Comparison of the environmental damage caused by vehicles with different alternative fuels and drivetrains in a Brussels context

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Abstract: A comprehensive methodology has been developed to compare the environmental damage caused by vehicles with different alternative fuels, such as CNG, LPG, etc., and drivetrains, such as electric and hybrid drives. This paper describes how the environmental effect of vehicles should be defined and includes parameters concerning vehicle emissions and their influence on human well-being and the environment. It then describes how the environmental effect of vehicles could be defined, taking into account the availability of accurate and reliable data. Rating systems are analysed as a means of comparing the environmental effect of vehicles, allowing decision-makers to dedicate their financial and non-financial policies and measures as a function of the ecological damage. Different types of pollution (acid rain, photochemical air pollution, noise pollution, etc.) and their effect on numerous receptors such as ecosystems, buildings and human beings (e.g. cancer, respiratory diseases, etc.) and global warming are considered.

The methodology described, known as Ecoscore, is based on a methodology similar to life cycle assessment (LCA) which considers the part played by emissions in certain types of damage (e.g. by using the exposure–response damage function). Total emissions involve oil extraction, transport and refinery, fuel distribution and electricity generation and distribution (well-to-wheel approach). Emissions due to the production, use and dismantling of the vehicle (cradle-to-grave approach) should also be considered. The different types of damage are normalized to make comparisons possible. Hence, a reference value (determined by a chosen reference vehicle) will be defined as a target value (the normalized value will thus measure a kind of distance to target). The contribution of the different normalized types of damage to a single value—Ecoscore—is based on a panel weighting method.

This new approach differs from other methodologies in that it has been especially developed for the assessment of the environmental effect of vehicle emissions in an urban context, such as the Brussels Capital Region. Additionally, this methodology not only considers conventional vehicles but can also evaluate all alternative fuels and drivetrains with new vehicle technologies. Some examples of Ecoscore calculation are illustrated.

Keywords: environment, pollution, modelling, alternative fuel, primary energy, emissions, vehicle technologies

NOTATION

ACEA	European Automobile Manufacturers Association
ACEEE	American Council for an Energy Efficient Economy
BIME	Brussels Institute for the Management of the Environment
CCGT	combined-cycle gas turbine
CEESE	Centre d'Etudes Economiques et Sociales de l'Environnement
CF	correction factor
CH_4	methane
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CtG	cradle to grave

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dir	direct tailpipe emissions
dis	fuel distribution
DALY	disability adjusted life years
DIV	Dienst voor Inschrijving van de Voertuigen
elec	electricity generation
extr	extraction
E	emissions (CO_2, NO_x, HC, SO_2, etc.) (g)
E_{CH_4}	emissions of CH_4 (g)
E_{HC}	emissions of HC (g)
E_{N_2O}	emissions of N_2O (g)
$E_{real\ life}$	real-life emissions (g)
E_{reg}	type approval emissions (g)
E_{SO_2}	emissions of SO_2 (g)
EC	European Commission
EEV	environmentally enhanced vehicle
Elec Belg01	electricity production based on average electricity production mix for 2001
Elec CCGT95	electricity production based on combined-cycle gas turbine data for 1995
Elec renew	electricity production based on renewable energy sources
ETEC	Department of Electrical Engineering and Energy Technology
EV	electric vehicle
FC	fuel consumption (L/100 km)
FD	fuel density (g/L)
GWP	global warming potential
HAP	polycyclic aromatic hydrocarbons
HC	hydrocarbons
HEV	hybrid electric vehicle
IFEU	Institute for Energy and Environmental Research
IPCC	Intergovernmental Panel on Climate Change
k_S	weight-related sulphur content of the fuel (kg/kg)
LCA	life cycle assessment
LPG	liquefied petrol gas
NMHC	non-methane hydrocarbons
NO	nitrogen oxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
N_2O	nitrous oxide
PDF	potential disappearance factor
PM	particulate matter
$Q_{acidification}$	relative acidification factor
$Q_{buildings}$	relative damage to buildings factor
$Q_{greenhouse}$	relative greenhouse factor
Q_{noise}	relative noise annoyance factor
$Q_{respiration+cancer}$	relative damage to respiration and cancer factor
ref	refinery
$R_{CH_4/HC}$	ratio of CH_4 emissions to HC emissions
R_{N_2O/CO_2}	ratio of N_2O emissions to CO_2 emissions
SO_2	sulphur dioxide
tran	transport of crude material
TSP	total suspended particulates
VITO	Vlaamse Instelling voor technologisch Onderzoek
VOC	volatile organic compound
WHO	World Health Organization
WtW	well to wheel
x	relative contribution of emission E to certain type of damage
ω_{ind}	relative contribution of indirect emissions

1 INTRODUCTION

The transport sector is responsible for a great amount of pollution, which has a direct and indirect effect on different receptors (people, buildings, agriculture and ecosystems, etc.). The pollution caused by transport is a heavy burden, especially in urban areas. The reason for this is the joint presence of a large number of sources of pollution (cars, vans, lorries, etc.) on the one hand, and a large number of receptors (people and buildings) on the other. Studies carried out under the auspices of the European ExternE project [**1**, **2**], which looked into the evaluation of the external costs of the energy and transport sectors, have shown that local effects constituted the bulk of the damage caused by emissions from road transport. In recent studies by the CEESE [**3**], the yearly effect of transport in the Brussels Capital Region is estimated to be €774 million.

The introduction of clean vehicles would be an interesting move in the direction of a significant reduction in harmful exhaust gases, with a view to a sustainable transport policy. A Brussels ordinance entitled 'Air' [**4**] states that, in the coming 5 years, at least 20 per cent of the vehicles belonging to institutions and administrative services from the Brussels Capital Region must be 'clean'. The question is, what are clean vehicles?

In this respect, the Brussels Capital Region commissioned a study via the BIME (Brussels Institute for the Management of the Environment, BIM-IBGE) entitled 'Clean Vehicles'. The Vrije Universiteit Brussel (ETEC) and the Université Libre de Bruxelles (CEESE) have carried out a joint study programme. After completion of this research project, the model was developed further to take into account the availability of reliable data and the current state of knowledge.

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2 ENVIRONMENTAL IMPACT RATING

A rather simple and pragmatic approach would be to state that all alternatively fuelled vehicles (LPG, CNG, EV, HEV, etc.) can be considered to be 'clean'. Another basic approach is to consider as 'clean' all vehicles satisfying stringent emission regulations such as EURO-IV or EEV. However, such approaches do not tell anything about the real environmental damage caused by vehicles.

To be able to compare different vehicle technologies and fuels, it is useful to have a representative statistical sample of vehicles, based on the same technology. However, in the case of some innovative vehicles, only a few models of specific types are available on the market. Their representativeness in terms of a technology is not always certain. When (abundant) data exist for specific vehicle types (fuels and drivetrains), it sometimes happens that they are contradictory.

A large number of factors influence vehicle emissions. The most important of these are driving behaviour [**5**], the characteristics of the vehicle technology used and the on-board accessories. All these factors influence vehicle emissions and make it very difficult to compare vehicles with each other. In order to compare the environmental burden caused by vehicles, a comprehensive methodology that uses comparable and available data to calculate environmental damage should be established.

2.1 Characterization and classification of different effects and damage

The basic idea behind comparing the environmental effect of vehicles is based on defining one single value representing the ecological damage for which they are responsible. Other methodologies already exist in different countries, such as the list of environmentally approved vehicles drawn up by the Verkehrsclub Deutschland and used in Germany, Switzerland and Austria [**6**], the ACEEE 'Green Book' in the United States [**7**], Ecolabelling in the Flemish Region (Belgium) [**8**], the Eco-indicators 95 and 99 in the Netherlands [**9**, **10**] and the current EC project 'Cleaner Drive' [**11**]. In almost all these methodologies, the ecological effect (greenhouse and acid rain, etc.), the effect on human health (cancer, respiratory diseases, etc.), and noise pollution, etc., are converted to one single value.

Figure 1 illustrates this approach: starting from the characterization of the different emissions (see below), the effects and damage are calculated on the basis of scientific expertise and converted into one single value by the weighting system chosen. Taking these studies as a basis, the different effects and damage can be calculated as a function of the pollutants emitted. The relative contribution of the different pollutants to certain types of damage is summarized in Table 1 [**7**, **10**, **11**].

A closer look at Table 1 indicates that the effect of emissions on human health can be assessed in different ways. The damage can be expressed in disability adjusted life years (DALY), for example, or can be monetarized by calculating the cost of the damage expressed in €/kg of emissions emitted. In addition to this emission-related damage, consideration can also be given to taking into account other effects such as noise, light pollution, stress and time wasting due to congestion, safety aspects, the consumption of resources, etc.

2.2 Life cycle assessment

What sources of emissions should be considered? Should only tailpipe emissions be taken into account? What is the damage caused by emissions from power stations?

Some methodologies are based on well-to-wheel (WtW), cradle-to-grave (CtG) or life cycle assessments (LCA), which take into account the different stages in the life and use of a vehicle, from its manufacturing and the production of its fuel, through its use and the con-

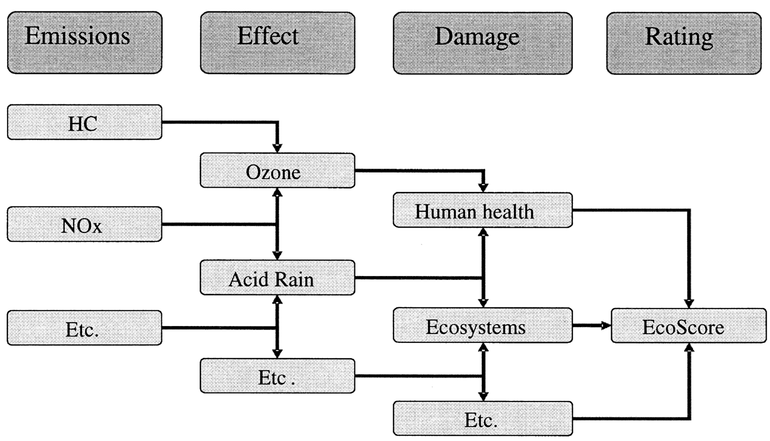

Fig. 1 One single value for the environmental impact rating

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Table 1 General characterization of the different possible effects taken into consideration

Possible effects	Global warming		Respiration–organic components (summer smog)	Respiration–non-organic components (winter smog)	Cancer	Human health	Air quality	Ecosystems—ecotoxical emissions	Ecosystems—acidification and eutrophication	Photochemical air pollution	Acid rain	Buildings
Unit*	DALY/kg	GWP	DALY/kg	DALY/kg	DALY/kg	Damage cost (€/kg)	€/t	PDF m^3 year/kg	PDF m^3 year/kg	ppb/O_3/Mt/an	%	(€/kg)
Source	Ecolabel 99	IPCC	Ecolabel 99	Ecolabel 99	Ecolabel 99	Green Book	Cleaner drive	Ecolabel 99	Ecolabel 99		VITO	ULB-CEESE
CO_2	2.1E−07	1.00E+00										
HC			6.46E−07			3.70E−01	1.20E+00			3.10E−01		
NO_x				8.87E−06		4.94E+00	3.00E+00		5.71E+00	3.70E−01	9.00E+01	
CO				7.31E−07		3.00E−02	1.03E+00					
CH_4	4.40E−06	2.30E+01	1.28E−08									
N_2O	6.90E−05	2.96E+02										
SO_2				5.46E−05		2.34E+01	6.76E+00		1.04E+00		1.00E+01	8.26E+00
PM					9.78E−06	3.97E+01						
PM10				3.75E−04			9.25E+01					2.59E+02
PM2,5				7.00E−04								
TSP				1.10E−04								
NO				1.37E−04					8.79E+00			
NO_2				8.87E−05					5.71E+00			
1,3 Butadiene			1.87E−06		1.58E−05							
Benzene			4.68E−07		2.50E−06			2.75E−03				
NMHC			1.28E−06									
Formaldehyde				1.11E−06		9.91E−07						
Methane			1.28E−08									
Toluene			1.36E−06					2.40E−04				
Xylene			2.21E−06									
HAP					1.70E−04			7.80E−04				
Benzo(a)pyrene					3.98E−03			1.42E+02				
Benzo(a)anthracene					5.68E−02							
Dibenzo(a)anthracene					3.10E+01							
Lead								2.54E+03				

* DALY = disability adjusted life years, GWP = global warming potential, PDF = potential disappearance factor with 60 per cent deposition in natural areas.

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struction and maintenance of the required infrastructure to its recycling. Figure 2 illustrates this approach.

2.3 Weighting systems

Different weighting systems [**6**–**8**, **10**] are compared in Table 2. The last column is the relative contribution of the different damage selected in the Ecoscore methodology.

As can be seen, the contribution of human health is considered in the proposed methodology to be more important than in the other references, while the contribution from global warming is considered to be less important. This choice is based on the fact that the methodology was developed for the Brussels Capital Region which places greater weight on the effects on health, since the Brussels Region is a very densely populated urban area. By modifying the weighting factors, the methodology can easily be applied to other regions and countries.

3 TRANSPARENT ECOSCORE MODEL

In the previous sections, the different possible effects and damages were described and characterized as a function of different types of emission. However, it is necessary to develop a transparent uniform methodology that is useful for all kinds of vehicle with different types of fuel and drivetrain. In this chapter, the Ecoscore methodology will be described in detail.

The different components of hydrocarbons that affect respiration and cause cancer (see Table 1) are especially difficult to obtain for all fuel types. A first attempt was based on the calculation of the emission data from the COPERT/MEET methodology [**12**, **13**]. However, this methodology was not adequate enough for all the new alternative fuels.

Furthermore, the accuracy required for these data needs to be very high owing to the fact that the emissions in question account for an important part of the final Ecoscore values. The Ecoscore value is very sensitive to emission values of some hydrocarbon components.

The methodology was therefore adapted in such a way that it is only based on regulated emissions (CO, HC, NO_x, PM) and emissions depending on fuel consumption (CO_2, SO_2); CH_4 was calculated out of the HC emissions and N_2O as a function of CO_2 emissions.

3.1 Emission inventory

3.1.1 Direct tank-to-wheel emissions

Table 3 shows the emission limits of the type approval tests for passenger cars. These data can be used as input for the model since they are available for all vehicles on the market.

Regulated emissions can be collected by using sources of data such as the Belgian vehicle registration service (DIV), the Vehicle Certification Agency in the United Kingdom [**14**] or the European project UTOPIA [**15**]. Hence, the emissions expressed in g/km for passenger

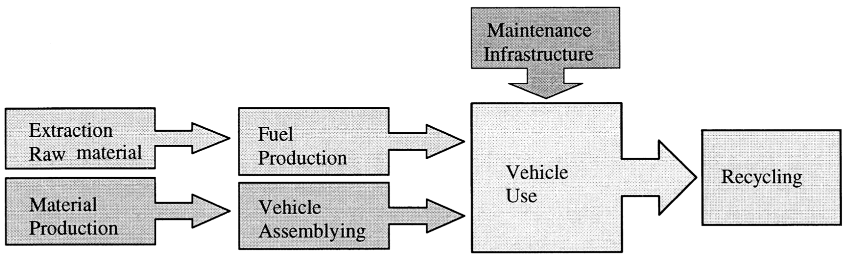

Fig. 2 Cradle-to-grave overview

Table 2 Weighting of the damage (%)

Damage	IFEU	Green Book	Aminal	Ecolabel 99	BIME
Health	10	50	20	40	
Cancer	15				20
Respiration—organic components					15
Respiration—non-organic components					15
Global warming	40	50	40		25
Environment	10			40	10
Acid rain			10		
Photochemical			20		
Resources				20	
Speed	5				
Noise	20		10		10
Buildings					5

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Table 3 European emission directives for passenger cars (in g/km)

	Year	CO	HC	HC+NO_x	NO_x	PM
			Diesel			
Euro-I	1992	2.72	—	0.97	—	0.14
Euro-II, IDI	1996	1.0	—	0.7	—	0.08
Euro-II, DI	1999	1.0	—	0.9	—	0.10
Euro-III	2000.01	0.64	—	0.56	0.50	0.05
Euro-IV	2005.01	0.50	—	0.30	0.25	0.025
			Gasoline			
Euro-I	1993	2.72	—	0.97	—	—
Euro-II	1997	2.2	—	0.5	—	—
Euro-III	2000.01	2.30	0.20	—	0.15	—
Euro-IV	2005.01	1.0	0.10	—	0.08	—

Table 4 Fuel characteristics [**11**, **12**, **16**]

	Energy content (kJ/kg)	Fuel density (g/l)	Ratio H/C	Sulphur content (ppm)	Ratio N_2O/CO_2	Ratio CH_4/HC
Reference	44 000	755	1.8	50	0.040244	12
Petrol	44 000	755	1.8	150	0.040240	12
Diesel	42 300	835	2	350	0.003540	4
CNG	44 800	859	3.97	0	0.031590	92
LPG	46 000	545	2.58	0	0.031590	3

vehicles are available for HC, CO, NO_x and PM as well as the fuel consumption and CO_2 emissions.

The SO_2 emissions can be calculated from the fuel consumption (FC) by taking into account the sulphur content (k_S) and the fuel density (FD) {see equation (1) and Table 4 [**16**]}. For example, a petrol vehicle with a fuel consumption of 5 L/100 km using petrol with a sulphur content of 150 ppm ($k_S = 150 \times 10^{-6}$) and a fuel density of 755 g/L will emit 0.0113 g SO_2/km (note that every gramme of sulphur is transformed into 2 g of SO_2)

$$E_{SO_2} = 2k_S\left(\frac{\text{FD FC}}{100}\right) \quad (1)$$

The CH_4 emissions are proportional to the total HC emissions and hence can be calculated by means of equation (2) as a function of the fuel type (Table 4)

$$E_{CH_4} = R_{CH_4/HC}E_{HC} \quad (2)$$

Similarly, the N_2O emissions can be calculated for each fuel type on the basis of the CO_2 emissions [**11**] (Table 4)

$$E_{N_2O} = R_{N_2O/CO_2}E_{CO_2} \quad (3)$$

However, in practice, vehicle emissions are mostly much higher owing to the fact that the typical accelerations throughout the type approval test cycle are much lower than in reality (by a factor of up to 2). The higher the acceleration and the driving dynamics, the higher the emissions [**5**]. In fact, real-life emissions, $E_{\text{real life}}$, may be 2, 3 or even 30 times higher than in the emission directives, E_{reg}. Additionally, on account of ageing and/or bad engine and catalyst tuning, real-life emissions will be higher than the emissions from the approved new car. Taking into consideration these factors, the Green Book (United States) introduces correction factors (CFs) into the homologation emissions [**7**] (see Table 5). Other references [**6**] take into account the maximum possible speed of the car to offset the optimistic emission regulations

$$E_{\text{real life}} = \text{CF}\ E_{\text{reg}} \quad (4)$$

Under the Ecoscore methodology, only the emissions from EC type approval are used in the final calculation of the Ecoscore. For a robust model, these correction factors should be made available for the European context (European type approval versus real life) for different vehicle classes and age, etc., as well as for alternative fuels.

3.1.2 *Well-to-tank emissions*

Indirect emissions are related to the extraction and transportation of raw materials as well as those related to the refinery and the distribution of the fuels. This well-to-tank approach is particularly required when comparing different alternative fuels and drivetrains (especially in the case of electric vehicles), since there can be huge differences in the emissions related to the production process of fuels and electricity.

The route from the extraction of crude oil to the use of individual refined components is long and complex.

Table 5 Real-life multiplication or correction factors [**7**]

	FC	CO	HC	NO_x	PM
Petrol	1.3	5.8	4	3	1
Diesel	1.3	1.2	1.4	2	2.1

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Emissions do result from the extraction (gas flaring, venting and gas turbines), transport (energy used, losses) and processing of crude oil (different refinery types), and also from the distribution of the fuel (mainly VOC evaporation in the case of petrol) [**12**]. The following stages are considered in the special case of biofuels: agriculture, transport, processing, distribution and storage.

The emissions related to electricity generation are a function of the type of power station (nuclear, coal, gas, air wind, hydro, etc.) and the relative contribution of each power station to the energy consumed. It is very difficult to attribute a particular energy use of an appliance (i.e. an electric vehicle) to one particular power plant. Using an average electricity production mix as a basis seems at first sight to be a straightforward approach. However, electric vehicles will be charged mostly at night, with totally different sources of electricity production from the average power station, taking into account that night-time electricity generation relies mainly on the so-called 'base' power stations, which are generally more efficient and have lower relative emissions. The average power station also includes old power plants. If the introduction of electric vehicles in the next 10 years is taken into account, it will be necessary to consider the investment policy of the electricity production companies. The Belgian electricity company Electrabel invests mainly in renewable energy or the combined-cycle gas turbine (CCGT) with low emissions and a high level of efficiency (55 per cent). Additionally, from 2003 the electricity market in Europe will be liberalized and consumers will be able to buy emission-free electricity (e.g. Dutch wind, French nuclear or Swiss hydro energy). Electric vehicles charged with these sources of electricity will therefore be emission free. Nevertheless, to simplify the model, the average electricity generation mix will be used and should be seen as a pessimistic case scenario for electric vehicles.

As can be seen in Table 6 [**13**, **17**], the biofuel-related emissions are high owing to the agricultural processes. CNG vehicles have high CH_4 indirect emissions, which is a greenhouse gas. Although the indirect emissions related to electricity production seem to be high, there are no direct emissions as is the case for the other types of vehicle. Emissions due to electricity production have decreased significantly in the last 10 years. Table 6 shows the emission values corresponding to the Belgian Mix in 1995 [**12**]. At that moment the share of electricity from coal power plant was 23.3 per cent of the total electricity production. However, this fraction was responsible for 85 per cent of CH_4 emissions due to coal extraction and more than 90 per cent of SO_2 and PM emissions due to production of electricity out of coal. At the moment, more and more CCGTs are being used. Additionally, emissions are more filtered at the chimneys of the power plants.

The energy used per kilometre for non-electric vehicles can be calculated from the fuel consumption (FC) and the energy content of the fuel (see Table 4). The consumption of electric vehicles is mostly expressed directly in kW h/km. The indirect emissions can easily be calculated on the basis of this energy consumption and Table 6.

Contrary to direct emissions, indirect emissions are not produced at the place of vehicle operation. Since refinery plants and electricity production plants are mostly situated far away from densely populated areas, their effects on human health are lower than those of direct tailpipe emissions because of the dispersion of these indirect emissions. One gramme of particulate matter emitted by a diesel car in a crowded city will cause much greater damage to human health than one gramme of particulate matter emitted from a chimney far away from the population. To take this into account, some studies such as reference [**7**] introduce a weighting factor (e.g. 50 per cent) in calculating the total emissions related to health effects; this is illustrated by the equation

$$E_{\text{total}} = E_{\text{direct}} + w_{\text{ind}} E_{\text{indirect}} \tag{5}$$

However, no weighting is allowed for overall damage such as global warming since every gramme of CO_2 makes the same contribution to this effect.

To be more exact, the relative effects of indirect emissions on health should be calculated for each step in the fuel production chain. This can be expressed by means

Table 6 Indirect emissions for Belgium

	CO (mg/kW h)	NMHC (mg/kW h)	CH_4 (mg/kW h)	NO_x (mg/kW h)	PM (mg/kW h)	CO_2 (mg/kW h)	SO_2 (mg/kW h)
Reference	18.4	761.4	62.6	151.9	8.6	33 100	236.2
Petrol	18.4	761.4	62.6	151.9	8.6	33 100	236.2
Diesel	16.6	315.4	56.5	129.6	3.6	24 500	174.2
Biofuel	493.2		280.4	871.9	66.6	108 700	245.5
CNG	5	99	805.3	38.2	2.9	14 800	60.8
LPG	14.8	202.7	58	116.3	5.4	21 600	114.1
Electricity renewable	0	0	0	0	0	0	0
Electricity Belgian Mix 2001	*18.4*	*44**	1.75	440	36	290 000	420
Electricity CCGT 1995	78	129	266	495	0	447 500	0
Electricity Belgian Mix 1995 (MEET)	60.1	44	865	1041.8	97.9	339 500	1920.6

* No new data available, data of MEET 1995 used.

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of equation (6) for each type of effect (global warming, acid rain, health, etc)

$$\text{Damage} = \sum_i x_i^{\text{extr}} E_i^{\text{extr}} + \sum_i x_i^{\text{tran}} E_i^{\text{tran}} + \sum_i x_i^{\text{ref}} E_i^{\text{ref}} + \sum_i x_i^{\text{elec}} E_i^{\text{elec}} + \sum_i x_i^{\text{dis}} E_i^{\text{dis}} + \sum_i x_i^{\text{dir}} E_i^{\text{dir}} \quad (6)$$

However, such detailed information is not available. Using the Ecoscore methodology, the relative contribution of indirect emissions to overall emissions is calculated as a function of the type of pollutant. The weight factor, ω_{ind}, for health-related pollutants can be found in Table 7 [**11**]. For all the other effects, ω_{ind} equals one.

3.2 Noise pollution

Since the methodology was developed in the first instance for a typical urban context (Brussels Capital Region), noise pollution should also be taken into account. Noise is one of the main causes of annoyance for the inhabitants of Brussels [**18**]. In the Brussels Capital Region, 28 per cent of the population is exposed to sound levels higher than 65 dB(A). The WHO considers that a daytime sound level of 50 dB(A) $L_{\text{Aeq,8h}}$ is irritating. On the basis of an enquiry, 43 per cent of the population considers the noise caused by traffic to be too high [**19**].

In some studies such as references [**6**] and [**8**], noise is compared by calculating the different intensity of sound levels expressed in dB(A). However, since this is a logarithmic scale, and every reduction of 3 dB(A) implies halving the real noise pollution. A reduction of 10 dB(A) even represents a 90 per cent decrease in the annoyance from noise. The noise level, L, expressed in dB(A) is therefore converted in the Ecoscore methodology, as shown in the equation

$$E_{\text{noise}} = 10^{\{L[\text{dB(A)}]/10\}} \quad (7)$$

3.3 Characterization and classification of different effects and damage

On the basis of the available data, the following damage is considered together with its effect on a number of receptors such as people, ecosystems and buildings: ‘global warming’, ‘respiratory and cancer diseases’, ‘acidification’, ‘damage to buildings’ and ‘noise pollution’. These effects are calculated as a function of the regulated fuel consumption dependent emissions in relation to the parameters indicated in the last column of Table 8.

Table 7 Relative contribution of indirect emissions to total emissions [**11**]

	HC	NO_x	CO	SO_2	PM
ω_{ind}	1	1	0.1	0.4	0.1

3.4 Normalization—the reference vehicle—weighting

Once the different effects on human health and ecosystems, etc., have been calculated on the basis of the different emissions identified, the next step is to relate them to a chosen reference vehicle. It is not possible to establish a comparison directly between the effect of greenhouse gas and those related to respiratory diseases, for example. However, dividing these effects by the effect of a reference vehicle (normalization) results in a relative value without units. Hence, it is possible to weight the different effects and to come up with one final score

$$\text{Damage (p.u.)} = \frac{\text{damage vehicle (g/km)}}{\text{damage reference vehicle (g/km)}} \quad (8)$$

In the proposed methodology, the EURO-IV emissions directive for petrol vehicles, compulsory from 2005, is used as a reference. This could be seen as the maximum allowable value for a ‘clean vehicle’. For non-regulated but fuel consumption dependent emissions, a 5 L/100 km petrol reference is used. The European car manufacturer (ACEA) voluntary commitment is to reduce the average of their new cars from 186 g CO_2/km in 1995 to 140 g/km by 2008. Another ACEA commitment is to introduce models emitting 120 g CO_2/km or less by the end of 2000.

The currently permitted regulated sound level for passenger cars is 74 dB (70/157/EC and 92/97/EC). A reduction of 4 dB is technically feasible. Hence, the level of 70 dB(A) has been chosen as a reference. Table 9 illustrates these reference values. The indirect emissions can also be calculated from these target values since they are proportional to the fuel consumption.

Once the different damage and effects have been calculated for the direct and indirect emissions per vehicle

Table 8 Characterization and classification of different effects and damages

Damage	Weighting	Emission	Unit	Contribution
Global warming	25	CO_2	GWP	1
		CH_4	GWP	23
		N_2O	GWP	296
Respiration and cancer	50	HC	Daly/kg	6.46E-07
		NO_x	Daly/kg	8.87E-05
		CO	Daly/kg	7.31E-07
		PM	Daly/kg	9.78E-06
Acidification	10	NO_x	PDF m^3 y/kg	5.713
		SO_2	PDF m^3 y/kg	1.04
Buildings	5	SO_2	€/kg	8.3
		PM	€/kg	259
Noise	10			1

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Table 9 Emission value of the reference vehicle

FC (l/100 km)	CO_2 (g/km)	SO_2 (g/km)	N_2O (g/km)	CO (g/km)	HC (g/km)	NO_x (g/km)	PM (g/km)	Noise [dB(A)]
5	120	0.0038	0.048	1.00	0.10	0.08	0.00	70

and compared with a reference vehicle, the per-unit damage can be weighted as expressed in equation (9) to come up with one single-value, labelled Ecoscore

$$\begin{aligned}\text{Ecoscore} = {} & 25\% Q_{\text{greenhouse}} + 50\% Q_{\text{respiration+cancer}} \\ & + 10\% Q_{\text{acidification}} + 5\% Q_{\text{buildings}} \\ & + 10\% Q_{\text{noise}} \end{aligned} \tag{9}$$

4 RESULTS

The methodology has been developed on some examples. These examples are only indicative and serve to evaluate the applicability of the methodology. Table 10 illustrates the different vehicles that have been evaluated to demonstrate it. Different fuel types and drivetrains were selected. Various engine capacities and vehicle sizes were taken to have an idea of the best and worst vehicles.

The total Ecoscore is given in Fig. 3. In a Belgian (even a Brussels) context, a good environmental impact rating (Ecoscore) can be seen for the electric vehicle (Peugeot 106 electric) in comparison with other technologies. Also, petrol hybrid, CNG and LPG vehicles score well and are mostly lower than the reference vehicle (EURO-IV). Most petrol and diesel vehicles examined cannot be considered as clean (in comparison with the reference) since they have higher values than the reference vehicle. Owing to their low fuel consumption, small and light petrol vehicles score well. The Ecoscore of ‘conventional’ EURO-IV vehicles is much lower than that of EURO-III vehicles. Diesel vehicles have bad Ecoscores. Also, no diesel vehicles appear in other clean vehicle lists, such as, for example, in reference [7]. This is due to the fact that the NO_x emissions (and PM emissions) from diesel vehicles are much higher than those from petrol vehicles. These NO_x emissions contribute heavily to damage to health. In the future, new NO_x clean-up devices and PM filters may bring the damage to health down. The highest scores (out of 2000 evaluated vehicles) correspond to heavy vehicles with large engine capacities. Figure 3 also shows the results of the different considered effects on global warming, health, acidification, buildings and noise pollution of the vehicles evaluated.

Generally, owing to their highly efficient drivetrain, electric, hybrid and diesel-powered vehicles contribute less to *global warming* than CNG, LPG and petrol-driven vehicles. Regarding *health* damage, the diesel vehicles have a very bad effect (owing to high NO_x and PM emissions), and CNG vehicles score best. Electric, hybrid and LPG vehicles also have a very good *health* score. In the case of *acidification*, NO_x emissions bring the diesel vehicle into a very bad position, and their PM emissions contribute greatly to the damage to *buildings*. In the future, NO_x and PM filters may make it possible

Table 10 List of vehicles evaluated [**14**]

Manufacture	Model	Fuel	Description	Trans	Engine capacity	Euro
Peugeot	106	Elec renew	Electricity—renewable	A		
Peugeot	106	Elec CCGT95	Electricity—CCGT—1995	A		
Peugeot	106	Elec Belg01	Electricity—Electrabel—2001	A		
Honda	Insight (2001 YM)	Hybrid petrol	Insight	M5	995	III
Fiat	Brava	CNG				IV
Micro compact car	Smart City Coupe Hatchback	Petrol	Smart and passion	A6	599	III
Vauxhall	Vectra, Model Year 2002	LPG	1.8 16v	M5	1796	IV
Volvo	S60 Model Year 2002	CNG	2.4 Bifuel (CNG)	M5	2435	IV
Volvo	S80 Model Year 2002	CNG	2.4 Bifuel (CNG)	A4	2435	IV
Opel	Astra	LPG	1.6 16v	M5	1598	IV
Toyota	Prius	Hybrid petrol	1.5 Hybrid	A		IV
Volkswagen	Polo (from February 2002)	Petrol	1.2 (55 bhp)	M5	1198	IV
Volkswagen	Golf Hatchback (3 Door)	Petrol	1.4 (75 bhp)	M5	1390	IV
Volvo	S60 Model Year 2002	LPG	2.4 Bifuel (LPG)	A5	2435	IV
Volvo	V70 Model Year 2002	LPG	2.4 Bifuel (LPG)	A5	2435	IV
Toyota	Avensis	Petrol	1.6 vvti liftback	M5	1794	IV
Volvo	S60	Petrol	2.4 Bifuel	M5	2435	IV
Peugeot	607	Diesel	2.0 HDi FAP (110 bhp)	M5	1997	III
Volkswagen	Golf Estate	Diesel	1.9 TDI PD (100 bhp)	M5	1896	III
Volvo	S60	Diesel	D5 (163 bhp)	M5	2401	III
Ferrari	All models	Petrol	456M GTA 2+2	A4	5474	III
Chevrolet	Blazer	Petrol	4.3L V6	A4	4300	III
Metrocab	TAXI TTT	Diesel	2.4 Turbo	A4	2446	III
Volkswagen	Window Van	Diesel	2.5 TDI (102 bhp) (high roof)	A4	2461	III

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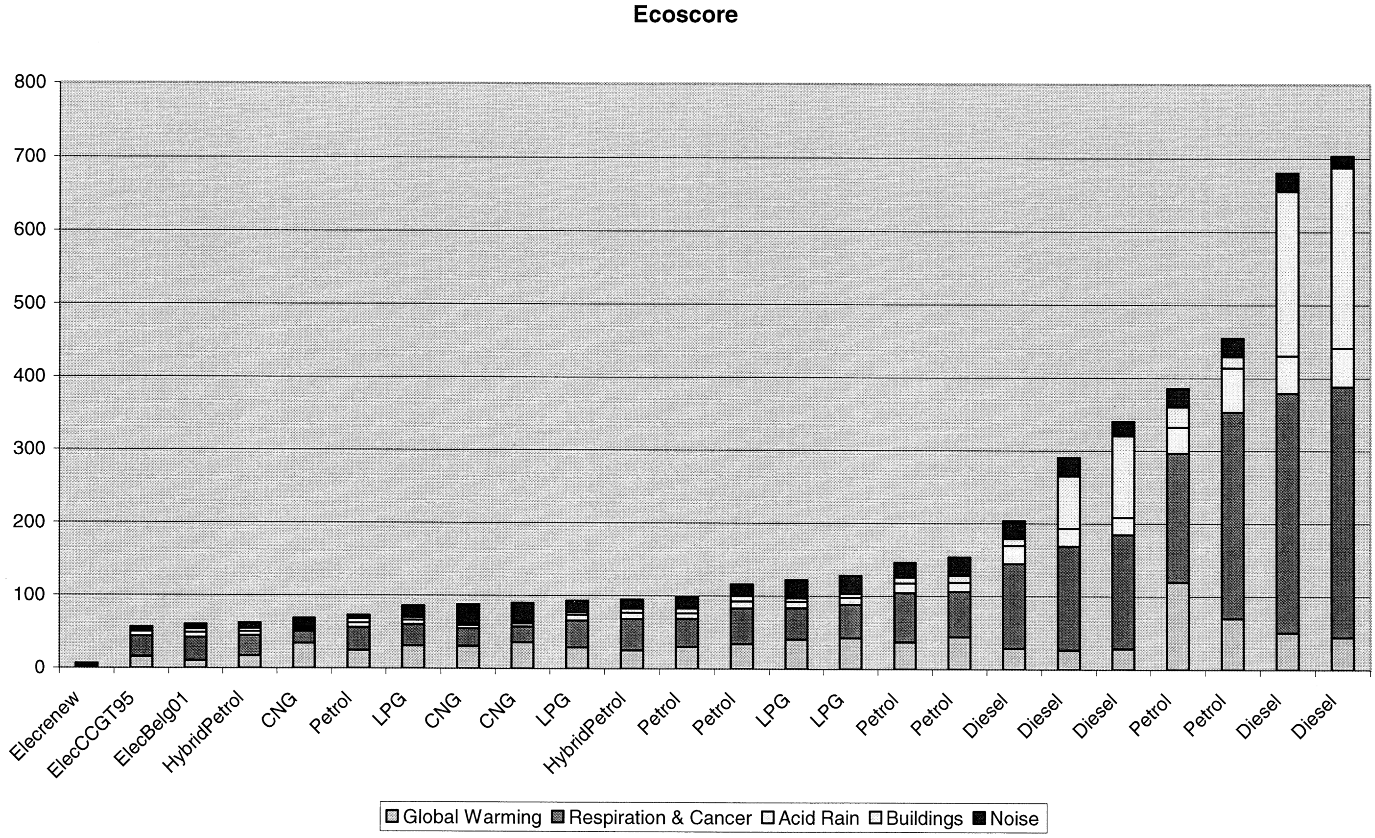

Fig. 3 Some examples of the Ecoscore (Belgium—Brussels situation)

to reduce these emissions in the case of diesel vehicles. *Noise* pollution is very low in the case of electric and hybrid vehicles.

5 CONCLUSIONS

A new methodology has been established that enables the environmental effect of different vehicles using different fuels and drivetrains to be compared. The methodology is specifically oriented towards urban areas.

The methodology is based on a comprehensive approach that classifies different types of environmental damage. This damage is calculated on a scientific basis (exposure–response damage functions, etc.) and is normalized with the help of the definition of a reference target vehicle (distance to target) and weighted (panel method) by defining the contribution of the different damage to the final score (Ecoscore).

An inventory of all the required emissions has been drawn up. It describes how to calculate environmental damage. However, a large amount of accurate and reliable emissions data is required to be able to use this methodology. These values are not always available, especially in the case of a number of alternatively fuelled vehicles. To establish accurate and comparable results, the methodology has been limited to the calculation of damage for which sufficient data are available.

A definition of a 'clean vehicle' is proposed on the basis of this methodology, and the Ecoscore has been calculated for some examples. Electric vehicles cause the lowest environmental damage. The hybrid, LPG and CNG vehicles examined could be considered 'clean'.

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