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Turn of the century refueling: A review of innovations in early gasoline refueling methods and analogies for hydrogen

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Abstract

During the first decades of the 20th century, a variety of gasoline refueling methods supported early US gasoline vehicles and successfully alleviated consumer concerns over refueling availability. The refueling methods employed included cans, barrels, home refueling outfits, parking garage refueling facilities, mobile stations, hand carts and curb pumps. Only after robust markets for gasoline vehicles had been firmly established did the gasoline service station become the dominant refueling method. The present study reviews this history and draws analogies with current and future efforts to introduce hydrogen as a fuel for vehicles. These comparisons hold no predictive power; however, there is heuristic value in an historical review of the first successful and large-scale introduction of a vehicle fuel. From an energy policy perspective, these comparisons reinforce the importance of a long-term and portfolio approach to support for technology development and innovation.

Keywords: Gasoline history; Hydrogen infrastructure; Technology innovation

1. Introduction

When Henry Ford began mass-producing the Model T in 1908, there were only a handful of gasoline refueling stations operating in the US. Most early motorists purchased gasoline in steel cans from general stores, or by the pitcher in automobile repair garages where it was ladled from wooden barrels. These and other types of non-station refueling methods diversified over time and made gasoline widely available before the service station emerged as the dominant refueling method during the 1920s. In contrast to the chicken-and-egg problem facing alternative fuels today, adequate gasoline refueling availability was established well before gasoline vehicle sales began to boom in response to cost reductions achieved through mass-production. What factors contributed to the successful introduction of gasoline for vehicles? What was the role of innovation in ramping up the availability of a new fuel in response to strong demand for new vehicles? What analogies can be drawn to modern alternative fuels such as hydrogen? This paper attempts to answer these questions by reviewing the early history of gasoline refueling and drawing analogies with hydrogen refueling systems.

Some alternative fuels, such as ethanol and biodiesel, can be utilized by the existing vehicle fleet to a limited degree by being blended with conventional fuels. Other alternative fuels, including hydrogen, electricity or pure blends of ethanol or biodiesel used in dedicated vehicles, face a chicken-and-egg infrastructure dilemma: consumers will be reluctant to purchase vehicles until a sufficient number of alternative refueling stations have been installed, vehicle manufacturers will not produce vehicles that consumers will not buy, and fuel providers will not invest in new infrastructure until there is sufficient demand for the alternative fuel (Sperling, 1988; Melaina and Ross, 2000; Melaina, 2003; Kuby and Lim, 2005; Struben, 2006). This dilemma is perhaps more complex for hydrogen than other alternative fuels, due to the great uncertainty surrounding fuel cell vehicle development, the multiple pathways by which hydrogen can be delivered to vehicles, and the diverse number of stakeholders that might be involved in

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early infrastructure development (Melaina, 2005). Several recent publications have reviewed this and other technical and policy challenges facing the introduction of hydrogen vehicles (NAS, 2004; Ogden et al., 2004; Romm, 2004; Sperling and Cannon, 2004).[1] Contemporary efforts to introduce alternative fuels have typically been unsuccessful, heavily subsidized, or both (GAO, 2000; Flynn, 2002; Goldemberg et al., 2004), leaving the history of gasoline infrastructure development as a prime example of the successful introduction of a new motor vehicle fuel.

The history of gasoline in the early 20th century reveals that a variety of delivery methods were employed to meet early motorists' refueling needs, and that the delivery infrastructure evolved through a series of phases before the service station emerged as the dominant refueling method (Abernathy and Utterback, 1978; Anderson and Tushman, 1990). An examination of these innovations and phases provides some insight into the service of providing a motor vehicle fuel, which is unique from that of other energy carriers such as natural gas or electricity. A key issue during the early phases of infrastructure development is the requirement to provide a fuel inexpensively and in small volumes from many locations dispersed across large geographic regions. While many studies have examined the early periods of growth in the electricity and natural gas systems (Casteneda, 1999; Hirsh, 2001), and early petroleum exploration and refining (Williamson et al., 1963a, b; Yergin, 1992), less attention has focused on the early stages of the gasoline retail sector.

Successfully addressing the hydrogen infrastructure chicken-and-egg problem will require a sustained effort over a period of time measured in decades. In 2001, vehicle manufacturers sold some 17 million internal combustion engine vehicles in the US, and fuel providers dispensed some 130 billion gallons of gasoline to support the national fleet of 222 million light-duty vehicles (Davis, 2003). This fuel was supplied through a vast network of public and private refueling outlets, including nearly 170,000 public stations (NPN, 2004). As discussed in a number of studies, a significant fraction of public stations will have to provide hydrogen fuel before consumers are comfortable purchasing hydrogen vehicles (Sperling and Kurani, 1987; Greene, 1998; Melaina, 2003; Melendez and Milbrandt, 2006; Kuby et al., 2007; Nicholas et al., 2004; Welch, 2006). Only after this infrastructure development point has been reached, and after consumers begin to embrace hydrogen vehicles, will the costs of these vehicles begin to drop as a result of mass production and learning. Significant capital, management and labor resources will be required to establish this early hydrogen infrastructure, and it may be some time before enough hydrogen vehicles are deployed to realize positive returns on these investments.

The magnitude of the infrastructure development effort needed to convert the US light-duty vehicle fleet to hydrogen can be examined alongside the history of gasoline use during the 20th century. Fig. 1 compares the historical consumption of gasoline during the 20th century with the optimistic scenario of hydrogen vehicle deployment made by the National Academy of Sciences (NAS, 2004), which has been extended an additional 50 years (dotted line) beyond the original projection. The bottom horizontal axis begins in the year 1900 for gasoline, and the top horizontal axis begins in 2000 for hydrogen. The vertical axes are roughly equivalent, showing billions of gallons of gasoline and billions of kilograms of hydrogen (1 kg of hydrogen has an energy content of 120.1 MJ on a lower heating value basis, while a gallon of gasoline has an energy content of about 121.3 MJ (NAS, 2004)) The NAS study assumes an average fuel economy of about 78 mpgge (miles per gallon of gasoline equivalent) for all hydrogen vehicles in 2050, which is about 3.5 times the average fuel economy of today's light-duty vehicle fleet.

The sustained hydrogen infrastructure expansion required to support this optimistic deployment scenario would occur more rapidly than any infrastructure growth observed in the history of gasoline vehicles. As indicated in Fig. 1, significant vehicle growth for both hydrogen and gasoline vehicles is shown beginning about 15 years after the turn of each century. Domestic gasoline consumption slumped during the depression and WWII, but subsequently regained robust growth until the first oil crisis in 1973–1974, with the strongest growth seen in the 1965–1973 period. The rate of growth in hydrogen fuel use projected by the NAS between 2030 and 2040 is unparalleled in the history of gasoline consumption. Moreover, the growth in hydrogen infrastructure under the NAS scenario would occur at the expense of domestic gasoline consumption, which would decline at a greater rate and on a larger scale than the decline of horse-drawn carriages in the 1920s and 1930s. This is one of many possible scenarios; different stakeholders will typically project different technology adoption rates, as demonstrated in the recent study of vehicle adoption rates by Collantes (2007).

Just as the major technological developments needed for rapid expansion of the gasoline infrastructure were complete by about 1920, major hydrogen infrastructure elements would have to be in place before the "take off" point of hydrogen demand in Fig. 1, which is projected in the NAS scenario to occur between 2020 and 2030. And just as some petroleum companies had started the shift from kerosene to gasoline as early as 1910, major contemporary energy and auto companies would have to have started taking concrete actions toward a hydrogen economy well before this takeoff point. By 1905, gasoline delivery systems were supporting some 78,000 internal combustion engine vehicles in the US (Census, 1976). By

[1]Three other commonly mentioned challenges to be overcome for the successful introduction of hydrogen vehicles are: producing cheap low-carbon hydrogen, reducing the cost and improving the performance of fuel cells, and improving the performance of hydrogen storage technologies (NAS, 2004).

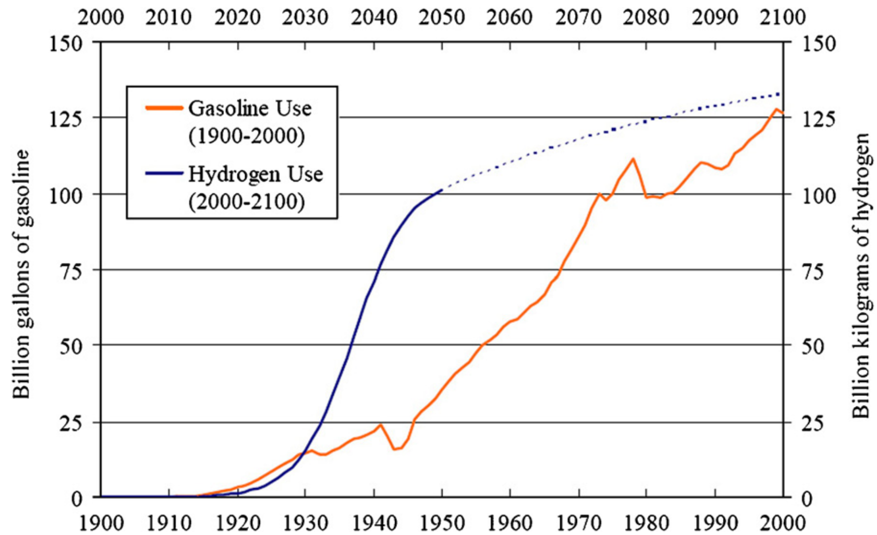

Fig. 1. Two centuries of fuel use. A comparison of historic gasoline use and the optimistic scenario of hydrogen use projected to 2050 by the National Academy of Sciences (2004). The dotted line is an extension of the NAS projection.

comparison, there were approximately 140 hydrogen stations installed worldwide (Crawley, 2006; cf. LBST, 2007), and approximately 600 fuel cell vehicles being tested on roadways by the end of 2006 (Crawley, 2007). Regardless of when the takeoff point for hydrogen may occur, a significant amount of government and industry stakeholder resolve will be required to overcome the chicken-and-egg problem (Melaina, 2005). Successful innovations in early hydrogen refueling technologies will both attract additional stakeholder commitment and facilitate the provision of adequate refueling availability for early hydrogen vehicles.

This study focuses on different types of innovative gasoline refueling methods employed at the turn of the century when gasoline vehicles were first introduced, and draws analogies to technological developments in existing hydrogen refueling systems. Sections 2 and 3 provide an important historical context for the early gasoline industry, and Sections 4 and 5 discuss two general types of refueling methods. Section 6 discusses the strategic and phased aspects of the history of gasoline and draws analogies to existing hydrogen refueling systems. The heuristic value of this history is an evolutionary perspective on the first successful, large-scale introduction of a new vehicle fuel, which may provide insights into the types of future innovations needed to support hydrogen or other alternative fuel systems. The energy policy lessons from this history are general: support for hydrogen technology development and innovation should include a variety of refueling methods and extend over a long time horizon.

2. Kerosene days

The petroleum industry's first five decades, from Colonel Drake striking oil in Pennsylvania in 1859 to the breakup of Standard Oil in 1911, were dominated by the sale of a single petroleum product: kerosene. As the largest corporation of the industrial era, Standard Oil had become a centerpiece of the American business landscape. But discontent with industrial trusts had been growing for several decades, and President Theodore Roosevelt stirred up even greater contempt, focusing on the "Mother of all Trusts", and Standard Oil was legally dismantled by the Supreme Court in 1911 (Yergin, 1992). Standard's rise to power occurred before the exploitation of oil fields in Texas, California or Saudi Arabia, and before Ford began mass-producing the Model T in 1908. By 1911, gasoline vehicle costs were coming within reach of a typical household, and real growth in the petroleum industry had just begun.

When kerosene production began to give way to gasoline production in response to demand for gasoline vehicles, the petroleum industry was ready for another major expansion period. Domestic markets for kerosene and lubricants began to show signs of saturation during the first decade of the century, and international oil producers had become more competitive. In addition, coal-based town gas and electrical lighting were becoming cheaper and superior alternatives to kerosene lamps in urban areas. Coincidentally, the introduction of motor vehicles and the corresponding increased demand for gasoline arrived just in time to sustain continued growth in the petroleum industry. Gasoline accounted for less than 10 percent of the volume of products recovered from the distillation of crude oil in 1904, but the fraction steadily increased and exceeded 40 percent by the 1930s. This shift occurred at the expense of kerosene recovery, which accounted for nearly 50 percent of crude products in 1904 but dropped to as low as 5 percent by 1930 (Williamson et al., 1963a).

The kerosene legacy played an important role in the petroleum industry's rapid shift away from lighting and toward the production and delivery of fuels and lubricants for vehicles. The elaborate kerosene production and distribution infrastructure was composed of more than

100 refineries and vast networks of bulk storage facilities and tank wagons. Kerosene distribution had evolved into an extensive and highly decentralized system, and providing gasoline through this existing delivery system was relatively simple, at least initially. In 1906, Standard Oil operated nearly 3573 bulk stations in the US. These storage facilities received barrels or tank wagons of petroleum products directly from refineries, and redistributed them to local populations. Due to the poor conditions of local roads before the 1920s, and a loosely applied Standard Oil policy, the typical delivery radius from a bulk station was about 12 miles. The result was a large number of dispersed and relatively small bulk stations, most of which operated with only one or two horse-drawn wagons (Williamson et al., 1963a, b).

This extensive petroleum product distribution system ensured that gasoline was accessible to both urban and rural populations in low volumes before the introduction of the automobile. Gasoline was also supplied in relatively large volumes to obscure niche markets in manufacturing and industry, and production capacity was far greater than demand by gasoline vehicles: early records suggest that about 7 million barrels of gasoline were produced yearly as early as 1905, and only 600,000 of these barrels were consumed by roughly 78,000 registered motor vehicles. Most of this gasoline was being used as a solvent in cleaning establishments or in chemical and industrial plants, but it was not uncommon for refineries to simply dump gasoline into nearby rivers if demand did not justify the cost of delivery (Pogue, 1939; Williamson et al., 1963a, b). A rural gasoline market did develop to support stationary engines used on farms and later gasoline-powered tractors, both of which proved superior to the use of steam engines. The widespread availability of gasoline, in both urban and rural areas, is suggested in a *New York Times* article from 1900 discussing the relative merits of electric, steam, and gasoline vehicles, where the author weighs in on the side of the gasoline vehicle in noting its "practically unlimited area of operation, as the gasoline with which it is operated may be bought at any country drug store" (Walker, 1900). This pervasive availability and excess capacity served as a foundation for rapid growth in gasoline retailing when gasoline vehicles began to be sold in large numbers.

3. One hundred years of gasoline retailing

Nearly 100 years ago in downtown Seattle, Mr. John McLean mounted a 30 gal tank on a wooden post, attached a flexible hose, and began selling gasoline to passing motor vehicles. The year was 1907, and Mr. McLean was soon dispensing gasoline to some 15 vehicles per day from what may have been the first urban gasoline station in the history of the US (Witzel, 1993). There are a variety of claims to the first gasoline station, but this station was unique for at least two reasons. First, it was located near an urban center and along a major transit route, Holgate Street, just off the Alaskan Way. Second, Mr. McLean, a sales manager for Standard Oil of California, had an innovative solution to the problem of storing and delivering large volumes of gasoline within an urban area: a small pipe connected his retail station to a nearby petroleum refinery. This first simple station would have taken minimal effort to construct, but it relied upon petroleum refining technology that had been evolving through decades of innovation. Mr. McLean's first refueling station was not a new technological invention, but rather the extension of a pre-existing infrastructure to provide a new type of energy service.

Mr. McLean's 1907 Seattle station was successful due in part to a steady supply of gasoline from a nearby refinery, but it was also successful due to a steady supply of customers. Reports that this first station was soon serving some 200 vehicles per day are not unlikely: by 1907 there were 142,000 registered motor vehicles consuming over 71 million gallons of motor fuel per year in the US (Pogue, 1919, p. 20; Williamson et al., 1963b, p. 194; Census, 1976). However, this success story poses a dilemma: if McLean's station was indeed the first US urban gasoline station, how had these tens of thousands of early gasoline vehicles refueled before 1907?

Various records suggest that strong growth in gasoline station populations did not begin until the early 1920s. Most records on the number of early refueling stations are vague and inconsistent, but two frequently quoted sources suggest there were 15,000 stations in place by 1920 and 30,000 in place by 1923 (Anonymous, 1924; Reiser, 1936). In 1924, the first year that the survey reported on fueling stations, the US Census reported 46,904 stations. Five years later, in 1929, the count had more than doubled to 121,513 stations. These numbers suggest that the takeoff period for gasoline stations occurred between 1915 and 1925, but exponential growth in vehicles began around 1910, so the rise of gasoline filling stations followed rather than preceded the rise of gasoline vehicles.

The explanation for this sequence is that gasoline was made available widely and in relatively large volumes through a variety of non-station delivery methods before service stations became the dominant method of refueling. Many of these non-station delivery methods were short-lived innovations, but they constituted a key phase in the evolution of the gasoline delivery infrastructure. Some of these methods, such as cans, barrels and home refueling pumps, emerged concurrently with the introduction of gasoline vehicles; other methods emerged as demand for gasoline increased. Due to the widespread availability of gasoline through non-station delivery methods, few motorists were inconvenienced by a lack of refueling after about 1910 or 1915—the same period in which gasoline vehicle sales reached their takeoff point. Non-station refueling methods allowed vehicles to be mass-produced without sales being inhibited by consumer concerns over limited refueling availability.

The significance of these early non-station delivery methods, which are discussed in detail in Section 4, becomes apparent when examined within the broader context of the history of gasoline retailing. Fig. 2 shows major trends in gasoline dispensing, gasoline consumption, and the growth of registered motor vehicles during the 20th century. Data points marked as *census stations* indicate the number of establishments identified as fueling stations by the US Census, which has typically defined service stations as any establishment deriving more than half of its revenue from the sale of motor fuels. Linear interpolations have been made between these census station values. Other reports of filling stations, taken from a variety of sources, including some census reports, are indicated in the figure as *other stations*. These data include alternative census definitions, such as franchise establishments or stations with paid employees, as well as non-census sources with alternative filling station definitions. Values shown for *total outlets* are taken from multiple non-census sources, and indicate the total number of establishments providing motor fuels, filling station or otherwise. The total outlet values shown after 1990 are from annual surveys conducted by *National Petroleum News* (NPN). Of these various sources, the NPN survey results are the most comprehensive recent estimates (Melaina and Bremson, 2007), but comparable data are not available before 1991.

An examination of these and other sources suggests that growth in non-station outlets began at least 10 years before significant growth in filling station populations. The second *outlet* data point shown in Fig. 2 (indicated by an empty square), represents roughly 18,500 garages dispensing gasoline as a service to accompany vehicle repairs in 1916 (Williamson et al., 1963b). However, garages composed only a fraction of the total outlets available at this time. Approximately 1.2 billion gallons of gasoline were consumed by vehicles in 1916 (Pogue, 1919, p. 20). If these 18,500 repair garages had been dispensing all of this fuel, they would have been dispensing, on average, about 4 barrels of gasoline per day. This rough calculation suggests that other types of outlets must have been providing significant amounts of gasoline. The third outlet data point indicated in Fig. 2 (87,500 outlets in 1919) is the midpoint of an estimate of 75,000–100,000 outlets in operation around 1919–1920 (Ashton, 1932, cited in Williamson et al., 1963b, p. 469). The fourth outlet data point is 317,000 outlets in 1927, which includes 52,000 garages, 125,000 drive-in stations (also shown as *other stations*) and 140,000 curb pumps (NPN, 1928b).

The trends shown in Fig. 2 suggest that the early gasoline retailing sector quickly became overdeveloped soon after the mass production of gasoline vehicles. With over 220 million registered vehicles being served by approximately 170,000 public gasoline stations in 2004 (NPN, 2004; Davis and Diegel, 2006), it is apparent that some 242,000 refueling stations, or a total of more than 400,000 gasoline outlets, was an excessive number of refueling locations for the 31 million vehicles registered in 1939. These numbers suggest some 1300 vehicles per station in 2004 compared to 75–130 vehicles per outlet in 1939. This period of over-development in the gasoline retail sector continued through the Great Depression and was followed by a period of moderate growth between WWII and the first energy crisis in 1973–1974. There has been a persistent decline in the total number of stations since the 10-year shakeout period following the first energy crisis, despite continued growth in both vehicle sales and gasoline consumption. Rather than developing at similar rates and in parallel over time, the 100-year history of change in the number of gasoline stations and gasoline vehicles suggests an almost inverse correlation, especially since the oil crisis of 1973–1974. While the economies of scale and logistics of providing

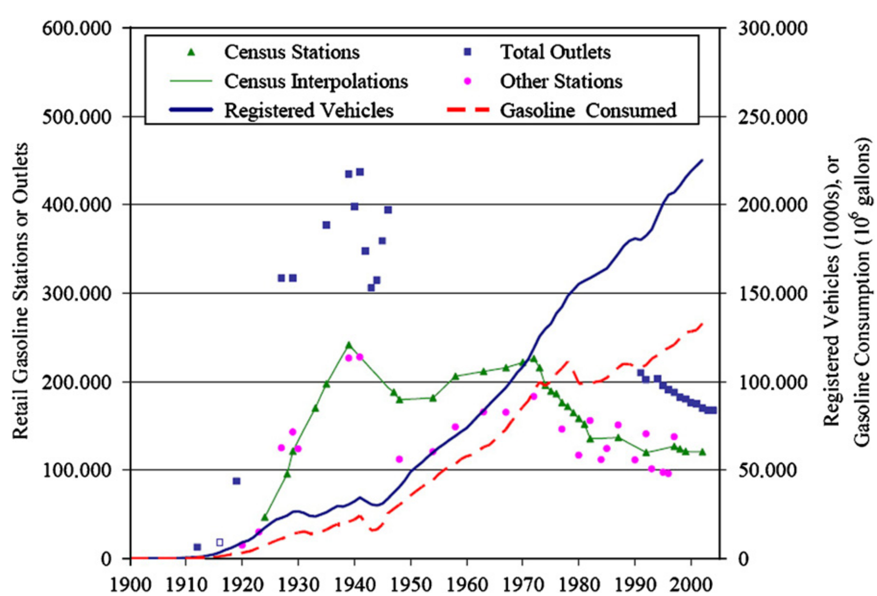

Fig. 2. One hundred year history of gasoline stations and outlets, with registered vehicles and gasoline consumption shown for reference.

motor vehicle fuels have improved over time, trends in the vehicle-to-station ratio suggest that the availability of refueling has decreased over time.

Gasoline was widely available to motorists in the early decades of the 1900s, but this historical development alone does not justify the claim that a large number of hydrogen stations must also be needed for the successful introduction of hydrogen vehicles. However, as a prime example of the successful introduction of a new motor vehicle fuel, the history of early gasoline infrastructure development is consistent with the ‘‘initiation’’ concept of requiring a sufficient threshold of stations before the introduction of large numbers of hydrogen vehicles (Melaina, 2003). More interesting, at least for the present discussion, is that the introduction of gasoline was completed not through the installation of a large number of gasoline refueling stations, but rather by supplying gasoline through a variety of innovative non-station delivery and dispensing methods, which were subsequently phased out as service stations became dominant. Characteristics of these non-station methods and how they evolved over time are discussed in the following section.

4. Dispersed gasoline delivery methods

A wide variety of gasoline delivery methods preceded the conventional gasoline station, which did not become the dominant refueling method until the mid-1920s. Six of these early delivery methods, categorized here as *dispersed* methods, tended to share common attributes, such as low output capacity, low upfront costs, location flexibility and distribution in parallel with other services. In addition, three types of early *dedicated* gasoline stations preceded the fully developed service station, which dominated gasoline refueling for most of the 20th century. The major difference between dispersed refueling methods and dedicated stations is that the latter required land dedicated to the service of refueling while the former did not. Most of these historical gasoline delivery methods have direct analogies to infrastructure systems that support hydrogen vehicles today, as discussed in Section 6. The six dispersed methods, discussed below in more detail and in their approximate order of introduction, are the following:

1. Canned gasoline.
2. Garage barrels.
3. Home filling pumps.
4. Local parking facilities.
5. Mobile refuelers.
6. Curb Pumps.

Canned gasoline: Cans of gasoline were delivered by truck along with cans of kerosene, and retailers placed them on store shelves alongside other petroleum products, such as heating oil, greases or wax. Delivered cheaply and easily by jobbers (i.e., independent distributors) or refiners, gasoline cans sometimes contained as much as five gallons of fuel, making them difficult for motorists to handle. But cans could be distributed to both urban and rural locations in low volumes, and most motorists considered them to be a convenient method of acquiring or even stockpiling gasoline. Canned gasoline was also used as a solvent for cleaning and as a fuel for stationary gasoline engines before the widespread adoption of motor vehicles.

Garage barrels: While many outlets sold cans of gasoline only occasionally, some establishments, such as popular general stores or automotive repair garages, soon attracted a steady stream of gasoline purchasing customers and required a higher capacity method of storing and dispensing gasoline. The common solution was to have a barrel of gasoline on hand, usually located around the back of a building or in the corner of a garage. Fig. 3, dating from 1901, depicts a storekeeper drawing gasoline into a bucket from a barrel with a spigot contained in a lockable outdoor cabinet. Notice the approaching chauffeur and sign proclaiming ‘‘Gasoline for Automobiles.’’ As the lockable cabinet suggests, drawing gasoline for motor vehicles was a cumbersome and probably rare activity for this 1901 storekeeper.

Dispensing gasoline from barrels was not necessarily a user-friendly activity. Both canned gasoline and barrels relied on the ‘‘pour-and-funnel’’ or ‘‘drum-and-measure’’ dispensing approach. For barrels, this would typically involve ladling gasoline into a pitcher, carrying it to the vehicle and pouring it into the fuel tank through a funnel lined with a chamois filter. The chamois filter was relied upon to remove impurities, a precaution that was probably important for environments such as garages, where gasoline was still used in its more traditional role as a solvent to clean parts, tools or clothing. The pour-and-funnel method was messy, dangerous, and inconvenient. This is apparent from Fig. 4, which shows a group of men testing an experimental filtering contraption mounted on a vehicle's sideboards. Notice the labor intensity of the task, the pitcher and funnel, the 5-gal can and the pool of gasoline below the vehicle. Very early motorists (i.e., early adopters)

Fig. 3. Drawing gasoline from a barrel in 1901 (Vieyra, 1979, p. 4).

Fig. 4. Demonstration of the pour and funnel method. (Courtesy of the Arizona Historical Society, Tucson, Arizona).

apparently accepted a significant amount of inconvenience in refueling their vehicles.

As the number of customers purchasing gasoline increased in any given location, can and barrel methods became increasingly inconvenient. Furthermore, barrel storage was inefficient and dangerous due to evaporative losses. The shift away from the pour-and-funnel method occurred with the introduction of a new core technology: the gasoline pump. Dispensing methods that employed pumps, and eventually hoses linking the pumps to vehicles, proved to be much more effective at storing and dispensing gasoline, eclipsing the can and barrel methods as demand for more convenient refueling increased.

Home refueling pumps: An early alternative to garages and canned gasoline was the installation of home refueling *outfits*, which consisted of a private pump located in the garage and connected to an underground tank. Work by Sim suggests that over 70 different models of private home and commercial indoor refueling pumps were introduced between 1900 and 1915 (Sim, 2002). One of the most famous names in gasoline dispensing history, Bowser and Company, published a brochure in 1905 that boasted a ‘‘dozen different styles’’ of home refueling outfits, each designed to ‘‘meet your careful consideration both as to equipment and price’’ (Bowser, 1905). The brochure displays a variety of pump and tank configurations, suggesting the existence of a discerning and possibly large clientele.

Home gasoline outfits removed most concerns about local refueling availability, and eliminated the need for special trips to a garage or general store to acquire fuel. Though convenient, ownership of a home refueling outfit burdened the homeowner with maintenance and an increased risk of fire or spills. Home refueling may also have limited an owner’s willingness or incentive to shop around for cheap fuel, though home outfits were more popular with wealthy motorists, many of whom were probably not concerned with fuel costs. The installation costs of home refueling outfits would have been a fraction of the cost of most early pre-mass production and luxury automobiles.

Local parking facilities: Early motoring often centered around the custom of touring on weekends or holidays. Many early motorists, not accustomed to daily driving and thus not in need of daily access to their vehicles, stored their vehicles in neighborhood or downtown storage facilities for extended periods of time. This, along with more frequent urban driving, led to increased demand for downtown parking facilities. Many of these facilities either dispensed gasoline as an additional service or were co-located with a refueling or auto repair establishment. While some facilities contained onsite filling stations open to the public, others refueled parked vehicles using push- or hand-carts (see below). Gasoline sales would not have been the main source of revenue for these facilities, especially if they were located in high-end sections of town and catered to wealthy customers.

Mobile refueling methods: Early gasoline distribution entrepreneurs employed at least three types of mobile refueling methods: dispensing tank wagons, mobile stations, and wheeled handcarts. There is little evidence that dispensing tank wagons or trucks were a popular refueling method, though some tank wagons were equipped with hoses and pumps and most were capable of dispensing via the pour-and-funnel method. Mobile stations also met with only limited market success, but not due to a lack of innovation. For example, *Eddy’s International Portable Service Station* was promoted in 1926 as a means of reducing the overhead associated with dedicated filling stations (Anonymous, 1926). This particular one-truck mobile station was equipped with two 300-gal gasoline tanks, two automatic visible pumps, eight lubricating oil compartments holding 15 gal each, a 60-gal water tank, an air compressor with a 60-gal air tank, two 30-ft dispensing hoses, and four storage batteries. Eddy’s mobile station also carried two fire extinguishers, multiple floodlights, and a canopy large enough to cover two driveways, one on either side of the station. Though elaborate, easily relocated, and probably inexpensive compared to most dedicated stations, Eddy’s and other types of mobile stations do not appear to have gained significant market share.

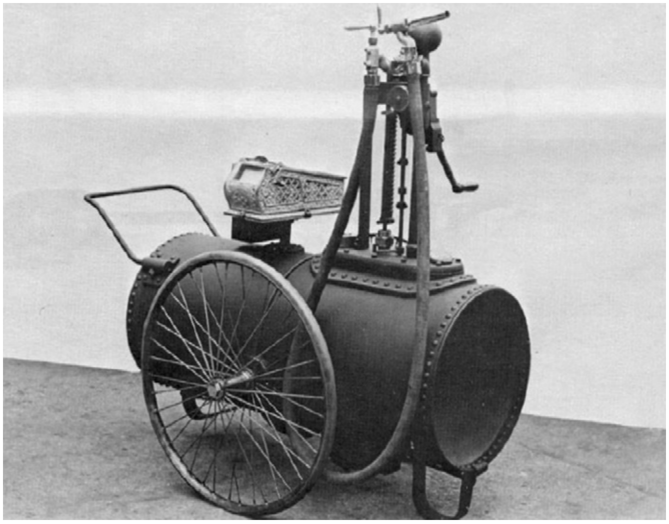

Fig. 5. Bowser handcart from 1912 (Milkues, 1978, p. 14).

Fig. 6. A horse-drawn tank wagon refueling an early Bowser curb pump in front of a King automobile dealer (Milkues, 1978, p. 82).

Fig. 7. Curb pumps on a busy street corner (Margolies, 1993, p. 121).

Of the three mobile refueling methods, wheeled handcarts were the most successful. The wheeled handcart shown in Fig. 5, an early Bowser model from 1912, is a hybrid of four preexisting technologies: a riveted storage tank, two bicycle tires, a Bowser hand pump equipped with dispensing hose and nozzle, and an elegant cash register. New handcart models continued to be introduced throughout the 1920s (Sim, 2002).

Curb pumps: Curb pumps proved to be the precursor to modern day gasoline pumps by enduring and adapting across multiple phases of gasoline infrastructure development. They offered a complete refueling system, and were composed of a gasoline pump, dispensing hose, flow meter and underground storage tank. The modifier "curb" refers to the placement of these early pumps just beyond the curb of a roadway, in the same relative position to the road as a fire hydrant or post office box. Curb pumps were introduced as early as 1907, and dominated refueling in the late 1910s and early 1920s before the rise of dedicated gasoline stations. Fig. 6 shows a horse-drawn tank wagon refilling an early Bowser curb pump located in front of a King auto dealer. Many curb pumps were located in front of, and were often owned by, businesses that either wanted to attract more customers or that catered specifically to a motoring clientele.

Bowser was one of the first companies to sell and begin mass-producing curb pumps, and their success resulted in curb pumps being known simply as "Bowsers", regardless of the actual manufacturer. Other major early pump manufacturers included Tokheim, Milwaukee, and Gilbert and Barker. Multiple models of curb pumps began to be produced around 1913. By 1915, approximately 150 different models had been introduced, and more than 380 additional models were introduced between 1915 and 1920 (Sim, 2002). Though consistent records of total production volumes are not available, curb pumps were probably produced both in great variety and in large numbers, as they could be mass-produced, delivered and installed at low cost. A survey conducted by Bowser in 1920 reported an average of one curb pump every 0.46 miles along 600 miles of major roads in New York, Nebraska, Texas and California (NPN, 1928a). Attendants handled the nozzle and pump at popular curb pumps, and were typically paid by the week and discouraged from accepting tips. As curb pumps proliferated, motorists became accustomed to the convenience of pulling alongside a curb to refuel without leaving their vehicle.

Curb pumps became both more profitable and more common as gasoline consumption began to grow exponentially after 1915. Many early filling stations had yet to embrace a service mentality, making curb pumps relatively equivalent to filling stations in terms of both convenience and amenity, yet having the advantages of low capital costs, low overhead costs, low labor costs, and typically prime locations. Describing this period of curb pump proliferation, Witzel (1993, p. 34) states, "The gasoline pump was everywhere and had become an integral part of the street side arrangement by 1920, taking its place on the sidewalk with the mailbox, the street lamp and the fire hydrant. Automobile owners could find fuel just by driving through any major portion of town and pulling up next to any one of many pumps lining the boulevard.'' A *National Petroleum News* survey estimated that some 189,000 curb pumps had been installed at 140,000 locations by 1927 (NPN, 1928b). The busy refueling center shown in Fig. 7 demonstrates that some locations had multiple pumps, some of which were ''split-pump'' stations offering different brands of gasoline. Eventually, after Standard Oil's breakup in 1911, oil companies responded to increased competition by exerting greater control over the retail sector, which put an end to the practice of offering multiple brands of gasoline at a single location (Vieyra, 1979).

Traffic congestion and concerns over public safety proved to be the demise of urban curb pumps. Long lines of waiting vehicles alongside curbsides became nuisances, especially as more and more vehicles took to the road. As accidents became more frequent, curb pumps began to be seen as a significant public hazard. In the early 1920s, certain municipalities began restricting licenses on new curb pumps, and they eventually began to ban them outright. By 1923, 14 major cities had banned the installation of curb pumps (Witzel, 1993, p. 36). This trend did not spread to rural areas, however, where congestion was less of a concern and the curb pump and general store combination continued to be the norm for most gasoline dispensing.

5. Dedicated gasoline stations

Gasoline refueling locations had become abundant by 1915, but many motorists were dissatisfied with the service provided by the various types of dispersed refueling methods. Curb pumps located in busy sections of town developed long waiting lines, and attendants were known to increase prices on the spot, charging ''what the traffic would bear.'' Garages could also take advantage of their position as key outlets by raising prices. And gasoline quality, in general, was an issue for almost any delivery method, as it was not uncommon for vendors to either use low-quality gasoline or dilute their gasoline blends with cheaper kerosene or naphtha fuels.

In response to consumer frustrations with unpredictable fuel prices and service quality, company-owned stations began to both embody and project a sense of reliability and legitimacy. An important marketing advantage that company stations had over most independents was their ability to standardize and associate brand image with quality. For example, in 1922, 40 percent of Shell Oil Company stations were consistent in terms of color schemes, pump equipment, signage graphics and attendants' white uniforms with black bowties (Witzel, 1993). Most company-owned stations began to emphasize service and amenities, though some independents outdid company stations in this respect, especially on the West Coast where the term ''service station'' was first established. Gasoline vendors continued to rely on dispersed methods such as curb pumps, but they could not easily compete with the non-price attributes of dedicated stations, which motorists increasingly embraced due to their reliability, predictability and range of amenities.

Given these trends, dedicated stations began to develop rapidly after 1920. In general, dedicated stations were distinct from dispersed methods in having higher output volumes, higher capital and operating costs, and land and building structures dedicated specifically to refueling and related services. With dedicated land use, urban real estate became a significant cost burden, and oil companies adapted by incorporating real estate expertise into their marketing operations. The increased capital costs of new building structures and higher capacity equipment, such as storage tanks, were dealt with through various innovations. Although service, quality and convenience eventually became standard attributes for major gasoline stations, several types of early stations predated conventional service stations, and some of these types shared attributes with earlier dispersed methods.

Four distinct types of dedicated refueling stations, each discussed in turn below, include the following:

1. Drive-in stations.
2. Trackside stations.
3. Prefabricated stations.
4. Service stations.

Drive-in stations: Service, amenities, and esthetics eventually dominated gasoline marketing, and many stations embraced an architectural beautification movement in the 1920s. This emphasis on esthetics was partly a response to the dismal appearance of early drive-in stations. These stations were typically little more than small industrial shacks, often made of sheet metal to reduce the risk of fire. Many station operators, especially independents, had little interest in the longevity, maintenance, or public perception of their stations, and some drive-in stations would literally appear overnight to avoid local protests. When enclosed vehicles became popular, and driving in inclement weather was possible, some stations extended their rooftops to provide a canopy. But many drive-in stations remained nothing more than a curb pump and a shack recessed into a side street or alleyway. The poor esthetics of these early drive-in stations, as well as their lack of amenities and sometimes less than friendly service, left many motorists with a negative image of the petroleum industry (Witzel, 1993).

Trackside stations: While an increasing number of new outlets were elaborate high-volume service stations, ruthless gasoline price wars simultaneously pushed for innovations to reduce costs. Many stations offered cut-rate prices during price wars to increase sales, but trackside or ''spur'' stations, located alongside railroad tracks or spurs and refueled directly from rail storage tanks, had an inherent cost advantage over other dedicated stations. This advantage was due to the elimination of tank wagon delivery and bulk storage costs, as well as a reduction in overhead costs. Trackside stations were first introduced in rural areas around 1925, and later became competitors in the increasingly intense price wars in overdeveloped urban markets (McLean and Haigh, 1954). These stations were not as convenient as other stations, due to the typically remote location of railroad tracks in urban areas, but low prices were often successful in attracting cost-conscious customers. The price of gasoline was not the only criterion for motorists, however, and trackside stations failed to capture large markets as urban stations increasingly competed by offering non-price attributes and services.

Prefabricated stations: Another filling station innovation was the prefabricated or "prefab" station. Offering reduced capital costs, ease of installation, and a relatively high esthetic standard, prefab stations were the entrepreneur's answer to the allure of gasoline marketing profits. Made entirely of metal parts, these stations were stored in crates in warehouses before shipment and could be assembled on site. A former oil company sales manager reflected on these stations: "If you had $500 and were breathing, I could get you a station" (Koenig, 1984). Witzel (1993), speaking of a more expensive and elaborate prefab model, describes the flexibility of deploying prefab stations: "They were easily bolted together at the building site and had the ability to be moved quickly when a station location proved unprofitable. For the economical price of $2200, one could purchase a future gas station on Monday, have it delivered that afternoon and be ready for the first customer to drive through the Ionic columns to get gas on Thursday." As early as 1915, Shell had devised a steel prefab building that could be erected in a single day, and similar stations

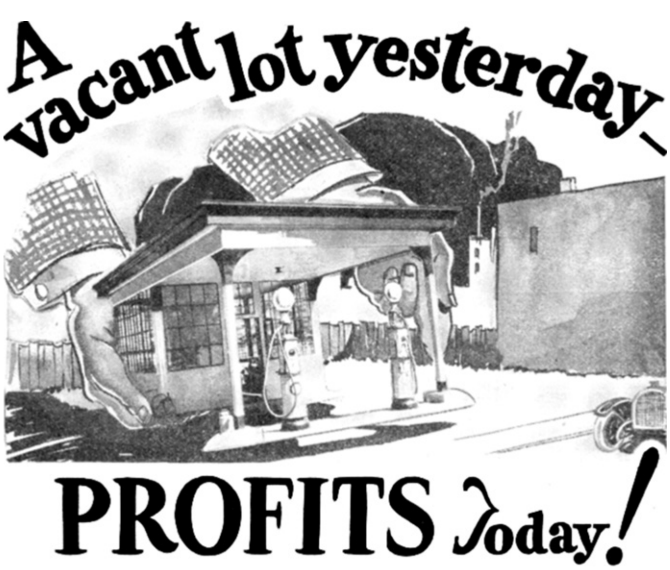

Fig. 8. A 1925 ad for Moss Fabricated Steel Service Stations (National Petroleum News, February 1925, p. 7).

continued to be adopted well into the 1930s (Howley, 1984). Fig. 8 is an ad from a manufacturer of prefab stations in 1925, when strong growth in dedicated stations was just beginning. The ad succinctly captures the appeal and simplicity of investing in prefab stations. Fig. 9 shows an elegant steel prefab station from the Pure Oil Company.

Service stations: Providing additional services and amenities at gasoline outlets was somewhat rare before 1920, but by the end of the 1920s the service mentality was firmly established across the gasoline marketing industry. Typical services included free air and water, a range of tires, batteries and accessories (TBA), oil and battery checks, free company maps, clean public restrooms, and one or more helpful, product-promoting attendants. In addition, many station dealers and oil companies embraced a general movement to increase the public acceptance of gasoline stations, typically through improving station appearance or by hosting community events. Many stations maintained shrubbery and flowers, and dealers prided themselves on having immaculate, well-maintained stations. Some oil companies went so far as to remove large billboard gasoline advertisements in order to improve their public image, and it was common for station dealers to actively engage their local communities, sometimes going door-to-door to promote special offers or products. Many dealers hosted grand 1-day carnivals to celebrate the opening of a new station, with prizes and rides, elephants and entertainers, and the traditional free gasoline and hot dogs (Witzel, 1993).

The number of architecturally extravagant stations increased in the late 1920s and 1930s, partly in response to the architectural City Beautiful Movement. This station beautification period was an effort to improve the image of the petroleum industry on several levels, and Washington, DC was often a beneficiary of the petroleum industry's enthusiasm for elaborate stations. For example, in 1925, the Parkway Filling Station was established in one of the most congested parts of the city, occupying a corridor between Kenyon Street and Park Road near 14th Street, with "ample room" for pumps, traffic and parking for 50 vehicles (Anonymous, 1925). Similarly, in 1931, Standard of New Jersey opened an extravagant station with 52 gasoline pumps in Washington, DC (Williamson et al., 1963a, b, p. 683). Like other grand stations across the country, these were clearly designed to impress, and were introduced with great fanfare. The Atlantic Refining Company of Pennsylvania built some of the first neoclassical gasoline stations, such the one depicted in Fig. 10. This architectural trend was indicative of an explicit campaign on the part of major petroleum companies to project an image of reliability, legitimacy and trust. The neo-classical style was only one of several gasoline station trends that occurred in different parts of the country at various times. Others included the English Cottage style pioneered by Pure Oil and the Japanese Pagoda stations of the Wadham Oil Company in Wisconsin (Vieyra, 1979; Margolies, 1993; Jakle and Sculle, 1994).

Fig. 9. A Pure Oil Company steel prefabricated station (National Petroleum News, 3 November 1926, p. 48G-H).

Fig. 10. One of the first ‘‘palace’’ refueling stations from the Atlantic Gasoline Company. Smithsonian Institute (Witzel, 1993).

6. Analogies to hydrogen systems

Hydrogen refueling methods that are in use today and proposed for the future share some of the strategic attributes associated with early gasoline refueling methods. In addition, the viability of different hydrogen delivery and refueling systems will change over time. Some hydrogen infrastructure technologies are available today, some are close to commercialization, and others will require more research and development, suggesting a future with distinct phases of infrastructure change and technology development. Analogies between gasoline and hydrogen systems are discussed below after reviewing the strategic attributes of different gasoline refueling methods and the phased adoption of different methods over time. The goal of drawing these analogies is not to predict technological success or extend any particular theory of innovation, but rather to invoke insight by exploring the innovations that occurred the first time that a fuel was introduced for vehicles on a large scale.

A summary of the strategic attributes of each gasoline dispensing method discussed in the previous sections is presented in Table 1. Ten strategic attributes are ranked on four levels, with a blank indicating that an attribute is lacking and an increasing number of plus signs indicating a stronger association. These rankings have been determined based on both quantitative data and various historic qualitative descriptions. They are meant to indicate relative and general attributes, rather than absolute and specific characteristics. The last three attributes are more time dependent than the others, and are therefore shown with rankings for both 1925, when dedicated stations had become firmly established, and 1910, when dispersed methods still dominated gasoline retailing.

Table 1 lists dispensing methods from left to right in the approximate order in which they were introduced historically. The first few strategic attributes are more strongly associated with earlier dispersed methods, while the later attributes are more characteristic of dedicated stations. For example, most dispersed methods were small-scale, mobile and easily located or relocated, and had low capital, labor, and operation and maintenance costs. With the exceptions of home pumps and street vendor handcarts, most early methods were deployed in parallel with other services or products. Dedicated stations tended to be high capacity, relatively convenient to motorists, less constrained to niche markets, and, eventually, esthetically appealing. Curb pumps, and to a lesser extent prefab stations, tended to be associated with all of the strategic attributes.

Gasoline marketing was very different before dedicated refueling stations established dominance, so the relative strengths of the last three attributes in Table 1 are also shown for dispersed methods in 1910. Garage barrels and curb pumps, the most common dispersed methods in 1910, are ranked high in both convenience and lack of market confinement. While curb pumps were initially quite plain, they quickly diversified into a number of different styles and types, many of them elegant and highly ornamental.

Table 1
Strategic attributes of early gasoline dispensing methods

Strategic attribute	Dispersed methods							Dedicated stations			
	Cans	Garage barrels	Home pump	Parking facility	Mobile Tank cart	Mobile hand cart	Curb pump	Drive-in	Trackside	prefab	Service station
Highly mobile	+ + +	+ + +			+ + +	+ +	+			+	
Easily dispersed, located, or relocated	+ + +	+ + +	+		+ + +	+ + +	+ +	+		+	
Low labor, overhead, and O&M costs	+ + +	+ + +	+	+	+ +	+ +	+ +	+	+ +	+	
Low upfront capital costs	+ + +	+ + +		+ +	+	+ +	+ +	+ +	+ +	+	
Distributed in parallel with other services	+ + +	+ +		+	+	+	+ +	+	+	+	+ + +
Distributed in parallel with auto services	+	+ + +		+ + +	+	+	+ +	+	+	+ +	+ + +
High capacity		+	+ +	+ +	+ +		+ +	+ + +	+ + +	+ + +	+ + +
Convenient to motorists (~1925)		+		+ +	+ +	+ +	+ +	+ +	+	+ +	+ + +
Not confined to small niche markets (~1925)		+		+	+ +	+ +	+ + +	+ + +	+ +	+ + +	+ + +
Esthetic appeal (~1925)	+						+ +			+ +	+ + +
Before dedicated stations											
Convenient to motorists (~1910)	+	+ +	+ + +	+ +	+ +	+ +	+ + +				
Not confined to small niche markets (~1910)	+ +	+ + +	+	+	+	+ +	+ + +				
Esthetic appeal (~1910)	+		+			+	+ + +				

Gasoline cans often had decorative labeling, and were more esthetically appealing than other methods such as barrels.

The six dispersed methods discussed in Section 4 comprise most of the total outlets shown in Fig. 2 until about the mid-1920s. Of the six methods, garage barrels and curb pumps supplied the majority of the gasoline consumed by vehicles before high-volume dedicated stations became dominant. The other four methods are interesting in that they met with limited or temporary success, and because they provided complementary support to the overall evolution of the gasoline delivery system. Despite the various successes of dispersed methods, only the core technology of the curb pump endured for use in more mature phases of gasoline infrastructure development. Most of the new outlets introduced after 1925 were dedicated stations, which simply integrated curb pump technology into station designs.

The emergence of dispersed and dedicated gasoline refueling methods may be considered distinct phases in the history of gasoline infrastructure development. Fig. 11 portrays five general categories of dominant refueling methods occurring in overlapping succession between 1900 and 1970. Curb pumps are shown as a distinct type of dispersed refueling, and dedicated stations are divided into three types: drive-in, service and self-service stations. The arrows indicated the time periods when each type of method prevailing within the gasoline retail sector. For example, curb pumps emerged as a major refueling method around 1910, and briefly dominated during the early boom period before the shift to drive-in stations around 1925. In turn, drive-in stations initially co-existed with and then gave way to service stations. Fig. 11 also indicates station and outlet populations, vehicle registrations, and gasoline consumption. While dedicated stations were all based upon similar technology, the early transition period from 1910 to 1925 experienced a diversity of technological innovations, with curb pumps proving to be a linking technology between dispersed and dedicated refueling methods. In summary, a variety of dispersed refueling methods emerged to allow the uninhibited mass production of gasoline vehicles, and most were subsequently phased out as larger dedicated stations became the dominant refueling method.

The analogies that can be drawn with hydrogen systems are conceptual and suggestive rather than predictive or deterministic in nature. The heuristic value of these comparisons derives from the systems perspective from which we can review the history of gasoline and observe how distinct but complementary technologies evolved over time. In contrast, we do not have a 100-year history of hydrogen refueling, and therefore cannot assess in hindsight what did and did not work. The comparisons below may be intuitively appealing, but it is too early in the history of hydrogen to identify with certainty which innovations will endure or to what degree their composite trajectory will resemble the early history of gasoline refueling.

This discussion of comparisons is also relatively narrow in scope. Many additional topics could be drawn upon to develop more robust comparisons between gasoline and hydrogen refueling systems. For example, gasoline and hydrogen have very different physical and chemical properties. Hydrogen, as a liquid or a gas, is much more challenging to handle and store than gasoline. This being said, our handling and storage technologies for gases are much more sophisticated today than in the early 1900s. Similarly, the drivers for technological change when gasoline vehicles were introduced were very different from the factors influencing alternative fuels today (WBCSD, 2001). Vehicle performance standards are much higher, and global concerns over energy security and climate change are critical strategic issues for energy providers. Moreover, a substantial body of literature has improved our understanding of innovation and technological change (Suarez and Utterback, 1995; Edquist, 1997; Auerswald and Branscomb, 2003), and some studies have been retrospectives on transportation innovations (Kirsch, 2000; Geels, 2005; Godoe and Nygaard, 2006). In future research, the analogies discussed here could be enriched (and perhaps reinterpreted) by a more in-depth discussion including these broader technical and social factors.

The ratings and sequence shown in Table 1 and Fig. 11 have been made in hindsight. It may be possible to develop similar descriptions of hydrogen refueling methods at some point in the future, but any such analysis should be based upon demonstrated success rather than speculation. Accepting that there are limitations to their relevance, the following analogies can be drawn between hydrogen systems and dispersed gasoline refueling methods. Cans of gasoline can be compared to the cylinders used to ship small quantities of hydrogen today, and it has been proposed that small containers of hydrogen, or "fuel in a box' systems, could be used within vehicle refueling systems (Melaina and Ross, 2000; Shell, 2001). Similarly, barrels of gasoline, being almost as mobile as cans but having greater capacity, could be compared to the small mobile refueler concept where hydrogen is produced offsite and trucked to a refueling location. Larger trailers of liquid or gaseous hydrogen that are parked at a refueling site to serve as a temporary station may be more comparable, in terms of capacity, to mobile gasoline tank trucks (Unnasch et al., 2003). Gasoline home garage outfits are analogous to electrolysis-based hydrogen home refueling systems (GCC, 2005), especially considering the utility-type service with which the same tank trucks delivered gasoline, heating oil or kerosene to homes. Mobile hand carts have no direct analogy with hydrogen systems, except to the extent that some hydrogen systems incorporate components originally designed for other purposes (see Fig. 5). Refueling services provided in parallel with garage parking facilities might be compared to the fleet strategy proposed for alternative fuels in general (Kemp et al., 1998; Nesbitt and Sperling, 1998). As for curb pumps, it is not clear which dispersed hydrogen methods may persist as core technologies, though a superior storage system would be a likely candidate (Schlapbach and Zuttel, 2001).

Analogies with dedicated stations can be made without suggesting which hydrogen methods will prevail in the long term. Drive-in, trackside and prefab methods all preceded dedicated gasoline service stations, and each can be compared to onsite hydrogen production facilities, which have been proposed as a method of "piggybacking" on existing natural gas or electricity infrastructures before a dedicated system is developed, such as a hydrogen pipeline network (Ogden, 1999). Drive-in stations were simply curb pumps set back from roadsides into some dedicated driving and parking area. Similarly, onsite production equipment can be installed at existing gasoline stations but requires dedicated space separate from the station refueling bays. In the case of trackside stations, hydrogen rail delivery does prevail over other delivery methods on a cost basis for certain ranges of distance and volume (Mann et al., 1999), and integrated rail-to-truck delivery systems would be a direct analogy. For a comparison with prefab stations, cost reductions through mass production, modularity and ease of installation have all been emphasized as strategic

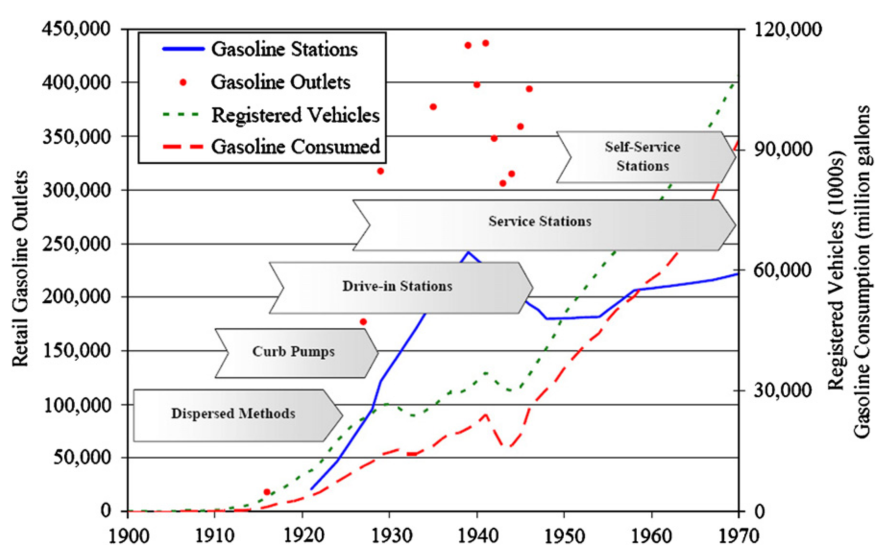

Fig. 11. Dominant gasoline refueling methods from 1900 to 1970.

features of small-scale steam methane reformer and electrolysis units (Myers et al., 2002). Many additional innovative designs have been proposed for dedicated hydrogen stations (HEF, 2007), and some existing stations have very innovative features (LBST, 2007). The degree to which these station designs may be consistent with or complementary to dispersed hydrogen delivery or refueling methods is itself a design question, and a topic for future research.

The early gasoline infrastructure for vehicles emerged from the kerosene industry, and today's hydrogen systems are supported in a similar manner by natural gas, petroleum and electricity infrastructures. Reliance on "black" or "grey" hydrogen produced from fossil fuel systems has been met with criticism (Romm, 2004), and is not sustainable over the long term, due to greenhouse gas emissions and other limitations. However, these systems are low-cost options, and they can be deployed on a small scale with few drawbacks during a transition phase before more advanced infrastructure components are commercialized. As was the case with gasoline, when hydrogen vehicles first begin to be deployed in large volumes, a diversity of innovative refueling methods can be relied upon to some degree before more advanced production, delivery and refueling methods begin to gain market share. As a precedent for the introduction of any new vehicle fuel, the early history of gasoline refueling is consistent with a long-term, adaptive and portfolio approach to support for technology innovation (Sandén and Azar, 2005).

7. Summary and conclusion

Insightful analogies can be drawn between the history of gasoline infrastructure development and potential developments in a future hydrogen infrastructure. Significant latent gasoline production capacity existed in the kerosene industry when the first prototype gasoline vehicles were being developed. And as demand for gasoline for vehicles grew, electricity and town gas were successfully competing in what had traditionally been kerosene-dominated markets. In response to increased demand, refiners increased gasoline production and retailers employed innovative delivery and refueling methods. Similarly, a hydrogen infrastructure today could evolve out of existing energy infrastructures, such as the petroleum, natural gas or electricity infrastructures. However, unlike kerosene at the turn of the century, these systems are increasingly in high demand, which suggests that this piggybacking strategy would be only a transitional phase on a pathway towards a fully developed hydrogen economy.

During the first decades of the 20th century, a variety of innovative non-station gasoline refueling methods successfully provided gasoline to consumers at low cost and from a large number of geographically dispersed locations. These dispersed refueling methods had low capacities and low capital costs, could be sited and relocated easily, and were typically deployed in parallel with other services or products. Examples include canned gasoline, gasoline storage and delivery in barrels, home refueling pumps, parking garage refueling facilities, mobile refueling stations, handcarts and curb pumps. The geographic density and magnitude of demand for gasoline increased throughout the 1920s, and dedicated service stations eventually became the dominant gasoline refueling method. Of the various dispersed methods, only curb pumps persisted beyond the early phases of gasoline infrastructure development and were eventually integrated into conventional refueling stations.

It is not clear which types of technological innovations may prove most useful in overcoming hydrogen infrastructure development challenges. However, the history of gasoline infrastructure development provides useful insights into this innovation process. Early gasoline delivery systems were diverse and distinct, but complemented and enabled one another to some degree as dedicated stations gradually became the dominant refueling method. The corresponding research and development support strategy for hydrogen delivery and dispensing technologies would be adaptive, broad in scope, and would extend over a long time horizon. Successful innovations will not eliminate the high levels of stakeholder engagement and commitment needed to overcome the hydrogen infrastructure challenge, but they may help reduce the financial and technological risks facing these stakeholders.

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