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An empirical analysis on the adoption of alternative fuel vehicles: The case of natural gas vehicles

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Abstract

The adoption of alternative fuel vehicles (AFVs) has been regarded as one of the most important strategies to address the issues of energy dependence, air quality, and, more recently, climate change. Despite decades of effort, we still face daunting challenges to promote wider acceptance of AFVs by the general public. More empirical analyses are needed to understand the technology adoption process associated with different market structures, the effectiveness of regulations and incentives, and the density of infrastructure adequate to reach sustainable commercial application. This paper compares the adoption of natural gas vehicles (NGVs) in eight countries: Argentina, Brazil, China, India, Italy, New Zealand, Pakistan, and the US. It examines the major policies aimed at promoting the use of NGVs, instruments for implementing those policies and targeting likely stakeholders, and a range of factors that influence the adoption of NGVs. The findings in this paper should be applicable to other AFVs.

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1. Introduction

The use of natural gas vehicles (NGVs), first introduced in Italy in the mid-1930s as an alternative to gasoline-powered vehicles, began spreading to other countries as early as 1940. Especially after the energy crisis of the 1970s, NGVs have been promoted by governments in both developed and developing countries as a clean alternative to gasoline and diesel vehicles, and also to reduce dependence on foreign oil. Today, more than 5.1 million NGVs are on the road and close to 9000 NG refueling stations are in operation worldwide (IANGV, 2006a). Most of the NGVs in use today are converted gasoline- or diesel-fueled vehicles. Prior to the late 1980s, the number of NGV models produced by original equipment manufacturers (OEMs) was very limited (IANGV, 1997). In recent years, however, the variety of OEM vehicles offered to consumers has increased dramatically. Natural gas has been applied to a wide range of vehicles, including passenger cars, heavy-duty trucks, gar-

bage trucks, three-wheelers (primarily in Asian countries), and buses. Applications of off-road transportation such as marine cargo ships, airplanes, and locomotives, although popular in some niche markets, are not included in this study.

The principal factors that motivate governments to promote the adoption of NGVs include

- *Environmental benefits of reducing local air pollution:* Compared with diesel buses or heavy-duty and light-duty diesel/gasoline vehicles, NGVs have the potential to emit lower levels of particulate matter, non-methane organic gases/reactive organic gases (NMOG/ROG), nitrogen oxides (NO_x), carbon monoxide (CO), and air toxics; to lower cold-start emissions and off-cycle emissions, and to reduce evaporative emissions and running-loss emissions (Goyal and Sidhartha, 2003; Nylund and Lawson, 2000). These benefits are seen as particularly attractive in countries where local urban air quality is poor, especially in many cities in Brazil, India, and China, where air pollution levels are significantly

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higher than the World Health Organization's air quality standards (Soubbotina and Sheram, 2000).

- *Availability of natural gas resources and existing pipeline and delivery infrastructure:* For some countries, there are also incentives to create volume and economies of scale to better utilize natural gas distribution infrastructure or to justify the need for new infrastructure.
- *Reduction of dependency on imported oil:* The urgent need to diversify away from oil is driving governments to promote natural gas fuel for transportation use. The abundant domestic natural gas reserves, and thus the strong economic advantage of natural gas over gasoline, provide additional incentives for countries in South America to promote the adoption of NGVs (Dondero and Goldemberg, 2005; Matic, 2005).

Most empirical studies examining NGV market penetration and the role of economic and policy factors have been limited to single-country analyses (Flynn, 2002; Fracchia, 2000; Harris, 2000; Zhaoa and Melaina, 2006) or provide only a snapshot of comparisons across countries (Janssen et al., 2006; Seisler, 2000). This paper systematically examines NGV adoption patterns and the evolution of pertinent market structures in eight countries: Argentina, Brazil, China, India, Italy, New Zealand, Pakistan, and the US. These countries were selected because they represent a wide range of market experience, spanning early development (India, China, and Pakistan), sustained growth/high penetration (Argentina, Brazil, and Italy), low penetration (US), and a collapsed market (New Zealand). Specifically, this paper examines how adoption of NGVs depends on policy instruments and factors that are pertinent to consumers' choices, including refueling-station density, fuel prices, and payback periods.

The paper is arranged as follows: Section 2 contains a general review of the world NGV market and adoption patterns over time in the case-study countries. Section 3 examines the types of policy instruments meant to directly influence NGV markets in the case-study countries. Section 4 discusses infrastructure and economic factors associated with the adoption of NGVs and how these variables evolve with

changes in market-share levels. Results and recommendations for future analysis are summarized in Section 5.

2. Natural gas vehicle markets in case-study countries

Compressed natural gas vehicles were first introduced to the market in Italy in the mid-1930s and started to gain wider international attention during the oil crisis of the 1970s and 1980s. But except in a few countries such as Italy, most efforts to promote NGVs during the oil crisis were short-lived. Starting in the mid-1990s, has interest in reducing air pollution and dependence on petroleum imports has stimulated new waves of governmental support for NGVs. Overall, the introduction of NGVs in many countries has begun to occur at faster rates and higher levels than in previous decades (Fig. 1).

Argentina has the most NGVs of any nation, followed by Brazil, Pakistan, Italy, India, the US, and China. Argentina also has the highest market penetration of NGVs, at approximately 17% of the current motor vehicle market. New Zealand had an NGV penetration rate just over 10% in 1985, but all other countries have NGV penetration rates below 5% (Fig. 2).

In the US, NGVs started to appear in 1969 on a very small scale, primarily through conversion kits sold by small natural gas utilities. Ford started producing its own OEM NGVs in the late 1980s. As a result of the Energy Policy Act (EPACT) of 1992, the market share of NGVs has grown significantly, as they are primarily adopted by government light-duty vehicle fleets (Davis and Diegel, 2006; EIA, 2000).

In Latin American countries, primarily Brazil and Argentina, strong government promotion of natural gas as a replacement for gasoline and diesel in order to reduce urban air pollution and increase energy independence has stimulated rapid growth of NGV use. Today, these two countries combined have more than half of the world's total NGVs (IANGV, 2006a). In Europe, a coalition of natural gas utilities, NGV equipment and vehicle suppliers, environmental groups, and individuals from 17 countries formed the European Natural Gas Vehicle Association

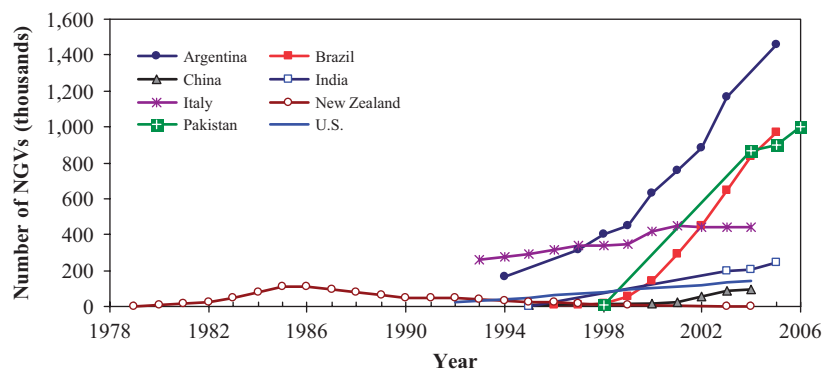


Fig. 1. Number of natural gas vehicles in case-study countries. Sources: EIA (2000), IANGV (2006a, b).

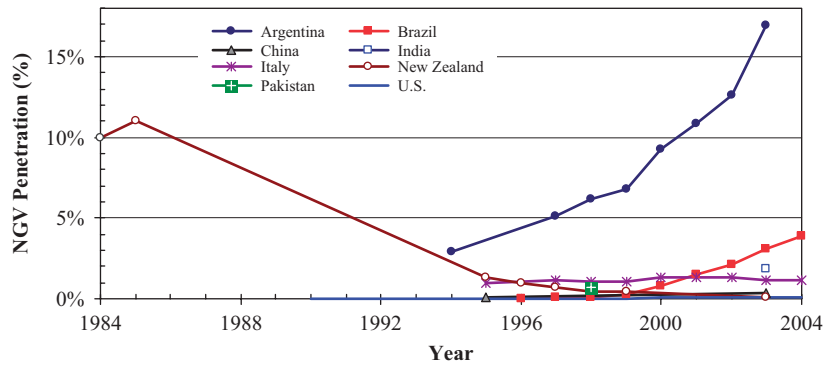


Fig. 2. Market share of natural gas vehicles in case-study countries.

(ENGVA) in 1994 to coordinate pilot programs, international codes and standards, and equipment- and fuel-industry activity.

Several Asian countries, notably India, China, and Pakistan, had significant NGV growth beginning in the late 1990s. The best-known success story took place in India, where in response to a citizen lawsuit initiated in 1985 over poor air quality in Delhi, the Supreme Court issued a series of resolutions instructing the government to ensure that all public transportation, buses, taxis, and auto-rickshaws switch to clean alternative fuel. Its 1998 resolution called for CNG in Delhi, and its 2003 resolution applied to 11 other cities. In spite of several hitches, including supply uncertainties and long waiting lines at refueling stations, by the end of 2003 more than 87,000 vehicles—mainly public-transit vehicles, taxis, and three-wheelers—in Delhi alone were using CNG (De, 2004). Today, more than 204,000 vehicles in India run on CNG.

In China, the primary reasons for moving to a larger NGV market are environmental concerns and energy security (Seisler, 2000). China's growing demand for imported gasoline was evidenced when it surpassed Japan in 2003 to become the world's second-largest oil consumer (with the US still first). Therefore, the Chinese government has played a major role in promoting liquefied petroleum gas (LPG) and CNG fuels in public transit buses—through various R&D programs, direct investments, incentive programs, and targets. The Beijing public transportation authority has committed to replacing 90% of its 18,000 city buses with CNG-fueled buses prior to the 2008 Olympic Games, and other Chinese cities are making similar commitments for other world events (Matic, 2005).

New Zealand presents a unique case, as by the mid-1980s, it already had a very successful NGV market as a result of government incentives, loan programs (such as a 100% loan for vehicle conversion), and targets to promote the adoption of NGVs. By 1985, NGVs in New Zealand had a little more than 10% of the market share; OEM vehicles were being imported from Japan, Australia, and Europe. However, after policy and political changes prompted the government to rescind favorable CNG loan conditions in 1985, the NGV market eventually disappeared (Matic, 2005) (Figs. 1 and 2).

The majority of NGVs worldwide are aftermarket conversions, although the number of OEMs has increased steadily to include more models (Seisler, 2000). Prior to 1985, Italy, Japan, and the US were the only major technology suppliers. Since the 1990s, many countries that were initially reliant on imported technologies have gradually developed OEM vehicles, domestic CNG conversion kits, CNG dispensers, CNG compressors, and CNG cylinders. Some countries (e.g., New Zealand, India, China, and South Korea) eventually became technology exporters, but Italy remains the worldwide NGV technology leader of OEM vehicles, vehicle-conversion kits, and compressor equipment (Fig. 3).

3. Policy instruments for promoting natural gas vehicles

3.1. Policy framework for promoting advanced vehicle technologies

Fig. 4 is a conceptual framework that illustrates the relationships between adoption of vehicle technologies and fuels as influenced by (1) technologies and fuel choices (cost, performance, availability, reliability, and safety), (2) context (social, economic, cultural, and spatial characteristics), and (3) impacts (economic, health, environmental, energy, and land-use changes). Also shown are five major classes of policy instruments that have been applied to influence the adoption and utilization of transportation technologies. These include

- Outcome-based regulation (impact-based performance requirements) such as the corporate average fuel economy (CAFE) standards and emission standards.
- Technology- or fuel-based regulation, including
 - Technology-based regulation: zero-emission vehicles, catalytic converters, on-board computer-emissions monitoring technology, etc.
 - Fuel-based regulation: ultra-low-sulfur diesel (ULSD), adoption of alternative fuels, and bans on leaded gasoline and oxygenates (methyl tertiary butyl ether—MTBE).
- Incentive-based instruments targeting consumers, such as tax credits and rebates. The term “consumers”

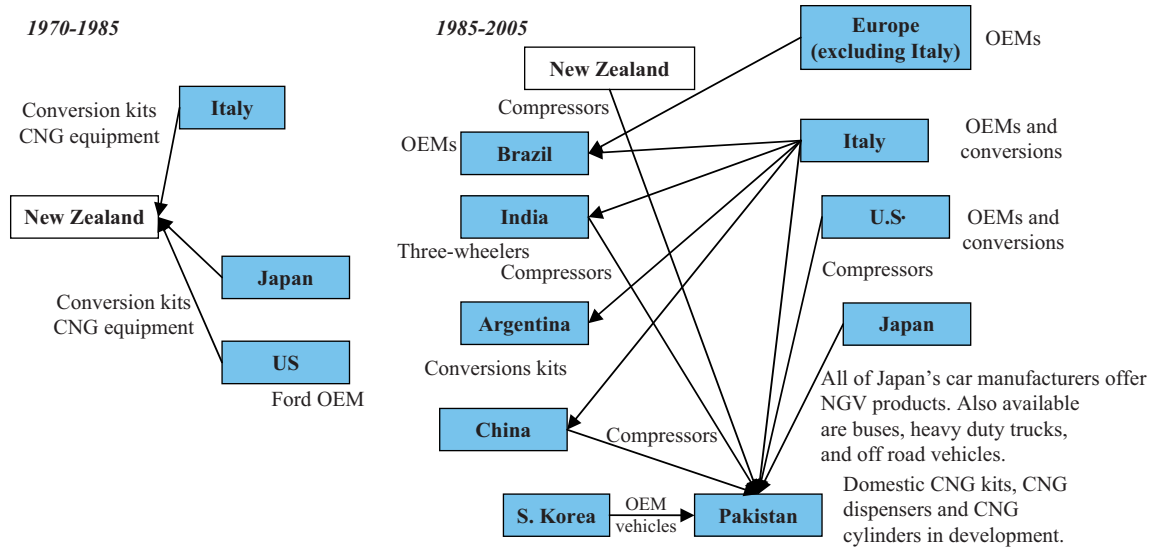


Fig. 3. Technology networks of NGV markets, 1970–1985 (left) and 1985–2005 (right). Shaded boxes represent countries that manufacture vehicles and/or equipment for both domestic and foreign markets.

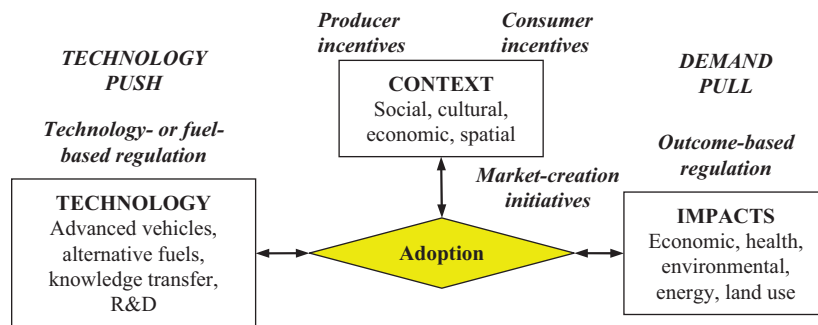


Fig. 4. Conceptual framework of policy instruments promoting the adoption of advanced transportation technologies, including alternative fuels and alternative fuel vehicles.

includes both individual purchasers and fleet operators such as businesses units and government agencies.

- Incentive-based instruments targeting suppliers, including R&D and government-funded demonstration projects and tax credits.
- Market-creation initiatives such as government procurement preferences; requirements for disclosure of fuel consumption, safety, and performance; adoption targets for alternative fuel fleet vehicles; direct investments in refueling stations, and service networks.

Successful policy interventions to promote alternative vehicles and fuels will require well-designed combinations of regulatory standards, information, incentives, and market creation. Any effective policy-intervention strategy must be designed to reduce the key barriers affecting each stakeholder group whose actions may determine the policy's success. In the next section, policy instruments used in promoting the adoption of NGVs in the case-study countries will be reviewed according to this framework.

3.2. Major policy instruments promoting the adoption of natural gas vehicles

Policy instruments promoting the adoption of NGVs target a wide range of stakeholders. Five groups of stakeholders are essential in NGV adoption: the natural gas industry/fuel suppliers; government at all levels; suppliers of equipment including systems, fueling stations, components, and OEM vehicles; consumers; and environmental groups that lend support and provide information to promote the use of clean fuels (IANGV, 1997). National and state policies implemented by governments to promote NGVs were gathered from the literature, categorized based on the policy framework proposed in Fig. 4, and summarized in the policy matrix in Table 1. The policy matrix, adapted from Sterner (2003), summarizes the main types of policy instruments implemented in the case-study countries (rows) and their targeted stakeholders or subjects (columns). Because the literature is yet to examine the relative effectiveness of various policies in promoting the adoption of NGVs, Table 1 presents the number of

Table 1
Policy matrix for promoting NGVs across eight countries

	Vehicle	Fuel	Supplier	Traffic
Regulation	6	0	7	0
Bans	1	1	0	3
Price (tax)	8	4	10	0
Market creation	10	2	3	0
Information/coalition	5	0	4	0

The columns represent the stakeholders or subjects targeted by the policy actions and the rows represent the type of policy measures.

instances of each frequently cited policy instrument implemented in the case-study countries.

To directly promote NGVs, governments frequently employ market-creation programs that require (1) mandatory conversion to or procurement of government fleets and urban buses that run on alternative fuels or (2) mandatory targets for the achievement of a particular market penetration rate of NGVs within a specific time frame. This corresponds to *market creation* (row)–*vehicle* (column) in Table 1. Another type of market-creation program, most popular in Latin American countries—especially Argentina and Brazil—creates markets through the supply side (*market creation–supplier*), for example, through direct governmental investment in refueling stations, pipeline infrastructure, and conversion kits.

All of the countries examined here have financial incentive programs offered to consumers and equipment suppliers, such as subsidies and tax breaks to reduce prices of natural gas specifically for transportation (*price–fuel*); rebates and loans to lower or eliminate consumers' vehicle conversion costs (*price–vehicle*); exemptions from import duties and the lowering or elimination of import tariffs on machinery, equipment, and kits (*price–supplier*); and exemption from sales taxes for the construction and operation of refueling stations (*price–supplier*).

Regulation-based policy often involves establishing industry standards, regulations, and certification programs; liberal licensing for CNG retailing; expedited approvals for the installation of CNG refueling stations (*regulation–supplier*); forced early retirement of old fleet vehicles, city buses, and taxis (*regulation–vehicle*); penalties for operating city buses on “dirty” fuels such as diesel (*bans–fuel*); and traffic restrictions for which NGVs are exempt (*bans–traffic*). Information- or coalition-type policies often include government/industry/non-governmental organization (NGO) coalitions and government-funded research and development programs (*information/coalition–vehicle* and/or *information/coalition–supplier*).

Table 1 can be further enhanced in the future to incorporate information on the effectiveness of the various programs. Interactions between stakeholder groups, such as incentives provided by equipment suppliers to consumers (e.g., the voucher scheme developed in New Zealand), have played important roles in some countries but are not captured in this table. Future studies to include

network analysis of the types of interactions and strength of the ties between stakeholders (e.g., Taylor et al., 2003) may provide useful information.

4. Infrastructure and economic indicators

4.1. Infrastructure: vehicle-to-refueling-station index (VRI)

The adoption of alternative fuel vehicles (AFVs) requires the co-existence of fuel supply, refueling stations, and AFVs. This has often been described as a “chicken and egg” dilemma (National Research Council, 2004). Luckily, in the case of NGVs, existing natural gas delivery and pipeline infrastructure are widely available in most countries, except for a few local regions. In some countries where local gas supplies are not yet well established (e.g., India, Columbia, and Brazil), governments often provide incentives for construction of natural gas pipelines that also help municipalities address other needs. In Brazil, for example, NGV fueling stations have helped justify the construction of pipelines in areas that otherwise may not have been viable (IANGV, 2006c). In addition, various “mother–daughter” systems (CNG is transported via high-pressure trailers to remote stations) that use trucks within a radius of 150–200 km from pipeline sources are common in local regions with poor fuel coverage.

Despite possibly advantageous fuel-supply situations, the introduction of NGVs still faces the challenge of attaining the optimum ratio of refueling stations to NGVs. There is insufficient knowledge in this subject from either modeling-based studies or empirical ones. This analysis is meant to provide actual data on this relationship, especially through transition periods.

NG vehicle-to-refueling-station index, or VRI, defined as $\#NG \text{ vehicles (in thousands)}/\#NG \text{ refueling stations}$, is an indication of two main factors: (1) the spatial density of refueling stations provided for NGV drivers and (2) the profitability of CNG refueling facilities for the station owners (Janssen et al., 2006). Another measure of refueling-station density is the ratio of the relative numbers of alternative-fuel refueling stations and gasoline refueling stations. Greene (1998), Nicholas et al. (2004), and Sperling and Kurani (1987), using techniques including consumer preference surveys and travel time/distance simulations, found that the sustainable growth of AFVs during transition from initial market development to mature market requires the number of alternative-fuel refueling stations to be a minimum of 10–20% that for conventional gasoline stations. These studies suggest that at levels greater than 10–20% of conventional refueling stations, consumers no longer view the availability of fueling stations as a major obstacle for the adoption of AFVs.

Though conceptually simple, the VRI measure, aggregated to the national level, is subject to wide variations. Factors such as spatial characteristics and socioeconomic differences, including consumer sensitivities to incremental increases in driving distance or waiting time for refueling,

capacities of fueling stations, and the number of public versus private refueling stations, can contribute to variations within and across countries and add additional variabilities and uncertainties to the analysis. The most widespread natural gas fueling options are slow-fill (used routinely for overnight refill of fleet vehicles), fast-fill (with a typical refueling time of less than 5 min), daughter stations (the refilling time varies, as each successive filling reduces the pressure inside the cascade system and increases the refueling time), and vehicle refueling appliances (VRAs, where the vehicle is refueled at the home or at a small business). Most public refueling stations are fast-filling, thus refuel time has not been a critical factor influencing public acceptance of the NGVs. Daughter stations are more common in areas where pipelined natural gas is not available, such as remote areas of the Asia-Pacific region, India, and some South American countries. VRAs are currently limited to a handful of countries, primarily the US and Canada. Due to limited data availability, the calculation of VRI treats all types of refilling stations (excluding VRAs) equally, irrespective of station capacity and refilling time.

In their survey of NGV penetration worldwide between 2003 and 2004, Janssen et al. (2006) found a VRI value roughly equal to 1 (i.e., 1000 vehicles per refueling station) for countries with a large number of NGVs, including Argentina, Brazil, India, Italy, and Pakistan. They concluded that this is the optimal balance between profitability for fueling stations and convenience to NGV drivers.

Fig. 5 shows the observed VRI in the case-study countries. In the US, the VRI for conventional gasoline vehicles has increased from 0.9 in 1993 to 1.35 in 2003 (US DOE, 2006). This is due to a continuous increase of conventional vehicles (+20%) and a declining number of gasoline-fueling stations (−20%) between 1993 and 2003. These changes may reflect two possible trends: (1) an increase in the average size (i.e., filling capacity and storage) of refueling stations or (2) an increase in the minimum profitability threshold to operate stations. By comparison, the VRI for NGVs in the US increased from

0.05 in 1995 to 0.10 in 2003, yet NG fueling stations comprise only 0.6–0.8% of conventional fueling stations (1247 and 1340 NG fueling stations to 194,984 and 168,020 gasoline stations in 1997 and 2003, respectively). In Italy, where NGVs have successfully maintained a mature market for decades, the URI index remains approximately equal to 1 except for the last period (2004), when the index fell due to direct government subsidies for the erection of NG fueling stations (IANGV, 2006b). The indices for countries with dramatic NGV growth in recent decades, including Argentina, Brazil, India, and Pakistan, all increased from less than 0.05 to approximately 1 within 10–15 years. Fig. 5 suggests that once minimum coverage by refueling stations is achieved, creating a strong demand for NGVs is essential for sustaining the growth of NGV markets. This hypothesis is confirmed by the lack of “demand pull” in New Zealand, when the termination of a favorable loan program for NGVs by the government in 1985 led to a declining number of NGVs and refueling stations. The trend shows that after 1985, the number of NGVs was declining at a faster rate than the number of refueling stations (Fig. 5).

Plotting the number of NGVs against the number of refueling stations shows that as the number of NGVs increases, the VRI tends to gravitate toward 1 or stagnate at 0.2 or below (Fig. 6); in other words, countries either seem to break away from the “chicken and egg” phenomenon and form relatively sustained networks, or continue to struggle. The underlying reasons for this are not clear, although a recent simulation effort by Struben (2006) might provide some theoretical explanation for the observed VRI bifurcation in Figs. 5 and 6. Similar results of bifurcation are also observed in Struben (2006) and Struben and Sterman (2006), suggesting that there is a diffusion tipping point, beyond which the adoption of AFVs can become self-sustaining. However, they imply that due to the long life of a vehicle fleet and social and economic penetration barriers, marketing and subsidy programs must be sustained for long periods before diffusion crosses the tipping point. The findings in this paper seem to suggest that at the current stage, none of the

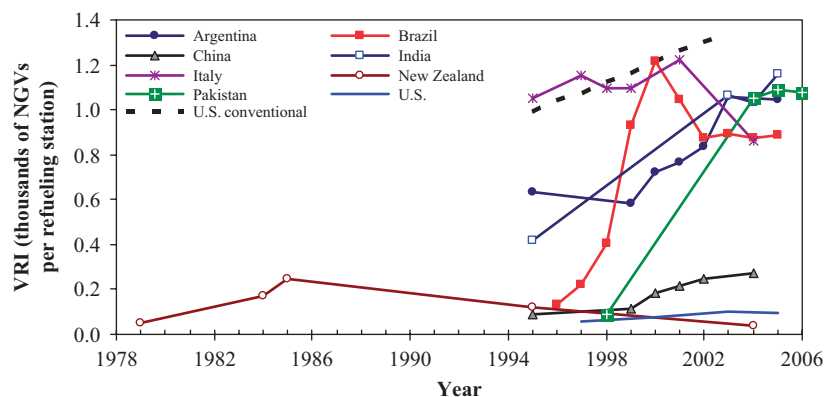


Fig. 5. Natural gas vehicle-to-refueling-station index (VRI) in case-study countries.

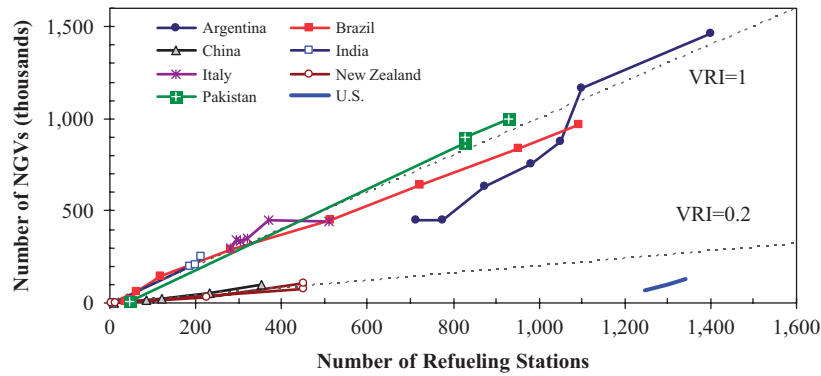


Fig. 6. Number of NGVs versus number of natural gas refueling stations in eight countries.

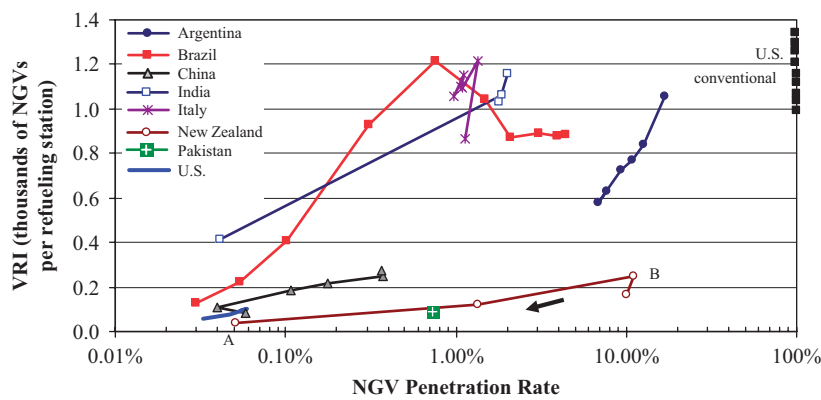


Fig. 7. NG vehicle-to-refueling-station index, VRI, versus NGV market penetration rate in case-study countries. The refueling station indices for Pakistan were 1.09 and 1.08 in 2004 and 2005, respectively, though the data for the NGV penetration levels for these 2 years are currently not available.

countries examined here is likely to achieve self-sustaining NGV markets if favorable government policies are removed.

Fig. 7 shows the relationship between VRI and NGV market penetration rates in the case-study countries. The VRIs of conventional gasoline vehicles in the US are also plotted for reference (0.9 with a 99.8% market share in 1993 and 1.35 with a 98.1% market share in 2003). The NGV penetration rates have been increasing for all countries except New Zealand. The curve for New Zealand describes a reversed chicken-and-egg phenomenon between a decreasing NGV adoption rate and the closure of fueling stations, from 1985 (the year that the NGV market peaked in New Zealand) to 2004. Thus it seems empirically that the line AB in Fig. 7 constitutes a lower bound for a sustainable alternative-fuel market.

Italy, Pakistan, and Argentina have the highest NG VRIs. VRI values in Italy and Brazil both declined after their VRIs exceeded 1.2 (Fig. 5), as the number of refueling stations increased at a faster rate than the number of NGVs. Similarly, though not shown in the graphs, a rush to convert to NGVs in India during the early-adoption phase caused long lines for refueling in many places. This problem was quickly addressed as more and larger refueling stations came into service. Thus, Figs. 5–7 suggest an upper limit for VRI of 1.1–1.3 across all countries.

In the US, reported NG VRI increased from 0.05 in 1997 to 0.10 in 2005. However, the effective NG VRI may be significantly lower because a large portion of the CNG vehicles in the US, particularly non-fleet vehicles, actually ran on gasoline instead of natural gas. This is due to a large number of AFVs being sold in response to the CAFE standard and the EPACT of 1992, which created economic incentives for manufacturers to produce AFVs (Rubin and Leiby, 2000) and required that bi- or flex-fuel vehicles merely be capable of operating on an alternative fuel (Shirk, 2000). According to an EIA report (Shirk, 2000), the actual use of E85 (85% ethanol) in E85-capable vehicles is 30%. Assuming that the actual use of natural gas in NGVs is similar, then VRI values in the US actually have fallen below the AB line in Fig. 7, indicating a less-than-sustainable level of profitability for refueling station owners.

4.2. Economic indicator: fuel price ratio

The price difference between natural gas and conventional fuels such as gasoline and diesel has often been cited as the most important factor in attracting users to switch to CNG vehicles (Dondero and Goldemberg, 2005; Gwilliam, 2000; Janssen et al., 2006; Matic, 2005). An NG pump price of at least 40–60% below the gasoline price is common in

most countries that have had successful NGV penetration (Fig. 8). The relative pump price of gasoline and CNG depends on two factors: the inherent pre-tax difference in cost between oil and natural gas and the social stimulus provided by variable taxation or direct grants. Countries such as the US that are net importers of both oil and natural gas reflect this in their wholesale pricing of fuels. Countries such as Brazil that have a surplus of natural gas and a relative shortage of oil will realize an economic advantage of natural gas over gasoline. For the countries examined here, the price advantage of natural gas over gasoline can be attributed to government incentives such as favorable taxation, tax breaks for natural gas, or higher taxes on gasoline and/or diesel fuel.

While low natural gas fuel prices have been credited with the displacement of conventional vehicles, many countries encountered the problem of active competition with diesel fuel (and ethanol in Brazil) due to insufficient price gaps between the two fuels. The average price ratio between natural gas fuel and diesel fuel in these countries is about 70%. In many of these countries, including Argentina, Brazil, and Italy, governments kept the price of diesel fuel low for a variety of socioeconomic reasons. For example, diesel fuel is also used for agricultural equipment and is interchangeable with heating oil in the residential sector. In Italy, diesel vehicles compete with NGVs and have many advantages: low taxes, good vehicle performance, wide model range, and existing infrastructure. Therefore, with natural gas unable to replace diesel and ethanol in these specialty markets, NGV markets have fallen in recent years in both Italy and Brazil. In countries where governments intend to replace diesel with natural gas, explicit policies are in place to establish a price advantage of natural gas to diesel fuel (e.g., in Pakistan) or to disallow the use of diesel in city buses (e.g., in India).

4.3. Economic indicator: payback period

Studies suggest that most consumers want a very short payback period—less than 3 years for an investment in fuel economy (Greene et al., 2005; Santini and Vyas, 2005). This is significantly shorter than the lifetime of most

passenger vehicles, suggesting that consumers have high implicit discount rates when making investments in new technology. Greene et al. (2005) pointed out that little is known about how consumers estimate the value of improved fuel economy and how they factor that information into their car-buying decisions. Overall, the short payback period preferred by the majority of consumers underestimates the true economic benefits of their investment. Energy models that simulate the patterns of technology adoption and the penetration of AFVs using the bottom-up (technology-rich) approach are sensitive to the assumption about the payback period. Using a short payback period (a high discount rate) assumption in these models results in higher social cost and lower penetration of AFVs when compared with perfectly rational consumers (in economic terms) that have lower discount rates (Schäfer and Jacoby, 2006; Yeh et al., 2006).

Payback periods are subject to a wide range of factors including the price difference between the new technology and conventional technology, fuel price differences, vehicle fuel efficiencies, and annual distances traveled. Fig. 9

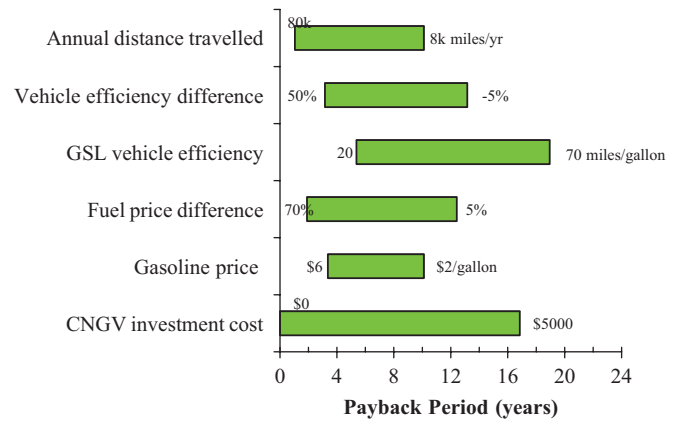


Fig. 9. Sensitivity analysis of the payback period of converting to NGVs in the US. The reference values are \$2000 investment cost (price difference between NGV and conventional vehicle), gasoline price of \$3/gallon, 15% fuel price difference, vehicle fuel efficiency of 25 miles/gallon, 7% NGV fuel efficiency advantage, and 12,000 vehicle miles traveled per year (1 mile = 1.61 km).

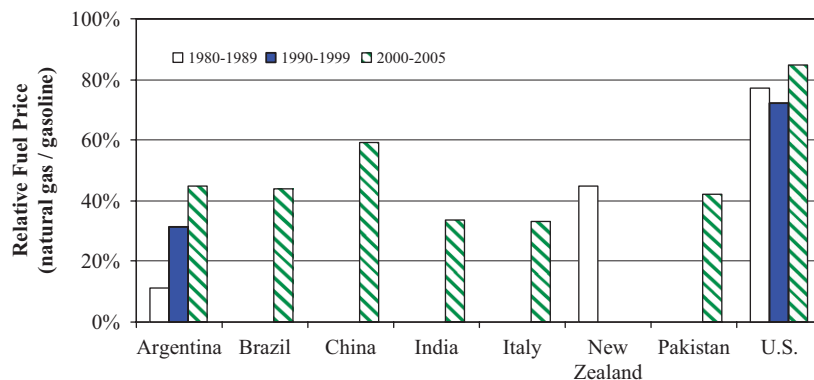


Fig. 8. Natural-gas-to-gasoline fuel price ratio, 1980–2005.

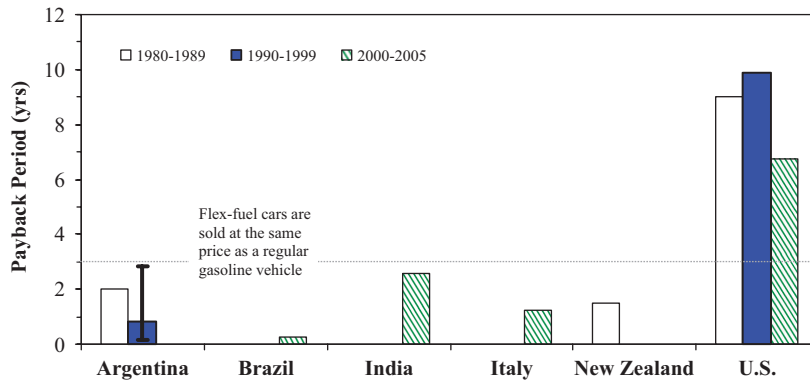


Fig. 10. Payback periods of NGVs in the case-study countries. The error bar represents the range of possible values for different users (e.g., cab drivers versus regular users).

shows a sensitivity analysis of the payback period of converting to NGVs in the US. An increase in gasoline prices from the reference value of \$3/gallon to \$5/gallon would reduce the payback period by roughly 40% (from 6.8 to 4 years). Similarly, if the fuel price difference between natural gas fuel and gasoline is increased from the current level of 15% (US DOE, 2005) to 50% (the level most experts suggest is necessary for the wide adoption of AFVs, as we found in Section 4.2), the payback period for NGVs in the US can be reduced to around 2.6 years.

An analysis of the payback period in the case-study countries found that for all countries where data are available—except the US—the average payback periods of light-duty vehicles are lower than 3 years for average users (Fig. 10), largely attributed to government policies in creating large fuel-price differences and subsidizing conversion costs. This finding is surprisingly consistent across countries with successful NGV penetration. The payback period for New Zealand was calculated prior to 1985, the year when the government terminated its support for NGVs.

Other factors not included in the payback-period analysis, such as vehicle image (Heffner et al., 2005) and functionality (e.g., performance and utility), also affect consumers' decisions to purchase AFVs. The New Zealand government's rush to push for the widespread deployment of NGVs from 1980 to 1985 resulted in poor quality of natural gas fuel and vehicle technologies; thus, consumers came to perceive NGVs as substandard. At that time, the only reason to switch to NGVs was that doing so was economically attractive. This is a typical tradeoff seen in many AFVs (Rouwendaal and de Vries, 1999). It remains to be seen, however, whether today's higher fuel quality and better vehicle technology can substitute for direct financial incentives toward a low payback period.

5. Conclusions

This paper analyzes the policy instruments, incentives, and economic drivers associated with the adoption of NGVs in selected case-study countries. All major stake-

holders, consisting of natural gas industry/fuel suppliers, governments, equipment suppliers, consumers, and NGOs, need to be involved. A wide range of policies has effectively targeted these stakeholders to promote the adoption of NGVs and CNG buses. A number of economic factors, including the purchase cost of NGVs (OEM, converted, or bi-fuel vehicles) compared with gasoline/diesel vehicles, natural gas fuel price at the pump compared with gasoline/diesel, profitability of operating refueling stations, and selling/installing vehicle equipment, can affect consumers' and investors' decisions to enter the NGV market. In general, the mere existence of OEMs did not seem to be a major factor in determining the success of NGV markets; it seems that the availability and reliability of vehicle technology and components were far more important factors for consumers' acceptance of NGVs.

Establishing retail natural gas fuel prices of 40–50% below gasoline and diesel prices and providing sufficient incentives to keep the payback period at 3–4 years or less are the keys for wide adoption of NGVs beyond fleet vehicles and buses in the case-study countries examined here. Without one or both of these conditions, as suggested in New Zealand's case, market failure will occur despite sufficient infrastructure. The review of VRI values suggests that successful NGV markets have the tendency to gravitate toward a VRI of 1; in addition, there seems to exist an upper boundary of 1.1–1.3, above which conditions such as overcrowding, long waiting lines, or high profit margins will tend to attract new market entrants and push the VRI value back down. The observations from a series of VRI graphs suggest that once refueling stations achieve critical coverage, government policies that focus on providing incentives to increase the adoption of NGVs (demand pull) become more effective. The VRI indicator can be a useful tool to monitor the effectiveness of government policies and make policy adjustments based on VRI values at given adoption rates, either to promote vehicle adoption or to stimulate the installation of refueling stations. However, because VRI is aggregated to the national level, it cannot be used as a detailed planning tool to guide the number and siting of refueling stations in

local areas. Nor does VRI reflect the consumer's decision process of adopting NGVs or the supplier's decisions in supplying fuel and building refueling stations.

These findings are also applicable to other alternative fuels such as ethanol, biodiesel, and hydrogen. Previous experience suggests that policies limited to niche markets or fleet-vehicle applications are not sufficient to grow AFVs into mainstream passenger vehicle markets (McNutt and Rodgers, 2004). The results of fuel-price ratios imply that in the US, where the average price of gasoline hovers at around \$3/gallon, the sale price of alternative fuel at the pump needs to be no more than \$1.50–1.80/gge (gallon gasoline equivalent) in order to achieve widespread acceptance among general consumers. For E85, which has a reported net 5–15% drop in fuel economy for most flex-fuel vehicles not optimized for it, the retail price needs to be even lower, in the range of \$1.30–1.70/gge. Alternatively, federal and state subsidies to lower AFV investment/conversion costs would need to be large enough to decrease the payback period to below 3 years. Other government-provided financial and non-financial incentives offered to a wide range of stakeholders, as well as regulations and programs to promote information sharing and industry coalitions, will play important roles in promoting the penetration of AFVs. The extent to which these factors affect penetration, and the mechanisms by which they do so, require further study.

Although the environmental factor is undoubtedly one of the main considerations for governments promoting NGVs, some of the emission results have been disappointing or even poorer than those of gasoline vehicles, due to poor conversion, maintenance, and system integration of NGVs (Dondero and Goldemberg, 2005; Flynn, 2002; Gwilliam, 2000; Matic, 2005; Zhao and Melaina, 2006). Air quality improvements from introducing CNG vehicles can take place at three levels: local, regional, and global. Local air quality is most affected by particulate emissions from diesel and by photochemical smog that arises from ozone and non-methane hydrocarbons (NMHCs). NGV in general improves tailpipe emissions of particulate matter and NMHCs; the push for NGV buses, for example, is often targeted to improve particulate emissions.

Regional emissions are primarily relevant to hydrocarbons (HCs), nitrous oxides, and carbon monoxide. Here the picture on NGV is more complex and depends in large part on the type of conversion system installed on the vehicle. North American OEM vehicles will have a high standard of emission control, while the literature indicates that traditional carburetion-type conversion kits shift but do not reduce emissions, because they are often "tuned" to non-stoichiometric air/fuel ratios. Dondero and Goldemberg (2005) compared the emissions of converted CNG vehicles with when they ran on gasoline and found them to exhibit average reductions of 53%, 55%, and 20% in CO, NMHCs, and CO₂ emissions, respectively, but average increases of 162% and 171% in HC and NO_x emissions, respectively. Several studies examined the impacts of air quality after

the introduction of CNG found mixed results (Chelani and Devotta, 2007; Goyal and Sidhartha, 2003; Kathuria, 2004; Ravindra et al., 2006). Goyal and Sidhartha (2003) compared the air quality in Delhi during the years 1995–2000 (without CNG) with the year 2001 (with CNG) and found decreases in ambient air concentration of CO, sulphur dioxide (SO₂), suspended particulate matter (SPM), and NO_x emitted from the transport sector. Kathuria (2004) used a simple linear regression model and a dummy representing CNG implementation (one after December 1, 2002 and zero otherwise) on daily air quality data from 1999 to 2003 in Delhi. No significant effect of CNG conversion was found for SPM, PM₁₀ (particles with aerodynamic diameter smaller than 10 μm), or NO_x. The author attributed the lack of improvements to improper retrofitting of liquid-fueled engines to run on CNG.

Global emission issues are related to greenhouse gases (GHGs). Therefore, a comparison should be based on life-cycle GHG (or so called well-to-wheel) emissions, which take into account the entire fuel cycle including emissions from fuel extraction at the well through emissions occurring during the operation of the vehicles, and the "global warming potentials" (GWPs) of non-CO₂ GHGs. The results are typically presented in total CO₂-equivalent emissions, which use GWPs to convert total emissions of all of the non-CO₂ gases into the mass amount of CO₂. Methane has 23 times the GWP of CO₂, according to the IPCC Third Assessment Report (2001). Compared with the life-cycle GHG emissions of a gasoline-fueled vehicle, a CNG bi-fuel vehicle has roughly 25% less total CO₂-equivalent emissions (Hekkert et al., 2005). Recent political efforts to reduce GHG emissions from the transport sector, such as the Low Carbon Fuel Standard in California (S-1-07, January 18, 2007), have stimulated new interest to include natural gas-fueled buses, trucks, taxis, and fleet vehicles as part of the solution to global warming. It remains to be seen, however, whether this will result in higher penetration as well as improved emissions, especially for converted vehicles.

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