Environmental rating of vehicles with different fuels and drive trains: a univocal and applicable methodology

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A new and applicable environmental rating tool for use as a policy tool, called EcoScore, was developed and allows evaluating the environmental impact of road vehicles with different drive trains or using different fuels. A single environmental indicator integrates different aspects of the environmental impact of the vehicles such as global warming, air quality depletion and noise pollution. To integrate these different aspects, the Ecoscore methodology includes different damage categories like: global warming, human health impairing effects and harmful effects on ecosystems. The contribution of the different normalised damages to the single value, called Ecoscore, is based upon a weighting system. The methodology can also be used for the ranking of heavy duty vehicles and two-wheelers. However, in this paper, the methodology will be explained using passenger vehicles and light-duty vehicles as an illustration. The methodology will be implemented by the Flemish government as a policy tool for the promotion of cleaner vehicles. An extensive database including vehicle records and their related emission data was used to develop, to validate and to analyse the environmental rating system. A sensitivity analysis was carried out which allowed the evaluation of the robustness of the methodology.

Keywords: environmental assessment, well-to-wheel, atmospheric pollution

1. Introduction

Nowadays environmental pollution is an issue that causes great concern, not only on a local, but also on an international and even on a global level. Tackling the air pollution problems forms a unique challenge. Based on global observations of important tropospheric pollutants, as described by (Beirle et al., 2004) the regions Flanders, Brussels and the south of The Netherlands appear to be one of the most polluted regions of the world, after Northern Italy and the north-eastern part of China. Persons and goods transportation cause an important part of the emissions of atmospheric pollutants (MIRA, 2005). It is essential to understand the correlation between transport and environment to be able to tackle transportation's negative impacts (European Commission, 2001). To reduce harmful emissions due to the transport sector, efficient policy measures have to be implemented by the relevant authorities, especially in strongly urbanized regions. The introduction of 'clean vehicles' is one of the most promising potential measures policy makers have at their disposal for energy use reduction and for cutting pollutant emissions (Van Mierlo et al., 2006). In this context the question: "*Which vehicles are environmentally friendly?*" remains a key issue (Van Mierlo & Macharis, 2005). A comprehensive and transparent methodology has been developed with the aim to compare the environmental burden caused by vehicles with different drive trains and using different fuels. This paper describes the methodology of a new and pragmatic environmental rating tool. This tool is called *Ecoscore* and was developed for use by the Flemish government. *Ecoscore* is going to be integrated in a consistent policy for the promotion of cleaner vehicles. Implementation pathways for a comprehensive and goal reaching policy should be based not only on the analysis of the environmental impact but also on the barriers for purchase and the use of road vehicles (technical, economical, market related, legislative and regulatory, psychological and institutional barriers). Fiscal measures should be based on the "polluter-pays" principle (De Borger and Proost, 1997). The Ecoscore methodology can be used as a basis for policy tools. It is based on two other environmental rating systems: "Clean Vehicles" and "Cleaner Drive" described in previous publications (Van Mierlo et al., 2003a; Van Mierlo et al., 2003b; Pohl, 2003). The new methodology includes knowledge of the state of the art impact factors and emission data. An important boundary condition of the methodology was that the rating method needed to be applicable to all Belgian road vehicles (passenger cars, vans, trucks and buses as well as motorised two-wheelers). Consequently three similar environmental ratings were defined, corresponding to three vehicle categories defined by the Council Directive (Directive 92/53/EEC): light duty vehicles (passenger cars and vans, M1 and N1), heavy duty vehicles (medium and heavy trucks and busses, N2, N3, M2 and M3) and two-wheelers (L1-L6). A well-to-wheel framework is used to compare damage to human health and to the environment. Three major impact categories (global warming, air quality and noise pollution) are combined through a weighting system to form the *Ecoscore* indicator. This allows an environmental assessment of road vehicles. The common methodology for all three vehicle categories will be discussed thoroughly in the following paragraphs of this paper. To illustrate the applicability and robustness of the rating tool, a sensitivity analysis was performed and the results of the analysis of a representative set of passenger vehicles are presented.

2. Framework

To be able to compare the contribution of different vehicles to air pollution, a rating methodology has been developed. This methodology is based on a well-to-wheel framework. This means that, next to the direct tailpipe (or Tank-to-Wheel) emissions, the indirect (or

Well-to-Tank) emissions, due to the production and distribution of the applied fuel, are taken into account as well. Moreover, an impact calculation allows to assess the health impact related to the inventoried emissions, incorporating their impact pathway. This evaluation method is more valuable for decision-making and policy, compared to evaluations based on emission levels only (Van Wee, 2005). This approach allows comparing vehicles with different fuel technologies (petrol, diesel, liquefied petroleum gas, compressed natural gas, bio-fuels, etc.) or different drive train technologies (internal combustion engines, hybrid electric drive trains, battery electric drive trains, fuel cell electric drive trains, etc). Emissions resulting from the vehicle assembly and from the production of its constituting components are not taken into account. Nor are the maintenance phase and recycling phase of end-of-life vehicles. The main reason for the limitation of the methodology to a well-to-wheel framework is data availability for all road vehicles (light duty, heavy duty and two-wheelers). The available literature states that the use phase (tank-to-wheel) is dominant for most considered pollutants and states that only small differences are expected when comparing different drive trains. The use of large secondary batteries in the case of hybrid and electric vehicles has a limited environmental impact due to the high recycling rate of this type of batteries (Van den Bossche et al., 2005).

The environmental assessment of the vehicle is performed through a sequence of five steps: inventory, classification, characterisation, normalisation and weighting. This structure is corresponding to the standardised LCA (Life Cycle Assessment) methodology. Each of these five steps will be discussed in detail in the following paragraphs.

3. Environmental assessment

3.1 Emissions inventory

As mentioned above, a well-to-wheel framework was chosen, comprising tailpipe emissions and emissions proportional to the fuel consumption of the vehicle. A large number of factors influence the vehicle's tailpipe emissions and fuel consumption. The most important factors are the vehicle's drive train technology and the vehicle's options, the traffic situation and the driving behaviour (Van Mierlo et al., 2004). Furthermore, aging effects of the motor can result in an increase of the emission levels of vehicles over time. Inclusion of 'in use compliance' to homologation directives (cfr. 98/69/EC) could ensure that emission limits are respected for longer operation times of the vehicle. These variations make it very difficult to compare vehicles with each other. Type approval emission values can present some differences as compared to real vehicle emissions, but provide a common evaluation basis for all vehicles to be assessed. Because this methodology will be used as a policy tool, it is important to use emission data that are available for all individual road vehicles. Since 2002 homologation data from passenger cars were collected by the Belgian federal ministry for mobility and transportation. Since 1998, the Belgian federation of the automotive industry, Febiac, also owns a vehicle database (Technicar) including vehicle fuel consumption measurements. Both of these information sources were used for the development of the methodology.

3.1.1 Fuel characteristics

The fuel used by the vehicle is an important parameter for the environmental assessment. Each fuel type is characterised by its energy content and energy density. The carbon content of a fuel is related to the amount of direct CO_2 emissions of the vehicle, while the sulphur content of the fuel determines the quantity of direct SO_2 emissions. The fuel characteristics of several fuels are shown in table 1.

Table 1. Fuel characteristics used in the Ecoscore methodology

	Energy content [kJ / kg]	**density** [g / L]	**CO_2 emission factor** [kg CO_2 / L]	**Sulphur content** [ppm]	**SO_2 emission factor** [g SO_2 / L]
Petrol	42715	755	2.212	50	7.55 E-4
Diesel	43274	850	2.697	50	8.50 E-4
CNG (G20)	49578	717	2.712	0	0
LPG	45114	550	1.549	15	1.65 E-4
Bio-diesel (RME)	37700	880	2.470	100	1.76 E-3

The energy content and density of the fuel are also used to calculate the indirect emissions linked to the fuel consumption of the vehicle. This will be described in more detail below. In case of light duty vehicles and two-wheelers, the consumption of the vehicle is given per 100 kilometres, whereas for heavy duty this characteristic is given per delivered kilowatt-hour.

3.1.2 Direct emissions

Direct emissions are linked to the use of the vehicle itself. Each vehicle sold on the European market has to be compliant with the type approval test. These tests give information about the so called *regulated emissions*: carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_X) and, in the specific case of diesel vehicles, particulate matter (PM).
In the case of passenger vehicles and light-duty vehicles (M1 and N1) these emissions are expressed in grams per kilometre. For heavy-duty vehicles (M2, M3, N2 an N3) emission levels are expressed in grams per delivered kilowatt-hour. The latter emissions are evaluated on the level of the motor of the vehicle. The emissions and consumption of the vehicle will thus further be dependent on the application (the same motor can be used in different types of vehicles).
Besides the regulated emissions, some unregulated emissions are considered as well: carbon dioxide (CO_2), sulphur dioxide (SO_2), nitrous oxide (N_2O) and methane (CH_4). Both carbon dioxide and sulphur dioxide can be calculated starting from the fuel consumption and using the corresponding emission factors from table 1. The direct emissions of N_2O are mainly dependent of the applied technology. Within the Cleaner Drive project (Pohl, 2003) estimations of N_2O emissions were performed for vehicles complying with the different "euro emission standards". For the older vehicles (pre-euro), no emission data are available, so estimations of the emissions and of the consumption were made based on the COPERT III methodology (Ntziachristos et al., 1999). The vehicle classification as proposed in COPERT III, was used to categorise these older vehicles within the Ecoscore methodology. Direct

methane (CH_4) emissions are technology dependent and emission values resulting from the well-to-wheel study of General Motors (Choudhury et al., 2002) were used.

3.1.3 Indirect emissions

The indirect emissions are those related to the extraction and transportation of the raw materials for the fuel production, together with the emissions linked to refining and distributing the carburant. When considering the use of electric or plug-in hybrid vehicles, emissions related to electricity generation and distribution are taken into account. Indirect emissions are directly proportional to the fuel consumption of the assessed vehicle. The formula used for the indirect emission calculation of the Ecoscore methodology in case of light duty vehicles or two-wheelers can be found:

$$E_{i,j,indirect} = \frac{1}{3{,}6.10^{11}} F_j . \rho . EC . FC \left[g/km \right] \qquad (1)$$

Where:

- F_j Indirect emission factor for pollutant j, expressed in milligram per kilowatt hour (see table 2)
- ρ Fuel density expressed in gram per litre
- EC Energy content of the fuel, expressed in kilojoules per kilogram
- FC Fuel consumption of the vehicle, Expressed in litre per 100 kilometres (in case of light duty vehicles or two-wheelers)

The factor $1/3{,}6.10^{11}$ in this formula is a conversion factor.

In the case of heavy duty vehicles, the consumption data are given in gram per kilowatt-hour and so the factor ρ in equation 1 becomes redundant. The indirect emission factors (F_j) used in equation 1 can be found in table 2. The classic fuels (petrol, diesel and LPG) are characterised using emission factors from the European MEET study (Joumard, 1999). The fuel consumption of natural gas vehicles is given in cubic meter per 100 kilometres. Because of important variations in the energy content of natural gas (poor and rich), the natural gas composition in Belgium was compared with different available gas data. The most comparable natural gas was G20, so this type was selected. Indirect emissions data related to Bio-diesel fuel are based on the well-to-wheel study of General Motors (Choudhury et al., 2002), as far as CO_2 emissions are concerned, and on the MEET study for the other emissions.

Table 2. Indirect emission factors

Fuel type	**CO** [mg/kWh]	**NMHC** [mg/kWh]	**NO_X** [mg/kWh]	**PM** [mg/kWh]	**CO_2** [mg/kWh]	**SO_2** [mg/kWh]	**N_2O** [mg/kWh]	**CH_4** [mg/kWh]
Petrol	18.4	761.4	151.9	8.6	33100	236.2	0	62.6
Diesel	16.6	315.4	129.6	3.6	24500	174.2	0	56.5
CNG (G20)	5.0	99.0	38.2	2.9	14759	60.8	0	805.3
LPG	14.8	202.7	116.3	5.4	21600	114.1	0	58.0
Bio-diesel (RME)	493.1	280.4	871.9	66.6	-172786	245.5	0	0
Elec. Renew	0	0	0	0	0	0	0	0
Elec. Belg. 03	30	*44**	392	42	277683	388	1.558	3.56

Source: based on MEET 1995, VITO 2005 and Electrabel 2003

3.2 Classification of the damage categories

The Ecoscore methodology encompasses three main damage categories: global warming, air quality and noise. The damage category *air quality* is subdivided into: human health effects and effects on ecosystems. Each of the considered categories is described below.

3.2.1 Global Warming

Global warming contributes to the rise of the sea level, to an increased occurrence of extreme weather conditions. It leads to shifts and extinctions of biotopes and to drinking water shortage. Possible effects on human health are among others: increased occurrence of respiratory effects and cardiovascular diseases due to heat waves and increased number of infections and diseases due to floods (Martens, 1998). On 16^{th} of February 2005, the Kyoto-protocol has officially come into application. It has the ambition to reduce the global emissions of green house gasses with at least 5 percent within the time slot 2008-2012, compared to the level of 1990. This included a reduction of 8 percent for the European Union and of 5,2 percent for the Flemish region (Pershing, 2000). CO_2 is the largest contributor to global warming and is mainly originating from the combustion of fossil fuels used for human activities. Nitrous oxide and methane, both emissions exhausted by road vehicles, are also contributing to climate change. Flemish industry and agriculture have succeeded in decreasing their emissions, but this reduction was largely compensated by the continuous increase of the CO_2 exhaust in the transport sector, mainly in road transportation (European Commission, 2001).

3.2.2 Air Quality

Carbon monoxide causes oxygen shortage and can lead to suffocation. The concentration of CO in the atmosphere can vary strongly and depends mainly on the traffic situation and on the wind. Carbon monoxide concentrations in the blood of people living in the city can be twice as high as concentrations in the blood of people living in the countryside. The concentration of CO can reach very high levels in closed spaces like underground parking lots, or inside vehicles (Carlisle and Sharp, 2001).

Nitrogen oxides (NOx) are forming a group of important pollutants mainly produced by road transportation. Nitrogen oxides are forming acids, when absorbed in the mucous membranes of the nose or the oral cavity, and cause irritation of the bronchial tubes, coughing, and in higher concentrations also lack of breath and even death (Pilkington et al, 1997). People suffering from asthma can be very sensitive for NOx. Nitrogen oxides also lead to eutrophication of soil, ground- and surface water and as a result leads to negative impacts on aquatic and terrestrial ecosystems, surface water and agricultural and forestry yields (Goedkoop and Spriensma, 2001).

Particulate matter (PM10) can remain in suspension in the air for hours or even days. As these particles are very small, they can penetrate very deep into the lungs. Because PM10 is often bound to other harmful substances, exposure and inhalation can lead to an important number of health problems and even to death (Pilkington et al, 1997).

Sulphur oxides (SOx) are very soluble in water and consequently can easily be absorbed through the mucous membrane of our bronchial tubes. People suffering from asthma are especially sensitive to sulphur oxides. Furthermore, sulphur dioxide causes acidification,

which in turn damages aquatic and terrestrial ecosystems, surface water, agricultural and forestry yields and buildings (Goedkoop and Spriensma, 2001).
Volatile organic compounds (VOC) is the name regrouping a large number of chemical compounds, like toluene, xylene, benzene, etc. Some of them present some important health damaging effects such as carcinogenicity.
Some of the previously described emissions also have indirect effects as they lead to other chemical reactions, once emitted into our atmosphere. The formation of tropospheric ozone for instance is triggered by sunlight and is an important secondary pollution of nitrogen oxides and hydrocarbons emissions (photochemical pollution). Ozone is toxic for living organisms and human beings and causes damage to the cells of the bronchial tubes.

3.2.3 Noise

Noise is one of the main annoyances related to traffic, especially for people living in city centres or close to busy traffic roads. During the last decades, an important deterioration of the ambient sound level was observed. This was accompanied by increased damages on human health due to sleep disturbance and deteriorated audibility during the daytime. The exact influence of noise on human health is hard to quantify, but long-lasting exposure to high sound levels can lead to direct effects like: quickened heartbeat rate, increased blood pressure, cardiovascular diseases, colitis, stomach ulcers, headache and dilatation of the pupils. Indirect health effects are triggered because noise leads to nervous tension and stress.

3.3 Characterisation of the damage effect

Depending on the considered damage category, different impact factors were used for the characterisation of the damage due to both the indirect and direct emissions. The damage caused to human health is related to the location of the emissions, thus requiring different impact factors for indirect and direct emissions.
The calculation of the partial damage of each pollutant can be represented by the following equation:

$$D_{i,j} = \delta_{i,j,indirect}.E_{j,indirect} + \delta_{i,j,direct}.E_{j,direct} \quad (2)$$

Where:
$D_{i,j}$ partial damage of pollutant j to the category i
$\delta_{i,j}$ impact factor of pollutant j to the category i
E_j total contributing emissions of pollutant j to the category i

The total damage of each damage category can be obtained summing up the partial damages for the different damage categories:

$$Q_i = \sum_j D_{i,j} \quad (3)$$

Where:
Q_i total damage of the category i
$D_{i,j}$ partial damage of pollutant j to the category i

The contributions of the different green house gasses to global warming are calculated using global warming potentials (GWP), as defined by the IPCC. External Costs were used to allocate a weighting for the contributions of the different inventoried air quality depleting emissions to effects on human health and to effects on ecosystems.
For the human health damage category, external costs are used. They are based on the EU ExternE project (ExternE, 1997) with updated values (baseline 2000), as described in (Friedrich and Bickel, 2001; Lindberg, 2003). These external costs are values expressed in monetary terms per kilogram of emission of a certain pollutant, and reflect the overall damage cost to human health. The external costs used for the damage calculation are obtained by a contingent valuation method and are available for both urban and extra urban (or rural) situations. A weighted average of urban and rural external costs is used for the Ecoscore methodology, using the national split between urban and rural mileage as a weight factor for each category of vehicles (light duty, heavy duty and two-wheelers). This average mileage distribution was obtained from the Belgian National Institute of Statistics (NIS) and is given in table 3.

Table 3. Overview of mileage distribution for different vehicle categories

Mileage distribution (σ)	urban	rural
Light duty	25%	75%
Heavy duty	10%	90%
Two-wheelers	40%	60%

The impact factors δ, as used in equation 2, can now be calculated as the weighted average of urban and rural specific external costs (SEC) following equation 4.

$\delta_{i,j,indirect} = SEC_{i,j,rural}$ and

$$\delta_{i,j,direct} = \sigma_{urban}.SEC_{i,j,urban} + \sigma_{rural}.SEC_{i,j,rural} \qquad (4)$$

Where:

$\delta_{i,j}$ impact factor of pollutant j to the category i
$\sigma_{urban/rural}$ urban/rural mileage distribution percentage
$SEC_{i,j,urban/rural}$ urban/rural specific external cost of pollutant j to the category i

For the damage calculation of impacts on ecosystems due to acidification and eutrophication, external costs are used. Abatement costs of emission reductions for NO_X and SO_2, as presented by Vermoote and De Nocker (2003), are used.

The damage calculation for noise is somewhat different compared to calculation for damage due to emissions of pollutants. The logarithmic decibels scale is used to describe emitted sounds. The A-weighting is used, because it takes the sensitivity of human hearing into account. In this methodology, the inventoried noise level is decreased with a base value of 40 dB(A), corresponding to a non-disturbing background sound level, to obtain values proportional to the inconveniences. The calculation of noise related damage is given through equation 5.

$$Q_{noise} = D_{noise} = E_{noise} - 40[dB(A)] \qquad (5)$$

3.4 Normalisation: reference vehicle

To quantify the relative severity of the evaluated damages of each damage category, a normalisation step based on a specific reference value is performed. The damage associated to a theoretical vehicle was taken as the reference point.

$$q_i = \frac{Q_i}{Q_{i,ref}} \quad (6)$$

Where:
q_i normalised damage on category i
Q_i total damage of the assessed vehicle on category i
$Q_{i,ref}$ total damage of the reference vehicle on category i

This reference vehicle can be considered to be a vehicle with target emission values. Therefore it was chosen to take the Euro IV emission limits for passenger cars, introduced by directive 98/69/EC as a reference for the light vehicles range. As far as CO_2 emissions are concerned, the reference level of 120 grams per kilometre was considered. It corresponds to the target value of the European Union to reach its overall CO_2 emissions reduction goal by the year 2012. The noise emission reference has been set to 70dB(A).
When using the Ecoscore methodology for the assessment of heavy duty vehicles (M2,M3,N2 and N3) a different reference vehicle is chosen. The Euro III EEV (Enhanced Environmental Vehicle) emission limits, introduced by directive 96/96/EC are used, together with a fuel consumption of 200g/kWh and a noise emission of 76dB(A). The emission data are, in contrast to light duty vehicles, expressed in gram per kilowatt-hour. To assess two-wheelers, another different reference vehicle has been selected, with emissions corresponding to the emission limits for 2006 from directive 2002/51/EC, a fuel consumption of 3 litres per 100 kilometre and a noise emission of 76dB(A).

3.5 Weighting system

The final step of the methodology consists in the weighting of the different damage categories, before aggregating them to obtain the total impact (TI) of the vehicle to be assessed.

$$TI = \sum_i \alpha_i . q_i \text{ with } \sum_i \alpha_i = 1 \quad (7)$$

Where:
TI total impact of the assessed vehicle
α_i weighting factor of damage category i
q_i normalised damage of category i

The reference vehicle itself presents a total impact of 100. A vehicle, with higher or lower emission levels when compared to the reference vehicle, will have a total environmental impact higher, respectively lower than 100.
The weighting factors α_i, used in the Ecoscore methodology, are based on a weighting method allowing to reflect policy priorities and decision maker's opinions. The weighting factors were determined by a stakeholder group including representatives from governmental

administrations, political parties, the automotive sector, environmental NGO's, consumer organisations and others and can be found in table 4.
For communication purposes towards a broad public, it is important to use a score that is easy to understand. That's why the total impact (TI) is transformed into a score ranging from 0 to 100, 0 representing an infinitely polluting vehicle and 100 indicating an emission free and silent (40dB(A)) vehicle. The reference vehicle corresponds to an Ecoscore of 70. The transformation is based on an exponential function (see figure 1), so it can not deliver negative scores.

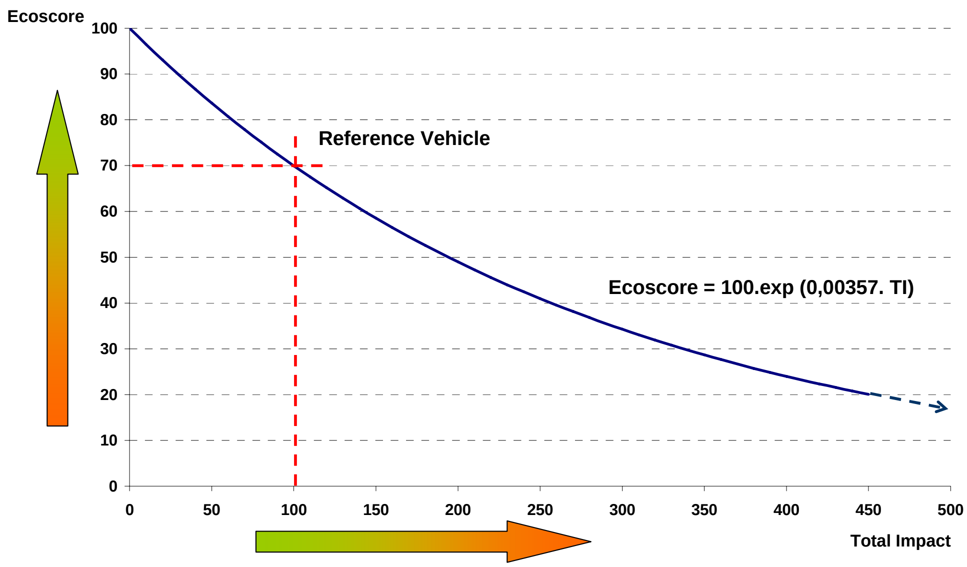


Figure 1. Transformation Total Impact to Ecoscore

3.6 Overview of the methodology

In figure 1 the Ecoscore methodology is shown schematically. The successive steps of the methodology, as described above, can be identified.

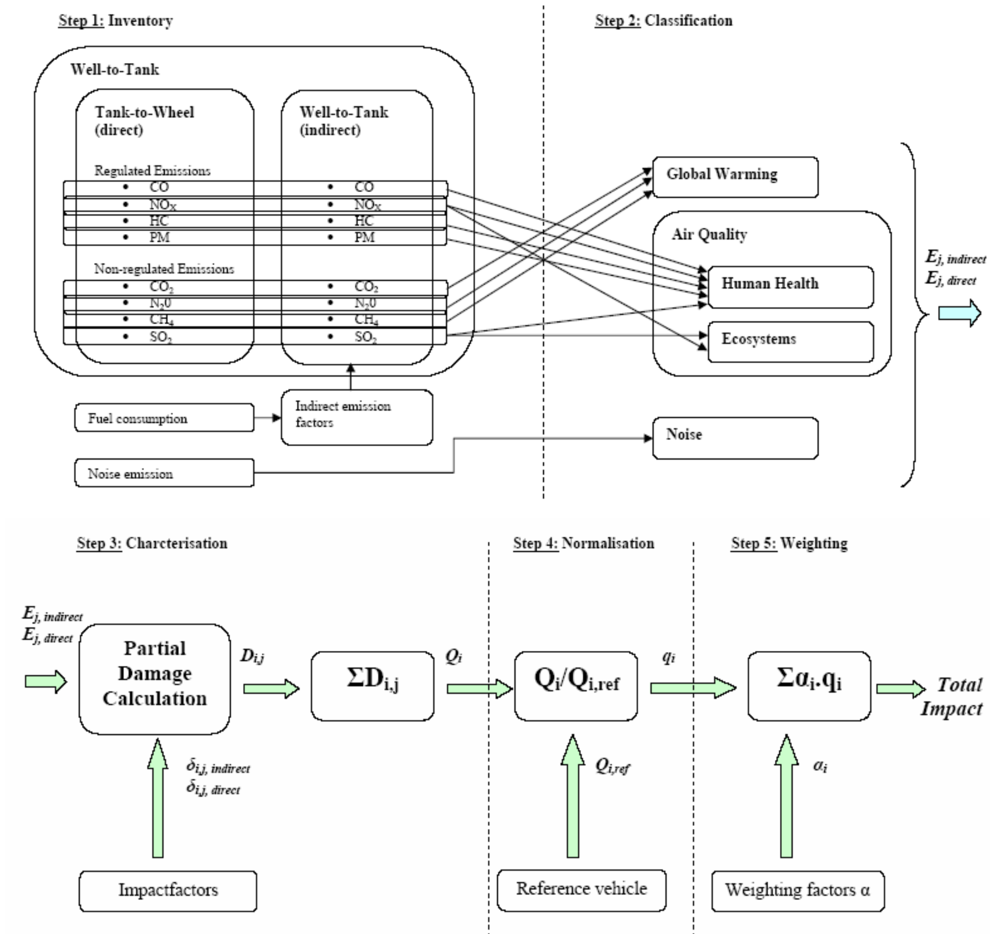


Figure 2. Ecoscore Methodology Overview

Table 4 shows an overview of the parameters used for the Ecoscore methodology. The different damage categories are given, with their contribution to the end score (weighting), their different contributing pollutants (inventory) and their damage factors (characterisation).

Table 4. Summary of the parameters used for the Ecoscore methodology

Classification	Weighting	Inventory	units	Characterisation	
	α			***rural***	***urban***
1) Global Warming	50%	CO_2	GWP	1	1
		CH_4	GWP	23	23
		N_2O	GWP	296	296
2) Air Quality	(40%)				
2a)Human Health	20%	KWS	€/kg	3	3
		CO	€/kg	0.0008	0.0032
		PM10	€/kg	103.49	418.61
		NO_X	€/kg	1.152	1.483
		SO_2	€/kg	6.267	14.788
2b) Ecosystems	20%	NO_X	€/kg	0.176	0.176
		SO_2	€/kg	0.113	0.113
3) Noise	10%	Sound level	dB(A)	x-40	

4. Results

To demonstrate the applicability of the methodology, a set of 22 passenger vehicles has been selected. Vehicles using different types of fuel and complying with different emission standards, were chosen. The selected cars have engine capacities representative for the national car fleet. This selection allows to analyse the evolution of the environmental impact of vehicles complying with different emission regulations and to analyse the differences between vehicles using different fuel types and drive train technologies. Characteristics of the selection of vehicles are detailed in table 5.

Table 5. Vehicle selection details

Emission standard	**Fuel use**	**Brand - Type**	**Engine capacity [cc]**	**Consumption [per 100km]**
PRE ECE	Petrol	No specific vehicle – based on COPERT III	1400 - 2000	14.2L
ECE 15/00-01	Petrol	No specific vehicle – based on COPERT III	1400 - 2000	10.1L
ECE 15/02	Petrol	No specific vehicle – based on COPERT III	1400 - 2000	9.2L
ECE 15/03	Petrol	No specific vehicle – based on COPERT III	1400 - 2000	9.2L
ECE 15/04	Petrol	No specific vehicle – based on COPERT III	1400 - 2000	8.7L
PRE EURO	Diesel	No specific vehicle – based on COPERT III	> 2000	7.5L
PRE EURO	LPG	No specific vehicle – based on COPERT III	> 2000	9.1L
Euro I	Petrol	No specific vehicle – based on COPERT III	1400 - 2000	9.7L
Euro I	Diesel	No specific vehicle – based on COPERT III	> 2000	6.7L
Euro I	LPG	No specific vehicle – based on COPERT III	> 2000	9.3L
Euro II	Petrol	No specific vehicle – based on COPERT III	1400 - 2000	9.7L
Euro II	Diesel	No specific vehicle – based on COPERT III	> 2000	6.7L
Euro II	LPG	No specific vehicle – based on COPERT III	> 2000	9.3L
Euro III	Petrol	VOLKSWAGEN GOLF	1595	6.9L
Euro III	Diesel	OPEL ASTRA	1686	4.7L
Euro III	LPG	TOYOTA AVENSIS	1598	9.6L
Euro IV	Petrol	VOLKSWAGEN GOLF	1595	7.0L
Euro IV	Diesel	OPEL ASTRA	1686	4.6L
Euro IV	LPG	OPEL VECTRA	1598	9.8L
Euro IV	CNG	OPEL ASTRA Caravan	1600	6.42m^3
Euro IV (Hybrid)	Petrol	TOYOTA PRIUS	1497	4.3L
(Battery-electric)	Electricity	PEUGEOT 106 Electric	-	17 kWhe

Figure 3 illustrates the total impact, split up per damage category, of this selection of passenger vehicles. This figure allows the comparison of the different damage categories for each vehicle. When considering global warming, diesel vehicles present a lower impact compared to their petrol counterparts. Thanks to their efficient drive train, of all conventional vehicles, diesel vehicles contribute the less to global warming. The use of electric vehicles however, is characterised by the lowest impact on global warming. Hybrid electric drive trains make it possible to lower the fuel consumption of thermal engines and thus to reduce their impact on global warming (Edwards et al., 2004). Furthermore, fuel efficiency has improved with time. Due to the high impact of particulate matter on human health, diesel vehicles perform significantly worse than all other vehicles regarding this damage category. However, this difference in impact is decreasing thanks to the latest emission regulations (EURO IV) and could be improved further in the future, with more stringent emission limits, imposing the use of particle filters. The lower impact of LPG and especially CNG vehicles, compared to a petrol vehicle, is mainly due to lower indirect emissions combined with lower air quality depleting emissions. Also, a positive evolution can be observed regarding the impact on ecosystems. This is due to the reduction of the NO_X emissions thanks to the use of advanced injection techniques. The NO_X exhaust level could be improved further by implementing $DeNO_X$ catalysts, selective catalytic reduction (SCR) systems or NO_X absorbers (Lenaers et al., 2003). Also the lower sulphur content of the fuels (50ppm) has had a beneficial influence on SO_2 emissions during the last decade. Further reduction to 10 ppm of the sulphur content of diesel and petrol fuels is foreseen and would be available starting from January 2007. As far as noise pollution is concerned, the consecutive noise directives have positively influenced the related damages with time. Hybrid and electric vehicle technologies show an even lower level of noise pollution than the most recent conventional technologies.

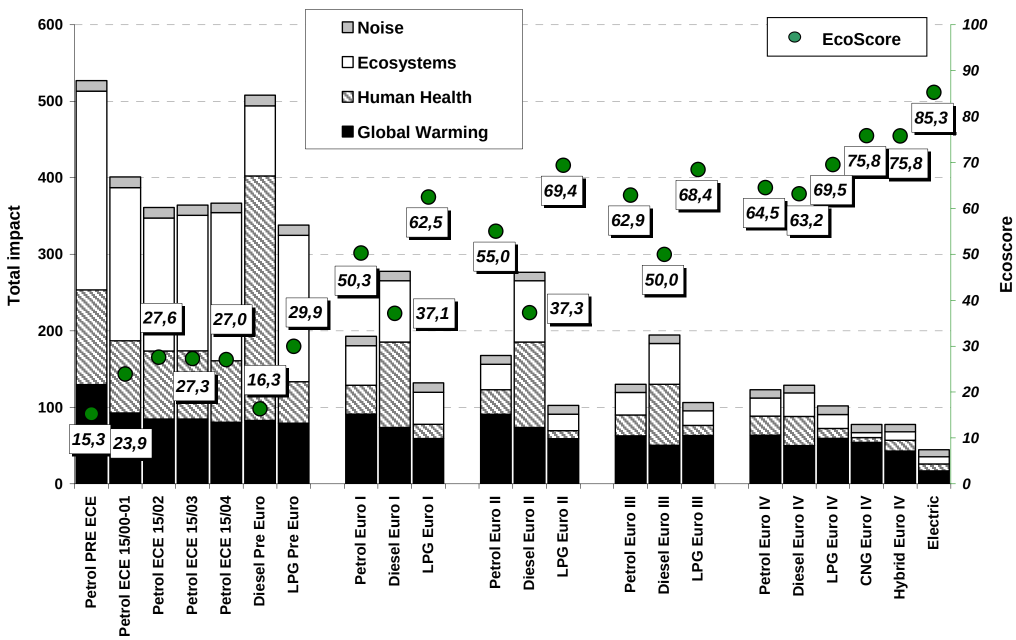


Figure 3. Total impact for the vehicle selection – category split up

To analyse the potential environmental improvements of vehicles with alternative fuels or drive trains more thoroughly, the last six cars of the selection of table 5 were analysed in more detail. Direct and indirect impacts were analysed separately and are shown in figure 4. Also the rating (Ecoscore) is indicated on the graphic for each vehicle. Because the environmental impact of an electric vehicle is strongly dependent on the electricity production, three different scenarios were worked out: the Belgian electricity production mix, anno 2003 (ElecBelg03), electricity generation with combined cycle gas turbines (ElecCCGT95), and electricity generated with renewable energy sources, yielding no emissions (ElecRenew).

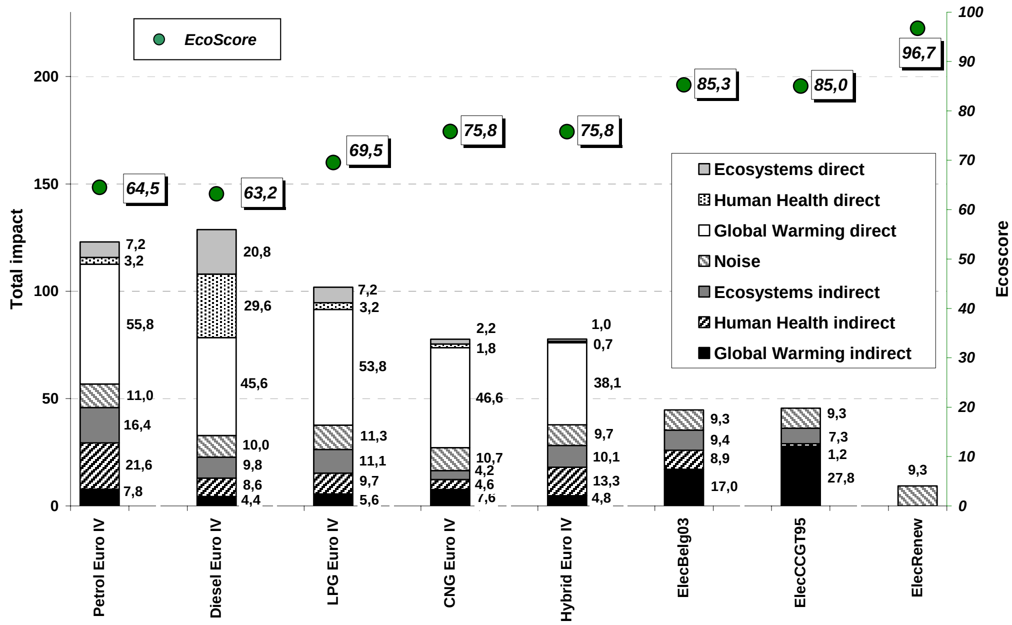


Figure 4. Total impact of different vehicle technologies and electricity production

When comparing the results for an electric vehicle charged with electricity originating from a CCGT plant, with an electric vehicle charged using the Belgian electricity production mix, we can observe an important difference in the exhaust of green house gasses. It's important to notice that the Belgian production park contains nuclear power plants delivering around 45% of the total electricity production. The potential substitution of nuclear power and coal power plants with new and highly efficient CCGT plants will alter the composition of indirect emissions related to electricity consumption. When charged with electricity originating only from CCGT plants, the impact of electric cars on human health and ecosystems is lower and nearly totally compensating the large contribution to global warming. Battery electric cars allow the use of renewable electric energy (wind turbines, photovoltaic cells, etc.), reducing the total impact of road transportation on the environment and on human health even further.

The direct impacts of LPG vehicles are comparable to those of petrol vehicles, but a substantial advantage can be noticed for the indirect emissions related to the LPG fuel production and transportation.

Compressed Natural Gas vehicles show a larger total environmental benefit than LPG vehicles. The benefit is comparable to that of the hybrid electric vehicle. When taking a closer look though, some important differences appear between both technologies. CNG vehicles have a lower indirect impact and the damage to human health and ecosystems is significantly lower than for the hybrid car. On the other hand, the contribution of CNG vehicles to global warming is slightly higher compared to that of the hybrid car. Previous observations demonstrate that the question "which vehicles are environmentally friendly?" is difficult to answer and therefore requires a univocal methodology allowing to evaluate the environmental performance of road vehicles using a pragmatic approach.

Another interesting analysis is, when talking about environmental impact of passenger vehicles, the long term potential of emission abatement technologies. An important aspect is also the difference between type approval emissions and real-world emissions (Van Mierlo et al., 2004). Based on the results of an assessment of the emission reduction potential for passenger cars, as described by Smokers et al. (2004), the Ecoscore of Euro 3 petrol- and diesel-engined cars (real world emissions in cold start tests with ambient temperatures of 9°C) and for the respective estimated attainable long term (LT) situation, was calculated. The figure below shows the results of the Ecoscore of these situations, together with the Euro 3 and Euro 4 limits and actual emissions measured during the Euro 3 type approval test. For the consumption data, two different situations were considered: vehicles with a mass of 1100 and 1300kg respectively.

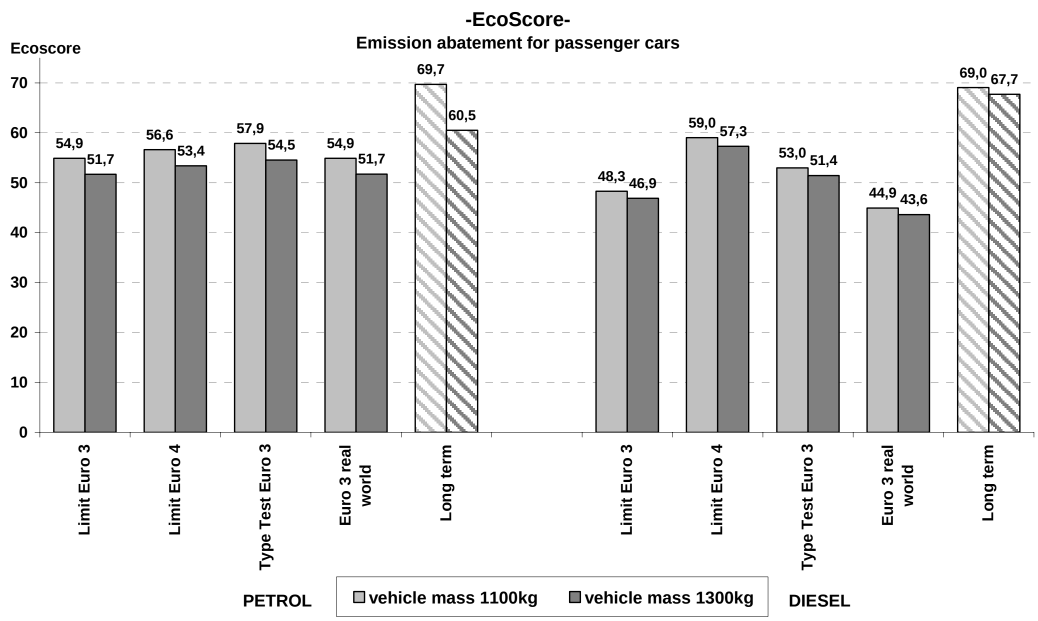
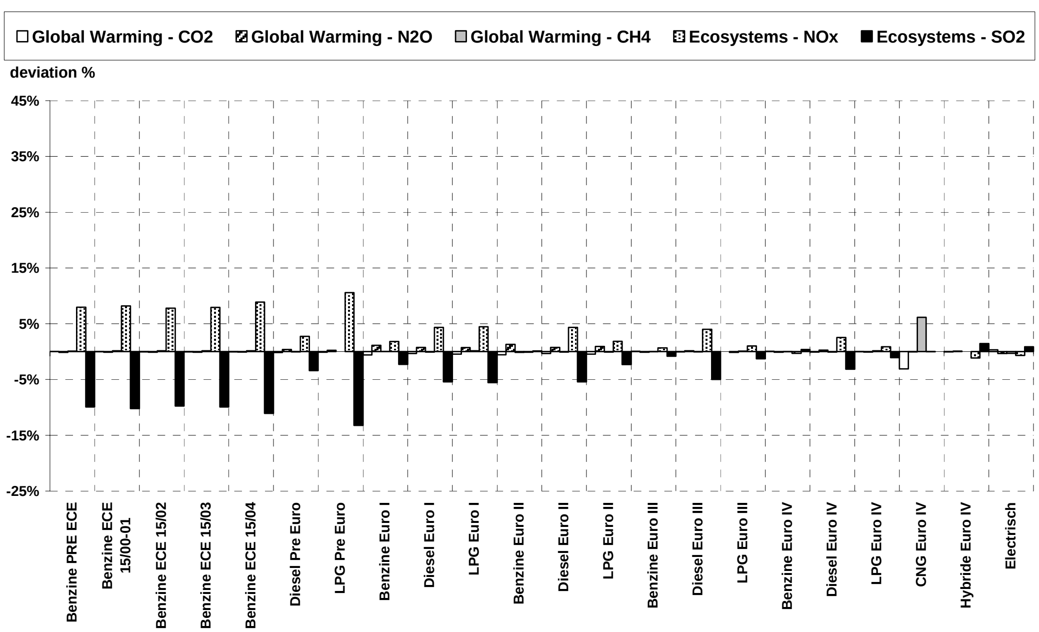


Figure 5. The Ecoscore of long term emission abatement estimations for passenger cars, based on Smokers et al. (2004)

The Ecoscore of the Euro 3 petrol vehicle, with the emission levels measured during the certification test (Type Test Euro 3), is even better than the Ecoscore corresponding to the Euro 4 emission limits. However, we see that the influence of driving under real world conditions, leads to an Ecoscore which is lower than the Ecoscore corresponding to type test emissions and results in an Ecoscore (almost) equal to that of the Euro 3 emission limits. This results from lower real world NOx emissions, compared to the emission Euro 3 limit, that are compensating the impact of higher real world CO and HC emissions. For the Euro 3 diesel-engined vehicle however, we see a difference between the Ecoscore of the Euro 3 emission limits and the one corresponding to the real world emissions. A significant improvement of the environmental performance is observed for the estimated long term emission abatement technologies for both petrol- and diesel-engined vehicles. The long term estimation of the fuel consumption depends on the technology and results in two different reduction percentages (Smokers et al., 2004). For the highest reductions, leading to the highest Ecoscore, the application of a hybridisation has been considered.

5. Sensitivity analysis

A sensitivity analysis was performed to evaluate the robustness of the ranking methodology. Different analyses have been performed, to investigate the influence of the successive calculations on the results of the Ecoscore methodology. The influence of the parameter mileage distribution σ (see paragraph 0) was investigated. When the rural mileage was increased, an increase of the total impact of the diesel vehicles (in particular the older ones) was observed. However the relative ranking of the different vehicles technologies was not influenced. The influence of the weighting system, parameter α (see paragraph 0) was also investigated. When changing the obtained weighting factors from table 4, to an equal weight for each damage category (α_i=25%, $\forall i$). No significant influence was observed and no influence on the ranking of the different vehicles occurred. Further, the influence of the impact factors $\delta_{i,j}$ (see paragraph 0) was analysed. Therefore the individual contributions $D_{i,j}$ (see equation 2) of each pollutant *j* to a corresponding damage category *i*, were each time multiplied by a factor 2 (100% increase of the contribution) for each pollutant and for each damage category. In this way the sensitivity of the environmental ranking methodology to the emission levels or to their damage factors can be assessed. The vehicle selection from table 5 was used again to demonstrate the results of the performed sensitivity analysis. The deviation of the total impact (TI), due to the multiplication with a factor 2, for each pollutant and for each damage category, was calculated for all these vehicles. The results of this analysis are shown in figure 6.



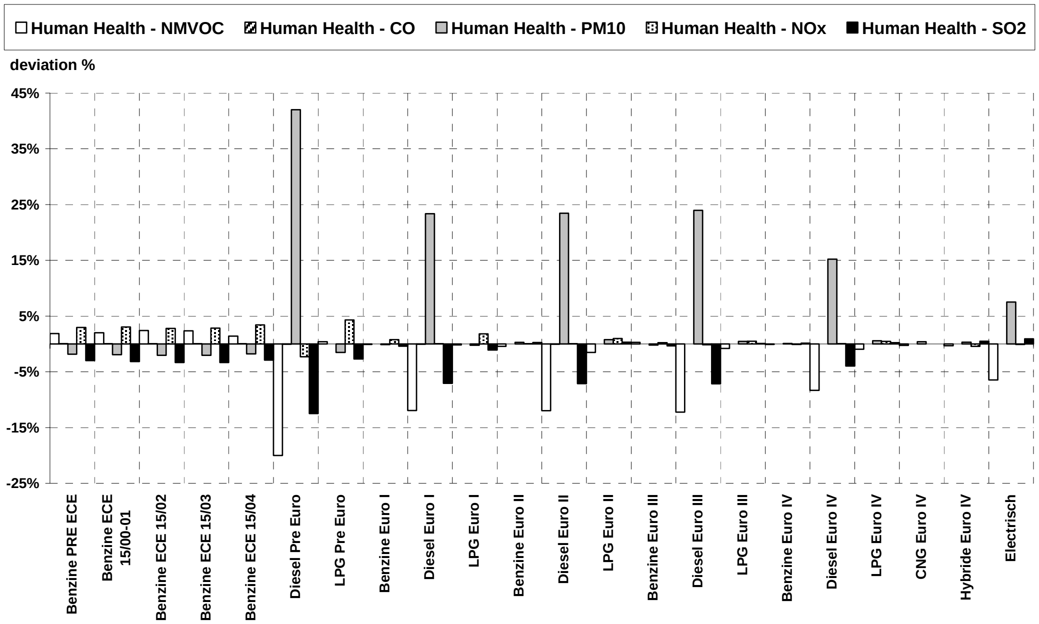


Figure 6. Sensitivity of each impact contribution for the Ecoscore methodology

The largest change of the total impact is obtained for diesel vehicles, when doubling the contribution of particulate matter (PM10) to the human health impact category. This means that in the case of diesel vehicles, the result of the Ecoscore methodology is significantly influenced by this pollutant, because of its important impact on the health of people. This observation is corresponding to the high external cost of particulate matter, used in the damage characterisation. To evaluate the robustness of the methodology and the relative positioning of the assessed vehicles, it is important to characterise the influence of the models' sensitivity on the end result for the assessed vehicle. The results of the sensitivity analysis are presented in figure 7. The environmental indicator Ecoscore was calculated and the range of results (up to their maximum deviation), are indicated with an error bar. These analyses indicate a high robustness of the methodology for vehicles complying with the latest emission levels. Older vehicles and diesel vehicles show a larger sensitivity for errors on emission values and/or damage factors.

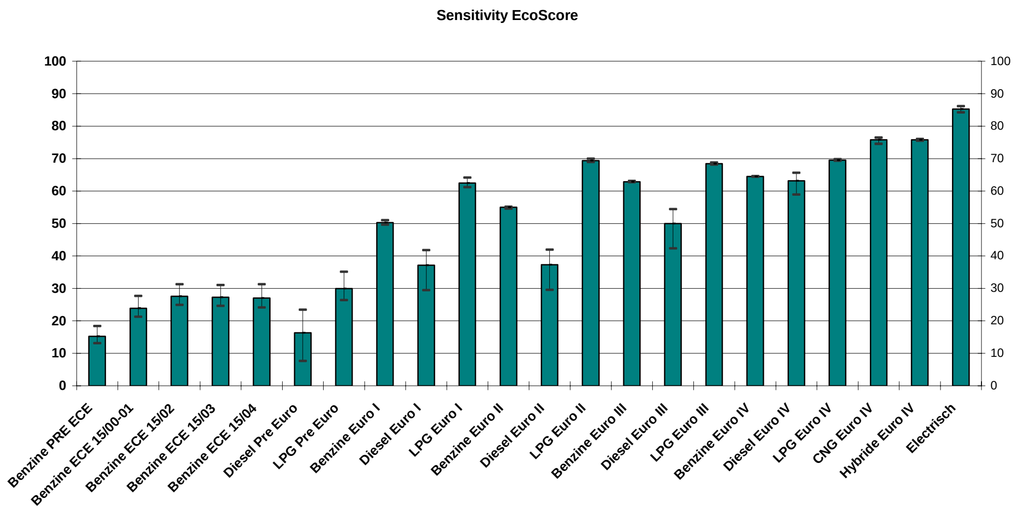


Figure 7. Sensitivity analysis – maximum deviation on the end result

Finally, the influence of the exponential transformation (see paragraph 0) was investigated by comparing with the use of a linear transformation. The main conclusion is that the introduction of an exponential transformation has no influence on the ranking of the different vehicles assessed with the Ecoscore methodology and has as an advantage that negative scores can be avoided, because very high total impacts will result in an Ecoscore approaching zero.

6. Conclusions and further research

This paper describes the methodology of the environmental rating tool called Ecoscore. A comprehensive and transparent overview and a summary of the environmental rating system for road vehicles, Ecoscore, have been presented. This methodology allows the assessment of vehicles with different drive trains and using different fuels.

Real vehicle results were calculated and discussed to demonstrate the applicability of this methodology. From the analysis made with the Ecoscore methodology, a positive evolution of the environmental performance of vehicles through time can be observed. This is mainly due to the ever more stringent European emission regulations. A low environment impact (and therefore a high Ecoscore) was obtained for the battery electric vehicle (Peugeot 106 electric). Also the hybrid petrol-electric vehicle (Toyota Prius) and the CNG vehicle (Opel Astra) obtained a favorable Ecoscore. The LPG vehicle shows the best environmental performance amongst all conventional vehicles, whereas Euro 4 petrol and diesel vehicles have a similar Ecoscore. On the other hand, the emissions of CO_2 from more recent vehicles, which are related to the fuel consumption, are not always reduced. The positive influence of an improved engine technology is sometimes annihilated by an increase of the vehicles' weight or an increased energy consumption caused by certain on-board options. It is noticeable that the newest generation of diesel vehicles has caught up its delay concerning their environmental performances on the petrol vehicles. Furthermore, the difference between the environmental performance of those vehicles and the environmental performance of the LPG vehicles has been reduced.

Finally, on the basis of a sensitivity analysis, the robustness of the methodology has been evaluated. As a general conclusion, one can state that the environmental rating system is robust and thus applicable as a policy instrument (taxation, incentives, consciousness rising campaigns, etc.) to support the use of environmental friendly vehicles.

The ambition of the Ecoscore environmental rating tool is to lead to a common system for policy measures in Belgium and possibly in other European countries, to promote the introduction and use of cleaner vehicles. In order to define implementation pathways for a consistent policy not only the environmental impact but also barriers for purchase (technical and economical barriers, market-related barriers, legislative and regulatory, psychological and institutional barriers) and the use of road vehicles should be taken into account. Fiscal measures should be based on the "polluter-pays" principle (De Borger & Proost, 1997) and the cost-effectiveness of possible policy measures (road pricing, fiscal measures, modulated vehicle taxation, subsidies, regulatory policy…) on the overall environmental performance, quantified by the Ecoscore, of the national vehicle fleet can be analysed as a next step. It is important to introduce the methodology on a European level, so that all vehicle manufacturers consider this rating tool as an important factor in their marketing and development strategies. Further research should be made at different levels. An update of the indirect emission data is important to be able to assess the current fuel production chains. Research related to both the indirect and direct emissions of different types of bio-fuels is needed to be able to make a comparison with fossil fuels. A recent study in this field shows big differences for the different possible production chains of different bio-fuels (De Ruyck et al., 2005). Also the production through gasification of second generation bio-fuels is promising from an environmental point of view (Boerrigter and Van der Drift, 2005).

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