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Environmental benefits of natural gas for buses

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Abstract

This paper presents a life cycle assessment comparing diesel buses with buses fueled by natural gas. The data for the emission of pollutants are based on the MEET Project of the European Commission (EC), supplemented by data measured for diesel and gas buses in Paris. The benefits of the gas fueled bus are then quantified using the damage cost estimates of the ExternE Project of the EC. A diesel bus with emissions equal to Standard EURO2 of the EC is compared with the same bus equipped with a natural gas engine, for use in Paris and in Toulouse. The damage cost of a diesel bus is significant, in the range of 0.4–1.3 €/km. Natural gas allows an appreciable reduction of the emissions, lowering the damage cost by a factor of about 2.5 (Toulouse) to 5.5 (Paris). An approximate rule is provided for transferring the results to other cities. A sensitivity analysis is carried out to evaluate the effect of the evolution of the emissions standard towards EURO3, 4 and 5, as well as the effect of uncertainties. Finally a comparison is presented between a EURO2 diesel bus with particle filter, and a gas fueled bus with the MPI engine of IVECO, a more advanced and cleaner technology. With this engine the damage costs of the gas fueled bus are about 3–5 times lower than those of the diesel with particle filter, even though the latter has already very low emissions.

Keywords: Life cycle assessment; Damage cost; Emission inventory; Air pollution; Diesel bus; Gas fueled bus; Automotive fuel

1. Introduction

This paper presents a life cycle assessment comparing diesel buses with buses fueled by natural gas. The goal of a life cycle assessment is to take into account all the effects that are relevant for a comparison of the technologies in question. For buses the life cycle includes not only the utilization phase but also upstream and downstream phases, such as the production of the fuel, the

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fabrication of the buses, and the disposal of the buses at the end of their useful life. To evaluate the environmental consequences, one needs an inventory of the pollutants emitted during each of these phases.

The data for the emission of pollutants are based on the MEET (1999) Project of the European Commission (EC), supplemented by data measured by Régie Autonome des Transports Parisiens (2000) for diesel and gas buses in Paris and data measured for the multipoint injection (MPI) gas bus by IVECO (1998). A diesel bus conforming with Standard EURO2 of the EC is compared with the same bus equipped with a natural gas engine, for use in Paris and in Toulouse.

The benefits of the gas fueled bus are quantified using the damage cost estimates of the ExternE (1998, 2000) Project of the EC. The methodology of ExternE involves an analysis of impact pathways, i.e. of the chain emission → dispersion → impact → cost. An impact pathway analysis begins by specifying the source: location (rural or urban), characteristics of the source (height of source, temperature, velocity) and inventory of the emissions. Automotive emissions occur at ground level and are expressed as emission factors (g/km), which depend on driving conditions (cold start, urban, highway, etc.) and vehicle characteristics (make, age, engine parameters, pollution control technology, etc.). Using models of atmospheric dispersion and chemistry, one calculates the resulting increase in ambient concentrations and exposures. Then the ensuing impacts are determined by means of dose–response functions. Finally the impacts are multiplied by the corresponding unit costs. The impacts that have been quantified cover damage to human health, agriculture and buildings, as well as global warming.

2. Inventory of emissions

Uncertainties of the emissions are considerable, because there are not enough measured data and the available data are not always consistent. The emissions can vary strongly with the conditions of utilization; in particular the emissions per km decrease with increasing speed. Since this paper concerns a comparative analysis, effects which change only little or not at all between diesel and gas are not examined in great detail; this is the case for the emissions during the manufacture of the buses, and for the contribution of CO_2. The following data are used here

- manufacture of the buses: ExternE (2000) (based on Lewis and Gover (1995));
- production and distribution of the fuels: Lewis (1997) of the MEET (1999) Project of the EC, the official project of the EC on the quantification of the transport emissions;
- use of buses: for buses in the current fleet the data of MEET (1999), and for future technologies the data measured on diesel and gas buses in Paris (Régie Autonome des Transports Parisiens, 2000) as well as data measured on a gas bus in Brussels (IVECO, 1998).

We have not found any data for the disposal of the buses at the end of their useful life, but we see no reason why there would be any significant difference in emissions between the two types of bus and so we do not consider this phase.

An analysis of the emissions due to the production of the fuels was carried out in the MEET Project by Lewis (1997). The numbers for France are reproduced here in Table 1.

Table 1
Emissions due to fuel production and distribution (g/GJ)

	CO_2	CO	CH_4	NMVOC	NO_x	SO_2	PM
Diesel							
Production	6700	4.6	15.7	87.8	35.8	44.9	1.0
Distribution	110	0.33	0.14	0.28	1.25	0.45	0.11
Total	6800	4.9	15.8	88.1	37.1	45.4	1.1
Natural gas							
Extraction of natural gas	1600	1	20	11	4.1	2	0
Distribution	0	0	198	16	0	0	0
Service stations	2500	0.4	5.7	0.5	6.5	14.9	0.8
Total	4100	1.4	223.7	27.5	10.6	16.9	0.8

Since these data are in terms of the energy content of the fuel, one needs the fuel consumption as energy per km. MEET does not provide any direct information on fuel consumption, but it can be calculated with sufficient accuracy from the CO_2 emissions, an approach that seems preferable here for consistency with the other MEET data, rather than using another data source for fuel consumption that may not be for the same bus models. In combination with the energy content 42.67 GJ/t of diesel fuel indicated by Lewis (1997) the quantity of CO_2 emitted per t of fuel can be calculated from the molecular weights, by taking the ratio of the number of H and C molecules for diesel fuel equal to 2 (Hickman et al., 1999). Thus 1 t of diesel fuel emits

$$(12/(12 + 2 \times 1)) \times ((12 + 2 \times 16)/12) \times 1\ \mathrm{t_{fuel}} = 44/14\ \mathrm{t_{CO_2}} = 3.14\ \mathrm{t_{CO_2}}. \qquad (1)$$

The emission of 1.31 $\mathrm{kg_{CO_2}}$/km of the diesel bus (see Table 2 below) thus implies a consumption of 1.31 $\mathrm{kg_{CO_2}/km \times 42.67\ MJ/kg_{fuel}/(3.14\ t_{CO_2}/t_{fuel}) = 17.67\ MJ/km}$ for the diesel bus; with a density of about 0.85 kg/l of diesel fuel this corresponds to about 0.5 l/km. For the gas fueled bus the 17.67 MJ/km is increased by the ratio 15.83/14.92 indicated by ExternE (2000), corresponding to the lower efficiency of gas engines. That gives 18.75 MJ/km for the gas fueled bus.

Establishing an inventory of the emissions during the manufacture of buses is difficult because of the great number of components and processes and because industries are reticent to reveal

Table 2
Different data for the emissions of EURO2 diesel buses

	MEET Fig. 1 at 15 km/h	Régie Autonome des Transports Parisiens (2000)	ExternE (2000)[a]	Choice for this paper
CO (g/km)	10.44	3.5	6.592	6.6 (±40%)
CO_2/1000 (g/km)	1.31	1.60	1.139	1.3 (±20%)
NO_x (g/km)	21.11	30	11.034	25 (±30%)
PM (g/km)	1.05	0.49	0.252	0.7 (±40%)
VOC (g/km)	2.88	1.2	1.729	2.0 (±30%)

The choice for this paper is a weighted average of columns 2–4 and the parentheses indicate an estimate of the uncertainties.

[a] At 60 km/h (much higher than the average 15 km/h typical of city driving).

information on their manufacturing processes. Moreover, thanks to the continual tightening of the environmental regulations, the emissions of the principal pollutants by industry have been greatly reduced during the last decade, typically by a factor between two and ten, except CO_2 for which the reductions are more difficult. Are the inventories based on the older or on the more recent emissions? Fortunately for this paper the uncertainties due to the manufacture of the buses are of little consequence because the differences between the diesel and the gas option are small; furthermore, most of the upstream emissions are small compared to those of the utilization stage. Since MEET (1999) does not provide any information on manufacture, the data of ExternE (2000) are taken here, without additional analysis; they come from Lewis and Gover (1995).

For the utilization phase MEET presents the emissions of heavy vehicles in terms of curve fits whose coefficients are listed in Hickman et al. (1999). Fig. 1 shows these emissions as function of the speed. For the average speed of buses in large cities 15 km/h is assumed here (Turin, 2000). The corresponding numbers are shown in Table 2, together with data from two other sources (Régie Autonome des Transports Parisiens, 2000; ExternE, 2000). The choice for this paper is a subjectively weighted average of columns 2–4. Like most studies of this kind, we do not have sufficient information for a formal uncertainty analysis and the parentheses in the past column indicate a subjective estimate of the uncertainties.

Particles emitted by diesel or gas engines are all smaller than 1 μm, by contrast to particulate matter (PM) emissions during the upstream phases that contain a large fraction in the size range 2.5–10 μm. While Fig. 2 does not show this distinction, we do account for it in the quantification of damage costs by using the PM_{10} concentration–response functions (CRF) for the upstream phases and those of $PM_{2.5}$ for the utilization phase.

MEET does not provide data for the composition of the VOC, but for diesel cars in the range from 0 to 55 km/h ExternE (2000) indicates the breakdown shown in Table 3; these numbers are assumed for diesel buses here.

Estimating the emissions of gas fueled buses is even more problematic than for diesel buses because this technology is little used till now and measured data are rare. Here the data of

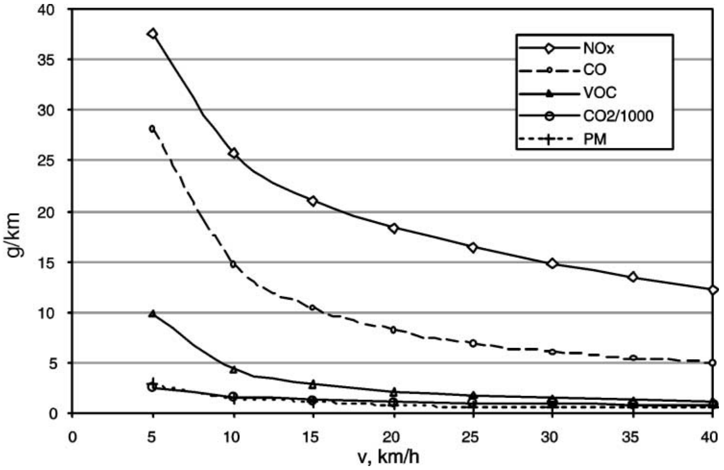

Fig. 1. Emissions of a diesel bus as function of speed v, based on the curve fits of Hickman et al. (1999).

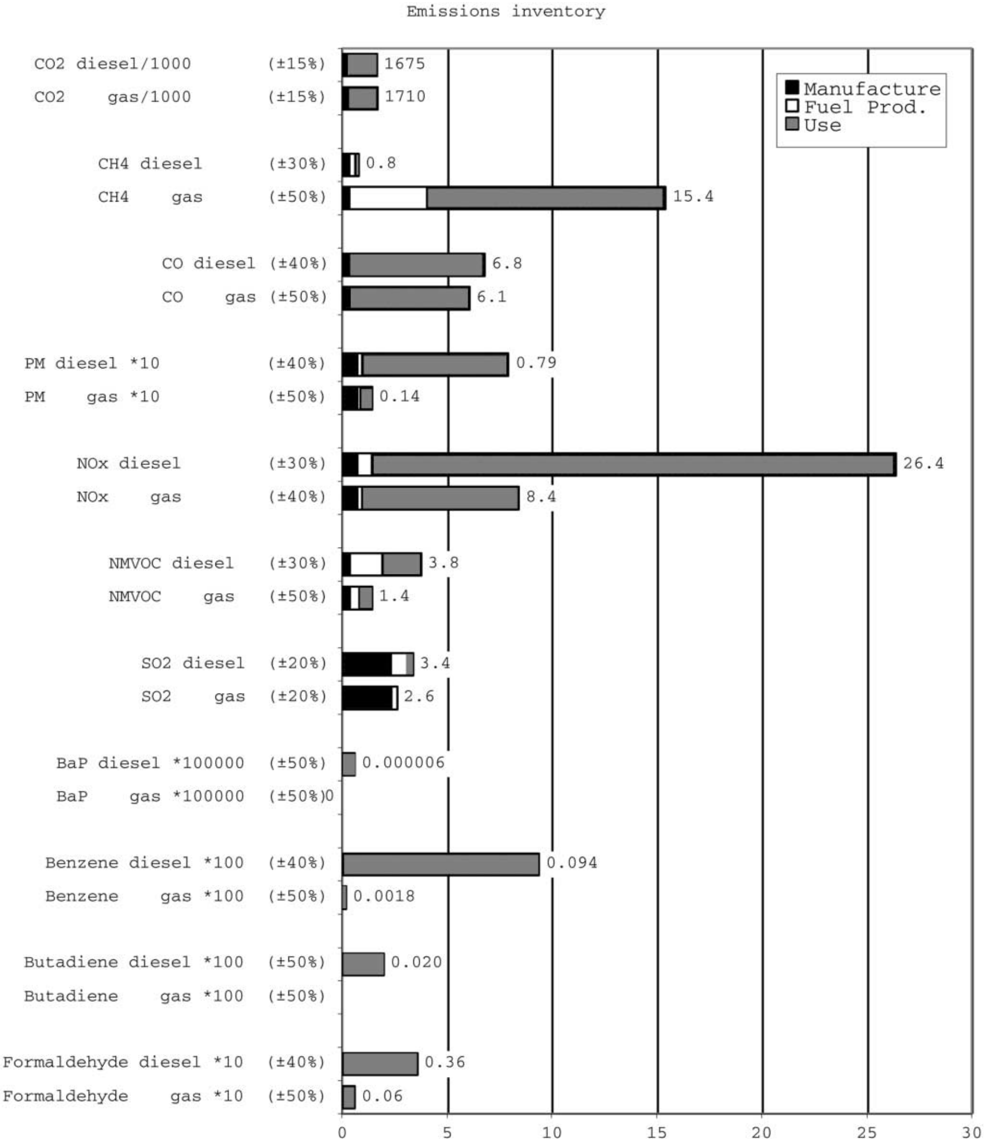

Fig. 2. Inventory of emissions. (The numbers to the right of the bars show total emission in g/km. The parentheses in the labels on the left indicate an estimate of the uncertainties. The bars include the multipliers in the labels, to make the comparison diesel—gas visible for all pollutants.)

Samaras et al. (1998) of the MEET Project are used, as well as data measured with buses in Paris by Régie Autonome des Transports Parisiens (2000). They are stated as ratios gas bus/diesel bus, as shown in Table 4, the last column indicating the choice for this paper. The uncertainties are considerable, because the emissions depend very much on the tuning of the engine and the type of emission control system.

Table 3
Composition of the VOC emitted by diesel buses (ExternE, 2000)

NMVOC	92.2%
Formaldehyde	18.0%
CH_4	7.8%
Benzene	4.7%
Butadiene	1.0%
BaP	0.0003%

Table 4
Emissions of gas fueled buses, expressed as ratio relative to diesel bus emissions

	Gas/diesel (Samaras et al., 1998)	Gas/diesel (Régie Autonome des Transports Parisiens, 2000)	Gas/diesel choice for this paper
CO	0.46	1.31	0.9
VOC	3.4	9.08	6[a]
NO_x	0.58	0.28	0.3
PM	0.09	0.07	0.08

[a] 95% CH_4 and 5% NMVOC.

The composition of the VOC is estimated according to the ratios of Samaras et al. (1998) which indicate that CH_4 accounts for approximately 95% of the VOC emitted by a gas fueled bus, consistent with the numbers of Régie Autonome des Transports Parisiens (2000). Formaldehyde accounts for 10% and benzene for 0.3% of the NMVOC. The emissions of butadiene and BaP are entirely negligible. The emissions assumed for the baseline comparisons are summarized in Fig. 2, together with an estimate of the uncertainties.

For the evolution of the technologies, the following are considered:

- a reduction of the diesel emissions in proportion to the limiting values of the standards EURO2,. . ., EURO5, see Table 5;
- a EURO2 diesel bus retrofitted with particle filter, according to the data measured by Régie Autonome des Transports Parisiens (2000), see Table 6;
- a gas fueled bus with the MPI engine of IVECO according to data measured on a bus in Brussels by IVECO (1998). This engine is especially designed for natural gas (stoichiometric combustion + exhaust gas treatment) and has much lower emissions than the bus tested by Régie Autonome des Transports Parisiens (2000); see Table 6.

Table 5
Limit values of the EC regulations and years when they become effective

Year	Standard	CO		HC		NO_x		PM	
		g/kW h	% Euro2	g/kW h	% Euro2	g/kW h	% Euro2	g/kW h	% Euro2
1996	Euro2	4.00	100%	1.10	100%	7.00	100%	0.15	100%
2000	Euro3	2.10	53%	0.66	60%	5.00	71%	0.10	67%
2005	Euro4	1.50	38%	0.46	42%	3.50	50%	0.02	13%
2008	Euro5	1.50	38%	0.46	42%	2.00	29%	0.02	13%

Table 6
Possible evolution of the emissions for more advanced technologies

	Diesel		Gas	
	EURO2	EURO2 with particle filter	Conventional	MPI engine
CO (g/km)	6.6	0.66	5.94	2.5
NO_x (g/km)	7.0	7.0	7.5	0.32
VOC (g/km)	1.84	0.184	0.6	0.6
PM (g/km)	0.70	0.0429		
CH_4 (g/km)			11.4	0.6

Emissions during use, for a EURO2 diesel bus retrofitted with particle filter, and for a gas fueled bus with MPI engine of IVECO (1998).

The emissions of EURO4 and EURO5 engines are not yet known, their appearance on the market being planned for 2005 and 2008, respectively. To obtain an estimate, proportionality to the respective limit values is assumed, as indicated in Table 5.

3. Damage costs—methodology

Here we can only give a very brief discussion of the key features of the methodology used for the analysis of impact pathways, i.e. of the chain emission → dispersion → impact → cost. For a more complete presentation we refer to the reports of the ExternE Project or to review papers (Rabl et al., 1998; Rabl and Spadaro, 2000).

Over the years, numerous dispersion models have been developed. Usually separate models are used for the local and the regional domains. In the local domain, up to about 50 km from the source, pollutant deposition and aerosol formation by chemical transformation are relatively insignificant and concentrations are influenced primarily by meteorological parameters, such as wind speed and wind direction. Beyond 50 km, one must account for removal of the pollutant from the air by chemical reactions and deposition, both dry and wet.

For dispersion of transport emissions ExternE uses the Gaussian plume model ROADPOL (Vossiniotis et al., 1996) at the local scale. Regional concentrations are calculated using the Lagrangian trajectory models of EMEP (Simpson, 1993) and of the Windrose trajectory model (WTM); the latter is an adaptation of the Harwell trajectory model. ROADPOL and WTM are implemented in the EcoSense software (Krewitt et al., 1995) used for the impact calculations of ExternE. EcoSense also contains databases for receptors.

Impacts are quantified using dose–response functions, also known as exposure–response or CRF in the case of air pollutants. They relate the pollutant concentration to the resulting impact on a receptor (human health, crop, etc.). Impacts on human health include asthma attacks, hospital admissions, chronic bronchitis, restricted activity days, and premature deaths. ExternE calculates mortality impacts as a reduction in life expectancy, expressed as years of life lost (YOLL), rather than a number of premature deaths. That is necessary to allow more meaningful comparisons with other causes of death, for instance accidents for which the YOLL per death are much higher than for air pollution (of course such comparisons are not perfect, since the affected individuals differ in age and health status).

For health impacts, the CRFs are derived from a survey of epidemiological studies (ExternE, 1998). In view of the available epidemiological evidence, we assume that the CRFs for health are approximately straight lines, without threshold (Wilson and Spengler, 1996; Daniels et al., 2000).

For crops and building materials, the CRFs have non-linear shapes. For agricultural crops there is even the possibility of a small benefit (fertilizer effect) when the background concentrations of SO_2 and NO_x are sufficiently low. For crops, one calculates the losses or gains in yield, and for building materials, the increase in cleaning and repair costs due to air pollution.

Monetization is a convenient method for aggregating health impacts and environmental burdens with different physical units into a single damage indicator. To obtain the damage costs, one multiplies the number of impacts (e.g. cases of asthma attack) by the unit cost per impact (e.g. € per asthma attack).

For health impacts, the unit costs include the cost of treatment and wage and productivity losses, which are market based, as well as non-market costs that take into account an individual's willingness-to-pay (WTP) to avoid the risk of pain and suffering. If the WTP 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 techniques for valuing non-market goods. In recent years, contingent valuation has become the method of choice; it obtains WTP estimates by asking individuals how much they are willing to pay to achieve a benefit. This method is problematic and the uncertainties are large, but for most environmental non-market costs no better alternative is available.

The most important impact is mortality. ExternE evaluates mortality according to the reduction of life expectancy, but there has been a lack of studies that determine the value of a life year (VLY). Therefore ExternE derives VLY from the so called "value of statistical life" (VSL), for which there are a very large number of studies, by assuming that VSL is the present value of a discounted series of annual VLY values. Here we use the VSL and VLY values of ExternE (1998), with VSL equal to 3.1 million $€_{1995}$ and VLY equal to 84330 $€_{1995}$ per YOLL.

The unit costs for crops and building materials are based on market prices. As crop damages are relatively small, they are estimated simply on the basis of quantity times constant price, without consideration of induced effects (compensatory producer behavior). The uncertainties of the current monetary values are large (for example, they are not determined by general equilibrium techniques, and costs of global warming depend on controversial assumptions about VSL in poorer countries and intergenerational discounting).

The damage calculations distinguish the upstream emissions from those during the utilization phase. This point is especially important for primary pollutants such as PM: the damage per kg of pollutant is much higher if the pollutant is emitted at street level in a large city rather than from a tall stack in a rural zone. For secondary pollutants (created by chemical transformation in the atmosphere) this variation with site is much weaker. For upstream emissions we assume typical industrial installations in Europe.

The damage costs quantified here cover global warming for the greenhouse gases (CO_2 and CH_4), and human health, crop losses and damage to materials for the other pollutants. While we believe that these are the most important damage categories, it is difficult to be complete in this type of work. Among missing categories we mention reduction of visibility due to air pollution (generally deemed of less concern in the EU than the USA), noise (gas buses are quieter than the diesel), road damage (gas buses are heavier than the diesel), and impacts caused by the use of oil (oil spills, supply security, etc.).

4. Damage costs—results

Fig. 3 shows typical results for the damage cost per kg of pollutants emitted in France. More than 90% of the damage costs, other than global warming, is due to health impacts. Note that the methodology has been evolving. The values in this paper are the numbers of ExternE (2000) for France, except for global warming for which the earlier estimate of ExternE (1998) is taken,

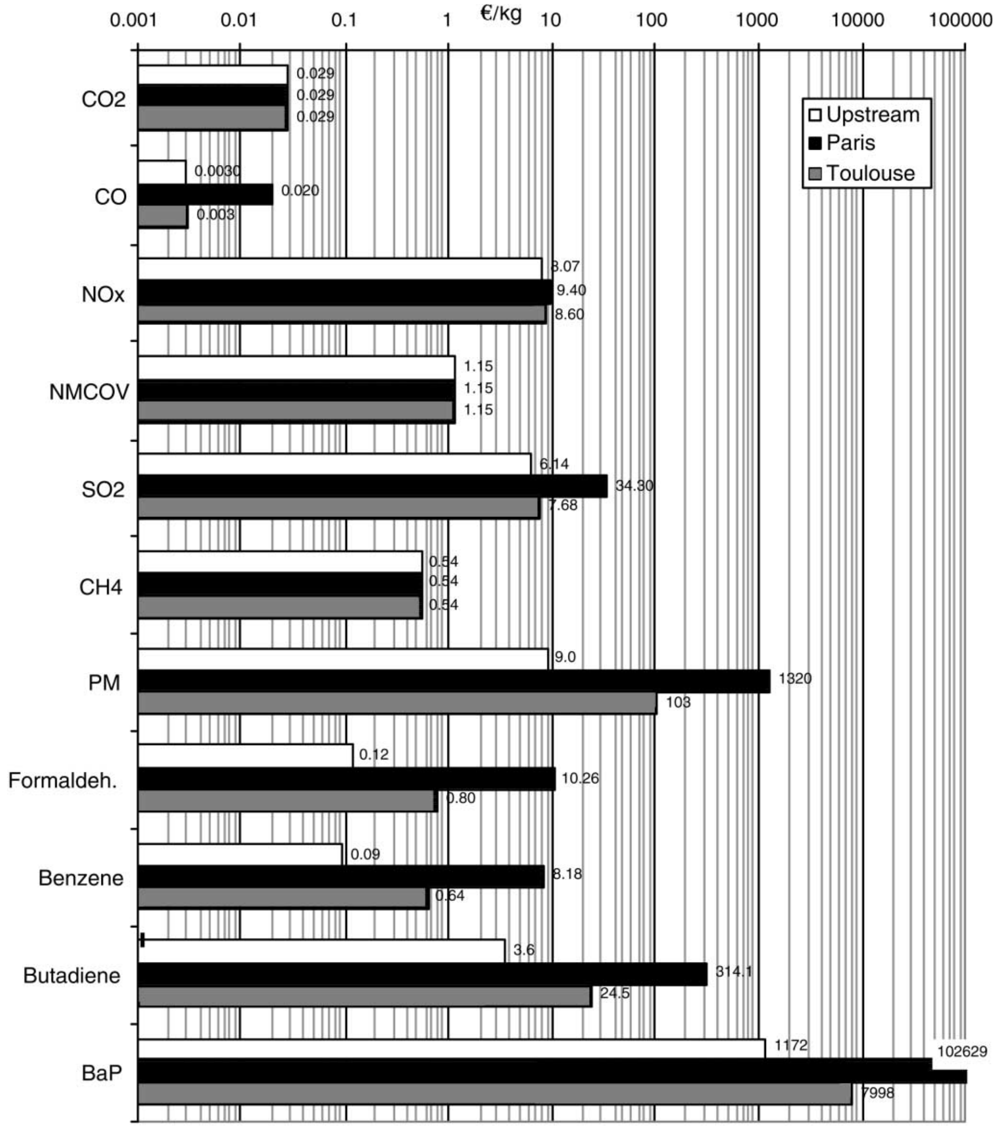

Fig. 3. Damage costs (in €) per kg of pollutant emitted by three sources: vehicles in Paris and in Toulouse, and typical industrial installations in France (upstream).

12 times larger than that of ExternE (2000). But in the Conclusion calculations with the global warming cost of ExternE (2000) are also presented. For NO_x, SO_2 and PM the costs of ExternE (2000) are approximately 0.6 times those of ExternE (1998).

How can the damage costs be transferred to other cities? To the extent that the costs, other than global warming, arise mostly from health impacts, they are proportional to the size of the affected population weighted by the respective concentration increments. For precise results one would have to repeat the analysis based on local meteorological and population data, but for a rough first estimation one can use the following rules of thumb (Spadaro, 1999; Spadaro and Rabl, 1999):

- for primary pollutants emitted by vehicles in cities the damage cost is roughly proportional to the population of the conurbation;
- for secondary pollutants the damage cost is roughly proportional to the average regional population density within a radius of 500–1000 km.

Here the populations of the metropolitan areas are approximately 10 million for Paris and 0.75 million for Toulouse. With the assumptions of ExternE, the impacts of SO_2 emissions arise almost entirely via secondary pollutants (sulfate aerosols), and those of NO_x and VOC entirely via secondary pollutants (nitrate aerosols and ozone). The other pollutants, apart from greenhouse gases, are assumed to act as primary pollutants.

The costs in €/km are the product of the emissions in g/km and the damage costs in € per g of pollutant. The results are reported in Figs. 4 and 5. The dominant damage costs arise from the health impacts of PM, SO_2, NO_x (via ozone and nitrates), and VOC (via ozone). The costs of CO, BaP, benzene, butadiene and formaldehyde are not significant.

For the diesel bus the total damage cost is 1.27 €/km in Paris and 0.38 €/km in Toulouse. For gas the corresponding numbers are 0.23 €/km in Paris and 0.15 €/km in Toulouse. Natural gas allows an appreciable reduction of the emissions, lowering the damage cost by a factor of about 2.5 (Toulouse) to 5.5 (Paris).

To put these numbers in perspective, it is instructive to compare them with the market price of the fuel. At the beginning of 2000 diesel fuel in France sold for about 1 €/l, of which about 65% was tax. With a consumption of 0.5 l/km (see Section 2) the fuel price amounts to 0.5 €/km. Thus the damage costs of the EURO2 diesel bus is of the same order of magnitude as the price of the fuel, higher in Paris, lower in Toulouse.

5. Sensitivity analysis

The gas fueled bus has much lower damage costs than the diesel, especially in large cities. Considering the notoriously large uncertainties of damage costs, it is natural to wonder how firm this conclusion is. Looking at Figs. 4 and 5 one sees that the most significant contributions to the difference diesel—gas come from PM and NO_x for which the gas option offers a clear advantage. CH_4 is the only pollutant for which the Diesel is much better, but its monetary contribution is so small, even at the higher value of 0.029 €/t of CO_2, that it does not change the ranking.

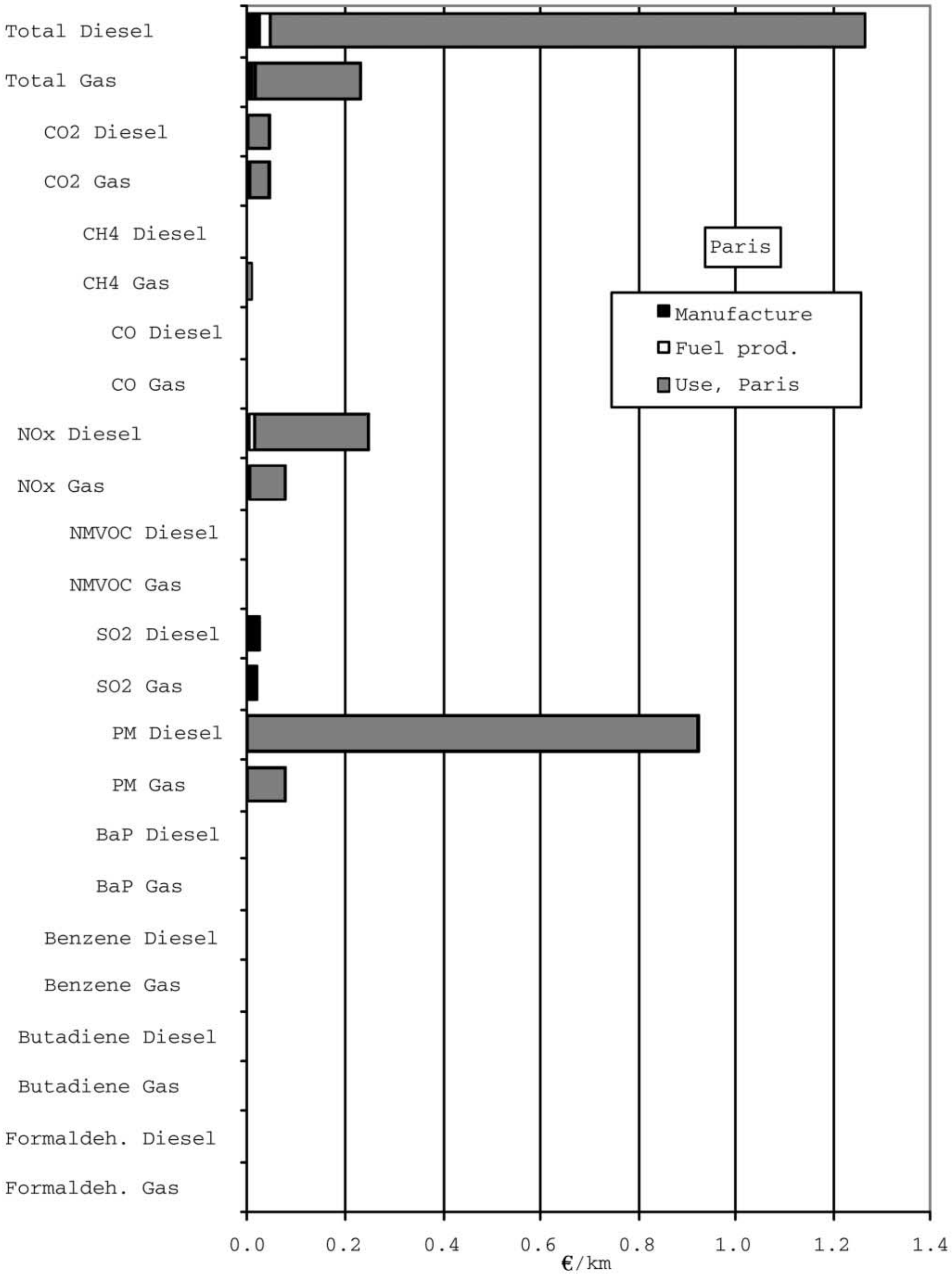

Fig. 4. Damage costs in €/km, in Paris (with 0.029 €/kg of CO_2).

The uncertainty of the damage cost per kg of pollutant is very large: the damage (other than global warming) could be in the range from 1/3 to 3 times the indicated value (Rabl and Spadaro, 1999).

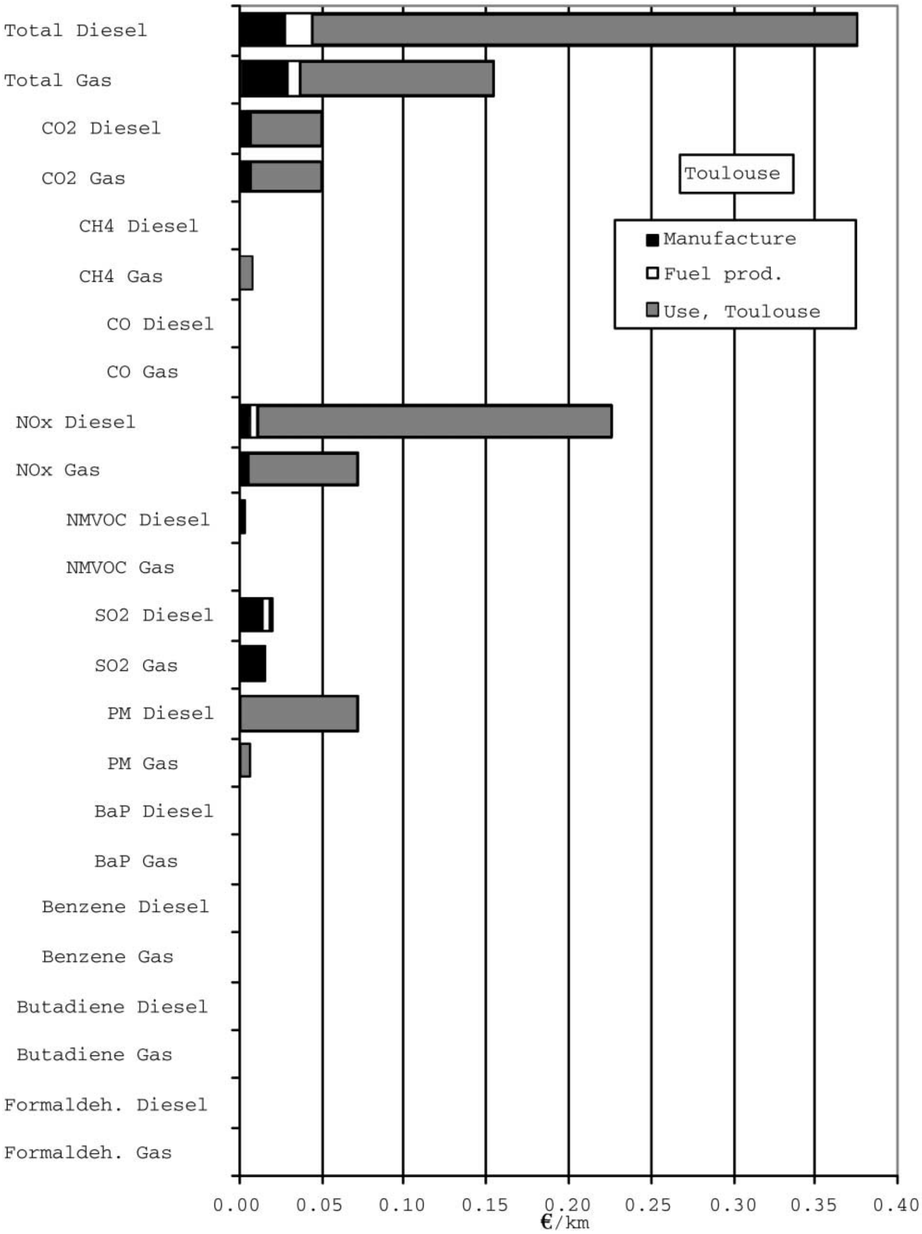

Fig. 5. Damage costs in €/km, in Toulouse (with 0.029 €/kg of CO_2).

The principal sources of this uncertainty are: atmospheric modeling, the dose–response functions, and the unit costs (especially the so-called ‘value of statistical life’). However, in the present paper this uncertainty plays only a secondary role because it affects the diesel and the gas option more or less the same way, therefore with little consequence for the ranking (by contrast to a cost-benefit analysis which would be very sensitive to this uncertainty).

The following tables present a sensitivity study to further explore how robust the environmental advantage of gas fueled buses is. To highlight the comparisons, the tables indicate the difference diesel—gas and the ratio gas/diesel.

Since the cost of the global warming is very uncertain (estimates of 0.029 €/kg$_{CO_2}$ by ExternE (1998) and 0.0024 €/kg$_{CO_2}$ by ExternE (2000)), both values are considered in Table 7. The cost of global warming is significant, but almost without influence on the comparison of diesel and gas because of the small difference in CO_2 emissions.

Finally Tables 8 and 9 consider the possible evolution of the emissions for more advanced technologies. Table 8 shows the passage from Standard EURO2 to EURO3 for diesel buses,

Table 7
Comparison of the damage costs between diesel and gas, both as difference and as ratio gas/diesel, for two values of the cost of global warming

	Paris	Toulouse
With 0.029 €/kg$_{CO_2}$		
Diesel	1.27 €/km	0.38 €/km
Gas	0.23 €/km	0.16 €/km
Diesel—gas	1.04 €/km	0.22 €/km
Gas/diesel	18%	41%
With 0.0024 €/kg$_{CO_2}$		
Diesel	1.22 €/km	0.33 €/km
Gas	0.18 €/km	0.10 €/km
Diesel—gas	1.04 €/km	0.23 €/km
Gas/diesel	14%	31%

Table 8
Comparison of diesel and gas options, if the diesel emissions are reduced by the respective ratios of EURO2 and EURO3 limit values (see Table 5) while emissions of gas option do not change

	Paris	Toulouse
EURO2 (>1996)		
Diesel—gas	1.04 €/km	0.22 €/km
Gas/diesel	18%	41%
EURO3 (>2000)		
Diesel—gas	0.66 €/km	0.13 €/km
Gas/diesel	26%	54%

Table 9
Comparison of EURO2 diesel bus with particle filter (Régie Autonome des Transports Parisiens, 2000) and gas bus with MPI engine of IVECO (1998) (emissions of Table 6)

	Paris	Toulouse
Diesel with filter	0.38 €/km	0.30 €/km
Gas MPI	0.08 €/km	0.08 €/km
Diesel—gas	0.30 €/km	0.22 €/km
Gas/diesel	21%	27%

without any change in the emissions of the gas option. Table 9 compares a EURO2 diesel bus with particle filter, and a gas bus with the MPI engine IVECO, technologies available already today. With the MPI engine the damage costs of gas fueled bus are well below the diesel with particle filter, even though the emissions of the latter are very low.

6. Conclusion

The results of this paper show that the damage costs of air pollution are large (for the EURO2 diesel bus comparable to the market price of the fuel) and merit attention. The numbers can serve as input to a cost-benefit analysis to see whether alternatives to the current diesel bus are preferable in terms of total life cycle social cost.

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