Making Markets for Hydrogen Vehicles: Lessons from LPG

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Abstract
The adoption of liquefied petroleum gas vehicles is strongly linked to the break-even distance at which they have the same costs as conventional cars, with very limited market penetration at break-even distances above 40,000 km. Hydrogen vehicles are predicted to have costs by 2030 that should give them a break-even distance of less than this critical level. It will be necessary to ensure that there are sufficient refuelling stations for hydrogen to be a convenient choice for drivers. While additional LPG stations have led to increases in vehicle numbers, and increases in vehicles have been followed by greater numbers of refuelling stations, these effects are too small to give self-sustaining growth. Supportive policies for both vehicles and refuelling stations will be required.

1. Introduction

While hydrogen offers many advantages as an energy vector within a low-carbon energy system [1, 2, 3], developing markets for hydrogen vehicles is likely to be a challenge. Put bluntly, there is no point in buying a vehicle powered by hydrogen, unless there are sufficient convenient places to re-fuel it. Nor is there any point in providing a hydrogen refuelling station unless there are vehicles that will use the facility. What is the most effective way to get round this "chicken and egg" problem?

Data from trials of hydrogen vehicles can provide information on driver behaviour and charging patterns, but extrapolating this to the development of a mass market may be difficult. One approach in the absence of (sufficient) data is to use a simulation model. Schwoon [4] uses an agent-based model, which captures the main interdependencies to simulate possible diffusion paths for fuel cell vehicles (FCVs) under six stylized scenarios, in terms of two types of tax on vehicles and three different infrastructure scenarios. He suggests that the "chicken and egg''

problem can be overcome if the taxes on conventional vehicles (or subsidies on FCVs) are high enough. Struben [5] discusses the very complex dynamics between consumers, vehicle manufacturers, and infrastructure providers, showing that adoption can be crucially dependent on the pattern of journeys and availability of fuel supplies. Stephens-Romero et al [6] show how systematic infrastructure planning can optimise the number and location of refuelling sites. Wang [7] uses a computable general equilibrium model to simulate the broader question of how the evolution of hydrogen vehicles could affect California's economy.

An alternative research strategy is to learn lessons for future hydrogen vehicles from other Alternative Fuel Vehicles (AFVs), including vehicles fuelled by compressed nature gas (CNG) or liquefied petroleum gas (LPG, or autogas). Previous work [8, 9, 10] shows that the 'chicken and egg' problem has been a strong barrier to the successful market development of AFVs. Melaina et al [10] report the results of a workshop held by the US National Renewable Energy Laboratory that drew on experiences from a range of alternative fuelled vehicles – this confirmed the importance of an adequate refueling network, perhaps initially based around "lighthouse" projects in selected areas, from which a wider network could be developed.

In this paper, we follow this second strategy, drawing on evidence from the market for vehicles powered by LPG. Many countries around the world have some vehicles powered by LPG, but the proportions vary widely, as do the policies adopted to promote the fuel. There is also a wide variation in the number of sites where LPG-powered vehicles can be refuelled. Just as with hydrogen, autogas requires a different fuelling system from petrol, and so the site owner must make a significant investment to install the facilities. (This is in contrast to unleaded petrol, which spread rapidly across Europe in response to regulatory changes, but could use existing dispensing systems.)

Our analysis has three parts. First, we discuss the need for policies that support AFVs (and hydrogen vehicles), and show that the break-even distance at which an AFV has the same cost as a conventional vehicle is a key determinant of the proportion of vehicles using LPG in a given country. In particular, few of the countries in our sample had a worthwhile penetration of LPG vehicles and a break-even distance of more than 40,000 km. Second, we take recently published predictions of the cost of hydrogen-fuelled and conventional vehicles in 2030 to ask whether the break-even distance will be less than this critical value. We find that for most combinations of hydrogen and conventional costs, the break-even distance will indeed be less than 40,000 km, and that a relatively modest tax on gasoline would be sufficient to bring down the break-even distance in the other cases. Finally, we consider the chicken and egg problem of developing vehicles and refuelling sites simultaneously. We estimate the elasticity of the number of vehicles with respect to the number of sites in the previous year, and vice versa. While the concept of elasticity is most usually used to measure the response of demand to price, elasticity can be calculated for any two related variables by dividing the percentage change in one of them by the percentage change in the variable believed to have caused it. If an increase in the number of sites is sufficient, on its own, to kick-start the purchase of vehicles, for example, we would see an

elasticity of more than one. In practice, the elasticities that we calculate are less than one, and it will be necessary to adopt policies to promote both the adoption of hydrogen vehicles and the creation of refuelling sites if the market for hydrogen vehicles is to develop well.

2. Incentive Policies

LPG is a by-product of natural gas processing and oil refining, and includes various mixtures of hydrocarbons. This means that its price is often tied to oil prices and tend to fluctuate widely. In areas where LPG is used as a heating fuel, seasonal rates in winter or unusually cold weather can suddenly increase the price. Hydrogen has the advantage that its production could be independent of oil, if it is produced by another approach, like electrolysis of water, biomass gasification or nuclear power, or solar photoelectric, instead of by reforming natural gas. However, the prospective bulk price of hydrogen fuel is currently much higher than that of conventional fuels. A very large reduction in tax (or even a subsidy) might be needed to make hydrogen competitive on price, unless oil prices (including carbon taxes) rise significantly in future. It is also necessary to assume that the technical issues of using and storing hydrogen have been solved and the cost of hydrogen is at least competitive with conventional fuel, when we discuss the economic path to a hydrogen economy [4, 11,12].

In most countries where it is available, the government encourages the use of autogas, as with other alternative fuels, for environmental reasons. The World LPG Association [13] has surveyed the incentive policies used by 20 governments, mostly from high-income countries. The survey divides government policies for promoting alternative fuels, including autogas, into financial incentives, regulatory measures and others, including support for technology development and public awareness programmes. The most common incentive policy is to give either an exemption or a large rebate on fuel taxes, compared to the rates levied on gasoline or diesel. In some countries, there are government subsidies or tax credits to meet part of the cost of converting vehicles to autogas. These are more likely to be needed in countries with high labour costs, such as France, Japan and the UK, than in countries with low labour (and hence conversion) costs. A few countries gave tax or other incentives to create refuelling stations. The most powerful regulatory measure is a positive requirement to use autogas or some other type of alternative fuelled vehicle.

The main lessons for hydrogen as a transportation fuel are that any government at least needs to design a sufficient incentive policy to reduce vehicle running costs, lower the end-user capital investment needed to switch to such fuel, and set up pilot schemes to increase public awareness. Di Pascoli et al [14] suggest that a lack of public awareness is a significant factor in the relatively low penetration of natural-gas powered vehicles in Italy. Martin et al [15] report that more than 80% of consumers at “ride and drive” clinics with a fuel cell vehicle in California had a positive overall impression, showing how pilot schemes can combat this problem. Struben and Sterman [16] model the importance of word-of-mouth in diffusing awareness from customers who have experienced alternative fuelled vehicles to those who have not. They find equilibria in which

many drivers are willing to consider alternative fuelled vehicles, which thus have a self-sustaining market share, and also find equilibria in which the vehicles are not widely adopted and few consumers are willing to consider them. Melendez [17] points out that while some programmes started successfully with large fleets, the transition to wide adoption among individual drivers is not straightforward and frequently failed to take off.

3. Autogas Break-even

We derive break-even distances for autogas vehicles using data from a number of sources. The World LPGA [13] provides information on the break-even distance for an LPG-powered car in a number of countries in 2006. This is given by the additional cost of purchasing or converting an LPG vehicle (in local currency units), divided by the saving in running cost per km driven (in local currency units per km). The resulting figure is the break-even distance in km at which the higher initial cost is just offset by the subsequent saving over the vehicle's lifetime (without any discounting to reflect the delay before the savings are received). The payback time required for consumers to recover the upfront cost of conversion is a related indicator, but this also depends on the annual distance travelled [18].

We use International Energy Association data [19] for fuel prices to calculate the break-even distance for each country in other years (holding the cost of conversion constant). Figures for the number of refuelling stations at which autogas is available are in [13]. We normalise these variables to take account of the size of each country. We divide the number of LPG-powered vehicles by the number of cars in the country, and the number of filling stations where LPG is available by the total number of petrol stations there in 2007. For an alternative normalisation, we divide the number of stations selling autogas by the length of roads in each country. The data for these normalisations is taken mostly from the 2007 edition of Transport Statistics GB [20].

The discussion above suggests that the market share of autogas vehicles is likely to be correlated with the financial advantages of adopting them. Figure 1 shows that this pattern does indeed exist, in broad terms. The horizontal axis gives the (lifetime) break-even distance at which the lower operating costs of an LPG-powered vehicle just outweigh the conversion cost (or higher purchase price), while the vertical axis shows the proportion of LPG-powered vehicles in 2004. Those countries with percentage penetration rates in the low to mid teens have a break-even distance of between 15 and 30 thousand km, while almost all the other countries with significant penetrations have break-even distances of less than 50 thousand km. Most of these have a break-even distance of 40 thousand km or less. There are a few exceptions – France has practically no LPG vehicles, despite policies that make them cheaper than conventional vehicles, whatever the running distance, and three countries have a number of vehicles, despite break-even distances in excess of 100 thousand km. In France, the reputation of LPG vehicles was badly damaged by safety fears following an explosion caused by an arson attack in 1999, which contributed to a relatively low take-up rate. In Canada, the presence of some autogas vehicles despite a very high break-even distance is mainly a legacy of earlier, more supportive, policies which led fleet

operators to convert their vehicles to autogas. When autogas became less attractive, many vehicles were converted to other fuels, but at the time of our sample, not all had been. In Mexico, many of the vehicles using autogas at the time of the sample would have been converted earlier, when conversion costs (and hence the break-even distance) were lower. In Japan, some cities require taxis to use LPG, boosting the proportion of vehicles by regulatory rules.

Figure 1 about here.

The presence of these outliers clearly shows that relative cost is not the only factor affecting the take-up of LPG vehicles. Fleet buyers may well be mostly motivated by costs, but an anonymous referee has pointed out that the take-up of LPG and hydrogen vehicles by private drivers will also be affected by societal impulses and popular received wisdom. Nonetheless, a regression analysis can be used to calculate the approximate impact of higher or lower costs on take-up. This would give a maximum break-even distance (after the effect of incentive policies) beyond which LPG vehicles are unlikely to have any significant role, and, by analogy, a target for hydrogen vehicles. Our dependent variable is the proportion of LPG vehicles in the 15 "central" countries (that is, excluding France, Mexico, Japan and Canada). The independent variables are the break-even distance and the number of filling stations selling LPG per thousand km of roads. Table 1 gives the means and standard deviations of these independent variables, and the regression results.

Table 1: Regression of the percentage of LPG-powered vehicles in each country

	Coefficients	*Standard Error*	*t statistic*	*Mean of data*	*Standard Deviation of data*
Dependent variable				6.3	5.86
Intercept	13.628	3.165	4.31	n.a	n.a.
Break even distance	-0.2685	0.0759	-3.54	34.6	12.79
Sites per km of road	0.2258	0.0894	2.53	8.67	10.86

$R^2 = 0.73$; 15 observations

In our sample, the mean proportion of LPG vehicles is 6.3 per cent, with a standard deviation of 5.9 percentage points. If the break-even distance increases by one standard deviation, then the regression implies that the proportion of LPG vehicles would fall by 3.4 percentage points. Increasing the number of refuelling sites per 1000 km of road by one standard deviation raises the

proportion of LPG vehicles by 2.5 percentage points. These effects are clearly important. Keeping the number of refuelling sites at its mean value, the proportion of LPG vehicles would fall to 1 per cent if the break-even distance rose to 54 thousand km.

In the appendix, we show that if we include the four outliers, the fit of the regression naturally worsens, with the R-squared falling from 0.73 to 0.54. The impact of the number of refuelling sites is stronger (a one standard deviation increase raises the proportion of LPG vehicles by 3.4 percentage points), but the impact of the break-even distance is weaker (a one standard deviation increase reduces the proportion of LPG vehicles by 1.8 percentage points). With a t-statistic of 1.908, the estimated coefficient on the break-even distance is also less significant statistically (so that a 95% error band for its impact would include a value of zero). The best estimate for the break-even distance at which the proportion of LPG vehicles would fall to 1 per cent is now 125 thousand km.

4. Hydrogen Break-even

If we accept that a 1 per cent market penetration for hydrogen vehicles is too modest a target for the medium to long term, the countries that have done better than this for LPG vehicles have all had a break-even distance of less than 40 thousand km. Is this an attainable target for hydrogen? Offer et al [21] report predictions of the cost of hydrogen vehicles in 2010 and 2030, compared to battery electric and conventional (gasoline) vehicles. We follow their lead in concentrating on a hybrid hydrogen-electric vehicle, in which a battery is used to aid short-term acceleration, thus economising on the size of fuel cell required, and hydrogen is used at cruising speed, thus economising on the size of battery needed.[1] On the basis of a 100,000 km vehicle life, and common designs for everything except the power train and energy storage, they predict that the hydrogen hybrid will generally be cheaper than a gasoline-powered vehicle, a result mirrored in [22]. They report "average", "optimistic" and "pessimistic" values for the capital cost and running cost of each vehicle design, which we reproduce in Table 2, together with the implied break-even distance.

[1] An anonymous referee has pointed out that a hydrogen economy could also use hydrogen in internal combustion engines, with somewhat lower efficiency but negating any problems in developing fuel cells.

Table 2: Relative costs of hydrogen and gasoline vehicles: predictions for 2030

	Capital costs ($)		Running costs ($/km)		Break-even distance (km)
	ICE	FCHEV	ICE	FCHEV	
Optimistic	2,400	4,000	0.120	0.022	16,319
Average	2,465	5,665	0.180	0.055	25,609
Pessimistic	2,530	7,330	0.240	0.088	31,607

ICE: Internal combustion engine, running on gasoline

FCHEV: Fuel cell hybrid electric vehicle, running 50% on hydrogen and 50% on mains electricity

Source: derived from data in [21]

All three of the break even distances (obtained by dividing the difference in capital costs by the difference in running cost per km) are below the critical level of around 40,000 km. However, we should consider the possibility that hydrogen vehicles develop less slowly than expected, or that the price of gasoline rises by less. Predictions for falling costs for any new technology depend at least in part on "learning by doing", which gives the possibility of a virtuous circle of rising sales and falling costs (and prices), or of its vicious opposite.

We therefore ran a small Monte Carlo exercise, based on the range of predictions for capital and running costs given by Offer et al [21]. We took their optimistic and pessimistic cases as the ends of the range, took values just above and just below their average case for the centre of the distribution, and linearly interpolated six other values for each variable (three between the pessimistic and the low central values; three between the optimistic and the high central values). There are ten thousand possible combinations of four variables, each with ten possible values, and we calculated the break-even distance for each of these, plotting them in Figure 2. We did not consider the possibility that running costs (for example) might be correlated – if gasoline prices are high, this might be correlated with high prices for other types of energy, including hydrogen.

Figure 2 about here

We found that almost 20% of our simulated break-even distances are greater than 40,000 km. While the centre of the distribution is clearly well within the acceptable range, there is a significant risk that the costs of hydrogen vehicles, relative to those of gasoline vehicles, will remain too high in 2030 to support a significant market penetration unaided. The caveat

"unaided" is important, because Offer et al base their calculations on estimated costs, rather than market prices. Gasoline is heavily taxed in many countries, and if the effective tax on hydrogen was less, this could significantly shorten the break-even distance.[2] In Figure 2, we therefore include a tax of $12 per GJ on gasoline. This raises the cost of gasoline by 40% in the average case (still very low by European standards), but is sufficient to reduce the chance of a break-even distance above 40,000 km to very low levels – just 34 cases out of 10,000. In other words, if the cost of hydrogen vehicles declines as predicted by Offer et al and there is a reasonable tax differential between hydrogen and gasoline, the break-even distance for hydrogen vehicles should be consistent with a respectable market share. However, those cost reductions are likely to depend heavily on the benefits of learning by doing, and this depends on sufficient customers being willing to become early adopters of hydrogen vehicles in the next two decades. The attractiveness of this will not depend only on the relative cost, but also on the convenience of owning a hydrogen vehicle, and in particular on the availability of refuelling sites. This is another area where the autogas market offers lessons.

5. Fuel Availability

While vehicle owners will buy a new type of vehicle only when it is convenient enough to refuel with the needed type of fuel, the fuel companies need enough profit from selling that fuel to justify building new distribution facilities. This is an example of a "chicken and egg" problem – which comes first? While policies to support both the purchase of vehicles and the creation of refuelling sites will clearly be important, should one be prioritised over the other? Is it the case that the mere presence of more vehicles will provide enough incentive for the creation of more refuelling sites? If so, should policy-makers concentrate on the vehicle market and allow the availability of refuelling facilities to take care of itself? We aim to shed light on these questions by studying the patterns of refuelling site availability and autogas vehicle use for a panel of countries in the early years of this century.

The first point to make is that the two variables are strongly correlated, and while this is evidence of the chicken and egg relationship, it means that we could not expect to disentangle it from regressing the number of sites and vehicles within a given year. Instead, our strategy is to regress each variable against its values from the previous year, first in levels and then in first differences. If the relationship of vehicles to sites (say) is stronger than the other way round, this would suggest that policy-makers should give more support to the expansion of refuelling sites than to vehicles – additional sites would encourage the purchase of more vehicles, while the vehicles would not, on their own, be sufficient for the industry to deliver more refuelling sites and create a virtuous circle.

[2] It is important to remember that even if hydrogen itself is not taxed directly, if it is produced using energy that is taxed, then this will raise the cost to users.

Our first results, for the regressions using the levels of each variable, are presented in Tables 3 and 4. These cover ten countries from 2001 to 2006 (inclusive) and each country has its own dummy variable (taking a value of 1 for that country and 0 otherwise), with the exception of Australia (since we also use an intercept). We also ran regressions that included the break-even distance, with and without the country dummies; the results presented have the highest adjusted R-squared values. In particular, adding the break-even distance to models with country dummies had little impact on those dummies or the overall fit of the model, and produced coefficients with low t-statistics and counter-intuitive signs.

Table 3 Regression of the percentage of LPG-powered vehicles in each country

	Coefficients	*Standard Error*	*t statistic*	*Mean of data*	*Standard Deviation of data*
Dependent Variable				51.03	51.20
Intercept	-68.91	12.49	-5.52	1	0
Nsite(-1)	187.11	20.70	9.04	0.277	0.219
Belgium	52.61	10.088	5.21	0.10	0.3025
Czech Republic	65.09	9.79	6.65	0.10	0.3025
France	47.01	10.59	4.44	0.10	0.3025
Italy	74.91	11.40	6.57	0.10	0.3025
Japan	64.33	12.36	5.20	0.10	0.3025
Korea	199.04	11.38	17.49	0.10	0.3025
Netherlands	-10.49	5.81	-1.81	0.10	0.3025
Poland	48.84	5.76	8.48	0.10	0.3025
Turkey	140.01	8.07	17.34	0.10	0.3025

$R^2 = 0.968$; 60 observations

Table 4 Regression of the percentage of LPG refuelling sites in each country

	Coefficients	*Standard Error*	*t statistic*	*Mean of data*	*Standard Deviation of data*
Dependent Variable				0.292	0.234
Intercept	0.39177	0.022328	17.55	1	0
N vehicles (-1)	0.00445	0.000401	11.09	46.881	45.19
Belgium	-0.2876	0.02468	-11.66	0.10	0.3025
Czech Republic	-0.3430	0.02317	-14.80	0.10	0.3025
France	-0.2699	0.02658	-10.16	0.10	0.3025
Italy	-0.4045	0.02355	-17.18	0.10	0.3025
Japan	-0.3641	0.02687	-13.55	0.10	0.3025
Korea	-0.8908	0.04551	-19.57	0.10	0.3025
Netherlands	0.0494	0.02295	2.15	0.10	0.3025
Poland	-0.0252	0.02597	-0.97	0.10	0.3025
Turkey	-0.5461	0.03751	-14.56	0.10	0.3025

R^2 = 0.976; 60 observations

We find that most country dummy variables are significant, which implies that the ratio of filling stations to vehicles differs across national markets. This is not surprising, given the very different population densities and stages of development of the countries in our sample. The coefficients on the lagged numbers of sites and of vehicles are both positive and highly significant. A one standard deviation change in the proportion of refuelling sites offering autogas will lead to an increase of 0.80 of a standard deviation in the proportion of vehicles using autogas in the following year, other things being equal. A one standard deviation change in the proportion of vehicles using autogas will lead to an increase of 0.86 of a standard deviation in the proportion of refuelling sites offering autogas in the following year, other things being equal. In other words, both relationships appear to be important – a change in one variable appears to lead to a noticeable change in the other.

Another way of denoting the responsiveness of two variables is to give the elasticity of one with respect to the other – while this is most often done (by economists) in terms of the percentage change in the quantity demanded of a good which would come about as a result of a one percent change in its price, the concept can be applied to other relationships. In our case, the elasticity of the proportion of vehicles running on autogas with respect to the proportion of refuelling sites offering that fuel (in the previous year) is almost exactly equal to 1 – a 1 per cent change in the proportion of sites would lead to a 1 per cent change in the proportion of vehicles, other things being equal. (The exact value is 1.01, given by 187.11 × 0.277 ÷ 51.03 (the regression coefficient, multiplied by the mean of the independent variable, divided by the mean of the dependent variable).) The proportion of sites offering autogas is less responsive to the proportion of vehicles using it, however, with an elasticity of 0.71. (The regression coefficient is 0.00445, multiplied by the mean of the independent variable (46.88) and divided by the mean of the independent variable (0.29) – these means differ from those above because each regression uses lagged values for one of the two variables.)

We repeat the analysis with regressions using the changes in the proportion of vehicles and sites using and offering autogas. The results are shown in Tables 5 and 6. We have fewer observations (since no changes can be calculated for the first year of data). A general feature of regressions focusing on changes is that their fit, measured by the R squared, is typically poorer than for regressions based on the levels of variables and these are no exception.

Table 5 Regression of the changes in the percentage of LPG-powered vehicles in each country

	Coefficients	*Standard Error*	*t statistic*	*Mean*	*Standard Deviation*
Intercept	2.975	1.176	2.53	n.a	n.a.
Change in Sites (-1)	73.87	23.31	3.17	0.0158	0.0484

R^2 = 0.173; 50 observations

Table 6 Regression of the changes in the percentage of LPG refuelling sites in each country

	Coefficients	*Standard Error*	*t statistic*	*Mean*	*Standard Deviation*
Intercept	-0.00038	0.006107	-0.06	n.a	n.a.
Change in vehicles (-1)	0.004145	0.000708	5.86	3.63	7.91

R^2 = 0.417; 50 observations

These regressions show that both variables appear to be affected by a change in the other variable in the previous year. A change in the proportion of refuelling sites offering autogas that is one

standard deviation above the mean leads to an increase in the proportion of vehicles that is 45% of a standard deviation above the mean change. A change in the proportion of vehicles that is one standard deviation above the mean leads to an increase in the proportion of refuelling sites that is 68% of a standard deviation above the mean change. Using these regression coefficients, but still basing the elasticity calculations on the proportions of autogas vehicles and refuelling sites (rather than the changes in those proportions) we get an elasticity of sites with respect to vehicles of 0.67, and an elasticity of vehicles with respect to sites of 0.40.

The coefficients reflecting the impact of the proportion of autogas vehicles on the proportion of refuelling sites offering autogas (in Tables 4 and 6) are close to each other – within one standard error – and so their derived elasticities are also very close. The coefficients and elasticities reflecting the impact of the proportion of refuelling sites on the proportion of vehicles (in Tables 3 and 5) are further apart. Subtracting two standard errors from the higher coefficient gives a value greater than adding two standard errors to the lower one ($187.11 - 2 \times 20.70 > 73.87 + 2 \times 23.31$), implying that the two estimates are not statistically consistent with each other. This may, however, reflect time lags in the relationship between sites and vehicles which are picked up in the (trended) levels data but not in the annual changes. Given the simplicity of our regressions, and a relatively small dataset, problems of this kind are not unexpected.

The regression of Table 3 suggested, with an elasticity of vehicles with respect to sites of 1, that growth in the availability of refuelling sites could lead to equivalent growth in the use of autogas vehicles, although the results of Tables 4 and 6 suggest that this would not be enough to lead to a sufficient rise in the proportion of refuelling sites to create a virtuous circle. The regression of Table 5, giving a lower elasticity, casts doubt on whether the increase in refuelling sites would create enough of an increase in vehicle use and thus reinforces the main thrust of the results. This is that while the proportion of autogas-powered vehicles does appear to respond to the proportion of refuelling sites selling autogas, and vice versa, the relationship is not strong enough for the market to reach self-sustaining growth without additional policy measures.

6. Conclusions

Autogas is by far the most widely used and accepted alternative automotive fuel in use in the world today. Its success has depended on government support, however, and the incentive polices used fall into three categories, financial, regulatory and other types. The financial policies play a dominant role in the LPG market development and the regulatory policies are mainly complementary in strengthening the quality of services from the supply chain. In several cases, regulations have required fleet operators to convert their vehicles to autogas. This increases the use of autogas directly, and, in providing a critical mass of customers for refuelling stations, helps create the network of refuelling stations that is needed to ensure private customers are willing to convert their vehicles.

We have shown that there is a strong link between the break-even distance at which an LPG vehicle would have the same costs as a conventional gasoline car and the market penetration of LPG vehicles. Few countries have a penetration of more than 1 per cent if the break-even distance exceeds 40,000 km. Unless significant funds are available to subsidise hydrogen vehicles, this implies that their long-term development depends on having costs that are sufficiently low to meet this break-even distance. Adapting data from Offer et al [14], we are able to show that most of the cases they analyse (and most of the possible combinations) do indeed meet this criterion and a relatively modest tax differential would give hydrogen a suitably low break-even distance in the other cases.

The break-even distance is not the only relevant factor, however, for customers must also find it convenient to use a hydrogen vehicle, which implies a ready availability of refuelling sites. Using panel data to track the level (and changes in) the proportion of autogas sites and vehicles over time in ten countries, we find that the proportion of vehicles responds positively to an increase in the proportion of refuelling sites and vice versa. However, these responses are not strong enough to reach self-sustaining growth without additional measures to encourage the adoption of autogas-powered vehicles and the availability of refuelling sites.

The hydrogen fuel cell is a novel automotive energy vector, which could eventually replace oil, and may prove superior to battery technologies. However, the cost of such novel energy is likely to be more expensive than other types of fuel, even when all the technical hurdles for producing and storing hydrogen fuel are overcome, and certainly in the early stages of adoption. This implies that government support will be essential for developing the market. The one clear lesson from international experience with autogas is that a mix of policies will be required, both financial and non-financial.

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Appendix

Table 7 gives the regression results for the percentage of LPG-powered vehicles in our full sample of countries, referred to in Section 3. We believe that we have a sufficient explanation for the four outliers (strong policies requiring taxis to use autogas in Japan, and a market share that is a legacy of more favourable past conditions than existed at our sample date in the other three countries) to prefer the regression on the smaller dataset, but report the results here for completeness.

Table 7: Regression of the percentage of LPG-powered vehicles in each country (full sample)

	Coefficients	*Standard Error*	*t statistic*	*Mean*	*Standard Deviation*
Intercept	5.048	1.842	2.74	n.a	n.a.
Break even distance	-0.0538	0.0282	-1.91	45.4	33.92
Sites per km of road	0.3397	0.0968	3.51	7.96	9.88

$R^2 = 0.54$; 19 observations

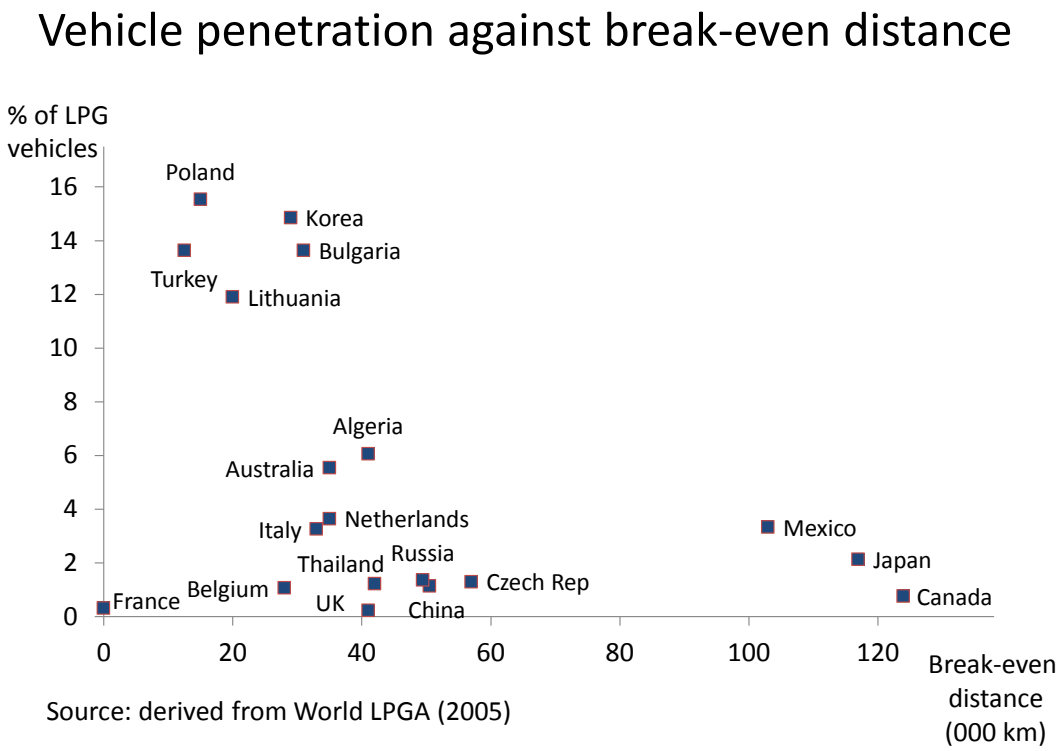


Figure 1

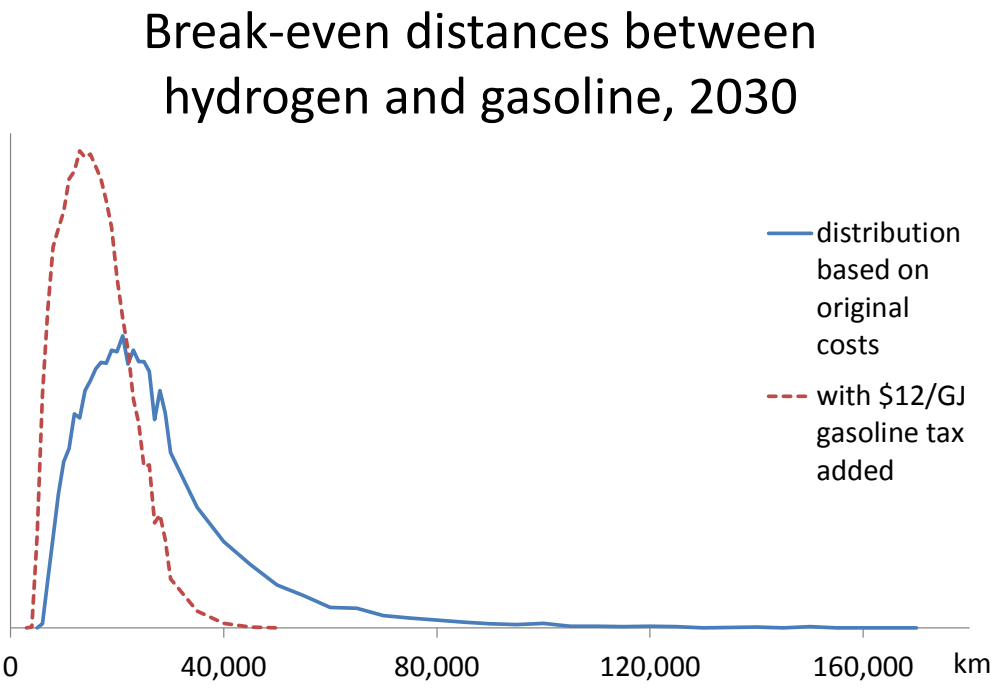


Figure 2