How alternative are alternative fuels?

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Could alternative fuel vehicles contribute to a substantial reduction of air pollution? Is there a market for alternative fuel vehicles? Could a market be created via a pollution tax? The article answers these questions on the basis of the available estimates.

1 Introduction

Gasoline and diesel vehicles are associated with high air pollutant emissions whereas alternative fuel vehicles (AFVs) are often considered clean and therefore a valid means towards a more sustainable motor vehicle mobility. The list of alternative fuels includes compressed natural gas (CNG), liquid petroleum gas (LPG), methanol, ethanol, hydrogen, electricity and fuel cells. The last two fuels are considered of special interest because they do not rely on internal combustion engines, but on electric engines which have zero local emission. The consequence of such widespread opinion is the request for more research into AFV technology and for a financial incentive to promote their diffusion among auto users. But although some States and Regions enacted grants for AFVs, the vast majority of vehicles are still powered by conventional fuels and CNG, LPG or electric vehicles represent only niche markets.

Michaelis (1995) provides an explanation to such market distribution in terms of costs. He shows that conventional vehicle costs are in most circumstances lower than AFV costs. A discussion of such findings is provided below. One might think that such results are due to the fact that air emission costs are not fully paid for by the auto users. It is well know that pollution costs represent a real cost (e.g. in terms of health morbidity and mortality) imposed on society but not paid for by whoever causes them. Such a situation is termed in the economic literature as an environmental externality that leads to market failure and to sub-optimal resource allocation.

Consequently, the question that we want to investigate in this article is the following. If externality costs would be paid for by vehicle users through an environmental tax, would AFVs be preferred to conventional fuel vehicles, since the latter would be charged a larger environmental tax? In other words, if prices would reflect the real costs, would AFVs acquire a larger share of the market?

Section 2 lists alternative fuels and discusses their pros and cons. Section 3 presents the estimation methodology, the data used and the results. Section 4 further discusses the results and presents some conclusions.

2 Alternative fuels

In this section we list the main alternative fuels and provide a brief description and discussion of the pros and cons of their adoption for vehicle combustion. Since alternative fuels, and especially the engines which use them, are undergoing a continuos research and improvement, we refer to the specialised literature for an in-depth and up-to-date analysis of their pro-

Fuel type	*Advantages*	*Disadvantages*
Compressed Natural Gas	• quality as a fuel • reduced atmospheric emissions • availability and distribution • relative safety	• storing the fuel on board • reduced driving range • small number of refuelling stations • vehicle cost • emission of unburned hydrocarbons (especially methane)
Liquid Petroleum Gas	• physical-chemical characteristics • reduced emissions • can be derived from various sources • the possibility of storage	• variability in composition • safety issue • availability and distribution
Methanol	• physical-chemical characteristics • the reduced emissions of regulated gases • storage possibilities	• costly to produce • low energy density • highly toxic and corrosive
Ethanol	• use of renewable resources • physical-chemical characteristics • reduction of regulated emissions	• costly to produce • low energy density • toxic and corrosive
Electricity	• zero local emissions • existence of alternative means of generating electricity • reduced noise • increased life of the vehicle	• limited driving range with the existing batteries • lack of recharging infrastructure • high cost of the vehicle • safety uncertainties

Table 1: Advantages and disadvantages of alternative fuels

perties (Soffritti, 1997; OECD, 1996).

1 Compressed Natural Gas

The compressed natural gas (CNG) is made mainly of methane (70-98 per cent), hydrocarbons C_2-C_6 (up to 16 per cent) and small amounts of N_2, CO_2, and H_2S. It is used as a engine fuel without further processing. CNG has more than 120 as octane number. Its combustion is clean because it does not generate soot.

The advantages of using CNG are: the quality as a fuel; the reduced atmospheric emissions; the availability and distribution and the relative safety. As to the end-of-pipe emissions vehicles fuelled by CNG emit 25 per cent less carbon dioxide (CO_2) than the average car because of the favourable hydrogen to carbon ratio and because of the high fuel efficiency (Michaelis, 1993). Emissions of carbon monoxide (CO), nitrogen oxides (NO_x) and hydrocarbons depends, as for all fossil fuels, on the efficiency and the control of the combustion process taking place in the vehicle's engine. Emissions of aromatic hydrocarbons such as benzene and other volatile organic carbons (VOCs) are almost negligible. Further, its contribution to ozone formation is almost zero.

The disadvantages are: the problem of stocking the fuel on board[1], the reduced driving range, the small number of refuelling stations, the vehicle cost and the emission of unburned hydrocarbons (especially methane). As to this last point, it should be underlined that methane is one of the greenhouse gases, so that there is a concern that substituting conventionally fuelled vehicles with CNG fuelled vehicles might simply substitute CO_2 with methane instead of solving the problem.

Liquefied Petroleum Gas

The liquefied petroleum gas (LPG) is mainly composed of propane and butane. These are gases that are liquefied by a modest decrease in atmospheric pressure and temperature. LPG is derived as a by-product of petroleum refinement or from natural gas separation.

The main pros of LGP are: the physical-chemical characteristics, the reduced emissions, the various sources from which it can be derived, the possibility of storage. LPG has a higher octane number than gasoline so that higher compression ratio engines can be used. LPG has also a high hydrogen-to-carbon ratio that implies that emissions of carbon dioxide per unit of energy are lower. LPG is convenient to use on board a vehicle, as it can be stored as a liquid under pressure. However it vaporises at atmospheric pressure, and this helps it to mix with the intake air before being burned in the engine. As a result LPG vehicles have lower emissions of unburnt hydrocarbons and carbon monoxide than gasoline vehicles, and with appropriate engine tuning they can also have lower nitrogen oxide emissions (Michaelis, 1993).

The disadvantages relate to: the variability in composition, the safety issue and the availability and distribution. The LPG composition (the relative percentage of propane and butane) varies among countries and among seasons making difficult for vehicle manufactures and user to optimise vehicles' performance. Contrarily to CNG, LPG in gaseous form is heavier than air and is highly inflammable, so that severe restriction are enacted on using LPG fuelled vehicle in tunnels or park them in underground parking lots.

Alcohol Fuels

Alcohol fuels, either methanol or ethanol, can be used in spark ignition or compression ignition engine with performance comparable with traditional fuels.

Methanol

Methanol can in principle be produced from any hydrocarbon or carbohydrate feedstock, including natural gas, coal or biomass. The advantage of using methanol for greenhouse reduction depends on how it is produced: "if a vehicle is fuelled with methanol from natural gas, there is no significant greenhouse gas benefit relative to using gasoline in the vehicle. If the methanol is made from coal, carbon dioxide emissions are twice as high as those from using gasoline in the vehicle. Provided process energy is provided by wood combustion, there is no net contribution to carbon dioxide emissions. When methanol is produced from biomass, produced on a sustainable basis, there is likely to be a significant greenhouse benefit" (Michaelis, 1993, p. 65).

As a fuel the pros are: its physical-chemical characteristics, the reduced emissions of regulated gases, the storage possibilities. The cons are the following. It is costly to produce (two or three times the current cost of bulk gasoline). It has half the energy density of gasoline, so that a larger tank is needed, significantly affecting the vehicle weight or driving range. Methanol is also highly toxic and corrodes some of the materials currently used in gasoline engines.

Ethanol

Ethanol has long been regarded as an alternative to traditional fuels. Its peculiarity is that it is a renewable resource since it can be derived from any sugar or starch feedstock such as sugar beet and cereals. The process for deriving ethanol is well developed but it is quite expensive. The crops tend to need high levels of agricultural inputs so that the energy and CO_2 emission savings of using ethanol are not much lower than those of using gasoline.

Then the pros could be summarised as follows: the use of renewable resources, its physical-chemical characteristics as a fuel, the reduction of regulated emissions. Similarly to methanol, the cons are: the cost of production, the low energy density, the toxicity and corrosiveness.

Electricity

So far we discussed fuels which have to be stored in the vehicle to be used by an internal combustion engine. Electricity is produced separately and is transmitted directly to the vehicle (train, tram) or stored in batteries in the vehicle. Since no combustion takes place, electric vehicles are defined zero emission vehicles. The advantages are easily identified as:

	CO	Non-methane VOC	NOx	PM
US average generating mix	0.2	0.002	0.31	0
EU average generating mix	0.04	0.007	0.64	0
Coal	0.03	0.003-0.02	0.51-1.33	0
Oil	0.03	0.005	0.34	0
Gas	0.08-0.12	0.004-0.01	0.14-0.26	0
Nuclear	0	0	0	0
Hydro	0	0	0	0

Table 2: Electric vehicles - estimated power station emissions

SOURCE: MICHAELIS (1995)

zero local emissions, the existence of alternative means of producing electricity (coal, natural gas, nuclear, solar or hydro power plants), the reduced noise, the increased life of the vehicle. The zero emission level associated with the use of the vehicle represents the greatest appealing in using an electric vehicle. But there are emissions associated with the production of energy at the site of the production facility which vary with the production technology used as shown in Table 2.

The main disadvantages are: the limited driving range with the existing batteries, the lack of recharging infrastructure, the high cost of the vehicle, safety uncertainties.

Other fuels

Some other fuels have been used or have received attention as potential alternative fuels but they are not yet commercially available on a large scale.

Biodiesel is produced out of oil of colza and is proposed as a substitute or component of traditional diesel fuel. Along with a reduction in emissions, the main difficulties arise from the limited availability and from the reduced vehicle performance.

Hydrogen, produced by electrolysis of water or from coal, natural gas or biomass, has long been tested but it proved technically difficult to store and costly. It is used in space voyages.

Fuel cells may be used for power provision in electric vehicles instead of batteries. The main difference between a battery and a fuel cell is that in a battery the electricity-producing reactants are regenerated by the recharging process whereas in a fuel cell the reactants (usually air and hydrogen) are continuously supplied from an external source (Hormandinger, 1996).

3 Are alternative fuels convenient? An economic and environmental analysis

We know that alternative fuelled vehicles (AVFs) are not convenient to use from a private point of view. The mere fact that AVFs represent such a limited share of the vehicle fleet demonstrates the statement. The reasons are fuel and vehicle prices and consumers' preferences. The latter are based on the perceived pros and cons of alternative fuels as listed in the previous section. An analysis of comparative cost of AVFs as opposed to conventional vehicles as been performed by Michaelis (1995). His results are reported in Table 3 and will be discussed below.

Given that there is no private drive towards the adoption of AFVs, the question we want to analyse is the following: is there a social justification for using AFVs when both the economic and environmental considerations are taken into account?

There is a widespread opinion that, since AFVs are more environmentally friendly, their adoption should be encouraged through financial incentives. The same opinion is sometimes phrased as follows: if conventional vehicles would be charged the true cost they impose (by charging them the environmental cost they create) then AFVs would be conveniently adopted by auto users. Phrased in economic jargon: if environmental externalities are fully internalised AVFs might become economically convenient.

In this section, we test this hypothesis using the best evidence we are aware of on vehicle emissions and on the monetary value of such emissions. Obviously, as with many valuation studies there are great uncertainties on data reliability and very often simplifying assumptions are needed.

3.1 Methodology

The analysis requires five steps. First, we need to identify the private costs for motor vehicles using different fuels. The cost components are the cost of the fuel and the cost of the vehicle. Costs are then expressed in terms of costs per kilometre driven. Such estimates require assumptions, *inter alia*, on fuel prices, manufacturing volumes and vehicle maintenance requirements. We rely on the estimates performed by Michaelis (1995) and refer to that article for details. Let us define pc_f the private cost per km of a vehicle fuelled by fuel *f*. Second, we need to take into account vehicle's emissions. Emissions take place not only during the vehicle use but also during the production of a vehicle and of the fuel. When all three components are considered, the total emission coefficient is termed life-cycle emission coefficient. An emission coefficient is defined as the grams of gas emissions per kilometre. Let us define ${}_{T}e^{i}_{f}$ the total (life cycle) emission coefficient of pollutant *i* from a vehicle fuelled by fuel *f*. It can be disaggregated into:

$${}_{T}e^{i}_{f} = {}_{vp}e^{i}_{f} + {}_{fp}e^{i}_{f} + {}_{vu}e^{i}_{f}$$

where ${}_{vp}e^{i}_{f}$ is the emission coefficient of pollutant *i* during the production of a motor vehicle fuelled by fuel *f*; ${}_{fp}e^{i}_{f}$ is the emission coefficient of pollutant *i* during the production of the fuel *f* used to power the vehicle; ${}_{vu}e^{i}_{f}$ is the emission coefficient of pollutant *i* during the use of a vehicle fuelled by fuel *f* on the road. Lewis (1996) estimates such emissions.

Third, we need to evaluate in money terms the cost of those emissions. Emission costs depends on many factors, including the location in which they take place. Let us define p^{i}_{l} the monetary cost of emitting pollutant *i* in a location *l* (with *l* equal to *u* or *r*). We will consider two locations: an urban and

	Pre-tax vehicle price ($)	Pre-tax fuel price ($/litre gasoline equiv.)	Levelised driving cost (pre-tax)	Cost relative to gasoline (cents/km)			
Annual distance travelled (km/year)			13,800	13,800	10,000	20,000	30,000
Gasoline	15168	0.26	0.29	0	0	0	0
Diesel	15168/17443	0.26	0.29/0.33	-0.35/3.64	-0.44/4.75	-2.13/1.11	-2.22/0.73
LPG	15384/16083	0.19/0.26	0.29/0.30	-0.55/1.02	-0.50/1.43	-0.66/0.71	-0.69/0.57
CNG	15601/16083	0.18/0.24	0.29/0.30	-0.28/0.90	-0.12/1.31	-0.46-0.58	-0.53/0.44
Ethanol from sugar beet	15168/16128	0.94/1.03	0.34/0.36	4.61/6.67	4.61/7.23	4.61/6.46	4.61/6.32
Ethanol from wood	15168/16128	0.68/0.82	0.32/0.34	2.79/5.27	2.79/5.76	2.79/4.99	2.79/4.85
Methanol from NG	15168/16128	0.25/0.35	0.28/0.31	-0.72/1.45	-0.67/2.00	-0.79/1.11	-0.81/0.95
Methanol from wood	15168/16128	0.68/0.82	0.31/0.34	2.30/4.79	2.35/5.33	2.24/4.44	2.22/4.29
Hydrogen	18048/19968	0.38/1.44	0.33/0.43	4.10/13.97	5.61/16.46	3.21/12.53	2.76/11.79
Electric	20928/24768	0.48/0.96	0.36/0.44	6.81/14.74	9.79/19.7	5.08-11.9	4.20-10.46

Table 3: Pre-tax levelised private costs from alternative fuel vehicles

SOURCE: MICHAELIS (1995)

a rural context. Estimates are provided by Eyre et al. (1997). Fourth, we define as social cost the sum of the private and environmental cost of a vehicle kilometre:

$$sc_f = pc_f + \sum_i (p^i_{l\,vp} e^i_f + p^i_{l\,fp} e^i_f + p^i_{l\,vu} e^i_f) \qquad with \quad l = r, u$$

Fifth, it is now possible to estimate all combination of costs when producing a vehicle, a fuel or using a vehicle in an urban or in a rural context. We select these two relevant cases:

a) Fuel and vehicle are produced and used in a rural setting

$$sc^a_f = pc_f + \sum_i (p^i_{r\,vp} e^i_f + p^i_{r\,fp} e^i_f + p^i_{r\,vu} e^i_f)$$

b) Fuel and vehicle are produced in a rural setting but the vehicle is used in an urban area

$$sc^b_f = pc_f + \sum_i (p^i_{r\,vp} e^i_f + p^i_{r\,fp} e^i_f + p^i_{u\,vu} e^i_f)$$

3.2 Results

The starting point is the Michaelis' (1995) estimate on private costs (Table 3). The first two columns show the cost of the vehicle and of the fuel. The third column reports the pre-tax levelised costs assuming an annual distance travelled of 13,800 km. The remaining columns report the difference between the AFVs cost and the gasoline car cost for various annual distance travelled. Each cell reports a range instead of a single value, reflecting a high and a low cost assumption. In most circumstances, the AVFs are more expensive than gasoline cars, therefore there is no private incentive to buy them. The main exceptions are diesel, CNG, LPG and methanol from natural gas. In these cases vehicle's cost is higher but fuel cost might be lower. Consequently, for high-mileage drivers the extra cost of the cars may be compensated by the lower cost of the fuels (Table 3).

Lewis (1996) provides data on emission factors. Table 4 reports emissions during vehicle use on the road. It can be noted that vehicles powered with alternative fuels reduce substantially particulate matter, SO_2 and CO, while they are less successful in reducing NO_x and CO_2. Electric cars, not using an internal combustion engine, represent a special case, since

	CO_2	CO	NO_X	HC	SO_2	PM
Gasoline	186.3	3.37	0.22	0.30	0.02	0.005
Diesel	149.6	0.43	0.69	0.08	0.08	0.1
LPG	148.6	1.48	0.19	0.11	0	0.004
CNG	148.7	0.82	0.19	0.44	0	0.004
Methanol	141.4	3.22	0.02	0.12	0.003	0
Electricity	0	0	0	0	0	0

Table 4: Vehicle use emission coefficients (g/km)

SOURCE: LEWIS (1996)

	CO_2	CO	NO_x	HC	SO_2	PM	N_2O
Gasoline	16 , 19 , 65	2 , 1 , 98	31 , 29 ,40	49 , 13 , 38	27 , 71 , 3	36 , 49 , 16	11 , 1 , 88
Diesel	10 , 24 , 66	8 , 4 , 88	13 , 16 , 71	52 , 27 , 21	18 , 70 , 11	10 , 12 , 79	85 , 15 , 0
LPG	14 , 24 , 62	4 , 1 , 95	26 , 34 , 39	50 , 24 , 26	21 , 79 , 0	25 , 60 , 15	95 , 0 , 5
CNG	14 , 25 , 62	2 , 3 , 95	19 , 39 , 42	51 , 10 , 39	5 , 95 , 0	1 , 78 , 21	95 , 0 , 5
Methanol	16 , 23 , 61	2 , 1 , 98	46 , 22 , 32	76 , 11 , 13	10 , 90 , 1	32 , 68 , 0	0 , 2 , 98
Bio-methanol	33 , 19 , 48	5 , 1 , 94	50 , 20 , 30	63 ,18 , 20	23 , 76 , 0	60 , 40 , 0	18 , 2 , 81
Electricity	74 , 26 , 0	67 , 33 , 0	67 , 34 , 0	75 , 25 , 0	47 , 53 , 0	57 , 43 , 0	90 , 10 , 0

Table 6: Percentage contribution of each phase of the life cycle (fuel production, vehicle production and vehicle use)

SOURCE: LEWIS (1996)

	CO_2	CO	NO_x	HC	SO_2	PM	N_2O
Gasoline	287.8	3.453	0.558	0.792	0.669	0.032	0.061
Diesel	227.1	0.489	0.981	0.384	0.702	0.131	0.005
LPG	239.0	3.889	0.482	0.443	0.649	0.027	0.505
CNG	242.0	0.863	0.457	1.137	0.575	0.022	0.815
Methanol	292.0	3.419	0.784	0.597	0.646	0.039	0.046
Bio-methanol	233.7	3.292	0.729	0.914	0.549	0.023	0.038
Electricity	228.1	0.068	0.520	0.451	1.005	0.040	0.008

Table 5: Life-cycle emissions

SOURCE: LEWIS (1996)

they have zero emissions when the vehicle is used.

Table 5 reports the aggregate life-cycle emissions for vehicles powered by a range of fuels measured in grams per vehicle km. Data for vehicle use assume a lifetime of 182,400 km, based on a vehicle lifetime of 12 years at 15,200 km per year. It can be seen that while some fuels present relatively low emissions of some pollutants, none of them is considerably cleaner than other fuels with respect to all pollutants. For example, CNG has a relative advantage in terms of CO but it is a high HC polluter. Electricity presents high levels of NO_x and SO_2. Notably, PM (a pollutant which is shown to increase the risk of premature death) is particularly high for diesel vehicles. It should also be noted that the CO_2 emission coefficient for bio-methanol is overestimated since it does not take into account the CO_2 absorbed by the plants which are used to produce the fuel.

Table 6 reports the percentage contribution of each phase of the life cycle (fuel production, vehicle production and vehicle use) to overall emissions. Methanol refers to methanol produced from natural gas, while bio-methanol is produced from renewable resources. Obviously such estimates required numerous assumptions with regard to fuel type, vehicle size, engine size, maintenance habits, congestion levels, driving behaviour, etc... Lewis' estimates, specifically, represent a summary of the available data on life-cycle energy use and emissions up to the year 1996.

The monetary cost of urban and rural emissions is estimated by Eyre et al (1997) as in Table 7. Costs include human morbidity and mortality costs and damages to the natural and built environment. Such estimation is obviously fraught with difficulties. There is an abundant literature on that topic but it will not be reviewed in this article (see Danielis 1996 for a survey). Values are higher for PM that is thought to be a dangerous pollutant, positively correlated with premature mortality. Estimates differ among urban and rural areas, reflecting the importance of population density for pollution exposure[2].

Using these data we can estimate the monetary cost of producing the fuel and the vehicle in rural areas (Table 8) and the monetary cost of using the vehicle in rural (Table 9) or urban areas (Table 10).

Table 8 shows, quite surprisingly, that electric cars cause a significant higher amount of damage (estimated in monetary terms) when producing the fuel and the vehicle in rural areas. As stated earlier, the emission involved in electricity generation depends upon the methods used. Lewis' results are derived by assuming that electricity is produced by an average of the UK and US generating mix and that electric cars are pro-

	CO_2	CO	NO_x	HC	SO_2	PM	N_2O
Rural area	0.00064	0.00112	0.9408	0.32864	0.704	1.44	0.096
Urban area	0.00064	0.00112	1.2608	0.32864	5.216	9.2	0.096

* The dollar/pound exchange rate used is 1.6

Table 7: Monetary cost of emissions (cent/gram*)

SOURCE: EYRE ET AL (1997)

	CO_2	CO	NO_x	HC	SO_2	PM	N_2O	Tot
Gasoline	0.065	0.000	0.318	0.162	0.478	0.039	0.001	1.062
Diesel	0.050	0.000	0.274	0.088	0.438	0.045	0.000	0.895
LPG	0.058	0.003	0.275	0.109	0.457	0.033	0.046	0.981
CNG	0.060	0.000	0.251	0.229	0.405	0.026	0.074	1.045
Methanol	0.059	0.000	0.460	0.261	0.384	0.033	0.000	1.198
Bio-methanol	0.097	0.000	0.521	0.157	0.455	0.056	0.001	1.287
Electricity	0.146	0.000	0.489	0.148	0.708	0.058	0.000	1.549

Table 8: The monetary cost of producing the fuel and the vehicle in rural areas

	CO_2	CO	NO_x	HC	SO_2	PM	N_2O	Tot
Gasoline	0.119	0.004	0.207	0.099	0.014	0.007	0.005	0.455
Diesel	0.096	0.000	0.649	0.026	0.056	0.144	0.000	0.972
LPG	0.095	0.002	0.179	0.036	0.000	0.006	0.002	0.320
CNG	0.095	0.001	0.179	0.145	0.000	0.006	0.004	0.429
Methanol	0.090	0.004	0.226	0.039	0.002	0.000	0.004	0.365
Bio-methanol	0.090	0.004	0.216	0.039	0.000	0.000	0.004	0.353
Electricity	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 9: The monetary cost of using vehicles in rural areas

	CO_2	CO	NO_x	HC	SO_2	PM	N_2O	Tot
Gasoline	0.119	0.004	0.277	0.099	0.104	0.046	0.005	0.654
Diesel	0.096	0.000	0.870	0.026	0.417	0.920	0.000	2.330
LPG	0.095	0.002	0.240	0.036	0.000	0.037	0.002	0.412
CNG	0.095	0.001	0.240	0.145	0.000	0.037	0.004	0.521
Methanol	0.090	0.004	0.303	0.039	0.016	0.000	0.004	0.455
Bio-methanol	0.090	0.004	0.290	0.039	0.000	0.000	0.004	0.426
Electricity	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 10: The monetary cost of using vehicles in urban areas

	Vehicle and fuel production in rural areas	Vehicle use in rural areas	Total Scenario A	Vehicle and fuel production in urban areas	Vehicle use in urban areas	Total Scenario B
Gasoline	1.062	0.455	1.517	1.062	0.654	1.717
Diesel	0.895	0.972	1.867	0.895	2.330	3.224
LPG	0.981	0.320	1.301	0.981	0.412	1.392
CNG	1.045	0.429	1.474	1.045	0.521	1.566
Methanol	1.198	0.365	1.563	1.198	0.455	1.653
Bio-methanol	1.287	0.353	1.640	1.287	0.426	1.713
Electricity	1.549	0.000	1.549	1.549	0.000	1.549

Table 11: Summary of costs

	Emission cost Scenario B (cents)	Levelised driving cost	Cost relative to gasoline (cents/km)			
Annual distance travelled (km/year)		13,800	13,800	10,000	20,000	30,000
Gasoline	1,72	30,72	0	0	0	0
Diesel	3,22	30,51/36.22	1,16/5.15	1,07/6.26	-0,62/2.62	-0,71/2.24
LPG	1,39	28,68/31.39	-0,87/0.70	-0,82/1.11	-0,98/0.39	-1,01/0.25
CNG	1,57	28,85/31.57	-0,43/0.75	-0,27/1.16	-0,61/0.43	-0,68/0.29
Methanol	1,65	27,94/32.65	-0,78/1.39	-0,73/1.94	-0,85/1.05	-0,87/0.89
Bio-methanol	1,71	31,00/35.71	2,30/4.79	2,35/5.35	2,24/4.44	2,22/4.29
Electric	1,55	35,83/45.55	6,64/14.57	9,62/19.53	4,91/11.73	4,03/10.29

Table 12: Pre-tax levelised social costs from alterantive fuel vehicles under Scenario B

duced with the vehicle assembler energy mix (7.2% fuel oil, 17.1% coal, 1.6% gas oil, 28.2% electricity and 45.8% gas by energy content). Based on these assumptions, electric cars have the most damaging first two phases of the life cycle, followed by bio-methanol, methanol and gasoline. In terms of pollutants, the main culprits are SO_2 (almost half the cost) and NO_x for their contribution to acid rain formation.

Table 9 instead shows that, when using the vehicle in rural areas, diesel vehicles (especially heavy-duty vehicles) cause by far the greatest damage in monetary terms mainly because of NO_x and PM emissions. Diesel vehicles are followed by gasoline vehicles (with half the damage), and by other alternative vehicles. Electric cars cause zero costs.

As Table 10 reports, within urban areas the use of diesel vehicles is even more damaging. They are estimated to be more damaging than gasoline cars almost by a factor of four[3]. In terms of pollutants, particulate matter becomes more responsible than NO^x. Gasoline vehicles are followed by CNG fuelled vehicles.

Table 11 presents a summary of the costs involved in the two scenarios A (fuel and vehicle are produced and used in a rural area) and B (fuel and vehicle are produced in a rural setting but the vehicle is used in an urban area). Scenario A shows diesel fuelled vehicles as the most damaging vehicles, but the alternative fuelled vehicles follow quite closely. Bio-methanol, methanol and electric vehicles generate more air emission costs than gasoline vehicles. This is mainly due to the emissions of the first two phases of the life cycle, whereas during the vehicle-driving phase they are actually cleaner. Only CNG and LPG fuelled vehicle have a globally better performance than the gasoline car. Such results change in Scenario B. Diesel vehicles' dramatically increase their damages, which appear to be almost twice as high as the gasoline vehicle. All alternative fuelled vehicles impose less environmental costs than gasoline vehicles (slightly for bio-methanol, electricity, and methanol, more substantially for CNG and especially LPG).

To conclude, let us re-estimate Table 3 by internalising the air emission cost, assuming drivers pay the social instead of the private costs. Results are reported in Table 12.

Alternative fuel vehicles, which have an emission cost lower than gasoline vehicles, become more convenient for users, but as previously there might be a private incentive to buy only LPG, CNG and methanol vehicles (if the values of the lower end of the range apply). Bio-methanol vehicles and electric vehicles are still more expansive than gasoline cars. Diesel vehicles, having almost twice the emission costs of gasoline vehicles, would not be as convenient as before. They would be advantageous only for an annual distance travelled of 20,000 km/year or more.

4 Discussion and conclusions

Michaelis (1995) concluded the article with the following statement:

"Analysis of life-cycle greenhouse gas emissions associated with alternative fuel use shows that some of them can achieve very substantial reductions. The alternatives that achieve the greatest reductions are ethanol and methanol from wood, hydrogen from renewable sources, and electric vehicles using power generated from non-fossil fuel sources. CNG, LPG and diesel all give small reductions in greenhouse gas emissions.

In general the alternative fuels that give the greatest emission reductions are the most expensive. Diesel, CNG and LPG can have a lower life-cycle costs than gasoline for vehicles with high annual mileage. This has made them relatively attractive options for commercial fleet operators, and this is likely to remain the main niche market for alternative fuels with CNG increasing its share".

In this article we have extended Michaelis' analysis by providing a monetary evaluation of air pollutant emissions, by distinguishing between rural and urban emission in each phase of the life cycle, and by calculating the social cost of motor vehicles. It turns out that:

- AFVs are a better alternative to conventional vehicles (especially to diesel vehicles) when vehicles are used in urban areas;
- when the vehicle is used in a rural area, only CNG and LPG vehicles are cleaner than gasoline vehicles, but all AFVs are better than diesel vehicles;
- if the vehicle user would be charged the social cost (instead of just the private one), in an urban area, methanol, LPG and CGN vehicles would be less costly than gasoline cars. Diesel vehicles would be convenient only with an annual mileage higher than 20,000 km.
- electric vehicles, which represent the only zero local emission technology already available in the market, has no justification in pure economic terms.

However, such strong conclusion need some caveats. The analysis rests on the use of present emission technology for vehicle and fuel production and operation, present fuel and vehicle prices and present preferences for clean air. Any change taking place in any factor might vary the picture.

The analysis is still rough with regard to vehicle specification since we did not consider the differences which might exist with regards to vehicle and engine type and size. Such aggregation might be particularly misleading for diesel vehicle which present a large variety of types.

The analysis also lacks spatial differentiation. Within an urban area air pollution concentration is quite diversified, for example, between the city centre and the periphery. It would therefore be useful to provide a different set of estimates with regard to different pollution concentration levels.

Furthermore, we have considered only traditional primary pollutants whereas new pollutants such as benzene are not accounted for because of uncertainties on concentration levels and relative health damages. Consequently, costs related to gasoline vehicles which use fuels containing benzene might be underestimated.

Notwithstanding these imperfections in the analysis, it seems to us fair to conclude that AFVs, though having some potential in some markets and for some trips, could deliver a substantial contribution to the shifting of the stage and location of air emissions but could not deliver an equally important contribution to the reduction of overall emissions, at least in the present technological and commercial circumstances.

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Note

[1] It requires a 220 bar compression and has one forth of energy density of gasoline.

[2] Danielis and Chiabai (1998) confirm such findings. They estimate that PM emission costs in cities with more than 500 thousand people are twice as much as in cities with 20-100 thousand people.

[3] Similarly, Danielis and Chiabai (1998) estimate that for PM emissions light-duty vehicles impose a cost much higher (by a factor of 17) than gasoline cars.