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Electric versus conventional vehicles: social costs and benefits in France

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Abstract

This article compares the social costs of electric vehicles with those of conventional, thermal vehicles for typical passenger use in the Ile-de-France region (Greater Paris), a case of particular interest because nearly 80% of the electricity is generated by nuclear power plants. A four-seat electric car is compared to a new conventional car of the same make and model; for the latter both the gasoline and the diesel version are considered because almost half of new car sales in France are diesel. These results are also compared to typical existing diesel and gasoline vehicles in the current French fleet. The methodology developed by the ExternE (External Costs of Energy) Project of the European Commission is used to estimate the costs associated with atmospheric pollution due to power plants, refineries and tail pipe emissions. Our discussion of externalities is limited to air pollution thus excluding others such as costs associated with noise or accidents. Our results imply that the external costs are large and significant, even when one considers the uncertainties. If internalized by government regulations, these externalities can render the total cost of an electric vehicle more competitive with that of currently available thermal vehicles in large urban centers if the electricity is produced by sources with low pollution. However, the current generation electric vehicles are so expensive that internalization of pollution damage would not give it a very clear advantage.

Keywords: Electric vehicles; Air pollution; External costs; Damage costs; Life cycle analysis; Diesel cars; Gasoline cars

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1. Introduction

Concern over urban air quality in recent years has propelled the electric vehicle (EV) to the forefront of debate concerning technologies and strategies to reduce the environmental and health impacts of urban transport, among the largest contributors to urban air pollution as well as to anthropogenic greenhouse gas emissions (see US Dept. of Energy, 1996; Walsh, 1995). With zero tailpipe emissions, compact size, and an essentially silent motor, electric vehicles could be the urban commuter's panacea were it not for its high purchase price. However, they have been criticized as "pollution elsewhere vehicles" because of the emissions by the power plants which supply the electricity.

Several studies have been effected to date comparing the emissions of electric vehicles and internal combustion engine (ICE) vehicles (Chapman et al., 1994; Lave et al., 1995; Martinez and Dessus, 1993; Sgoutas, 1995). Most agree that there are emissions trade-offs, and that the net reduction due to the use of electric vehicles depends on the source of fuel for electricity generation as well as the type and age of the conventional vehicle default.

There are few regions where the emissions trade-off is as spectacular as in Ile-de-France (Greater Paris). 90–95% of the electricity of France comes from sources with negligible air pollution, nuclear providing almost 80% and hydro about 12% (for an explanation of the damage costs of nuclear, see the section on nuclear electricity below). Furthermore, because of the large population (about 11 million inhabitants) and population density, any air pollutants that are emitted here can have considerable health impacts.

The damage costs due to pollution from power plants, refineries and tail pipe emissions are estimated using the methodology of the ExternE (External Costs of Energy) Project of the European Commission (ExternE, 1995; see also ORNL/RFF, 1994; Rowe et al., 1995). This involves an analysis of the impact pathway for each pollutant, from source to receptors (population, crops, buildings, etc.):

- specification of the technologies and emissions (e.g., kg/yr of NO_2 from tailpipe);
- calculation of increased pollutant concentration in all affected regions (e.g., $\mu g/m^3$ of O_3, using models of atmospheric dispersion and chemistry for O_3 due to NO_2);
- calculation of physical impacts (e.g., number of asthma attacks due to O_3 using dose-response functions);
- economic valuation of impacts (e.g., multiplication by cost of asthma attack).

The damage is summed over all affected receptors. For details of this analysis, the reader is referred to publications by the ExternE (1995, 1998) Project, by Rabl and Spadaro (1999a) and by Spadaro et al. (1998).

The economic valuation is based on individual preferences; it necessarily involves subjective (and often controversial) choices that should be decided by political consensus, in particular with regard to intergenerational discount rate and the so-called value of statistical life (really the collective willingness to pay for reducing the risk of premature death). For the present paper it is sufficient to assess only those external costs that differ between electric and conventional vehicles, namely those due to the emission of pollutants. We do not address accidents, congestion or noise, though we note in passing that lower noise could be an appreciable external benefit of electric vehicles. Since the uncertainties are large, we also consider the sensitivity of our results to uncertainties in the damage cost estimates.

2. Key assumptions

2.1. Dispersion modeling

For most air pollutants from combustion, atmospheric dispersion is significant over hundreds to thousands of kilometers (Seinfeld and Pandis, 1998; Zannetti, 1990; Curtiss and Rabl, 1996a). Both local and regional effects are important. We have therefore used a combination of local and regional dispersion models to account for all significant damages. For modeling dispersion over the short range we have used two gaussian plume models: ISC (Wackter and Foster, 1987) and ROADPOL (Vossiniotis et al., 1996). At the regional scale we have used two different models, the Harwell Trajectory model (Derwent and Nodop, 1986) as implemented by the ExternE Program, and the EMEP model of the Norwegian Meteorological Service (Sandnes, 1993), the model chosen for the official allocation of acid rain budgets among the countries of Europe.

We have coupled these dispersion calculations with an integration over population data, using two software packages that have been developed independently for this purpose: ECOSENSE (Krewitt et al., 1995) and PathWays2.0 (Curtiss and Rabl, 1996b). ECOSENSE includes the Harwell Trajectory Model; for the PathWays2.0 calculations we have used EMEP results for atmospheric dispersion. A comparison of damages calculated with these different models shows agreement within 20% (Rabl and Spadaro, 1999b).

For ozone (O_3) damage due to the precursor NO_x we use a recent estimate of 1500 Euro/t_{NO_2} [1] for typical European conditions (Rabl and Eyre, 1998), based on EMEP results for atmospheric dispersion and chemistry (Simpson, 1993).

2.2. Health impacts of air pollution

Of special importance are health impacts because, according to ExternE (1998), they account for more than 95% of the damage costs of particles, NO_x and SO_2. A consensus has been emerging among public health experts that air pollution, even at current ambient levels, is associated with a variety of significant health problems. There is strong evidence that air pollution aggravates respiratory and cardiovascular diseases and leads to premature mortality (Lipfert, 1994; Dockery and Pope III, 1994; Wilson and Spengler, 1996; Bascom et al., 1996). There is less certainty about specific causes, but most recent studies have identified fine particles as a prime culprit; ozone has also been implicated directly. In addition there may be significant direct health impacts of SO_2, but for direct impacts of NO_x the evidence is less convincing.

For air pollutants the dose-response functions are usually based directly on air concentrations, hence the names E–R function (exposure–response) or C–R function (concentration–response) are in use. Depending on the epidemiological approach used to determine a C–R function, one talks about acute and chronic C–R functions. The most common approach is to carry out a time series study of a population by identifying short-term correlations (over a few days) between air pollution and a health end-point. This approach has the great advantage of being easy to

[1] 1 Euro = 6.56 FF = \$1.10–1.25 in recent years, here taken as \$1.16.

implement and insensitive to the confounders (such as smoking), but it identifies only short-term effects and yields acute C–R functions.

End-points that show up only after a longer period require observations of individuals or populations that are exposed to different levels of pollution (Dockery et al., 1993; Pope et al., 1995; Abbey et al., 1995). Quantitative links between chronic effects and air pollution are notoriously difficult to establish with confidence, and there are few studies that have determined chronic C–R functions. Of particular importance are the studies of Dockery et al. (1993) and Pope et al. (1995) that find significant chronic effects of air pollution on mortality. The difference between chronic and acute C–R functions is not so much in the exposure (most people are chronically exposed) as in the effects that are measured: Do they include long-term effects or only effects that show up within a few days after exposure to pollution? By analogy the terms acute and chronic are also applied to C–R functions for mortality, even though the attributes appear strange in that context.

In ExternE (1995, 1998) the working hypothesis has been to use the C–R functions for particles and for O_3 as basis. Effects of NO_x and SO_2 are assumed to arise indirectly from the particulate nature of nitrate and sulfate aerosols, and they are calculated by applying the particle C–R functions to these aerosol concentrations. With this assumption the impacts of NO_2 and SO_2 become very large, but this is uncertain because there is insufficient evidence for the health impacts of the individual components of particulate air pollution, especially for nitrates. The reason for the lack of epidemiological studies of nitrate aerosols is that until recently this pollutant has not been monitored by air pollution monitoring stations. All C–R functions for health impacts of air pollution have been assumed linear, in view of the lack of evidence for thresholds at current ambient concentrations (note that a C–R function in the form of a hockey stick has the same effect as a linear function of the same slope if the threshold is below background concentrations).

2.3. Monetary valuation

Our approach to the monetary valuation of damages is to account for all costs, market and non-market. For example, the valuation of an asthma attack should include not only the cost of the medical treatment but also the willingness to pay to avoid the suffering. If the willingness to pay for a non-market good has been determined correctly, it is like a price, consistent with prices paid for market goods. Economists have developed several tools for determining non-market costs; of these tools contingent valuation has enjoyed increasing popularity in recent years. As far as the damage costs in this paper are concerned, the valuation is sufficiently reliable that the costs can be aggregated for use in a social cost-benefit analysis, without serious risk of error due to certain biases such as the embedding effect that have been observed in some contingent valuation studies.

It turns out that damage costs of air pollution are dominated by the valuation of mortality. The key parameter is VSL (value of statistical life), the valuation of a loss of life. In ExternE (1998), a European-wide value of 3.1 MEuro ($3.6 million) was chosen for VSL, close to similar studies in the USA (for an interesting review of 78 VSL studies, see Ives, Kemp and Thieme (1993). A crucial question for the valuation of air pollution mortality is whether one should simply multiply the number of premature deaths by VSL, or whether one should take into account the years of life lost (YOLL) per death (Rabl, 1998). The difference is very important because premature deaths from air pollution tend to involve a much smaller number of YOLL per death than accidents (on which VSL is based). The ExternE numbers, cited here, are based on YOLL and thus significantly lower (for the same dose–response function) than the simple VSL valuation assumed in most previous external cost studies. For the value of a YOLL we have assumed 0.083 MEuro for chronic mortality, and 0.155 MEuro for acute mortality, the difference arising from assumptions about latency and discounting (ExternE, 1998).

3. Damage cost per kg of pollutant

The damage costs per kilogram of pollutant depends on the site and nature (stack height and flow velocity) of the pollution source, and within the ExternE Project they have been calculated for a wide range of sources. For the present paper we need them for typical traffic emissions in Paris and for emissions from refineries. For power plants we only cite the ExternE damage cost per kilowatt hour (kW h) of electricity (Section 5). The damage costs per kilogram of pollutant are listed in Table 1. For particles one can assume that emissions from power plants and refineries are PM_{10} whereas those from cars are the smaller and more harmful $PM_{2.5}$ (where PM_d designates particles with diameter less than d microns).

Some comments to explain the variation with emission site. For the long lived greenhouse gases there is no variation with emission site because these gases can be assumed uniformly mixed in the

Table 1
Damage costs, in Euro per kilogram of pollutant, from Spadaro and Rabl (1999); for secondary pollutants the dependence on emission site is weak and as first approximation one can take same value for all of France (1 Euro = $1.16)

Pollutant	Damage costs (Euro/kg)
Greenhouse gases, CO_{2equiv}	0.029
Secondary pollutants, per kilogram of primary pollutant	
SO_2 via sulfates	10.0
NO_2 via nitrates	14.5
NO_2 via ozone	1.5
NMVOC via ozone	0.93
Primary pollutants from refineries	
PM_{10}	15.4
Primary pollutants from cars	
$PM_{2.5}$, Paris	2190
$PM_{2.5}$, highway Paris-Lyon	159
$PM_{2.5}$, rural France	22
SO_2 direct, Paris	28
SO_2 direct, highway Paris-Lyon	2.2
SO_2 direct, rural France	0.3
CO, Paris	0.02
CO, highway Paris-Lyon	0.002

entire atmosphere. Here we consider CO_2, CH_4 and N_2O, grouped together as CO_{2equiv}; of these CO_2 makes the most important contribution. The damage cost in Table 1 is the ExternE estimate, derived by Eyre et al. (1998) on the basis of IPCC (1995).

For the other pollutants in Table 1, one must distinguish between primary and secondary pollutants. Primary pollutants, for instance particles, cause damage in the form in which they are emitted. Some pollutants are transformed in the atmosphere to secondary pollutants and cause damage in the latter form. For example, SO_2 is transformed into sulfate aerosols and NO_x into nitrate aerosols; NO_x is also a precursor of ozone. SO_2 can be harmful both directly as a primary pollutant and as a precursor of sulfates (especially sulfuric acid).

Damage due to primary pollutants varies strongly with local conditions, especially when emitted at ground level. That is why the $PM_{2.5}$ damage from cars differs so much between rural and urban settings, PM_{10} damage from refineries, power plants and the like being relatively small because such emission sources tend to be from tall stacks in less urban areas. The damage of secondary pollutants, by contrast, is quite insensitive to the conditions in the vicinity of the source. This is because the chemical reactions take some time and the formation of nitrate and sulfate aerosol particles occurs over distances of tens to hundreds of kilometers. The formation of ozone is somewhat faster and occurs over several kilometers to tens of kilometers. Here we assume a single Euro/kg value for all secondary pollutants from emission sources in France.

It may be surprising that our estimate for NO_x damage via ozone is so much smaller than that for damage via nitrate aerosols. This is a consequence of the ExternE hypothesis that nitrate aerosols have the same health effects as PM_{10}, including chronic mortality, whereas for ozone only acute mortality is taken into account (Rabl and Eyre, 1998). This may well be due to a lack of epidemiological data rather than a difference in real impacts; however, for the present paper only the sum of the nitrate and ozone damages matters, and it seems plausible that the total damage per kilogram of NO_2 be comparable to that for PM_{10} and SO_2.

Our damage cost for $PM_{2.5}$ includes an estimate for cancers, based on the International Agency for Research on Cancer who concluded in 1988 that diesel particulate matter is probably carcinogenic to humans, coupled with other studies that imply that PM itself, when stripped of the soluble organic fraction, is also carcinogenic (Walsh, 1995). However, the cost of these cancers is only a small portion of the total.

4. Vehicle technologies and costs

Table 2 presents key figures and hypotheses used to calculate the total cost for each vehicle. Since costs are realized throughout the lifetime of the vehicle, the choice of discount rate becomes an issue. Here we choose 5% real, i.e., above inflation. All costs are in constant currency, without any escalation beyond general inflation.

The new vehicles studied here are representative of four-passenger subcompact cars popular in France. They are electric, gasoline and diesel versions of the same model, the Peugeot 106. The prices are for the model with electric windows, electric locks and power steering in 1998. The electric car has a Nickel–Cadmium battery because that is the preferred choice for vehicles of this size in France. Lead–Acid batteries contain nearly half the energy density, and are disfavored in a

Table 2
Key data and assumptions for economic analysis; these costs include taxes: approximately 80% of gasoline and 72% of diesel fuel are a fuel tax, and 17% of all other costs are a value added tax (values for existing (old) cars are in parentheses; 1 Euro = $1.16)

	Electric	Gasoline	Diesel
Lifetime	10 yr	10 yr	10 yr
Discount rate (above inflation)	5%	5%	5%
km/yr	9125	9,125	16,425
Purchase price, without battery, Euro[a]	14,204	10400 new (0 old)	11577 new (0 old)
Lease of battery, Euro/yr[b]	1122		
Registration, Euro	89	149	149
Insurance, Euro/yr	336	437	437
Maintenance, repairs + technical control, Euro/yr	89	200	200
Electricity or fuel/km, urban driving[c]	0.25 kWh/km	0.070 l/km new (0.192 l/km old)	0.060 l/km new (0.113 l/km old)
Energy price	0.0696 Euro/kWh	0.955 Euro/l	0.649 Euro/l
Energy cost Euro/yr	159	611 new (1676 old)	640 new (1205 old)

[a] Peugeot (1998).
[b] Club du Véhicule Electrique de Paris (1998).
[c] Electricité de France (1998).

detailed lifecycle assessment comparison conducted by Electricité de France (Ollivier, 1996). We assume that the battery is leased rather than bought.

For existing cars (labeled "old" in our figures and tables), we take a purchase price of 0 because from the point of view of society it is a sunk cost. For simplicity we assume the same number of km/yr and the same costs for maintenance, insurance, etc. While real repair costs are higher, this is compensated by the fact that the numbers for old cars represent an average over the current fleet and include models that are much larger than the subcompact Peugeot 106. That can be seen from the fuel consumption data in Table 2.

This point illustrates the difficulty of obtaining representative data about the current vehicle fleet. There is continual evolution in technologies, tastes and driving patterns, and reliable data about the current situation are hard to get. The evolution has been particularly rapid with regard to emissions. Furthermore, a single average number fails to capture the variability. For instance, a key parameter for the life cycle cost per kilometer is the distance driven per year which varies greatly between different owners. Rather than trying to analyze a large number of cases, we present the results in a graphical format that we hope enables the reader to visualize how a change in one of the cost components would affect the ranking of choices.

5. Emissions and damage costs per kilometer

Emissions from the following phases are taken into account: emissions from electricity production, emissions from fuel production, and tailpipe emissions. Emissions for other lifecycle phases, such as vehicle production and disposal, are more difficult to estimate given the multitude of options and actors involved throughout the lifecycle. Since the data provided by Lewis and Gover (1995) suggest that emissions from the production of cars are in any case small compared to those from the tailpipe, we will not consider them in this analysis, implicitly assuming that their external costs are equal among EVs and ICEs.

5.1. Tailpipe emissions

Table 3(a) shows the tailpipe emissions assumed in this study. For existing cars they are based on emissions measured by Joumard et al. (1995), as interpreted by Spadaro et al. (1998) for a driving cycle of urban trajectories, representative of the likely usage of electric vehicles. For new cars they are taken as the regulatory limits imposed in France for all new vehicles as of 1 January 1997 (with exceptions noted). The real emissions may turn out to be different, but they are unlikely to be much lower since urban driving always involves the driving modes with the highest emissions. Greenhouse gas emissions are not regulated but they can be determined from the fuel consumption.

There are no regulations for particle emissions from gasoline cars, an item not considered significant in the past. However, in view of the high damage cost per kilogram of particles even small emissions can make an appreciable contribution to the total cost. They have been measured by CONCAWE (1998) for two gasoline cars of the kind being sold now with catalytic converter, and we base our $PM_{2.5}$ calculations on this report. The uncertainties of this item are high, not only because it is based solely on two cars but because the emissions are close to the detection limits of

Table 3
Emissions and damage costs/km (1 Euro = \$1.16)

	Emissions (g/km)				Damage costs (Euro/km)			
	Diesel new	Gasoline new	Diesel old	Gasoline old	Diesel new	Gasoline new	Diesel old	Gasoline old
(a) *Tailpipe emissions*								
$PM_{2.5}$	0.08[a]	0.002[b]	0.21[c]	0.0214[c]	0.1776	0.0044	0.4741	0.0470
SO_2	0.0258[d]	0.0258[d]	0.05[d]	0.07[d]	0.0010	0.0010	0.0018	0.0027
NO_2	0.511[a]	0.125[a]	1.24[c]	0.47[c]	0.0082	0.0020	0.0199	0.0075
NMVOC	0.189[a]	0.375[a]	0.45[c]	1.37[c]	0.0002	0.0003	0.0004	0.0013
CO_{2equiv}	192	224	361	616	0.0056	0.0065	0.0105	0.0179
CO	1[a]	2.2[a]	2.4[d]	12.8[d]	0.0000	0.0000	0.0000	0.0003
Total					0.1926	0.0142	0.5067	0.0767
(b) *Refinery emissions, based on Lewis and Gover* (1995) *with fuel consumption of Table* 2								
PM_{10}	0.0108	0.00946	0.020	0.026	0.0001	0.0001	0.0003	0.0004
SO_2	0.112	0.145	0.211	0.399	0.0012	0.0015	0.0022	0.0041
NO_2	0.113	0.134	0.213	0.369	0.0018	0.0021	0.0034	0.0059
NMVOC	0.179	0.306	0.337	0.841	0.0002	0.0003	0.0003	0.0008
CO_{2equiv}	22.7	35.4	42.7	97.3	0.0007	0.0010	0.0012	0.0028
Total					0.004	0.005	0.0074	0.014

[a] Emissions for new vehicles are limits imposed by directive 94/12/CEE, 23 March 1994 applicable to new vehicles as of 1 January 1997. The limits are specified for CO, HC + NO_x, and fine particles. HC and NO_x emissions are calculated with a split factor equal to the ratio of HC:NO_x in the emission factors from Joumard et al. (1995), calculated for our representative driving cycle.
[b] Based on CONCAWE (1998).
[c] Based on Joumard et al. (1995), as interpreted by Spadaro et al. (1998).
[d] Calculated by multiplying fuel consumption by 0.05%, the admissible sulfur content as of 1996 (CERTU 1997).

the instrumentation. We interpret the numbers in the CONCAWE report to imply a $PM_{2.5}$ emission of 2 mg/km for urban driving (with uncertainty range from 1 to 4 mg/km).

5.2. Emissions from fuel production

Emissions from the production of fuel for thermal vehicles are not negligible. Lewis and Gover (1995) have assembled data from five life cycle assessment (LCA) studies (two in the UK, and one each in the Netherlands, Sweden and the USA) for the production of gasoline and diesel, acknowledging that the disparity among them is considerable though they all claim to take the entire fuel cycle into account. Table 3(b) presents the average of these studies.

5.3. Emissions from electricity production

We assume that the electricity for charging the batteries comes from nuclear power plants because they provide approximately 80% of the total kW h produced in France, and 100% of the base load. Fossil fuels are used only during cold weather, providing 4–8% of the total, and the remainder comes from hydro. The damage cost of nuclear electricity in France, 2.52 MEuro/kW h, has been calculated by the ExternE Project (ExternE, 1995; Rabl et al., 1996). This includes all stages of the fuel chain, even waste disposal and major accidents (though any estimate of the latter items is controversial).

All of the damage cost of low-level radiation is due to human health effects (cancers and hereditary effects), whereas environmental impacts are negligible. These costs are almost certainly an upper bound because they have been calculated with very conservative assumptions: impacts are considered for the entire population of the world, at zero discount rate, counting all cancers as fatal and assuming that no cure for cancers will be found during the entire 100,000 yr time horizon of the analysis. With the assumptions in Table 2 this implies a damage cost of 0.0006 Euro/km for the EV. This is so small as to be invisible on the scale of Figs. 1 and 2 which is why we do not even show it in Fig. 1.

The damage costs per kilometer are shown in Fig. 1. The contribution of CO, according to the assumptions of ExternE, is so small that we do not even show it in the figures. We emphasize that they are for the Paris metropolitan area. Because of the high population density, the damage is dominated by particle emissions. For more rural driving the damage of the primary pollutants, especially the particles, would be 1–2 orders of magnitude smaller, while damage from NO_2 would change very little.

6. Life cycle costs/benefits

Results of the life cycle cost per kilometer are shown in Fig. 2. Since diesel and gasoline cars are used differently, we show the EV both for 25 km/day and 45 km/day utilization, so the comparisons can be made on the basis of equal driving distance (where we neglect that higher utilization is likely to increase repair costs or decrease vehicle life time). Part (a) shows the private costs, part (b) the social costs. Since, from the point of view of society, general taxes represent a transfer of funds rather than a cost, we have removed all general taxes from part (b), keeping only

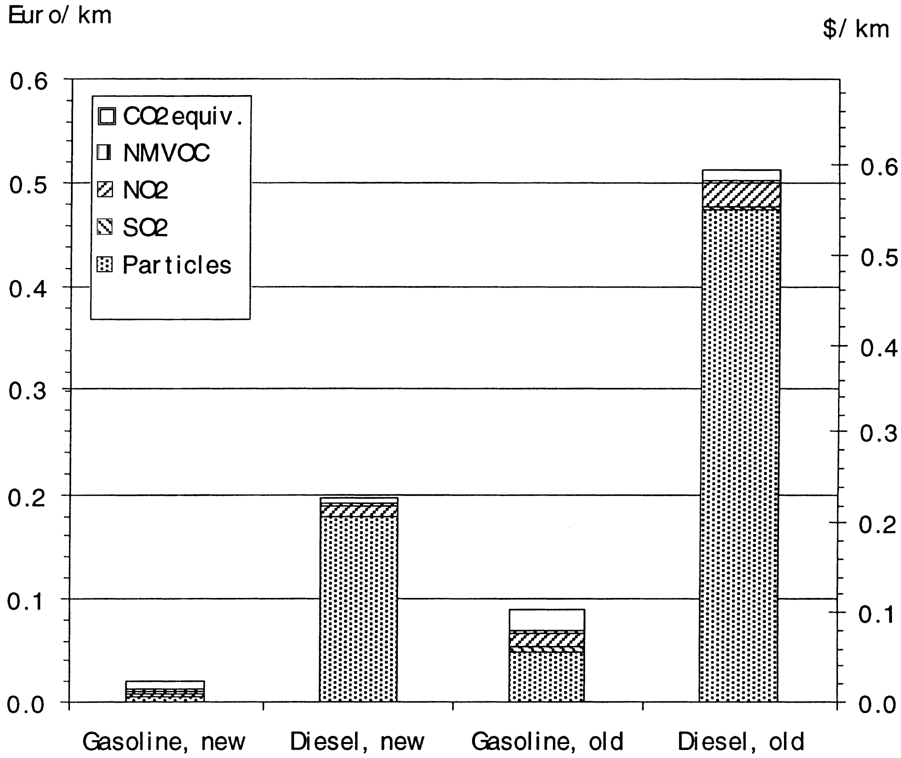

Fig. 1. Damage cost due to emissions from tailpipe and from refinery, for new diesel and gasoline cars driven in the Paris metropolitan area.

vehicle registration fees because they are paid for expenses related to road transport (the Vignette, a national auto tax based on vehicle size, age, and location of registration, and the carte grise, a car registration fee).

The removal of taxes between parts (a) and (b) is not perfect. Fuel taxes could be considered as payment for public expenditures for transport, but their level is set by politics without direct relation to specific expenditures. However, the resulting uncertainties are small compared to the other items in Fig. 2(b).

Likewise subsidies should be included in part (a) but not in part (b) of Fig. 2. Currently the EV benefits from a subsidy by Electricité de France to car manufacturers (10,000 F = 1524 Euro, i.e., 11% of purchase price) and a subsidy by the State to consumers (5000 F = 762 Euro, i.e., 5.5% of purchase price). It is not clear how much of the Electricité de France subsidy is passed on to the consumer. For simplicity we did not consider these subsidies in Fig. 2; in any case they would only change the contribution of the purchase price by a small amount.

In terms of private costs the EV is about 30–40% more expensive than a new ICE car, comparing respectively the gasoline car with an EV driven 25 km/day and the diesel with an EV driven 45 km/day. For existing cars the comparison is even less favorable for the EV; this would not change appreciably if one were to include the resale value (highly variable) which we have neglected because it is a sunk cost from the perspective of society.

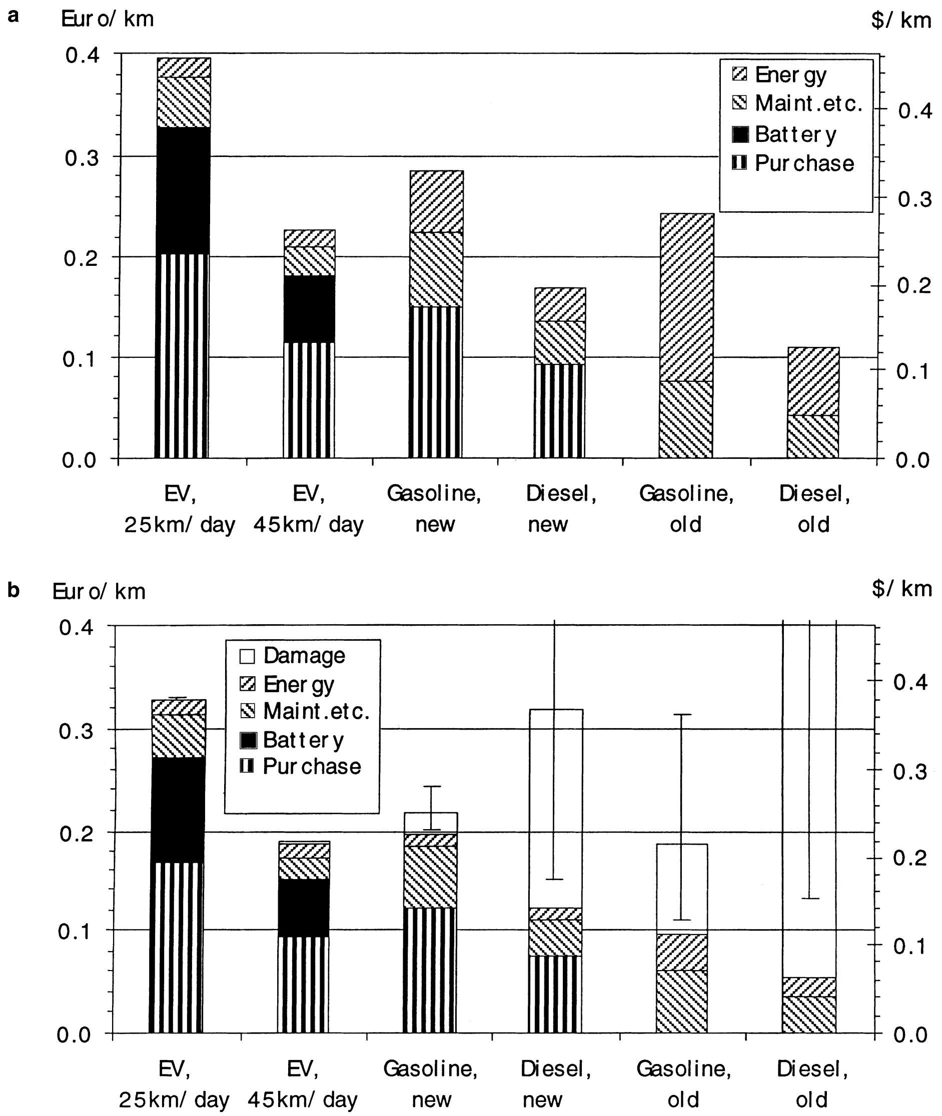

Fig. 2. Life cycle costs per kilometer. All vehicles are assumed to be used 10 yr, but 9125 km/yr for electric and gasoline and 16425 km/yr for diesel: (a) private costs (including general taxes); (b) social costs (excluding general taxes). Error bars indicate uncertainty of damage cost.

In terms of total social cost the EV is at least 50% more expensive than the gasoline cars, both old and new, but about 40–70% less expensive than diesel cars. The latter is due to the high damage cost of primary particle emissions in a metropolis like Paris.

These estimates are based on currently available EV technology, and battery usage over 10 yr. This lifetime requires the equivalent of two battery packs (leased or purchased), which represent almost as much cost as the purchase of the vehicle itself. Costs are sure to decrease as technology improves (with production economies of scale, higher autonomy, advanced batteries, etc.). It remains to be seen if this results in more rapid reductions in total cost than those from incremental improvements in advanced ICE vehicles themselves.

7. Uncertainty

The error bars in Fig. 2(b) indicate the uncertainty of the damage costs only. They have been estimated by Rabl and Spadaro (1999) by considering the uncertainty distributions for each element of the impact pathway analysis. They are stated as geometric standard deviation σ_g and can be interpreted in terms of multiplicative confidence intervals of the lognormal distribution: if a cost has been estimated to be μ_g (geometric mean $\approx$ median) with geometric standard deviation σ_g, the probability is approximately 68% that the true value is in the interval $[\mu_g/\sigma_g, \mu_g \times \sigma_g]$ and 95% that it is in $[\mu_g/\sigma_g^2, \mu_g \times \sigma_g^2]$. For most of the damage costs σ_g is approximately 4. In view of the difference between medians and means of the uncertainty distributions we estimate that the 1 s.d. confidence interval ranges from approximately 0.15–2.4 times the mean damage cost.

The greatest uncertainties stem from the validity of the dose-response functions, and from their translation into monetary values. Since more than 80% of the ExternE damage costs arise from mortality, the results are extremely sensitive to the way in which one evaluates mortality. The key parameter is the value of statistical life, here chosen as 3.1 MEuro.

A cost-benefit analysis of a policy to encourage the use of EVs involves many other uncertainties, especially driving patterns and the evolution of cost and performance of the technologies. Can improvements in battery technology keep pace with emission reductions of the ICE? This kind of uncertainty is best addressed by considering different scenarios, but it is beyond the scope of the present paper. However, the magnitude of the cost components in Fig. 2 gives an idea of the sensitivity to different assumptions.

8. Conclusion

Using the damage cost estimates of the ExternE Project, we have calculated the external cost of air pollution for electric vehicles and for conventional cars fueled by gasoline or by diesel. We find that the cost of air pollution from cars in Paris is large, even for cars that meet the rather strict emission limits of the latest regulations. The damage cost amounts to approximately 7% of the private life cycle cost for new gasoline cars, and to 120% for new diesel cars. If these costs were internalized, the EV would be competitive at current prices against diesel cars but not against gasoline (the precise comparison depends on the individual situation, especially the number of kilometers traveled per year). In terms of total social cost the EV is at least 50% more expensive than the gasoline cars, both old and new, but about 40–70% less expensive than diesel cars.

It is ironic that the diesel would look so poor in this comparison; after all it had been encouraged on the grounds of higher energy efficiency and lower emissions. Indeed, except for particle emissions the diesel is relatively clean, especially compared to gasoline cars without catalyst (required in France only since 1993). The perspective presented here results from the recent epidemiological studies that have highlighted the health effects of particles, coupled with the fact that primary pollutants can have large impacts if emitted in the streets of large cities.

However, the cost of air pollution is not enough to give the EV a clear advantage against all conventional cars, even in Paris. If the EV can barely be justified in a large metropolitan area where the external costs of electricity are small, the concept loses much of its appeal. This conclusion comes on top of questions about the appeal of vehicles whose range and performance is still significantly below their conventional counterpart.

For policy decisions it would be helpful if the uncertainties could be reduced, but that is unlikely in the near future, at least as far as the damage costs are concerned. A key consideration is the evolution of the respective technologies. One can expect significant cost reductions in a new technology such as the EV (including development of the infrastructure). On the other hand, the emission control of the internal combustion engine has been making impressive progress in recent years and technologies for the reduction of diesel particle emissions are under development. It may be more cost-effective to curb pollution by technologies other than the EV (e.g., hybrid or fuel cell vehicles) or by policies such as scrapping older highly polluting cars.

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References

Abbey, D.E., Lebowitz, M.D., Mills, P.K., Petersen, F.F., Beeson, W., Burchette, R.J, 1995. Long-term ambient concentrations of particulates and oxidants and development of chronic disease in a cohort of nonsmoking California residents. Inhalation Toxicology 7, 19–34.

Bascom, R., Bromberg, P.L., Costa, D.L., Devlin, R., Dockery, D.W., Frampton, M.W., Lambert, W.J., Samet, M.F., Speizer, E., Utell, M., 1996. Health effects of outdoor air pollution. Amer. J. Resp. Critical Care Med. 153, 3–50 (Part 1) and 477–498 (Part 2).

CERTU, 1997. Pollutions atmosphériques et circulation routière: Données de base (Air pollution and road traffic: basic data). Dossier du CERTU no. 74, Novembre 1997. Centre d'études sur les réseaux, les transports, l'urbanisme et les constructions publiques Ministère de l'Equipement, des Transports, et du Logement. Paris, France.

Chapman, F., Calwell, C., Fisher. D., 1994. What's the charge? Estimating the emissions benefits of electric vehicles in Southern California. Environmental Defense Fund, Natural Resources Defense Council, New York.

Club du Véhicule Electrique de Paris, 1998. Personal Communication.

CONCAWE, 1998. A study of the number, size and mass of exhaust particles emitted from European diesel and gasoline vehicles under steady state and european driving cycle conditions. Report No. 98/51. CONCAWE (the oil companies' European organization for environment, health and safety), Madouplein 1, B-1210 Brussels.

Curtiss, P.S., Rabl, A., 1966a. Impacts of air pollution : General relationships and site dependence. Atmospheric Environment 30 (19), 3331–3347.

Curtiss, P.S., Rabl, A. 1996b. Impact Analysis for Air and Water Pollution: Methodology and Software Implementation. In: Zannetti, P. (Ed.), Environmental Modeling, vol. 3, Chapter 13, pp. 393–426.

Derwent, R.G., Nodop, K., 1986. Long range transport and deposition of acidic nitrogen species in North-West Europe. Nature 324, 356–358.

Dockery, D.W., III, C.A., 1994. Acute respiratory effects of particulate air pollution. Ann. Rev. Public Health 15, 107–132.

Dockery, D.W., III, C.A., Pope Xiping, Xu., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris B.G, , Speizer, F.E., 1993. An association between air pollution and mortality in six US cities. New England J Medicine 329, 1753–1759.

Electricité de France, 1998. Groupe Véhicule Electrique Urbain. Personal Communication.

ExternE, 1995. ExternE: Externalities of Energy. Vol. 1: Summary; Vol. 2: Methodology; Vol. 3: Coal and Lignite; Vol. 5: Nuclear. ISBN 92-827-5210-0. European Commission, Directorate-General XII, Science Research and Development, L-2920 Luxembourg.

ExternE, 1998. ExternE: Externalities of Energy. New results. ExternE Program of European Commission, Directorate-General XII, Science Research and Development, to be published.

Eyre, N., Downing, T., Hoekstra, R., Rennings, K., RSJ Tol, 1998. Global Warming Damages. Final Report, September 1998, Contract JOS3-CT95-0002. ExternE Program of European Commission, Directorate-General XII, Science Research and Development, to be published.

IPCC, 1995. Climate change 1995: Economic and social dimensions of climate change. In: Bruce, J.P., Lee, H., Haites, E.F. (Eds.), Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Ives, D.P., Kemp, R.V., Thieme, 1993. The statistical value of life and safety investment research. Report No. 13, February 1993. Environmental Risk Assessment Unit, University of East Anglia, Norwich, UK.

Joumard, R., Vidon, R., Paturel, L., Pruvost, C., Tassel, P., De Soete G., Saber, A.I., 1995. Évolution des Émissions de Polluants des Voitures Particulières lors du Départ Moteur Froid (Evolution of pollutant emissions from cars, beginning with cold start). Report INRETS No. 197. Bron, France.

Krewitt, W., Trukenmueller, A., Mayerhofer, P., Friedrich, R., 1995. ECOSENSE – An Integrated tool for environmental impact analysis. In: Kremers, H., Pillmann, W. (Eds.), Space and Time in Environmental Information Systems. Umwelt-Informatik aktuell, Band 7, Metropolis-Verlag, Marburg, Germany.

LaveLester, B., Hendrickson, C.T., McMichael, F.C., 1995. Environmental implications of electric cars. Science 268, 993–995.

Lewis, C.A., Gover, M.P., 1995. Life-cycle analysis of motor fuel emissions. In: Pre-proceedings of the workshop Estimation of pollutant emissions from transport. European Commission Directorate General for Transport COST 319, 27–28 November 1995 at Université Libre de Bruxelles, Belgium.

Lipfert, F.W., 1994. Air Pollution and Community Health: A Critical Review and Data Sourcebook. Van Nostrand Reinhold, New York.

Martinez, N., Dessus Décembre, et B., 1993. Les Enjeux Environnementaux de la Pénétration du Véhicule Electrique en Europe: étude comparative des émissions de polluants des véhicules électriques et thermiques, dans les conditions actuelles et à l'horizon 2010'' (Environmental considerations of electric vehicles in France: comparative study of emissions, now and in 2010). CNRS/ECOTECH. Paris, France.

Ollivier, C. Octobre 1996. Analyse du Cycle de Vie des Batteries Nickel–Cadmium Pour Véhicule Electrique (Life cycle analysis of Nickel–Cadmium batteries for electric vehicles). EDF rapport HE-51/96/028/A et Annexes. Some of the results are available at http://www.edf.fr/der/html/actu/faitsmarquants/page29.fr.htm.

ORNL/RFF, 1994. External Costs and Benefits of Fuel Cycles. Prepared by Oak Ridge National Laboratory and Resources for the Future. Edited by Russell Lee, Oak Ridge National Laboratory, Oak Ridge, TN 37831.

Peugeot, 1998. Personal Communication.

Pope, C.A., Thun, M.J., Namboodri, M.M., Dockery, D.W., Evans, J.S., Speizer, F.E., Heath, C.W., 1995. Particulate air pollution as a predictor of mortality in a prospective study of US adults. Amer. J. Resp. Critical Care Med 151, 669–674.

Rabl, A., 1998. Mortality risks of air pollution: The role of exposure-response functions. J. Hazardous Materials 61, 91–98.

Rabl, A., Spadaro, J.V., 1999a. The cost of pollution and the benefit of solar energy. Series Background Papers for the International Energy Society, to be published.

Rabl, A., Spadaro, J.V., 1999b. Environmental damages and costs: An analysis of uncertainties. Environment International 25 (1), 29–46.

Rabl, A., Eyre, N., 1998. An estimate of regional and global O_3 damage from precursor NO_x and VOC emissions. Environment International 24, 835–850.

Rabl, A., Curtiss, P.S., Spadaro, J.V., Hernandez, B., Pons, A., Dreicer, M., Tort, V., Margerie, H., Landrieu, G., Desaigues, B., Proult, D., 1996. Environmental impacts and costs: The nuclear and the fossil fuel cycles. Report to EC, DG XII, Version 3.0, June 1996. Centre d'Energétique, Ecole des Mines, 60 boul. St.-Michel, F-75272 Paris, France.

Rowe, R.D., Lang, C.M., Chestnut, L.G., Latimer, D., Rae, D., Bernow, S.M., White, D., 1995. The New York Electricity Externality Study. Oceana Publications, Dobbs Ferry, NY.

Sandnes, H., 1993. Calculated budgets for airborne acidifying components in Europe. EMEP/MSC-W Report 1/93. July 1993. Norwegian Meteorological Institute, P.O. Box 43, Blindern, N-0313 Oslo 3, Norway.

Seinfeld, J.H., Pandis, S.N., 1998. Atmospheric Chemistry and Physics: From Air Pollution to Climate Change. Wiley, New York.

Sgoutas, K., 1995. Effectiveness of Electric Vehicles vs. Other Vehicle Technologies: A Case Study in Environmental Transportation Policy. Master's Thesis, Massachusetts Institute of Technology.

Simpson, D., 1993. Photochemical model calculations over Europe for two extended summer periods: 1985 and 1989. Model results and comparison with observations. Atmospheric Environment 27A, 921–943.

Spadaro, J.V., Rabl, A., 1999. Estimates of real damage from air pollution: Site dependence and simple impact indices for LCA. Internl. J. Life Cycle Assessment, in press.

Spadaro, J.V., Rabl, A., Jourdain, E., Coussy, P., 1998. External costs of air pollution: Case study and results for transport between Paris and Lyon. Internl. J. Vehicle Design 20, 274–282.

US Dept. of Energy, 1996. Describing Current and Potential Markets for Alternative Fuel Vehicles, DOE/IEA-0604, March 1996, Energy Information Administration, Office of Environmental Markets and End Use, United States Department of Energy.

Vossiniotis, G., Arabatzis, G., Assimacopoulos, D., 1996. Description of ROADPOL: A Gaussian DispersionModel for line sources. Program manual. National Technical University of Athens, Greece.

Wackter, D.J., Foster, J.A., 1987. Industrial source complex (ISC) dispersion model users guide, 2nd ed., Vol. 1, EPA 450/4-88-002a. US Environmental Protection Agency, Research Triangle Park, NC.

Walsh, M.P., 1995. Motor vehicle pollution in China: An urban challenge. In: Stephen Stares, Liu Zhi, (Eds.), Proceedings of the Symposium on China's Urban Transport Development Strategy, Beijing, 8–10 November, World Bank Discussion Paper No. 352.

Wilson, R., Spengler, J.D., 1996. Particles in Our Air Concentrations and Health Effects. Harvard University Press, Cambridge, MA.

Zannetti, P., 1990. Air Pollution Modeling: Theories, Computational Methods and Available Software. Van Nostrand Reinhold, New York.