations could provide adequate coverage for early markets in Europe (E4Tech, 2005; Wurster, 2002).

Refinements to these types of necessary coverage estimates will allow for more effective policy support for AFVs, and will clarify the market opportunities and investment risks faced by businesses pursuing AFV technologies. However, the broader issue of refueling availability remains poorly understood, partly due to ambiguity surrounding the coverage being provided by the existing network of gasoline stations. The following section provides a historical review of gasoline retailing, which serves as a context for the improved characterizations of the existing network presented in Sections 4 and 5.

3. A brief history of gasoline retailing

The history of gasoline retailing can provide a context for estimates of future levels of refueling availability. Fig. 1 presents various metrics spanning the 100-year history of gasoline retailing, including various types of station counts, total registered light-duty vehicles, and total gasoline consumption. As indicated, in 1929, some 20 years after the introduction of the Ford Model T, the number of registered vehicles had reached 24.5 million. This corresponded to one car for every five persons, compared to roughly four cars for every five persons today. Fig. 1 also indicates fuel consumption by motor vehicles, primarily gasoline, which increased in step with the number of registered vehicles until the first energy crisis in 1973. Several subsequent price spikes resulted in fluctuations in gasoline consumption, but both registered vehicles and gasoline consumption have followed an upward trend since WWII. Projections from the Energy Information Administration suggest that this growth will continue, though fuel economy improvements from the Energy Independence and Security Act of 2007 will temporarily dampen the growth rate of fuel consumed by light-duty vehicles (EIA, 2008).

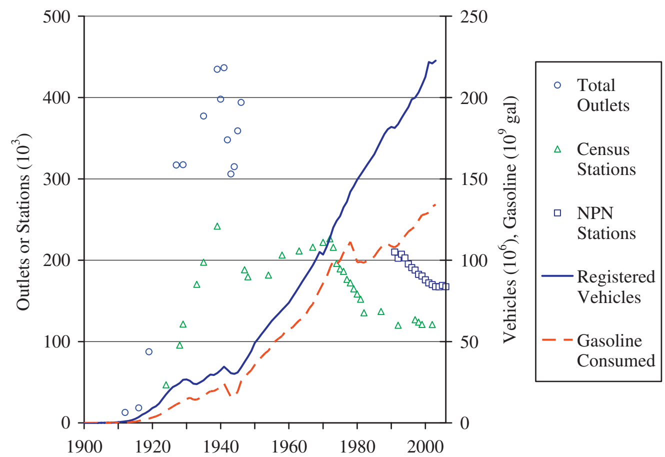

Fig. 1. Historical trends in gasoline outlets and stations, registered vehicles and gasoline consumption (NPN: National Petroleum News).

Fig. 1 also indicates various estimates of the total number of refueling locations between 1900 and 2006. Station growth trends have not followed registered vehicle or fuel use trends. On the contrary, they have had a nearly inverse relationship over most of the last century, and especially since the early 1970s. Data points for this period of time are taken from a variety of sources, some of which are inconsistent in scope and over time, but each being a nationwide estimate of the total number of establishments providing motor vehicle fuels. Two types of gasoline refueling establishments are indicated before 1950: stations and outlets. In general, "station" data are taken from relatively consistent census records and represent establishments that primarily provide gasoline to vehicles but may also provide some additional services. By comparison, "outlet" data are taken from a broader collection of sources and represent any establishment or location providing gasoline, perhaps as just one of multiple services. Data adhering to this definition of outlets could not be found after 1946 (though NPN data from some states may comply with this definition, as discussed below). The outlet numbers, which are inclusive of the census station data, provide insight into the degree of refueling availability provided for early vehicle markets: approximately 100,000 refueling locations had been established by the early 1920s and more than 300,000 were in operation by the early 1930s. As discussed elsewhere (Melaina, 2007), these early outlets proliferated rapidly and included a variety of gasoline refueling methods, including cans sold in general stores, barrels located at repair garages, handcarts operated by roaming vendors, and curb pumps located alongside urban streets and in front of rural general stores. These innovative "non-station" refueling methods ensured a sufficient level of refueling availability for early adopters of gasoline vehicles. Over time they were replaced by high-volume refueling stations.

According to census records, station numbers grew slowly but steadily between the end of WWII and the first energy crisis in 1973. As indicated in Fig. 1, the number of census stations peaked at approximately 226,000 stations in 1972, dropped rapidly between 1973 and 1982, and have continued to decline at a slower rate up to the present. This atrophy occurred despite continued growth in registered vehicles and fuel consumption. This trend probably applies to all gasoline stations, but the census station counts reported after WWII are underestimates of the total number of gasoline stations due to the census definition of establishments that qualify as gasoline stations. The definition has varied over time, but recent counts only include establishments that attain more than 50 percent of total revenue from gasoline sales. This census criteria tends to exclude busy convenience stores and does not capture the recent rise in stations co-located with big box stores (EIA, 2001).

In an attempt to compensate for the shortcomings of the census gasoline station count, NPN began conducting a state-by-state survey in 1991 that would report "…all retail outlets of any kind at which the public can buy gasoline." (NPN, 2006) The data reported in the annual NPN survey are collected from a variety of state agencies, such as Weight and Measures or Departments of Agriculture. A cursory examination of the historical NPN data suggests that state agencies use distinct and inconsistent methods to collect information on gasoline stations. For example, of the 510 data points reported for the 50 states and Washington, DC, for the years 1997 through 2006, 95 counts are reported in round numbers in the hundreds of stations, suggesting an imprecise accounting or estimation method. On 26 occasions during this same time period, different state counts change by more than 25 percent in a single year, though average annual fluctuations have become smaller over time. NPN offers explanations for some of these inconsistencies, which are often due to changes in state accounting systems. Moreover, and importantly for our purposes, the NPN survey probably overestimates the total number of gasoline stations to some degree by including a wide range of establishments that sell gasoline, such as marinas or card-lock private fleet pumps (Richards, 1999). The NPN counts are therefore best interpreted as an approximate upper bound on the total number of gasoline stations. These shortcomings aside, the NPN survey appears to be improving in precision over time and is the most comprehensive estimate available of the total number of gasoline stations. NPN data are used as the basis of our analysis of rural stations in Section 4.

The persistent trend of an increasing number of vehicles being served by fewer and larger stations suggests that refueling availability has historically been more than sufficient. Station numbers have fluctuated over time, but from the perspective of spatial convenience and accessibility, there does not appear to have been a period of real inconvenience since the early 1920s. By some measures, today's nationwide network may be considered sparser and more spatially efficient than any previous network. For example, based on the numbers shown in Fig. 1, the vehicle per station ratio has increased from a low of around 100–250 vehicles per station (or outlet) in the 1940s to approximately 1400 per station today. But the historical decline in station numbers shown in Fig. 1 does not necessarily suggest that reductions will continue into the future. Continued growth in registered vehicles and fuel use, as well as continued urban sprawl, must eventually result in a leveling off and increase in the total number of stations. On the other hand, if super stations such as those being installed at large box stores continue to capture market share, station numbers could remain steady or continue to decline for some time. Whether station numbers continue to decline, stabilize, or begin to increase is uncertain. Given this uncertainty, the present analysis does not attempt to forecast future station counts. As will become clear in Section 5, our parametric representation of sufficient urban coverage is relatively independent of these trends. This is not the case, however, for the estimates of urban and rural station counts presented in the following section.

4. Urban and rural fueling stations

The distinction between urban and rural refueling availability is pertinent for the deployment of AFVs that will likely be first introduced in large volumes in urban markets. Concentrating AFV deployment in urban areas would reduce the infrastructure capital needed to provide necessary refueling availability, and the limited range of some early vehicle models may make them less appealing in rural markets (e.g., hydrogen or electric vehicles). Refueling availability between major urban areas can be achieved by installing stations along interstates and other major arterial corridors (Melaina, 2003; Melendez and Milbrandt, 2005). After vehicle markets have been established in urban areas, and increased inter-urban travel justifies greater refueling coverage between urban areas, rural populations near interstates may begin to adopt more AFVs. Estimates of investments required to establish early station networks can therefore benefit from a more detailed characterization of stations in urban and rural areas.

There are various sources of data on US gasoline station counts, but none provide an accurate distinction between urban and rural station networks. Census records report station numbers within Metropolitan Statistical Areas (MSA), but these counts are underestimates, as discussed above, and MSA boundaries are based upon county boundaries that often include rural areas, especially in the west. Surveys of particular urban markets are available from various market research organizations, such as MPSI, OPIS, and the Lundberg Survey (Lundberg, 2007; MPSI, 2007; OPIS, 2007). However, these sources typically focus on a subset of competitive urban markets and rarely survey rural markets. The volunteer-based Gas Price Watch has accrued an impressive listing of both urban and rural stations, providing price data on 128,500 stations in March of 2008, 22 percent less than the 2007 NPN survey result. By comparison, the 2002 Economic Census reported 120,902 stations, 30 percent less than the NPN survey result for the same year. Unlike more detailed surveys, the NPN survey reports aggregate station counts by state, making no distinction between urban and rural stations.

In the present analysis, urban area survey results acquired from MPSI are used to estimate the number of stations in all major US urban areas. The resulting urban station counts are then subtracted from NPN state counts to provide an estimate of rural stations by state. Given this approach, our estimates of rural station counts are overestimates to the same extent to which NPN survey results are overestimates of state-level station counts. Despite this tendency, and the inevitable incongruence associated with combining two distinct data sources, the resulting rural station estimates are reasonably consistent when compared with various state metrics.

A unique definition of urban area has been developed to accommodate the MPSI survey boundaries and to provide a consistent representation of urban and rural areas. On a conceptual level, refueling availability can be discussed in terms of a unified urban area served by a continuous network of fueling stations. Unified urban areas are identified here as *urban basins*, suggesting a boundary within which there is a high density of refueling activity and outside of which refueling activity diminishes significantly. Urban basins are defined with respect to population density and on a census tract basis. Urban basins include contiguous census tracts with population densities greater than 250 persons per square mile (ppsm), resulting in 438 urban basins in the lower 48 states, all containing at least 30,000 persons. These urban basins are comparable to the 447 Urban Areas in the lower 48 states identified by the year 2000 census as contiguous densely populated areas containing at least 50,000 persons (US Census Bureau, 2002). The discrepancy between the number of urban basins and census Urban Areas is due to two factors: (1) a reduction resulting from adjacent Urban Areas being combined into single urban basins, and (2) an increase resulting from additional urban basins meeting the 250 ppsm criteria and falling within the MPSI survey boundaries

Table 1
Characteristics of different urban area types in the lower 48 states

Urban area definition	Number of areas	Population (millions)	Population (% Total)	Land area (sq. mi.)	Average population density (ppsm)
Metropolitan statistical area	278	228.1	81.2	705,762	289
Urban area	447	191.1	68.0	71,655	2162
Urban basin (this study)	438	191.0	68.0	109,203	1825

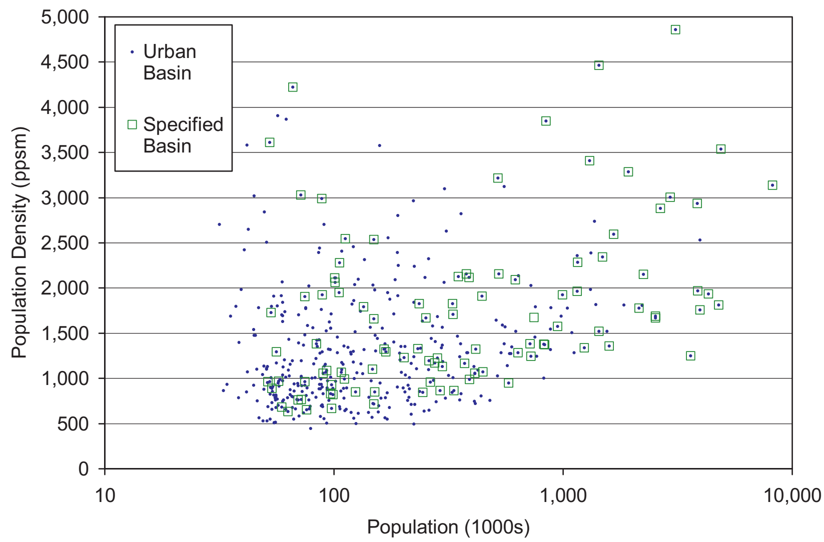

Fig. 2. Population density vs. population for urban basins and specified basins.

(as discussed below). The net effect is a reduction in total urban areas, with nine fewer urban basins than census Urban Areas. Urban basins tend to have total populations similar to corresponding Urban Areas but are more inclusive in terms of land area. In Table 1 urban basin characteristics are compared with census Metropolitan Statistical Areas and census Urban Areas, as defined by the 2000 census.

The criteria used to characterize urban basins are relatively consistent with the spatial distribution of the MPSI data. The MPSI survey results include the latitude and longitude coordinates for all gasoline stations located within the boundaries specific to each survey. Of the 438 urban basins discussed above, 103 are located within the MPSI boundaries of various surveys conducted between 1998 and 2002. These 103 urban basins are referred to as *specified basins*. These basins are a subset of the total number of urban basins, and MPSI survey results indicate the total number of stations located in each of the 103 specified basins. Gasoline stations reported by the MPSI surveys but not located within specified basins (i.e., rural stations) are excluded from the analysis.

The 103 specified basins are representative of large US urban areas in that they include a range of urban area sizes and population densities and are located in multiple geographic regions. Fig. 2 demonstrates that specified basins are well distributed across the range of urban basin populations and population densities. Table 2 demonstrates the geographic distribution of specified basins, indicating the percent of urban basins and urban basin populations within five regions: Pacific, Mountain, Midwest, South, and Northeast.[2] Specified basins account for 16–37 percent of all urban basins in each region, and 50–79 percent of the total urban population in each region. In total, specified basins include 24 percent of all urban basins and 62 percent of the total US urban population.

Fig. 3 shows the number of stations in each of the 103 specified urban basins as a function of population.[3] The dotted line is a linear fit to all specified urban basins and is shown for reference. In general, there tend to be fewer stations in Pacific cities than in other cities with similar populations, and there tend to be more stations in Southern cities than in other cities with similar populations. The number of stations in cities within the Mountain, Midwest, and Northeast regions are closer to the linear fit to all cities. Likely explanations for this variation include the higher population density of cities in the Pacific versus the South, higher market entry barriers due to stricter regulations, and perhaps the more recent development of urban areas in the Pacific region. Additional analysis would be required to determine the influence of these and other factors.

If we assume that the correlations between station numbers and specific urban basin populations are representative of all major urban areas in each region, we can estimate the number of stations contained within unspecified urban basins. The following power function has been fit to specified basin data for each region:

$$N = aP^b$$

where the number of stations (N) is a function of the total population in a given urban area (P). The a and b parameters and R^2 values shown in Table 2 represent the correlation between station numbers and specified basin populations within each region. Using these parameters, we estimate the number of

[2] The Northeast region includes Maryland and Delaware, otherwise the regions correspond to the regions and divisions used by the US Census (http://www.census.gov).

[3] The correlation between station counts and population ($R^2 = 0.93$) is much stronger than that between station density and population density ($R^2 = 0.45$).

Table 2
City attributes and estimation parameters by region

Region	Number of specified basins	Percent of all urban basins	Population of specified basins (1000 s)	Percent of total urban population	Equation parameters		r^2
					a	*b*	
Mountain	11	30	8,290	69	0.00059	0.964	0.984
Midwest	16	16	23,313	59	0.00099	0.930	0.988
Northeast	13	19	30,936	63	0.00202	0.879	0.987
Pacific	26	37	28,357	79	0.00081	0.922	0.976
South	37	22	27,404	50	0.00298	0.877	0.967
All regions	103	24	118,300	62	0.00175	0.891	0.931

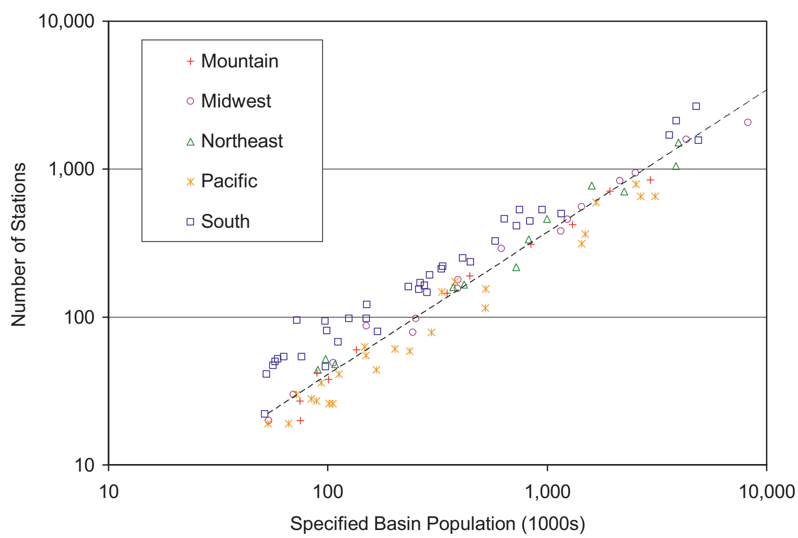

Fig. 3. Station numbers and populations for 103 specified basins.

Table 3
Summary of urban and rural station estimates

Region	Average urban population density (ppsm; by basin)	Urban stations		Average rural population density (ppsm; by state)	Rural stations	
		No.	(per 100 sq. mi.)		No.	(per 100 sq. mi.)
Mountain	1695	4200	78	9	6700	0.8
Midwest	1422	14,300	62	42	27,300	3.7
Northeast	1275	16,100	67	135	9400	6.3
Pacific	2168	9600	76	30	6900	2.3
South	1109	31,600	73	62	48,800	6.0
Nationwide	1425	75,800	70	63	99,200	3.5

stations contained in unspecified basins within each of the five regions. The number of urban stations is then subtracted from the total number of stations reported for each state in the year 2000 NPN survey, resulting in an estimate of rural stations by state. Our estimates of rural stations therefore tend to be overestimates to the same degree that NPN state data are overestimates, while the urban station estimates are derived from more consistent and precise data from MPSI. Additional details regarding the urban basin data analysis are provided in Melaina and Bremson (2008).

Table 3 indicates estimation results by region and the aggregate nationwide result of approximately 75,800 urban and 99,200 rural stations (for the lower 48 states). The average urban population densities are basin averages and the average rural population densities are state averages. The nationwide average station densities are 70 stations per 100 square miles in urban areas and 3.5 stations per 100 square miles in rural areas. Average urban station densities in each region vary from the national average by no more than 12 percent, while rural station densities have a higher degree of variability. Both urban and rural station densities tend to increase with population density, with two notable exceptions: (1) urban stations in the south, which tend to have a higher than average density despite the low average southern urban basin population density, and (2) rural stations in the northeast, which have an average density similar to rural areas in the south but twice the population density. These exceptions are consistent with the observation that there are a larger number of urban stations in the south in general, as discussed above, and the fact that most rural areas in the northeast have relatively high population densities and include many residents with regular access to stations located in nearby urban basins.

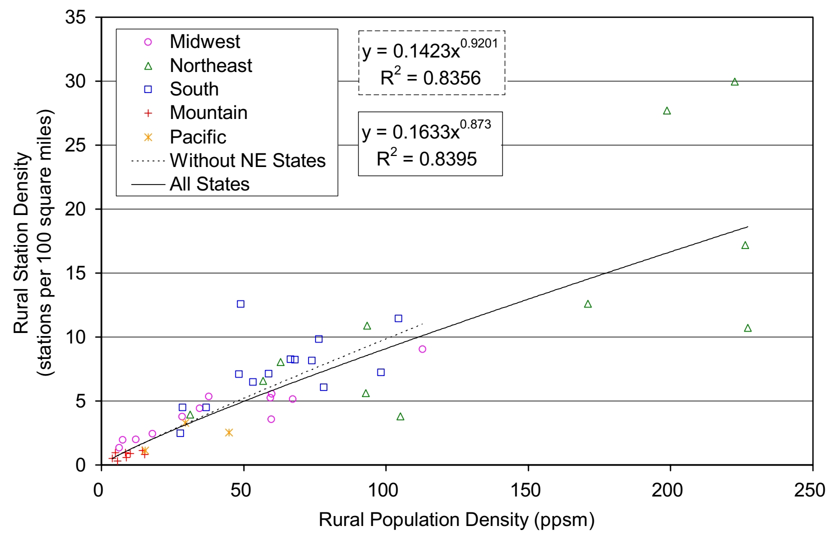

Fig. 4. Rural station coverage vs. rural population density by state and region.

Three trends suggest that our rural station estimates are relatively consistent between states, despite the fact that NPN station counts tend to be overestimates and vary among states in their accuracy (see Section 3). The first trend is indicated in Fig. 4, where rural station densities by state are shown to increase with rural population density. The highest rural station and population densities are seen in Northeastern and Southern states. A power function can be used to represent this trend, and Fig. 4 includes two power functions, one with Northeastern states and one without. One of the outliers in this figure, Louisiana (47 ppsm), can be explained as an overestimate in the count reported by NPN for the year 2000; between 2000 and 2005 the state's NPN count dropped by 38 percent, 10 times faster than the nationwide reduction over the same time period. Two additional state-level trends involve the correlation between the number of rural stations and annual rural vehicle miles traveled (VMT) ($R^2 = 0.74$), and the correlation between rural VMT per rural station and the number of rural residents per station ($R^2 = 0.86$). These trends are discussed in more detail in Melaina and Bremson (2008). Taken together, these three trends suggest a reasonable degree of consistency among state-level data and improve our confidence that combining data from two different sources, MPSI and NPN, provides a meaningful representation of rural station networks.

5. Sufficient urban station coverage

From the perspective of spatial coverage, the number of gasoline stations serving many urban areas is more than sufficient. The density of stations in a particular urban network is dependent upon a number of factors, such as market entry barriers, profit margins, codes and standards, traffic patterns and local retail competition dynamics. These issues have been discussed in economic studies (e.g., Barron et al., 2004; Shepard, 1993) and industry profiles (EIA, 2001). There are consumer advantages to a high density of fueling stations, including greater convenience and price reductions due to increased competition, but these advantages will not necessarily push emerging alternative fuel station densities as high as the gasoline station densities observed today. Examples of factors that may hold alternative fuel station networks at lower densities include higher market entry barriers due to high capital costs (especially for hydrogen stations), increased real estate costs, the trend toward larger stations, urban sprawl and reduced searching times due to onboard vehicle navigation systems. Factors that may require higher station densities include limited vehicle range and any redundancy needed to compensate for more frequent station maintenance or equipment failures.

Estimating stable levels of future gasoline or alternative fuel station densities is beyond the scope of this paper. However, the present analysis can be drawn upon to characterize an existing level of sufficient refueling availability by examining variations in urban station densities. A sufficient level of coverage can be quantified based upon a subset of specified basins with relatively sparse networks of gasoline stations. Fig. 5 shows specified basin station densities and population densities, and indicates six population categories (in millions). Most specified basins have population densities between 1000 and 3000 ppsm and station densities between 0.5 and 1.0 stations per square mile (spsm). Station densities tend to increase with population density and vary significantly among specified basins with similar population densities.

In Fig. 5, the solid line represents a fit to all specified basins and the dashed line is the proposed lower bound for a sufficient level of refueling availability. The lower bound is a fit to a selected number of specified basins with relatively low station densities. Most of these specified basins are located in the Pacific region, as suggested by Fig. 3, but several major urban areas outside the Pacific region also have densities near the lower bound, including Chicago, IL, Washington, DC, Rochester, NY, and the New York-Newark urban area. This station density equation represents the number of alternative fuel stations needed to provide a sufficient level of refueling availability for the general population in a given urban area, while still allowing for some degree of retail competition. Providing this level of refueling availability to all urban basins would require about 51,000 urban stations, 33 percent less than the total number of urban stations estimated above and indicated in Table 3. With projected urban population growth (and sprawl), a greater number of stations may be required to provide the same level of coverage to future urban areas. With regard to the level of refueling availability required to support the widespread commercialization of AFVs, this sufficient level of coverage is a more consistent and appropriate basis than the total number of existing urban gasoline stations.

These results can also be interpreted in terms of consumer travel distance or driving time. Consider a hypothetical city served by a network consisting of pairs of refueling stations distributed uniformly across the city. If this city contained 0.5 million persons and had a population density of 2000 ppsm, approximately 0.5

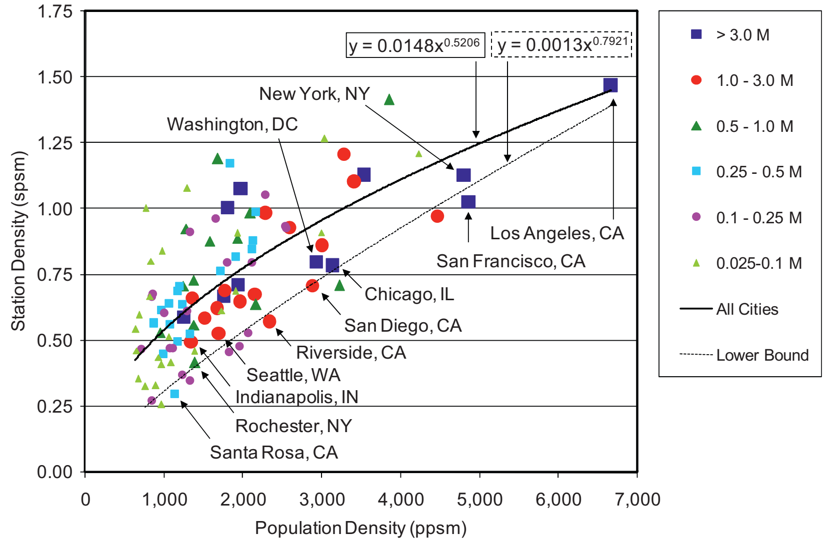

Fig. 5. Sufficient urban station coverage as a function of urban population density. Urban basin populations are indicated in millions of persons.

stations per square mile would be required to satisfy the sufficient station coverage indicated in Fig. 5. With this level of coverage, an urban driver would never be further than 1.4 miles from a pair of refueling stations, and would usually be about 1.1 miles from a pair of stations. Traveling an average of 25 mph, and assuming travel through a grid, this is a maximum driving time of about 4 min and a typical driving time of about 3.3 min. This level of convenience exceeds the consumer preferences suggested for early markets in previous studies (Greene, 1998; Nicholas et al., 2004; Welch, 2007) and allows for some degree of station clustering or retail competition.

It may be argued that existing station networks represent a spatially efficient distribution of stations due to the highly competitive nature of retail station markets. However, Fig. 5 demonstrates that spatially efficient coverage is not a consistent outcome of retail market dynamics. Existing gasoline and diesel stations, and especially stations that are also convenience stores, or "c-stores", compete in markets for a variety of products and services, not just convenient refueling availability. Many c-stores receive substantial support from non-fuel product sales, including sales of snacks, beverages, and cigarettes (NACS, 2003). In addition, some urban areas may experience larger than normal seasonal fluctuations in fuel demand due to driving between cities. Existing station densities may be an economically efficient response to these broader markets, but in many urban areas they are excessive with regard to geographic coverage. The subset of urban areas with station densities near the sufficient coverage threshold indicated in Fig. 5 involve some degree of retail competition, but they do so with a more spatially efficient distribution of stations. In theory, urban networks monopolized by a single firm and selling only motor fuel could remain profitable with even lower station densities. The degree to which competitive dynamics within future alternative fuel retail markets may encourage or suppress investment in higher density networks remains to be seen, and will depend in part upon the business models supporting future station networks.

6. Summary

A lack of refueling availability at the retail level is a fundamental barrier to the adoption of alternative fuel vehicles (AFVs). This problem is more pronounced for dedicated vehicles that operate exclusively on a single fuel, such as hydrogen or electric vehicles, but it is also important for flex-fuel and bi-fuel vehicles that can operate on more than one fuel. A commonly cited source, NPN, reports that there are currently approximately 164,300 refueling stations in operation in the United States. However, our analysis of station counts on a city-by-city basis suggests that this aggregate value is a poor frame of reference for understanding the issue of refueling availability with respect to the commercialization of AFVs. This study offers an improved characterization of the refueling availability provided by existing gasoline station networks. Previous studies have examined refueling availability on the city scale, and have focused on a *necessary* level of coverage needed to support early AFV markets. In contrast, this study outlines an improved national and regional perspective by estimating the following: (1) the number of gasoline stations serving urban areas and the number serving rural areas, and (2) a *sufficient* level of station coverage that meets the refueling needs of the general population in urban areas, while still allowing for some degree of retail competition.

Station counts have declined over the past 30 years of gasoline retailing, and recent trends towards fewer and larger stations suggest that today's network may be more spatially efficient than previous networks. Forecasting future station counts or coverage is challenging due to a general lack of detailed data, and the variety of factors influencing market entry and exit dynamics. This analysis therefore focuses on station counts and coverage provided in the year 2000. Survey data from a market analysis company, MPSI, are analyzed for 103 representative urban areas. These data are relied upon to estimate the number of stations in 335 additional urban areas, with all urban areas summing to 191 million persons, or 68 percent of the total population in 2000. These urban area station counts are then subtracted from NPN state-level data to estimate the number of rural stations by state. Of the approximately 175,000 gasoline stations reported by NPN in 2000, we estimate that 75,800 stations (43 percent) served urban areas and 99,200 stations (57 percent) served rural areas. This distinction is relevant for AFVs that are likely to be first introduced in urban markets.

An examination of station coverage on a city-by-city basis reveals that some cities are being provided with more than sufficient refueling availability—station densities (stations per square mile) can vary by a factor of two between cities of similar size and population density. This suggests that existing retail station markets do not consistently result in spatially efficient coverage, though they may be an economically efficient response to broader markets such as non-fuel products and services provided by convenience stores. Given this observation, we propose a sufficient level of urban station coverage based upon a subset of urban areas served by relatively sparse station networks. This sufficient coverage is expressed in terms of station density and as a function of urban area population density. We conclude that some 51,000 stations could provide a sufficient level of refueling availability for the general public in urban areas, while still allowing for some degree of retail competition. This sufficient coverage estimate for urban areas offers an improved representation of refueling availability needs for AFVs. It can serve as a conceptual upper bound that alternative fuel station networks will evolve towards as AFVs are commercialized, and can therefore contribute to engineering, economic, and policy analyses of alternative fuels. These results improve on the aggregate nationwide station counts that typically serve as a frame of reference for discussions of adequate refueling availability for AFVs.

References

Barron, J.M., Taylor, B.A., Umbeck, J.R., 2004. Number of sellers, average prices, and price dispersion. International Journal of Industrial Organization 22, 1041–1066.

Birky, A., Greene, D., Gross, T., Hamilton, D., Heitner, K., Johnson, L., Maples, J., Moore, J., Patterson, P., Plotkin, S., Stodolsky, F., 2001. Future US Highway Energy Use: A Fifty Year Perspective. Office of Transportation Technologies, Energy Efficiency and Renewable Energy, US Department of Energy.

CEPA, 2005. California Hydrogen Blueprint Plan, vol. 1. California Environmental Protection Agency.

DeCicco, J.M., An, F., Ross, M., 2001. Technical Options for Improving the Fuel Economy of US Cars and Light Trucks by 2010–2015. American Council for an Energy-Efficient Economy, Washington, DC.

DOE, 2007. Clean Cities Website. US Department of Energy, Energy Efficiency and Renewable Energy, [accessed Oct 3, 2007]; Available from ⟨http://www.eere.energy.gov/cleancities⟩.

E4Tech, 2005. The Economics of a European Hydrogen Automotive Infrastructure. A study for Linde AG.

EIA, 2001. Restructuring: The Changing Face of Motor Gasoline Marketing. Energy Information Administration, Washington, DC.

EIA, 2006. Annual Energy Outlook 2006: With Projections to 2030. Department of Energy, Energy Information Administration, Washington, DC.

EIA, 2008. Annual Energy Outlook 2008 (Revised Early Release). Energy Information Administration 2008 [accessed March 14, 2008]; Available from ⟨http://www.eia.doe.gov/oiaf/aeo⟩.

FDEP, 2007. Florida's Hydrogen Program: H2 Florida. Florida Department of Environmental Protection. [accessed October 3, 2007]; Available from ⟨http://www.dep.state.fl.us/energy/sources/hydrogen⟩.

Flynn, P.C., 2002. Commercializing an alternative vehicle fuel: lessons learned from natural gas for vehicles. Energy Policy 30, 613–619.

Fracchia, J.C., 2000. An Overview of the Argentine NGV Experience. World Bank Workshop on CNG Vehicles, Washington, DC.

GAO, 2000. Energy Policy Act of 1992: Limited Progress in Acquiring Alternative Fuel Vehicles and Reaching Fuel Goals. General Accounting Office, Washington, DC.

Goldemberg, J., Coelho, S.T., Lucon, O., 2004. How adequate policies can push renewables. Energy Policy 32, 1141–1146.

Greene, D.L., 1998. Survey evidence on the importance of fuel availability to choice of alternative fuels and vehicles. Energy Studies Review 8, 215–231.

Greene, D.L., Schafer, A., 2003. Reducing Greenhouse Gas Emissions from US Transportation. Pew Center on Global Climate Change, Arlington, VA.

Greene, D.L., Patterson, P.D., Singh, M., Li, J., 2005. Feebates, rebates and gas-guzzler taxes: a study of incentives for increased fuel economy. Energy Policy 33, 757–775.

Gross, B.K., Sutherland, I.J., Mooiweer, H., 2007. Hydrogen Fueling Infrastructure Assessment. GM Research and Development Center.

H2A, 2005. H2A Analysis [accessed 2005 June 27]; Available from ⟨http://www.eere.energy.gov/hydrogenandfuelcells/analysis/model.html⟩.

HyNor, 2007. HyNor—The Hydrogen Road of Norway Last accessed October 3, 2007.

Kemp, R., Schot, J., Hoogma, R., 1998. Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. Technology Analysis & Strategic Management 10, 175–195.

Kurani, K., 1992. Application of a behavioral market segmentation theory to new transportation fuels in New Zealand. Ph.D. Dissertation, Institute of Transportation Studies, University of California, Davis, CA.

Leiby, P., Rubin, J., 2004. Understanding the transition to new fuels and vehicles: lessons learned from analysis and experience of alternative fuel and hybrid vehicles. In: Sperling, D., Cannon, J.S. (Eds.), The Hydrogen Energy Transition: Moving Toward the Post Petroleum Age in Transportation. Elsevier Academic Press, Burlington, MA.

Lundberg, 2007. Lundberg Survey Homepage [accessed January 16, 2007]; Available from ⟨http://www.lundbergsurvey.com⟩.

MacDonald, T., 2005. Alcohol Fuel Flexibility—Progress and Prospects, Staff Paper. California Energy Commission, Transportation Fuels Division.

McCormick, J.B., 2003. Hydrogen and Fuel Cell Overview: Transition to the Transportation of Tomorrow. Senate Science and Technology Caucus, Washington, DC.

McNutt, B., Rogers, D., 2004. Lessons learned from 15 years of alternative fuels experience—1988 to 2003. In: Sperling, D., Cannon, J.S. (Eds.), The Hydrogen Energy Transition: Moving Toward the Post Petroleum Age in Transportation. Elsevier, Burlington, MA.

Melaina, M., Bremson, J., 2008. Documentation of the Specified Basin Dataset on Urban Gasoline Stations. Institute of Transportation Studies, University of California at Davis. Forthcoming.

Melaina, M.W., 2002. Initiating hydrogen infrastructures: preliminary analysis of a sufficient number of initial hydrogen stations in the US, Market Challenges of Fuel Cell Commercialization. Berlin, Sorat Hotel, Spree Bogen.

Melaina, M.W., 2003. Initiating hydrogen infrastructures: preliminary analysis of a sufficient number of initial hydrogen stations in the US. International Journal of Hydrogen Energy 28, 743–755.

Melaina, M.W., 2005. Initiating hydrogen infrastructures: analysis of technology dynamics during the introduction of hydrogen fuel for passenger vehicles. Ph.D. Dissertation, School of Natural Resources and Environment, University of Michigan, Ann Arbor, MI.

Melaina, M.W., 2007. Turn of the century refueling: a review of innovations in early gasoline refueling methods and analogies for hydrogen. Energy Policy 35, 4919–4934.

Melaina, M.W.J., Ross, M.H., 2000. The ultimate challenge: developing an infrastructure for fuel cell vehicles. Environment 42, 10–22.

Melendez, M., Milbrandt, A., 2005. Analysis of the hydrogen infrastructure needed to enable commercial introduction of hydrogen-fueled vehicles. In: National Hydrogen Association Annual Conference, Washington, DC.

Melendez, M., Milbrandt, A., 2006. Hydrogen Infrastructure Transition Analysis: Milestone Report. National Renewable Energy Laboratory.

MPSI, 2007. MPSI Homepage [accessed 2007 January 16], available from ⟨http://www.mpsisys.com⟩.

NACS, 2003. State of the Industry Highlights: Highlights of the Convenience Store Industry's 2003 Performance. National Association of Convenience Stores.

NAS, 2002. Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards. National Academy of Sciences, Washington, DC.

NAS, 2004. The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs. National Academy of Sciences/National Research Council, National Academies Press, Washington, DC.

Nesbitt, K., Sperling, D., 1998. Myths regarding alternative fuel vehicle demand by light-duty vehicle fleets. Transportation Research Part D: Transport and Environment 3, 259–269.

Nicholas, M., Ogden, J., 2006. Detailed analysis of urban station siting for the California Hydrogen Highway network. Transportation Research Record 1983, 129–139.

Nicholas, M.A., Handy, S.L., Sperling, D., 2004. Using geographic information systems to evaluate siting and networks of hydrogen stations. Transportation Research Record 1880, 126–134.

Norberg-Bohm, V. (Ed.), 2002. The Role of Government in Energy Technology Innovation: Insights for Government Policy in the Energy Sector. BSCIA Working Paper 2002-14, Energy Technology Innovation Project, Belfer Center for Science and International Affairs.

NPN, 2006. Annual station count reflects dip in industry. National Petroleum News, Mid-July, p. 96.

Ogden, J.M., Williams, R.H., Larson, E.D., 2004. A societal lifecycle cost comparison of cars with alternative fuels/engines. Energy Policy, 7–27.

OPIS, 2007. OPIS Homepage [accessed January 16, 2007], available from ⟨http://www.opisnet.com⟩.

PCAST, 1999. Powerful Partnerships: The Federal Role in International Cooperation on Energy Innovation. President's Committee of Advisors on Science and Technology, Washington, DC.

Popper, S.W., Wagner, C.S., 2002. New Foundations for Growth: The US Innovation System Today and Tomorrow. Science and Technology Policy Institute, RAND, Arlington, VA.

Richards, M.E., 1999. Quantification of Public Gasoline Fueling Stations with Access to Natural Gas Service. Institute of Gas Technology, Des Plaines, IL.

Shepard, A., 1993. Contractual form, retail price, and asset characteristics in gasoline retailing. The RAND Journal of Economics 24, 58–77.

Sperling, D., 1988. New Transportation Fuels: A Strategic Approach to Technological Change. University of California Press, Berkeley, CA.

Sperling, D., Kurani, K., 1987. Refueling and the vehicle purchase decision: the diesel car case. Society of Automotive Engineering Technical Paper no. 870644.

US Census Bureau, 2002. Urban area criteria for Census 2000. Federal Register 67, 11663–11670.

WBCSD, 2001. Mobility 2001: World Mobility at the End of the Twentieth Century and its Sustainability. World Business Council for Sustainable Development.

Welch, C., 2007. Using HyDIVE^{TM} to Analyze Hydrogen Scenarios. National Renewable Energy Laboratory, Golden, CO. NREL/TP-560-41363 (forthcoming).

Wurster, R., 2002. Pathways to a Hydrogen Refueling Infrastructure between Today and 2020—Time Scale & Investment Costs, Fuel Cell Teach-in. European Commission DGTren, Brussels.

Yeh, S., 2007. An empirical analysis on the adoption of alternative fuel vehicles: the case of natural gas vehicles. Energy Policy 35, 5865–5875.