Externalities and Subsidies: the Economics of Hydrogen-based Transportation Technologies

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1. Introduction

This paper reviews life cycle analyses of alternative automotive engine technologies in terms of both their private and societal (that is, inclusive of externalities and net of taxes and subsidies) costs. The economic viability of hydrogen-based technologies is shown to be heavily dependent upon the removal of these market distortions. In other words, the removal of subsidies to oil-based technologies and the appropriate pricing of oil products to reflect the environmental damage (local, regional, and global) created by their combustion are essential policy strategies for stimulating the development of hydrogen-based renewable energy technologies in the transportation sector. However, a number of non-quantifiable policy objectives are also of significance in the planning of future technology options. Currently, the most important of these would appear to be security of oil supplies and associated transportation and distribution systems.

2. Environmental Externalities.

Externalities are defined as benefits or costs generated as an unintended by-product of an economic activity that do not accrue to the parties involved in the activity. Environmental externalities are benefits or costs that manifest themselves through changes in the biophysical environment.[1] Pollution emitted by road vehicles is known to result in harm to both people and the environment. In addition upstream and downstream externalities, associated with securing fuel and waste disposal respectively, are generally not included in fuel costs. To the extent that the ultimate consumer of these products does not pay these environmental costs, they do not face the full cost of the services they purchase (i.e. implicitly their energy use is being subsidised). As a consequence, oil resources will not be allocated efficiently.

Environmental externalities of oil production/consumption can be divided into two broad (net) cost categories that distinguish emissions of pollutants with local and/or regional impacts from those with global impacts:

- costs of the damage caused to health and the environment by emissions of pollutants other than those associated with climate change; and
- costs resulting from the impact of climate change attributable to emissions of greenhouse gases.

The distinction is important, since the scale of damages arising from the former is highly dependent upon the geographic location of source and receptor points. The geographic source is irrelevant for damages arising from emissions of greenhouse gases (GHGs).

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[1] A more extensive examination of environmental externalities in the energy sector is given in Owen (2004a).

In the transport sector, externality costs are also incurred as a result of congestion, noise, accidents and road damage.[2] However, since this paper assesses differences between vehicles based upon alternative fuels and engines, these costs will be assumed to be common to all vehicles and consequently ignored.[3]

Costs borne by governments, including direct subsidies, tax concessions, indirect energy industry subsidies (e.g. the cost of oil supply security), and support of research and development costs are not externalities. They do, however, distort markets in a similar way to negative externalities, leading to increased consumption and hence increased environmental degradation.

In order to address effectively these environmental matters, together with energy supply security concerns, radical changes in automotive engine and fuel technologies will probably be required. Such changes must offer the potential for achieving “near zero” emissions of air pollutants and greenhouse gases (GHGs), and must diversify the transportation sector away from its present heavy reliance on gasoline. Only hydrogen and some biofuels currently appear to be a viable technical options.

3. Life-cycle analysis

When comparing the environmental footprints of alternative energy technologies, it is important that the combustion stage of the technology not be isolated from other stages of the “cycle”. For example, fuel cells emit virtually no GHG in their operation. However production of their “fuel” (hydrogen) from fossil fuels may involve increases in GHG emissions in excess of those that would arise from using current commercial fossil fuel technologies. To avoid such distortions, the concept of life cycle analysis has been developed.

Life cycle analysis (LCA) is based upon a comprehensive accounting of all energy and material flows, from “cradle to grave”[4], associated with a system or process. The approach has typically been used to compare the environmental impacts associated with different products that perform similar functions, such as plastic and glass bottles. In the context of an energy product, process, or service, a LCA would analyse the site-specific environmental impact of fuel extraction, transportation and preparation of fuels and other inputs, plant construction, plant operation/fuel combustion, waste disposal, and plant decommissioning. Thus it encompasses all segments including upstream and downstream processes and consequently permits an overall comparison (in a cost benefit analysis framework) of short- and long-term environmental implications of alternative energy technologies. Central to this assessment is the valuation of environmental externalities of current and prospective fuel and energy technology cycles. It should be noted, however, that only material and energy flows are assessed in an LCA, thus ignoring some externalities (such as supply security) and technology reliability and flexibility.

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[2] A comprehensive assessment of the full costs and benefits arising from the transportation sector has been provided by Greene et al. (1997).

[3] A referee has pointed out that variations in noise impacts across different types of vehicles has effectively been ignored by imposing this assumption.

[4] Often referred to as “well to wheels” in the context of applications in the transport sector.

For the purpose of this paper, life-cycle analysis will involve the following methodological steps[5]:

- Definition of the product cycle's geographical, temporal, and technical boundaries;
- Identification of the environmental emissions and their resulting physical impacts on receptor areas; and
- Quantifying these physical impacts in terms of monetary values.

Traditionally, LCA has omitted the third of these steps and the final analysis has therefore been expressed in terms of just the biophysical impacts that can be quantified. The extension to include costing of these impacts is generally known as the "impact pathway" methodology. Essentially, however, it can be considered as a specific application of LCA. This methodology formed the theoretical basis for the European Commission's ExternE (1997) study, which was the first comprehensive attempt to use a consistent "bottom-up" methodology to evaluate the external costs associated with a range of different fuel cycles.

3.1 Definition of the product cycle's boundaries

The first task is to identify, both in terms of activities and geographic locations, the various stages of the fuel/technology cycle. Each energy form is viewed as a product, and impacts are included for the actual pathway. The precise list of stages is clearly dependent on the fuel chain in question, but would include both "upstream" and "downstream" activities in addition to the fuel combustion stage itself. "Upstream" activities would include stages such as exploration, extraction, refining and transportation of fuel. "Downstream" activities would include the treatment and disposal of wastes and by-products and, ultimately, refinery demolition and site restoration impacts.

The extent to which the boundaries must encompass indirect impacts is determined by the order of magnitude of their resulting emissions. In theory, externalities associated with the construction of plants to make the steel that is used in the construction of gasoline delivery trucks should be included. In reality, however, such externalities are likely to have a relatively insignificant impact

The system boundary will also have spatial/geographical and temporal dimensions. These will have major implications for the analysis of the effects of air pollution in particular. For many air pollutants, such as ozone and SO_2, the analysis may need to focus on a regional, rather than local, scale in order to determine their total impact. For emissions of GHGs, the appropriate range is clearly global. Impacts must also be assessed over the full term of their impact, a period that may extend over many decades or even centuries in the case of emissions of GHGs and long-term storage of some nuclear waste products. This introduces a significant degree of uncertainty into the analysis, as it requires projections to be made of a

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[5] These steps describe a "bottom up", as distinct from a "top down", methodology for life cycle analysis. Top-down studies use highly aggregated data to estimate the external costs of emissions. They are typically undertaken at the national or regional level using estimates of total quantities of emissions and estimates of resulting total damage. The proportion of such damage attributable to certain activities (e.g. the transport sector) is then determined, and a resulting monetary cost derived. The exercise is generic in character, and does not take into account impacts that are site specific. However, its data requirements are relatively minor compared with the "bottom up" approach. The latter involves analysis of the impact of emissions from a single source along an impact pathway. Thus all technology data are project specific. When this is combined with emission dispersion models, receptor point data, and dose-response functions, monetised values of the impacts of specific externalities can be derived. Data requirements are relatively large compared with the "top down" methodology, and therefore omissions may be significant.

number of variables that will form the basis of future society. Among these would be the size of the global population, the level of economic growth, technological developments, the sustainability of fossil fuel consumption, and the sensitivity of the climate system to anthropogenic emissions.

3.2 Identification of the environmental emissions and their resulting biophysical impacts on receptor areas

Comparisons of alternative transport technologies utilising LCA are generally standardised as emissions per vehicle km in order to allow for different technologies and emission profiles. However, data used to quantify burdens are, to varying degrees, technology specific. For example, emission of CO_2 from cars depends only on the efficiency of the equipment and the carbon/hydrogen ratio of the fuel; uncertainty is negligible. Conversely, emissions of SO_2 can vary by an order of magnitude depending on the grade of oil and the extent to which emission abatement technologies have been incorporated in the vehicle. In general, one would adopt the best available technology currently in use in the country of implementation.

Quantifying the physical impacts of emissions of pollutants requires an environmental assessment that ranges over a vast area, extending over the entire planet in the case of CO_2 emissions. Thus the dispersion of pollutants emitted from fuel chains must be modelled and their resulting impact on the environment measured by means of dose-response functions. Ideally, in the context of damages to humans, such functions are derived from studies that are epidemiological, assessing the effects of pollutants on real populations of people. However, the relevance and reliability of current methodologies for putting financial estimates on human suffering in terms of increased levels of mortality and morbidity has been the subject of some debate.[6]

4 Total Societal Life Cycle Costs

The road transport sector emits (directly or indirectly) a similar range of pollutants to the electric power sector. However, the resulting impacts are not directly comparable. Power station emissions are generally from high stacks in rural areas. In contrast, road transport emission sources are more diverse, invariably closer to ground level and frequently in urban areas. Nevertheless, consideration of environmental externalities of road transport fuels does provide an order of magnitude for calculation of environmental adders[7] for the purpose of fuel taxation policy. Ultimately this may justify a fiscal incentive for accelerated development of “renewable” transport fuels, in conjunction with hydrogen and fuel cell technology.

Delucchi (2002) has developed a Lifecycle Emissions Model (LEM) that estimates energy use, emissions of pollutants, and CO_2-equivalent GHG emissions from the complete lifecycles of fuels, materials, vehicles, and infrastructure arising from a variety of transportation technologies. Such models permit identification and calculation of the biophysical emissions, from which a total societal life cycle cost for each technology can be

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[6] Pearce (2002) has raised concerns with the methodology used to derive monetary estimates of health impacts.

[7] An “externality adder” is simply the unit externality cost (expressed as cents per vehicle kilometre for passenger vehicles and cents per ton kilometre for goods vehicles) added to the standard resource cost of energy to reflect the social cost of its use.

derived by calculating the present value of lifecycle costs (PVLC) associated with each stage; *viz*:

> Total Societal Life Cycle Costs ($/vehicle)
> =
> Initial cost of vehicle (before tax)
> + PVLC (fuel + non-fuel operation and maintenance)
> + PVLC (full fuel cycle air pollutant damages + GHG emissions damage)
> + PVLC (full fuel cycle subsidies – full fuel cycle taxes).

5. Application of Fuel Cell Technology in the Road Transport Sector

Concerns over the health impacts of small particle air pollution, climate change, and oil supply insecurity, have combined to encourage radical changes in automotive engine and fuel technologies that offer the potential for achieving near zero emissions of air pollutants and GHG emissions, and diversification of the transport sector away from its present heavy reliance on gasoline. The hydrogen fuel cell vehicle is one technology that offers the potential to achieve all of these goals, if the hydrogen is derived from a renewable energy resource.

Fuel cells convert hydrogen and oxygen directly into electricity. They have three major advantages over current internal combustion engine technology in the transport sector:

- Gains in energy efficiency. “Well to wheels” efficiency for gasoline engines averages around 14 per cent, for diesel engines 18 per cent, for near-term hybrid engines 26 per cent, for fuel cell vehicles 29 per cent, and for the fuel cell hybrid vehicle 42 per cent.[8] Thus, up to a three-fold increase in efficiency is available relative to current vehicles.
- Near-zero emissions.
- Very low emissions of local air pollutants. Irrespective of the fuel, fuel cells largely eliminate oxides of sulphur and nitrogen, and particulates. All of these pollutants are associated with conventional engines.

In order to compare competing transport technologies on a basis that includes the cost of externalities as well as private costs, the societal life cycle cost of each technology must be calculated.

5.1 Fuel cell buses

Prototype fuel cell buses powered by liquid or compressed hydrogen are currently undergoing field trials in North America, while the European Commission (EC)[9] is supporting the demonstration of 30 fuel cell buses in 10 cities over a two-year period, which commenced in 2003. In addition, the United Nations Development Program Global Environmental Facility is supporting a project to demonstrate the technology using 46 buses powered by fuel cells in

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[8] Fuel cells can more than double the efficiency of an internal combustion engine, but energy used in making and storing hydrogen offsets these gains to the benefit of fuel cell hybrid vehicles.

[9] The EC’s Cleaner Urban Transport for Europe (CUTE) program involves a two-year trial of three fuel cell buses, using compressed hydrogen, in each of 10 cities: Amsterdam, Barcelona, Hamburg, London, Luxembourg, Madrid, Porto, Reykjavik, Stockholm and Stuttgart. A further three buses are undergoing trials in Perth (Western Australia). All buses have been manufactured by Daimler/Chrysler under the Citaro (Mercedes) brand. They have a range of about 200 km and a maximum speed of 80 km/h. Their unsubsidized cost is estimated to be around $3 million each.

the heavily polluted cities of Beijing, Cairo, Mexico City, New Delhi, Sao Paulo and Shanghai.

There are a number of reasons why hydrogen (in compressed form) would appear to be a likely option for large vehicles, such as buses:

- they return regularly to a depot thus minimising fuel infrastructure requirements;
- they are “large”, thus minimising the need for compactness of the technology;
- in urban areas, low or zero emissions vehicle pollution regulations will assist their competitiveness as compared with diesel-powered buses;
- subsidies may be available from urban authorities in order to demonstrate urban pollution reduction commitments;
- they avoid pollution problems specifically related to diesel buses;
- They operate almost continually over long periods, thus making fuel-efficient technology more attractive.

Hörmandinger and Lucas (1997) have investigated the life cycle financial and economic cost of fuel cell buses utilising hydrogen as fuel. They assessed the costs that a private operator would face in running a fleet of fuel cell powered buses, inclusive of a new fuel supply infrastructure, compared to those of a fleet of conventional diesel powered buses of similar performance. Given the presence of economies of scale in the production of hydrogen, they concluded that the fuel cell bus would be marginally more competitive than its diesel counterpart. Extending the analysis to societal life cycle costs, the analysis favoured the diesel option. Adding in the cost of environmental externalities led to a significantly greater increase in the cost of the diesel, as opposed to the hydrogen, bus. However, this was more than offset by the removal of the excise duty on diesel.

The Hörmandinger and Lucas base-case model assumed a fleet of just 10 buses, operating over a 20-year time horizon and travelling 200 km a day, 7 days a week. The central hydrogen reformer plant, using natural gas feedstock, and the refuelling station were based upon currently available technology. Both were exclusively for the use of the bus fleet. The cost of the fuel cell stack was set at $300 per kilowatt, and it was assumed that it would be replaced every five years. Although this cost was rather low by 1997 standards, the authors speculated that it would be reasonable for their assumed time frame (5 to 10 years in the future). The fuel cell buses were assumed to be of the same weight (without the power train) as the diesel buses. The cost of the tank for on-board storage of compressed hydrogen represented one of the major uncertainties of the model, since the technology is still under development.

Sensitivity of Results: Private costs

The annualised life cycle private costs, using a discount rate of 15 per cent, showed that the fuel cell bus was from 23 per cent (large bus) to 33 per cent (medium size bus) more expensive than the diesel bus. The difference was due to both the provision of fuel and the initial cost of the investment.

A sensitivity analysis indicated that the medium size fuel cell bus reacted to changes in the base case parameter values in a similar way to its larger counterpart. The most important parameter with regard to impact on life cycle costs was the discount rate. However, although variations in the discount rate had a major influence on the individual life cycle costs of both technologies, since their investment and running cost profiles were very similar their relative costs remained fairly static. For large buses, a drop in the discount rate from 15 per cent to 8 per cent reduced the cost differential from 23 per cent to 19 per cent.

Fleet size was found to be an important parameter, since the on-site production of hydrogen was subject to significant economies of scale. Thus an increase in fleet size from 10 to 25 gave the fuel cell bus a marginal cost advantage over the diesel alternative.

Price variations of feedstock (gas) had a relatively minor impact on bus costs, since it was a relatively minor cost component of the hydrogen reformer plant investment and operating costs. However, the diesel bus was much more sensitive to fuel cost increases. In the base case, an increase of 80 per cent in the price of diesel would remove its cost advantage.

As might be expected, the size and cost of the fuel cell stack was critical, although not compared with the costs of the reformer. Note that if hydrogen could be "delivered" in the context of a hydrogen economy, then it is likely that reforming cost in the context of this example would be greatly reduced.

Sensitivity of Results: Societal Costs

The societal cost of life cycle emissions involved augmenting the private costs by the damage costs arising from the environmental externalities created by the two options, and removal of the excise duty (56 per cent of the price) from the diesel fuel in the calculations. A lower discount rate of 8 per cent was also imposed, to reflect societal rather than private expectations[10].

Externality costs were based upon previous studies of estimated damages arising from comparable emissions from the electricity and transport sectors. This transfer of results may not be appropriate if the characteristics of the exposure-response relationship differ from those of the reference studies. This is because in urban areas exposure to emissions from fossil fuel combustion in vehicles involves higher concentrations of pollutants than in rural areas due to the close proximity of emission and receptor points. However, even taking social costs at the higher end of the range only gave fuel cell buses a marginal benefit over their diesel counterparts.

A number of other social benefits were not quantified. In the context of this particular application, their impact would have been extremely small. However, widespread adoption of fuel cell buses would have reduced other forms of local urban pollution from diesel buses (such as fuel spills and noise) and would have provided enhanced levels of security of domestic fuel supplies.

It is important to note that the GHG emission reduction benefits of hydrogen in the Hörmandinger and Lucas model were based upon the use of natural gas as feedstock, with no CO_2 sequestration. As a higher cost alternative, utilising electricity generated from renewable sources to produce the hydrogen or adopting CO_2 sequestration with natural gas as the feedstock would have produced near zero fuel-cycle GHG emissions and consequently significantly greater societal benefits for the fuel cell buses. In this context, however, it is important that energy from renewable resources is "additional" to that which was currently being generated. Simply utilising existing renewable resources and making up the shortfall

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[10] In the context of climate change damages arising from emissions of GHG this discount rate would still be regarded as unreasonably large (ref: Pearce (2002)).

elsewhere from fossil fuels would not have contributed towards a net reduction in global GHG emissions[11].

5.2 Fuel Cell Cars

Ogden et al. (2004) have estimated the societal lifecycle costs of cars based upon alternative fuels and engines. Fifteen different vehicles were considered. These included current gasoline combustion engines and a variety of advanced lightweight vehicles: internal combustion engine vehicles fuelled with gasoline or hydrogen; internal combustion engine/hybrid electric vehicles fuelled with gasoline, compressed natural gas, diesel, Fischer-Tropsch liquids or hydrogen, and fuel cell vehicles fuelled with gasoline, methanol or hydrogen (from natural gas, coal or wind power). The analysis assumed a fully developed fuel infrastructure for all fuel options and mass production of each type of vehicle.[12] This permitted all vehicles to be compared on the basis of their individual cost of construction, fuel costs, oil supply security costs and environmental externalities over the full fuel cycle. All costs were expressed net of direct taxes and subsidies, and all fuel costs were assumed to remain constant (in real terms) over the lifecycle of all vehicles.[13] A discount rate of 3 percent was applied to environmental impact valuations and 8 percent otherwise.

The present value of total societal lifecycle costs, excluding external costs, favoured current and advanced gasoline cars (Table 1), with fuel cell vehicles being upwards of 60 per cent more expensive. This imbalance was reversed when lifetime air pollutant and GHG emission damage costs were included (Table 2). Now, hybrid vehicles utilising traditional fossil fuels held a significant cost advantage over their fuel cell counterparts. It was only the introduction of an Oil Supply Insecurity (OSI) cost, that was intended to measure the cost of ensuring oil supply security from the Middle East, that those fuel cell vehicles based upon hydrogen (derived either from renewables or from fossil fuels with carbon sequestration) became

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[11] In fact, such a practice could actually increase net emissions of CO_2. This is because 1 GWh of electricity provided from renewable resources avoids 972 tonnes of CO_2 if it replaces coal-fired generation. If the same 1 GWh was used to produce hydrogen by electrolysis for use in a fuel cell vehicle to replace a gasoline hybrid vehicle the avoided CO_2 emissions would amount to 390 tonnes.

[12] Thomas et al. (1998) utilise a market penetration model to develop a plausible scenario that gives government and industry incentives to make the necessary investments to permit a smooth transition from fossil fuels to a hydrogen-based transportation sector.

[13] This implies that fuel price volatility is also irrelevant in the analysis. Yet hydrogen derived from renewable resources that have no fuel costs (e.g. wind or solar power) is likely to exhibit considerably less price volatility than (direct use of) gasoline, natural gas or diesel fuels.

Table 1: Projected base case societal lifecycle costs for automobiles with alternative fuel/engine options.

Technology	**Present value: Lifetime Fuel costs**	**Retail cost: Drive train + fuel storage**	**Cost of aluminium frame**	**Present value: Total private lifecycle costs**	**Present value: Lifetime cost of externalities**	**Present value: Total societal lifecycle costs**
Current gasoline SI ICEV	2828	2837	0	5665	6723	12388
Advanced lightweights ICEs						
Gasoline SI ICEV	1674	2837	936	5448	3579	9026
H_2 (NG) SI ICEV	3381	2837+2500	936	9654	1270	10924
Advanced lightweights ICE/HEVs						
Gasoline SIDI ICE/HEV	1316	2837+1342	936	6432	3015	9446
CNG SI ICE/HEV	1552	2837+1556	936	6881	1160	8040
H_2 (NG) SI ICE/HEV	2823	2837+2780	936	9376	1081	10457
Diesel CIDI ICE/HEV	996	2837+1863	936	6632	2809	9441
FT50 (NG) CIDI ICE/HEV	1058	2837+1863	936	6694	2253	8947
Lightweight fuel cell vehicles						
Gasoline FCV	2009	2837+5097	936	10879	3243	14122
Methanol (NG) FCV	2238	2837+3220	936	9231	916	10147
H_2 (NG) FCV	2169	2837+2459	936	8402	736	9138
H_2 (NG) FCV w/CO_2 seq.	2411	2837+2459	936	8644	225	8869
H_2 (coal) FCV	2200	2837+2459	936	8432	1247	9679
H_2 (coal) FCV w/CO_2 seq.	2435	2837+2459	936	8667	314	8981
H_2 (wind electrolytic) FCV	3394	2837+2459	936	9626	182	9808

Abbreviations:

AP: air pollutants; CIDI: compression-ignition direct-injection; CNG: compressed natural gas; CO_2: carbon dioxide; FCV: fuel cell vehicle; GHG: greenhouse gas emissions; H_2: hydrogen; HEV: hybrid electric vehicle; ICE: internal combustion engine; ICEV: internal combustion engine vehicle; NG: natural gas; OSI: oil supply insecurity; SI: spark-ignition; SIDI: spark-ignition direct-injection.

Source: Modified from Table 1 of Ogden et al. (2004)

Table 2: Projected base case lifecycle costs for externalities of automobiles with alternative fuel/engine options.

Technology	Externalities: original estimates Present value of lifetime costs			Present value: Lifetime cost of externalities
	AP	GHG	OSI	Original
Current gasoline SI ICEV	2640	1429	2654	6723
Advanced lightweights ICEs				
Gasoline SI ICEV	1162	846	1571	3579
H_2 (NG) SI ICEV	524	746	0	1270
Advanced lightweights ICE/HEVs				
Gasoline SIDI ICE/HEV	1097	683	1235	3015
CNG SI ICE/HEV	644	515	0	1160
H_2 (NG) SI ICE/HEV	458	623	0	1081
Diesel CIDI ICE/HEV	1150	590	1069	2809
FT50 (NG) CIDI ICE/HEV	1122	596	535	2253
Lightweight fuel cell vehicles				
Gasoline FCV	338	1019	1886	3243
Methanol (NG) FCV	248	668	0	916
H_2 (NG) FCV	257	479	0	736
H_2 (NG) FCV w/CO_2 seq.	119	106	0	225
H_2 (coal) FCV	366	881	0	1247
H_2 (coal) FCV w/CO_2 seq.	215	99	0	314
H_2 (wind electrolytic) FC	68	114	0	182

Abbreviations: see Table 1.
Source: Modified from Table 1 of Ogden et al. (2004)

competitive. However, the OSI was a rather arbitrary control-type cost[14] and the fact that it was so critical to the viability of the hydrogen fuel cell car was unfortunate.

In a sensitivity analysis, higher values attached to the environmental externalities, as might be expected, favoured the fuel cell vehicles and particularly those fuelled by hydrogen derived from fossil fuels with CO_2 sequestration.

5.3 London Taxi Cabs

Mourato et al. (2004) report the results of a contingent valuation study conducted amongst London taxi drivers designed to assess their willingness to pay (WTP) to drive hydrogen fuel cell taxis. In the short term this would involve participation in a pilot project, whilst in the longer term it would involve production line fuel cell taxis. The intention was that six fuel cell London taxis would be introduced and operated over a period of a year and a half, following which a decision would be taken of whether to move to series production.

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[14] Control costs are what it costs society to achieve a given standard that restricts the extent of an environmental or other specific adverse impact to an acceptable level. Damage costs are a measure of society's loss of wellbeing resulting from the damage arising from the same impact. Although control costs are often seen as estimates of damage costs, conceptually they are very different. For the purpose of economic impact analysis, the use of control costs is an inappropriate methodology. The distinction is discussed at length in Owen (2004b).

The London taxi is suitable for fuel cell and hydrogen technology because:

- They are low range vehicles principally operating in Greater London and therefore refuelling points would not be required outside of this area;
- They are high-profile vehicles which would serve to promote zero emissions technology in the road transport sector;
- London's current fleet of 20,000 diesel taxis contributes significantly to the city's air quality problems, particularly with emissions of NO_x and particulates;
- Current taxis subject the driver and passengers to significant levels of engine noise, whilst fuel cell taxis would be virtually silently in operation.

Despite concerns about daily exposure to air pollution and a supportive attitude towards cleaner vehicle fuels and technologies, the study concluded that the WTP of London taxi drivers to participate in a fuel cell pilot project was dictated principally by considerations of their own personal financial benefits arising from the project. In contrast, the premium that drivers were prepared to pay for production fuel cell taxis was influenced by the degree of concern about air pollution, their level of education, and their knowledge of fuel cells.

7. Concluding Comments

This paper has addressed the topic of environmental externalities and other market distorting influences in the context of hydrogen-based transportation technologies[15]. However, as noted earlier, since this paper assesses differences between vehicles based upon alternative fuels and engines, externality costs that are incurred as a result of congestion, accidents and road damage are assumed to be common to all vehicles and consequently ignored. In addition, the paper also ignores the important interaction between urban transport policy and near-zero emission transport technologies, which is beyond the scope of this particular study.

On the basis of the major studies concluded to date, it is evident that the societal benefits arising from the introduction of near zero emissions technologies based upon hydrogen rely heavily on their environmental and supply security benefits to offset their private cost disadvantages. Unfortunately, the precision of such benefits is questionable due a range of complex methodological issues and the absence of markets in environmental "goods". Nevertheless, the degree to which gasoline is either directly or indirectly subsidised is a significant factor in assessing the commercial viability of emerging alternative technologies.

Justification of energy subsidies to developing technologies may be based upon the desire of a government to achieve certain environmental goals (e.g. enhanced market penetration of low GHG emissions technology), to "level the playing field" by offsetting implicit and explicit fossil fuel subsidies, or for enhancing levels of domestic energy supply security. However, in general, case specific direct action is likely to give a more efficient outcome. Thus penalising high GHG emitting technologies not only creates incentives for "new" technologies, but it also encourages the adoption of energy efficiency measures with existing

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[15] In principle, the same approach can be adopted for hydrogen and fuel cell technologies in the stationary power sector. However, in this context, renewable energy can be used directly to substitute for fossil fuel-based technologies. In addition, a range of alternative fuels and technologies are currently available that offer significant emission reduction potential per unit of energy output using established technologies. Thus opportunities for the widespread adoption of hydrogen-based technologies are currently very limited. Perhaps the greatest potential for growth is in the distributed generation market but, again, competing technologies are available.

technologies and consequently lower GHG emissions per unit of output. In addition, if the existence of market failures is restricting the diffusion of zero or low emission energy technologies, then (again) addressing those failures directly may provide an efficient outcome.

If sustainable development and energy security of supply can be regarded as public goods, then their level of provision through competitive market forces would be sub-optimal. This would justify market intervention designed to raise their supply to a level that would be optimal to society. The hydrogen economy is one option available for addressing this situation.

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