JRC Scientific and Technical Reports

Environmental Improvement of Passenger Cars (IMPRO-car)

Françoise NEMRY, Guillaume LEDUC,
Ignazio MONGELLI, Andreas UIHLEIN

EUR 23038 EN - 2008

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Institute for Prospective Technological Studies

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March 2008

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EUROPEAN COMISSION

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European Commission
Joint Research Centre
Institute for Prospective Technological Studies

Contact information
Address: Edificio Expo. c/ Inca Garcilaso, s/n.
E-41092 Seville (Spain)
E-mail: jrc-ipts-secretariat@ec.europa.eu
Tel.: +34 954488318
Fax: +34 954488300
http://ipts.jrc.ec.europa.eu
http://www.jrc.ec.europa.eu

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JRC 40598
EUR 23038 EN
ISBN: 978-92-79-07694-7
ISSN: 1018-5593
DOI 10.2791/63451

Luxembourg: Office for Official Publications of the European Communities

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Printed in Spain

Acknowledgment

The JRC thanks the following individuals for their contribution to the IMPRO-car study:

- Rolf Frischknecht (ecoinvent Centre, Empa)
- Laurent Gagnepain (ADEME)
- Azkarate Garay-Olaun Gotzon (Inasmet)
- Savas Geivanidis (Aristotle University, LAT)
- Stephane His (Institut Français du Pétrole)
- Bart Jansen (Vito)
- Véronique Monier (BIO Intelligence Service)
- Zissis Samaras (Aristotle University, LAT)
- Joeri Van Mierlo (VUB)
- Bo Weidema (LCA 2.0 Consulting)
- Wulf-Peter Schmidt (representative of the European Automobile Manufacturers' Association (ACEA))

The authors of this report also wish to thank Robert Edwards, Jean-François Dallemand, Vincent Mahieu, David W. Pennington and Marc-Andree Wolf from the JRC Institute for Environmental Studies (IES) for their comments and suggestions on the final report.

Preface

This report on "Environmental improvement potential of passenger cars" is the second scientific contribution to the European Commission's Integrated Product Policy framework which seeks to minimise the environmental degradation caused the life cycle of products. A previous study coordinated by the JRC (EIPRO study) had shown that private transport is responsible for 20% to 30% of the environmental impact of private consumption in the EU.

This report presents a systematic overview of the life cycle of cars, from cradle to crave. It also provides a comprehensive analysis of the technical improvement options that could be achieved in each stage of a car's life cycle and which could be marketed within the next two decades. The report assesses the different options, their environmental benefits, their cost-effectiveness, their trade-offs, and the socio-economic barriers that these options would have to face.

The report has focused on the technical improvements related to the design of cars, such as the reduction of weight, improvement of the power train, reduction of rolling resistance of tyres. It also analyses improvements that rely on the driver's behaviour as speed control and eco-driving. The report examines each of the options taking into account the technical potential, the existing legislation and policy developments, and the barriers and drivers for the implementation of the different options.

The study presents the consequences that the adoption of these options might have on the environment such as global warming, generation of solid waste, acidification, energy consumption, etc. The study has also quantified the costs associated with the different options were implemented.

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Executive summary

1 Introduction

The Communication on Integrated Product Policy (COM(2003) 302 final), announced that the European Commission would seek to identify and stimulate action on products with the greatest potential for environmental improvement. This work was scheduled into three phases:

- the **first phase** consisting of research to identify the products with the greatest environmental impact from a life cycle perspective;
- the **second phase** which consists in the identification of possible ways to reduce the life cycle environmental impacts of some of the products with the greatest environmental impact;
- in the **third phase** the European Commission will seek to address policy measures for the products that are identified as having the greatest potential for environmental improvement at least socio-economic cost.

The **first phase** was completed in May 2006 with the EIPRO study which was entrusted to the JRC-IPTS by DGENV. The study identified the products consumed in the EU having the greatest environmental impact from a life-cycle perspective. The study showed that groups of products from only three areas of final consumption – food and drink, private transportation, and housing, which account for some 60% of consumption expenditure – are together responsible for 70% to 80% of the environmental impacts of final consumption.

Based on these conclusions, and on DG ENV's request, three parallel projects were launched by the IPTS, dealing with the Environmental IMprovement of PROducts (IMPRO, respectively IMPRO-car, IMPRO-meat, and IMPRO-buildings).

The present report presents the results and conclusions from the IMPRO-car project.

2 Objective and scope of the IMPRO-car project

The objectives of the IMPRO-car project are to:

- estimate and compare the environmental impacts of the passenger cars under a life-cycle perspective;
- identify the main environmental improvement options that are technically feasible and available on the car market within the two coming decades, addressing all the different life cycle stages and estimate the size of the environmental improvement potentials;
- assess the main improvement options regarding their feasibility, the main barriers for their adoption and the economic aspects.

The IMPRO-car project has been carried out in the context of Integrated Product Policy and therefore its focus is the **environmental performance of cars** through a change of their inherent characteristics (engine, car design, material composition). As a complement, some options consisting of a change in the **car use pattern**, resulting in less environmental impacts were also assessed.

3 Methodology

3.1 Life cycle analysis

The life cycle analysis was implemented by applying the process chain approach to quantify the more relevant environmental impact categories for passenger cars from the production to the disposal phase, which are:

- climate change (GWP)
- acidification (AP)
- eutrophication (EP)
- ozone depletion (ODP)
- photochemical oxidation (POCP)
- consumption of primary energy resources (PE)
- abiotic depletion (excluding primary energy depletion) (AD)
- solid waste (BW)
- 2.5 microns particulate matter ($PM_{2.5}$)

Two generic car models – one petrol car and one diesel car – which constitute the benchmarks for the analysis of the improvement options were defined and subjected to a life cycle inventory of their different material and energy/environmental flows. The so-called **"midpoint" indicators** of the different environmental impacts considered were quantified.

The **indicators** of the overall impacts from cars are calculated by assigning **monetary values** to the different impact categories. These indicators provide a rough estimate of the overall impacts and allow to gauge the direct costs of the options analysed to the avoided environmental impacts.

3.2 Benchmark definition

The two reference car models have been defined taken into account the statistics and data of the automotive market and, in particular of the new car fleet, since many of the improvement options, especially those that imply technological changes, concern this car fleet segment. The reference cars are representative of the most commonly purchased cars in the EU-25 today.

Statistics show an increasing share of more powerful and bigger cars (cylinder >1 400 cm^3). The range of power and capacities has been widening with the fast growing share of bigger cars sales. The share of sport utility vehicles (SUV) in new car sales in Western Europe has also rapidly increased (the share in car sales increased from 2.9% in 1997 to 8.2% in 2006). This trend prevails together with the growing share of diesel cars in the entire passenger car fleet. Overall, around 30% of the European car fleet in 2005 is diesel powered (in EU-25).

The average characteristics derived from statistics of new cars sold in Europe concerning power, cylinder, size and weight are shown in Table A which provides the definition of the two reference cases. The two reference car models differ in terms of weight and power and do not perform in the same way (in terms of acceleration, for instance). They may also differ in terms of comfort and space.

Table A: Main characteristics of the car models considered

	Petrol car	Diesel car
Lifespan (years)	12.5	12.5
Emission standard	**EURO4**	**EURO4**
Annual distance (km)	16 900	19 100
Cylinder capacity (cm^3)	1 585	1 905
Power (kW)	78	83
Weight (kg)	1 240	1 463
Body model	Saloon	Saloon

Both the petrol and the diesel car reference cases are assumed to comply with the **EURO4** standard regarding exhaust air pollutant emissions.

The average lifespan assumed is in line with generally reported information. Derived from the traffic volume and the total new car fleet, the average annual mileage of the petrol and diesel cars was found to be around 16 900 km and 19 100 km (medium/big category) respectively.

4 Life cycle impacts of the two generic new cars

The life cycle of a car includes all transformation processes from cradle to grave. The different processes are grouped into five main ones:

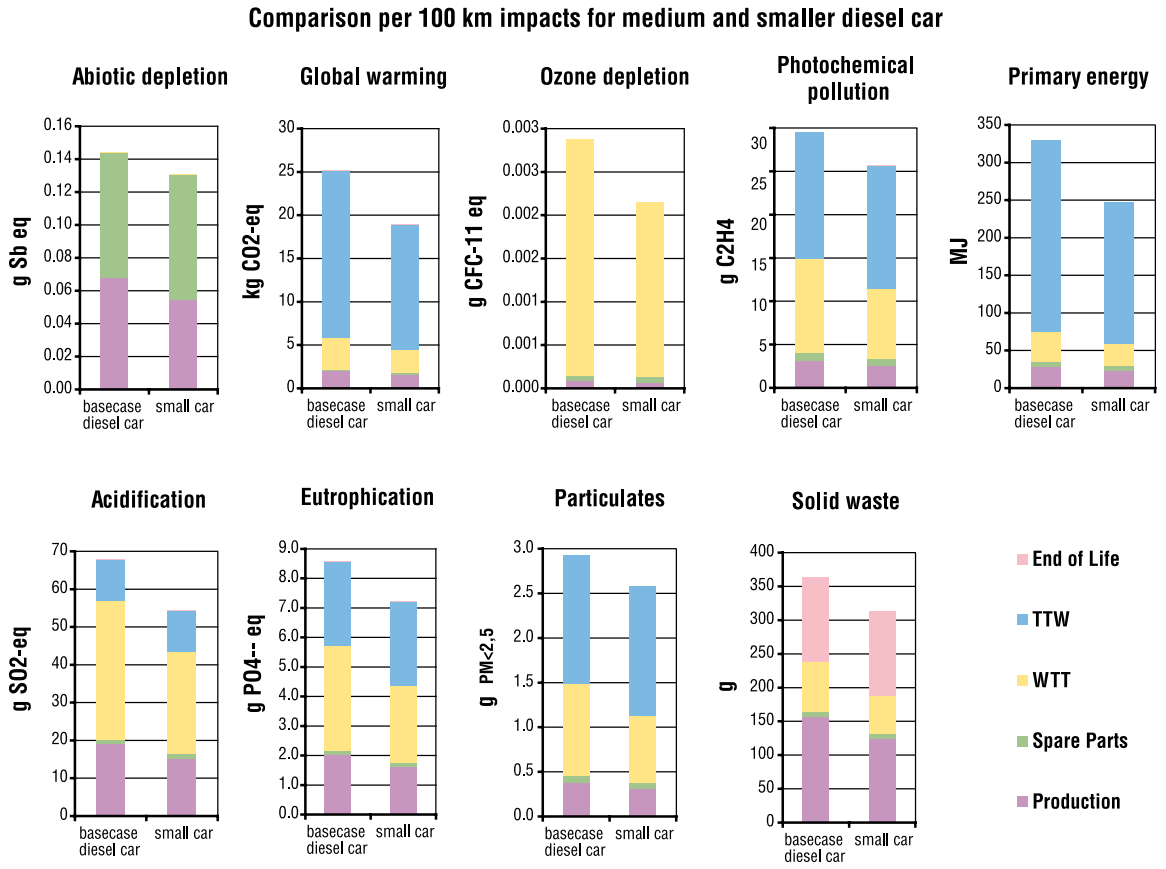
1. Car production (raw material extraction, material transformation and car assembly)
2. Replacement and spare parts production (tyres, battery, lubricants and refrigerants)
3. Fuel transformation process upstream to fuel consumption (well-to-tank - WTT)
4. Fuel consumption for car driving (tank-to-wheel - TTW)
5. Car disposal and waste treatment (end-of-life - EOL)

The WTT and TTW together correspond to the Well-to-Wheel (WTW), i.e. the complete fuel chain.

The impact of processes like transport of materials and car components, lighting, etc. was not considered due to their low contribution to the life cycle balance or because their contribution would not be affected by any of the improvement options considered in the study (road infrastructure).

Figure A compares the results **normalised to a driven distance of 100 km** obtained for the two car systems to take into account the effect of different mileages of the reference cars. These figures allow comparing the environmental impact of the two reference cars, but not their environmental performance, which should take into consideration other parameters, like weight, power, and, possibly, comfort. However, as far as energy and GHG emissions are concerned, the estimations are in line with what the Well-to-Wheel JRC/Concawe/EUCAR study previously showed, namely that diesel cars has slightly lower fuel-chain related GHG emissions per km than petrol cars (for the same car performance in terms of acceleration and comfort).

Figure A: Life cycle impacts of the two car systems (impacts normalised to a 100 km driven distance)



The study has shown a significant degree of sensitivity of the life cycle impacts to parameters such as the weight or the car mileage. However one can robustly conclude that:

Primary energy use and **GHG emissions** are dominated by the TTW part, followed by the WTT and production phases.

The size and breakdown of the other energy-related impacts, namely **photochemical oxidation, eutrophication and particles** differ from one case to the other: For the petrol car, the WTT part dominates, followed by the production phase, whereas, for the diesel car, the TTW part dominates, followed by the WTT part and then the production phase.

The generation of **solid waste** is shared between the production phase, WTT phase and EOL phase. **Abiotic depletion** is dominated by the production and replacement and spare parts (lead). Emissions of **ozone depleting substances** are entirely dominated by the WTT phase.

The analysis indicates that, per 100 km driven, the petrol system is the least environmentally performing with respect to greenhouse gas emissions, ozone depletion, bulk waste, abiotic depletion and primary energy. However, when considering the aggregated impacts as proxied by the monetary value assigned to the different impacts, the two cars perform similarly. What differs is the relative contribution of the different impact categories.

5 Improvement options

The identification of improvement options was carried o ut by a literature review. This included technical information from the industry, scientific publications and, also, the most recent and ongoing studies – and Commission's impact assessments – supporting policy developments which have been significant since the launch of this project covering:

- the new air pollution standards (EURO5 and EURO6);
- the review of the Community's strategy to reduce CO_2 emissions and improve fuel efficiency from passenger cars and light commercial vehicles;
- the proposal for a new Directive regarding fuel quality;
- the targets contained in the Directive on end-of-life vehicle;
- the review of the progress made in the use of biofuels.

Based on that, a long list of options technically proven and likely to be on the market within the next 20 years was compiled. For each option, the technical and analytical background related to each improvement options was covered.

Several criteria were considered when selecting options that should be further assessed and quantified:

1. Relevance in the context of IPP;
2. Potential to improve processes that generate significant impacts;
3. Coverage of the existing technical potential by the existing legislation;
4. Reliability of data and information to quantify the environmental impact.

The options groups are listed in Table B. Some of these groups actually include several sub-options so, in total, 16 options mainly of technical nature were quantified. Only the two last options depend, to a large extent, on a change in consumer behaviour..

Table 2 summarises for each of the improvement options selected the required technological changes, the main barriers and benefits and the trade-offs.

Table B Summary of the improvement options assessed

Improvement option	Technological change	Consumer change	Barriers and benefits	Trade-off
1. Car weight reduction: • 5% reduction • 12% reduction • 30%reduction • Magnesium	High strength steel, aluminium Other (less promising): composites, magnesium	-	New investments in production lines; need for new safety and control equipment	More limitations for recycling (composites); impacts of production phase may increase and total life cycle impacts would highly depend on the actual car mileage
2. Car body and tyres • Aerodynamics • Tyres	Reducing the aerodynamic drag, low rolling resistance tyres (LRRT), tyre pressure monitoring system (TPMS)	-	Customer's desire for comfort; safety	-
3. Mobile air conditioning (MAC) • MAC imporvement • Efficient use of MAC	New refrigerants; leak tightness; recovery at servicing; better design of the cabin	Reducing cooling demand	-	-
4. Tailpipe air emission abatement systems • Air abatement option (I) (diesel car) • Air abatement option II (diesel and petrol car)	Engine management options (EGR); catalytic converters	-	Higher purchase costs and possible higher maintenance costs	Higher fuel consumption and CO_2 emissions; higher demand for PGM
5. Powertrain improvements	Various engine and transmission improvements	-	-	-
6. Hybrid cars	Micro hybrid; mild hybrid; full hybrid		Lack of information amongst the public; need for information regarding batteries	Could entail special development of recycling technologies (batteries)
7. Biofuels • Bioethanol • Biodiesel	First generation: biodiesel, bioethanol; second generation (Fischer-Tropsch synthesis)	-	Land availability; potential conflict with food supply	Land use and biodiversity; higher NO_x emissions
8. End-of-life vehicle recycling and recovery	To some extent design for dismantling and further dismantling post schredder technologies	-	Low value for waste plastics; dismantling is time consuming	Possible minor increase in GHG emissions for some recycling options
9. Speed control		Yes	Fewer accidents	-
10. Driving behaviour	Eco-driving behaviour assisted by gear shift indicator system (GSI)	Yes	Need eco-driving training; durability of effects of the training may vary a lot from one driver to the other; fewer accidents	-

Table C and Table D present, for each of the different improvement options analysed for the petrol car and diesel car, their environmental impact relative to the impact estimated for the reference case. The last row of each table presents the aggregated impacts, in monetary values that are expected to be avoided by each option. The years indicate the time horizon when the options are expected to be available on the market.

Table C: Overview of the environmental benefits and costs associated with the different options (petrol car)

	Impacts normalised to a 100 km distance	Reference	2005				2010							2020	Car use efficiency		
			Weight reduction 5%	Weight reduction 12%	MAC improvement (HFC-134)	Hybrid car	Higher recovery / recycling rates	Bioethanol	Aerodynamics	Tyres	Weight reduction 30%	Power train improvements	Air abatement option I	Weight reduction Mg	Driving behaviour	Speed limitation	MAC efficient use
Absolute	AD (g Sb-eq)	0.149	0.148	0.147	0.149	0.082	0.149	0.149	0.149	0.149	0.143	0.149	0.149	0.143	0.149	0.149	0.149
	GWP (kg CO_2-eq)	26.6	25.8	25.0	26.4	20.8	26.6	24.5	26.2	25.5	22.5	21.4	26.6	24.9	25.5	26.2	26.4
	ODP (mg CFC-11-eq)	3.18	3.09	2.98	3.18	2.46	3.18	3.18	3.14	3.05	2.69	2.54	3.18	2.68	3.05	3.14	3.15
	POCP (g C_2H_4)	22.7	22.2*	21.7*	22.7	17.0	22.7	23.7	22.5*	22.1*	20.3*	19.7*	22.7	20.2*	22.1	22.3	22.6*
	AP (g SO_2-eq)	77.6	75.9*	74.7*	77.6	70.3	77.6	82.2	76.8*	75.2*	70.3*	66.1*	77.6	69.2*	75.2	76.8	77.0*
	EP (g PO_4-eq)	7.03	6.89	6.79	7.03	5.84	7.02	8.09	6.97	6.84	6.44	6.13	7.03	6.46	6.84	6.96	6.99
	PM2.5 (g)	1.86	1.82	1.88	1.86	1.64	1.86	1.86	1.84	1.80	1.90	1.57	1.86	1.83	1.80	1.84	1.85
	PE (MJ)	358.3	348.3	337.7	358.3	281.7	358.3	396.6	353.6	344.3	307.0	289.7	358.3	307.0	344.3	353.7	355.2
	BW (g)	403.1	392.9	416.6	403.1	420.7	308.5	403.1	401.7	398.7	436.9	381.2	403.1	408.2	398.7	401.7	402.2
	Aggegated impacts (Euro)	1.77	1.71	1.67	1.75	1.47	1.77	1.68	1.74	1.70	1.52	1.44	1.76	1.64	1.70	1.74	1.75

(*) For this option, the impact on TTW air emission levels was not quantified. One can expect some reduction

Relative (Reference = 100)	AD	100.0	99.2	98.4	100.0	55.1	100.0	100.0	100.0	100.0	96.0	100.0	100.0	95.6	100.0	100.0	100.0
	GWP	100.0	97.2	93.9	99.4	78.4	100.1	92.3	98.7	96.0	84.8	80.5	100.0	93.7	96.0	98.7	99.2
	ODP	100.0	97.2	93.7	100.0	77.2	100.0	100.0	98.6	95.9	84.4	79.7	100.0	84.3	95.9	98.6	99.1
	POCP	100.0	97.8	95.7	100.0	75.0	100.0	104.5	99.1	97.3	89.2	86.6	99.9	88.8	97.3	98.4	99.4
	AD	100.0	97.8	96.3	100.0	90.6	100.0	106.0	99.0	97.0	90.6	85.2	100.0	89.2	97.0	99.0	99.3
	EP	100.0	98.0	96.7	100.0	83.1	99.9	115.1	99.1	97.4	91.6	87.2	100.0	91.9	97.4	99.0	99.4
	PM2.5	100.0	97.8	100.8	100.0	88.0	100.0	100.0	98.9	96.8	102.1	84.3	100.0	98.1	96.8	99.0	99.3
	PE	100.0	97.2	94.3	100.0	78.6	100.0	110.7	98.7	96.1	85.7	80.9	100.0	85.7	96.1	98.7	99.1
	BW	100.0	97.5	103.3	100.0	104.3	77.0	100.0	99.6	98.9	108.4	94.6	100.0	101.2	98.9	99.6	99.8
	Aggregated impacts	100.0	97.1	94.4	99.3	83.1	100.0	95.3	98.5	96.0	86.3	81.5	99.7	92.7	96.0	98.5	99.0

94	lower than 95%
97	between 95% and 100%
101	higher than 100%

AD: Abiotic Depletion	POCP: Photochemical Pollution	PM2.5: Particulate Matters (<2.5 µ)
GWP: Global Warming Potential	AD: Acidification Potential	PE: Primary Energy
ODP: Ozone Depletion Potential	EU: Eutrophication Potential	BW: Bulk Watse

Avoided impacts (Euro)	0.05	0.10	0.01	0.30	0.00	0.08	0.03	0.07	0.24	0.33	0.00	0.13	0.07	0.03	0.02
Direct costs (Euro)	0.02	0.11	0.03	1.51	0.00	0.19	0.02	-0.01	0.59	0.30	0.03	0.59	-0.01	-0.02	-0.02

Table D: Overview of the environmental benefits and costs associated with the different options (diesel car)

	Impacts normalised to a 100 km distance	Reference	2005			2010							2020			Car use efficiency		
			Weight reduction 5%	Weight reduction 12%	MAC improvement (HFC-134a)	Higher recovery/ recycling rates	Biodiesel	Aerodynamics	Tyres	Weight reduction 30%	Power train improvements	Air abatement option I	Air abatement option II	Hybrid car	Weight reduction Mg	Driving behaviour	Speed limitation	MAC efficient use
Absolute	AD (g Sb-eq)	0.145	0.143	0.142	0.145	0.145	0.145	0.145	0.145	0.138	0.145	0.145	0.145	0.077	0.138	0.145	0.145	0.145
	GWP (kg CO_2-eq)	25.2	24.4	23.6	25.0	25.2	23.3	24.9	24.2	21.1	21.5	25.2	25.2	18.0	23.6	24.2	24.6	25.0
	ODP (mg CFC-11-eq)	2.89	2.80	2.70	2.89	2.89	2.89	2.85	2.77	2.42	2.45	2.89	2.89	2.02	2.41	2.77	2.81	2.86
	POCP (g C_2H_4)	29.6	29.2*	28.8*	29.6	29.6	30.8	29.4*	29.1*	27.6*	27.8*	28.0	21.5	26.3	27.5*	29.1	28.4	29.5*
	AP (g SO_2-eq)	68.0	66.7*	66.1*	68.0	68.0	80.1	67.4*	66.4*	63.4*	62.0*	66.7	61.5	62.0	62.2*	66.4	66.2	67.6*
	EP (g PO_4-eq)	8.61	8.48	8.41	8.61	8.60	16.04	8.56	8.45	8.10	8.03	8.27	6.93	7.50	8.13	8.45	8.31	8.58
	$PM_{2.5}$ (g)	2.93	2.90	2.97	2.93	2.93	2.23	2.92	2.89	3.02	2.76	1.93	1.93	2.70	2.95	2.89	2.84	2.92
	PE (MJ)	331.0	321.3	311.1	331.0	331.0	354.9	326.7	318.1	281.3	283.2	331.0	331.0	237.5	281.5	318.1	322.6	328.2
	BW (g)	364.6	354.7	379.5	364.6	280.8	364.6	363.5	361.3	402.0	352.5	364.6	364.6	378.0	373.7	361.3	362.4	363.8
	Aggegated impacts (Euro)	1.75	1.70	1.66	1.74	1.75	1.70	1.73	1.69	1.52	1.53	1.70	1.64	1.41	1.64	1.69	1.70	1.74

(*) For this option, the impact on TTW air emission levels was not quantified. One can expect some reduction

Relative (Reference = 100)	AD	100	99.2	98.3	100	100	100	100	100	95.8	100	100	100	53.0	95.3	100	100	100
	GWP	100	97.0	93.6	99.5	100.1	92.4	98.7	96.1	83.9	85.3	100	100	71.5	93.8	96.1	97.5	99.2
	ODP	100	97.0	93.5	100	100	100	98.6	95.9	83.6	84.7	100	100	69.9	83.5	95.9	97.3	99.1
	POCP	100	98.6	97.3	100	100	103.9	99.5	98.4	93.4	94.0	94.5	72.7	88.9	93.0	98.4	95.8	99.6
	AD	100	98.1	97.3	100	100	117.9	99.2	97.6	93.2	91.3	98.1	90.5	91.2	91.6	97.6	97.4	99.5
	EP	100	98.5	97.6	100	99.9	186.3	99.4	98.2	94.1	93.3	96.1	80.5	87.1	94.4	98.2	96.6	99.6
	PM2.5	100	98.9	101.3	100	100	76.1	99.5	98.5	103.2	94.3	65.8	65.8	92.0	100.7	98.5	97.1	99.7
	PE	100	97.1	94.0	100	100	107.2	98.7	96.1	85.0	85.6	100	100	71.8	85.0	96.1	97.5	99.2
	BW	100	97.3	104.1	100	77.0	100	99.7	99.1	110.3	96.7	100	100	103.7	102.5	99.1	99.4	99.8
	monetarised aggregated impacts		97.2	94.6	99.4	100	97.2	98.7	96.4	86.9	87.3	97.1	93.8	80.2	93.7	96.4	97.0	99.1

94	lower than 95%
97	between 95% and 100%
101	higher than 100%

AD: Abiotic Depletion	POCP: Photochemical Pollution	PM2.5: Particulate Matters (<2.5 µ)
GWP: Global Warming Potential	AD: Acidification Potential	PE: Primary Energy
ODP: Ozone Depletion Potential	EU: Eutrophication Potential	BW: Bulk Watse

Avoided impacts (Euro)		0.05	0.09	0.01	0.00	0.05	0.02	0.06	0.23	0.22	0.05	0.11	0.35	0.11	0.06	0.05	0.02
Direct costs (Euro)		0.03	0.15	0.02	0.00	0.17	0.01	-0.01	0.77	0.22	0.36	0.45	1.21	0.77	-0.01	-0.04	-0.01

Environmental benefits

Most of the options are shown generate an environmental improvement in respect of the majority of environmental impact categories. The size of these benefits varies from option to others and from environmental problem to others. The environmental benefits are particularly high for power train improvements, hybrid cars and weight reduction options for almost all the environmental impact categories. Moreover, these are the options that have the most significant impacts on the dominating life cycle phases – WTT and TTW parts -. The benefits are actually driven by the higher energy efficiency of the fuel use which, on its turn, leads to reduced air emissions and upstream energy use. When considering the overall benefit as proxied by the monetary impacts, the benefit of these options achieves for the petrol and diesel car respectively 17 and 20% for the hybrid technology, 18% and 13% for the power train improvements and 14-15% with the weight reduction option.

The various options have similar impacts (compared to the reference) when comparing the diesel car and the petrol car. There are two main exceptions:

- The technical and environmental potential of the power train petrol car is shown to be higher than for the diesel car.
- The environmental benefit expected from air abatement systems is the highest for the diesel car.

Noticeable is also the fact that some options are expected to generate disadvantages for at least one of the impact categories. The main potential trade-offs suggested concern the energy-related impacts (especially GHG) and waste (in the case of recycling/recovery, hybrid car, weight reduction options):

- **Lightweight cars** are beneficial in reducing the fuel consumption in the use phase. Depending on the weight reduction option, increased waste generation and PM emissions in the production phase are expected.
- **Hybrid cars** are shown to offer an overall high environmental performance. On the other hand, they may entail new environmental challenges related to their batteries (NiMH). Further investigation is needed about the available recycling technologies and detailed characteristics (e.g. material breakdown) of the used batteries. Ultimate conclusions are also difficult to draw as only a few hybrid car models are currently marketed in Europe.
- **Increasing recycling/recovery rates** at the end-of-life of vehicles results in lower volumes of waste (and landfilling). On the other hand, very small increases in GHG emissions, acidifying substances and in eutrophication are expected. This, however, does not take into account the impacts that are potentially avoided by the substitution of primary fossil energy or raw material outside of the car system.
- In the case of **biofuels**, as far as the 1st generation is concerned, additional eutrophication effects and slight $PM_{2.5}$ emission increases are expected for the petrol car (using ethanol). Acidification is also expected to increase with biodiesel. Despite the fact that fossil fuel energy is reduced by using biofuel, it has to be stressed that primary energy is generally increased. In addition, the increased use of land is not taken into account here. The 2nd generation of biofuels was not analysed in this project. However, the literature generally reports that these negative effects are not expected or are likely to be significantly reduced.

In these different cases, there are many possible technological pathways which could not be singled out or quantified in great detail. Some of the particular pathways may lead to better environmental performance whereas some would entail worse performances.

Besides the car efficiency options, those that would rely more on changes in driver behaviour are also shown to have environmental improvement potential. This is the case regarding speed limitation and eco-driving. This last option relies on smoother driving behaviours.

Cost effectiveness

Figure B and Figure C provide an indication of the relative cost effectiveness of the options as compared with each other by displaying the direct costs alongside with the avoided environmental costs (as expressed by the monetary value of the different avoided environmental impacts).

These figures are illustrative and should be interpreted with caution. On the one hand, direct costs reported in literature are subject to a degree of uncertainty. On the other hand, the monetary costs assigned to the environmental benefits are highly uncertain and omit some of the environmental impact categories. Besides, not all costs and benefits are taken into account in these figures. For instance, speed limitation control may entail both benefits (less accidents) and costs (time loss) that were not quantified.

Generally, the higher the avoided environmental cost is, the higher the direct cost is. Some options are however, suggested to be more cost-effective than others. The hybrid car is shown to be more costly than the other improvement options.

Options that are not so reliant on technological changes, such as driving behaviour, have also an economic benefit (see also speed limitation and AC efficient use). The same is true for the option improving the car aerodynamic (reduced tyres rolling resistance).

Figure B: Avoided impacts and direct costs of the different improvement options (petrol car)

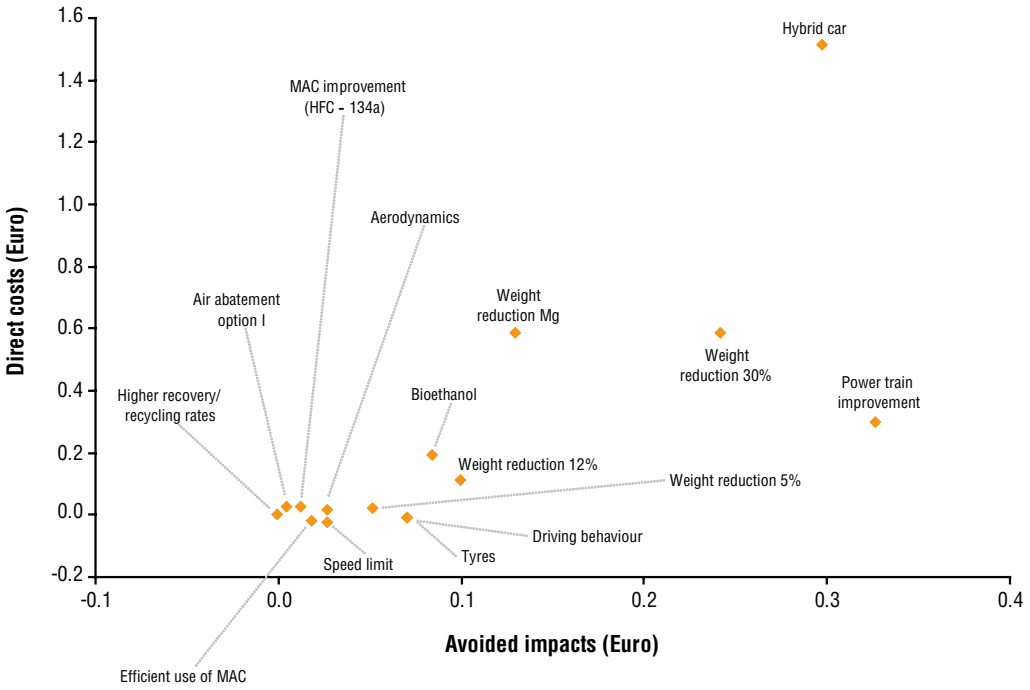
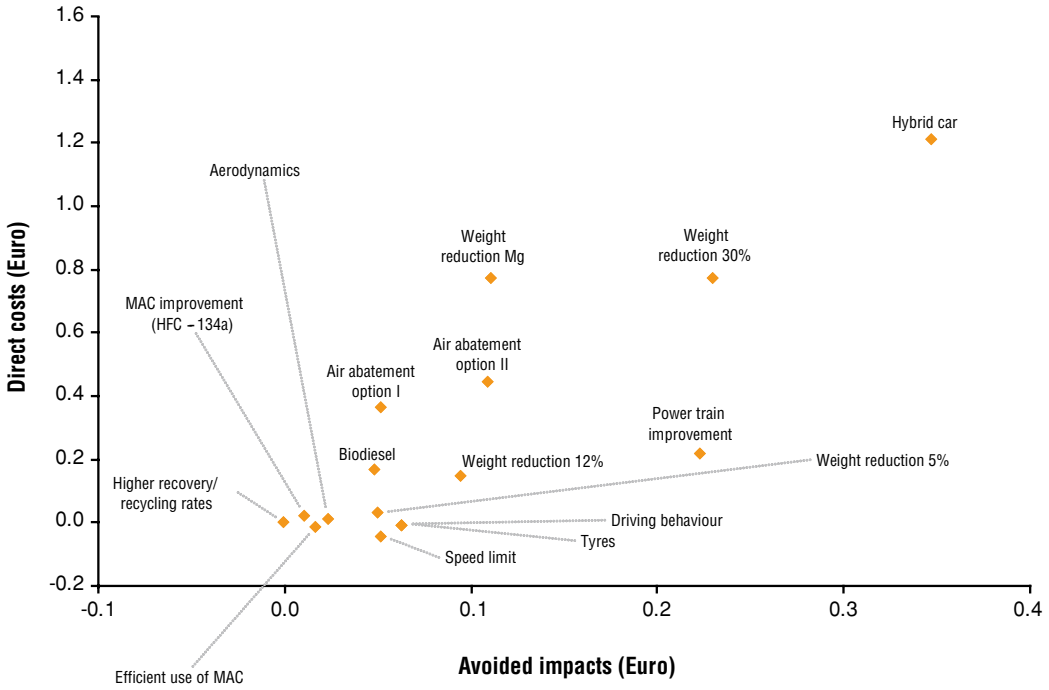


Figure C: Avoided impacts and direct costs of the different improvement options (diesel car)



Improvement options and regulatory framework

The results of this project illustrate substantial technical potential for cars environmental improvement. The existing and developing legislation was also considered to assess any possible untapped technical potential. The European policy (and also the national policy) is actually being considering the environmental impacts from cars over years and already addresses some of the important environmental aspects at different stages of the car life cycle (e.g. air pollution, CO_2 emissions, end-of-life waste, batteries, etc.). This has already fostered substantial technical improvements.

Further technical improvements have recently been considered in the policy framework, giving rise to new proposed actions which, if adopted and implemented, will further exploit the identified technical potentials of cars. This concerns:

- The review of the Community strategy to reduce CO_2 emissions and improve fuel efficiency from passenger cars and light commercial vehicles;
- The proposal for a new Directive regarding the fuel quality;
- The report on the targets contained in the Directive on End-of-life vehicle.

Overall, a majority of the options considered in this project (either qualitatively or quantitatively) are considered in the policy framework which is also evolving towards more ambitious targets, especially when considering two particularly important environmental challenges, namely greenhouse gas emissions and air pollution.

A regular assessment of the actual effect of these policies will of course answer the question of their success in fostering the technological progress targeted. One also have to keep in mind that the car fleet is characterized by a long turn over which makes that technological progress takes time to penetrate the market.

Other options, if implemented, could help reducing the impacts of the overall car fleet immediately. For some of them, the actual effect is, however, highly dependent on consumer choice and the possible policies to support their implementation.

1. Introduction

1.1. Background

The Communication on Integrated Product Policy (COM(2003) 302 final), announced that the European Commission will seek to identify and stimulate action on products with the greatest potential for environmental improvement. This work had been scheduled into three phases:

- the **first phase** consisting of research to identify the products with the greatest environmental impact from a life cycle perspective consumed in the EU
- the **second phase** which consists in the identification of possible ways to reduce the life cycle environmental impacts of some of the products with the greatest environmental impact
- in the **third phase** the European Commission will seek to address policy measures for the products that are identified as having the greatest potential for environmental improvement at least socio-economic cost.

The **first phase** was completed in May 2006 with the EIPRO study led by the IPTS (JRC) in cooperation with ESTO research network organisations. The study identified the products consumed in the EU having the greatest environmental impact from a life-cycle perspective. In that project, the final consumption had been grouped into almost three hundred product categories and assessed in relation to different environmental impact categories, such as acidification, global warming, ozone depletion, etc.

The study showed that groups of products from only three areas of consumption - food and drink, private transportation, and housing - are together responsible for 70% to 80% of the environmental impacts of private consumption and account for some 60% of consumption expenditure.

The EIPRO project conclusions thus suggested initiating the second phase of the work scheduled in the Integrated Product Policy (IPP) communication on these three groups of products. To this end, three parallel projects were launched in late 2005 – beginning of 2006 and coordinated by the IPTS. These projects deal with the Environmental IMprovement of PROducts (IMPRO, respectively IMPRO-car, IMPRO-meat, IMPRO-buildings).

1.2. Objectives

This report presents the methodology, results and conclusions of the IMPRO-car project dealing with passenger cars.

The objective is to analyse the different improvement options that are technically feasible and that could help reduce the life cycle impacts from passenger cars used in the EU-25. The analysis covers the following aspects:

- estimating and comparing the environmental impacts of the products under a life-cycle perspective
- identifying and assessing the main improvement options regarding their feasibility, environmental impacts and potential social and economic impacts.

When assessing the different improvement options, the existing and evolving legislative framework was taken into account in order to identify the untapped improvement potentials compared to the "autonomous" development of technologies. However, as already noted, **the study did not consider the next step, i.e. the definition and assessment policies that could help to implement these options**.

2. Scope definition and Methodology

2.1. Introduction

In order to develop a study bringing scientific know-how together with policy relevant conclusions in the specific IPP policy area, three important principles influenced the design of the methodological approach used in the study:

1. **Life cycle thinking,** which is inherent to a product-oriented policy and which:
   - considers the product's full life-cycle from the cradle to the grave
   - investigates ways of reducing the product's cumulative environmental impacts also **avoiding burden shifts** among different environmental and human health problem fields or shifts of impacts from one country or region to another.
2. The seek for a coherence between the different policies addressing the products considered (**policy coherence**).
3. The encouragement of measures to reduce environmental impacts at the point in the life-cycle where they are likely to be most **effective** and cost saving for business and society.

The general approach is described in Figure 1.

The project started with a general overview (see Chapter 3) of road transport, especially passenger cars, with regard to the current situation and main trends in the new car fleet.

In Chapter 4, the life cycle environmental impacts associated with passenger cars are analysed for new generic petrol and diesel cars. This analysis uses a process-chain approach.

The environmental impacts induced by today's car fleet at the EU-25 level are also quantified.

An extensive literature review was carried out in order to identify and analyse the different options for improving the environmental life cycle performance of cars. This review considered the various aspects (technical potential, environmental benefits, socio-economic barriers and existing or developing legislation) of the options. Chapter 6 provides an overview of the improvement options identified, selects those that are considered in more detail and includes the quantification of their environmental effects as well as their costs.

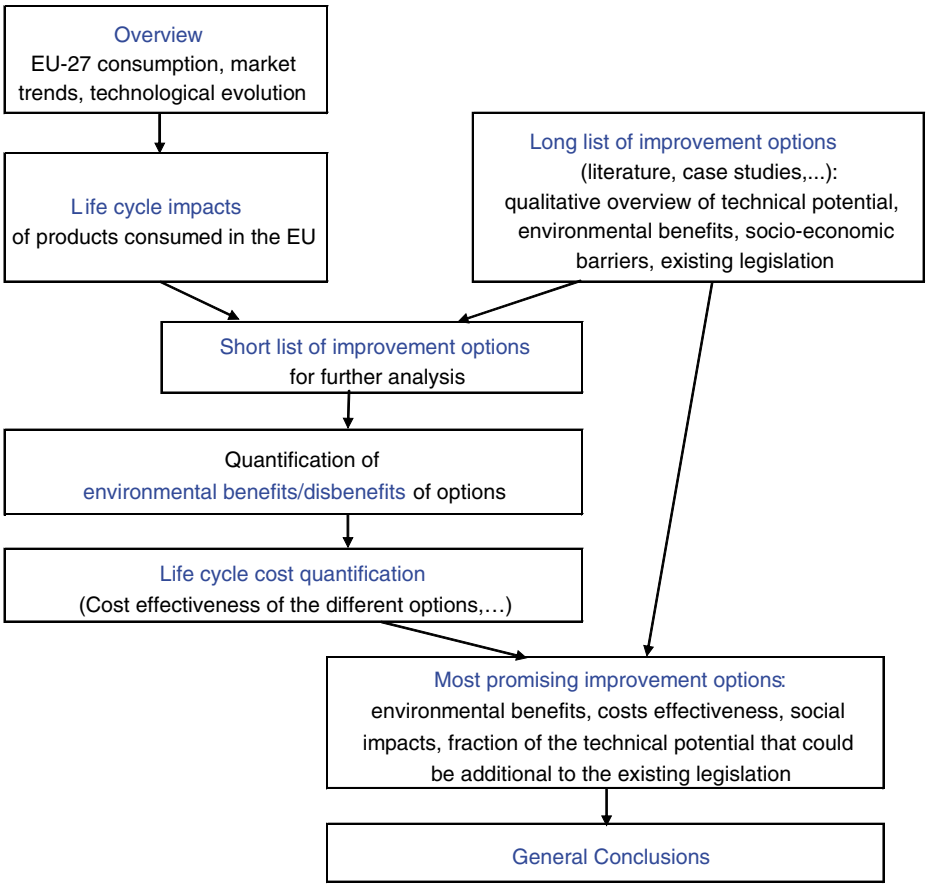
A general picture of the results of the detailed analysis is presented in Chapter 7, where the different improvement options are compared against both their environmental performance and their costs.

2.2. Approaches for analysing the environmental impacts

The environmental impact assessment of the passenger cars is performed on two different scales:

First, the **process-chain approach** is applied to some generic passenger cars and general characteristics are derived from the existing literature, statistics and other existing data about the new car fleet as described in Chapter 3. Based on this information, the product system considered is specified in parametric terms with a view to establishing the life cycle inventory of the product and to quantifying and interpreting the different life cycle impacts. These models and their parameterisations also represent benchmarks to subsequently assess the different improvement options.

Figure 1: General approach for the project



The first approach provides an overview of the different life cycle impacts from a new car purchased today in the EU-27. Nevertheless, environmental impacts from passenger cars today are also generated by the whole EU-27 car fleet which is composed of different age cars, and also of cars that are disposed of today. Hence, a second approach, which consists in the assessment of the environmental impacts associated with activities related to the overall **car fleet,** is used to complement the previous results. Also in this type of analysis, a life cycle perspective including the manufacturing of the cars purchased, the use of the cars and the disposal of end-of-life cars is adopted.

For each of these two approaches we need to specify what we are assessing:

- in the first case, the functional unit was considered as one-unit distance driven with the car (100 km), which means that the different environmental life cycle impacts are normalised to that distance driven
- in the second case, the environmental impacts associated with today's car traffic volume in the EU-25 were assessed.

2.3. Environmental impacts considered

As is consistent with Integrated Product Policy, the study considers the different types of environmental aspects related to cars at their different life cycle stages.

2.3.1. Definition of the cause-effect chain level considered

One first stage is the **quantification of elementary flows of substances** (CO_2 emissions for instance) linked to the product system under study. This quantification implies the use, in a consistent way, of different sets of data reflecting the manufacturing processes and technologies, the fuel type and quality, and any other relevant factors that would influence emissions during car driving (i.e. emission factors). Some of these data sets already exist (emission factors defined internationally, data from the industry, LCA databases, etc.). These emission factors have to be combined carefully to maximise the accuracy of the evaluation.

The study primarily uses the so-called "**midpoint" indicators** as the core indicators of the different environmental impacts estimated. With these indicators, the elementary flows contributing to the same impact categories[a] are aggregated (Jolliet et al., 2003)[1]. This means that once elementary flows are estimated they are grouped into the impact categories they contribute to. The EIPRO study followed the same approach.

The core indicators were complemented with **indicators** of the overall impacts from cars. This was done by assigning **monetary values** to the different impact categories which were then summed up (see Appendix I). There are obviously various uncertainties affecting such a valuation approach and due to the lack of harmonised and agreed methods to produce aggregated impacts.

Such aggregated indicators clearly deviate from the ISO standard guidelines on LCA[2,3]. They must be interpreted cautiously, keeping in mind the uncertainty entailed by the underlying assumptions and methodological choices made for their calculation. These assumptions concern the various complex physical, chemical and biological mechanisms (physico-chemical mechanisms, density of the exposed populations, exposed ecosystems, etc.) and, on top of that, the value assigned to life or any human being. It should also be remembered that some impact categories cannot be monetarised, leading to underestimations and to also some biases that need to be considered in the interpretation.

These indicators enable a first attempt to provide a rough estimate of the overall impacts and also to gauge the direct costs of the options analysed to the avoided environmental impacts.

2.3.2. Environmental impact categories considered

The project seeks to achieve the highest coverage of environmental impact categories. The EIPRO study considered the following categories:

- abiotic depletion
- acidification
- climate change
- photochemical ozone creation
- eutrophication
- human toxicity
- ecotoxicity
- ozone layer depletion.

a For instance CO_2, CH_4 and N_2O all contribute to climate change. However their respective contribution depends notably on their ability to absorb infrared and to their chemical stability. The global warming potential (GWP) enables to express one kg of each greenhouse gas in terms of CO_2-equivalent.

This list was nevertheless amended both to:

- better reflect some typical environmental aspects associated with cars
- further take into account some anticipated data gaps and problems of interpretation.

Although **abiotic depletion**, by definition, includes primary energy resources depletion, it was decided to explicitly quantify the life cycle **primary energy consumption**[b] associated with cars. Energy is indeed of crucial importance when dealing with transport and passenger cars, both in terms of energy resource depletion and energy security supply. Energy use is excluded under "abiotic depletion" in order to avoid double counting.

To calculate the midpoint indicators for the different impact categories, the CML 2001[4] methodology was used. However, for **photochemical pollution,** non zero factors have been used for NO_X. The factors used in IMPRO are given and justified in Appendix I. The category "solid wastes" (or "bulk waste") as suggested by the EDIP 97 methodology[5,6] was added. Some impact categories, despite their relevance, are not considered in this study.

Human and eco-toxicity are important when considering cars. However, quantifying the amount of toxic releases is a difficult task. This category involves a huge amount of different substances and toxicity types and there is still a lack of harmonisation in the different LCA databases. Moreover, emission factors from processes for many of the substances involved are fragmented and subject to high uncertainty; indeed, despite improving knowledge, toxicity potentials are still determined with high uncertainty (see Huijbregts, 2003)[7].

Emissions of benzene, toluene and xylene (BTX fraction) are known to be carcinogenic and should, in principle, be included in the analysis, but their quantification is difficult. BTX are volatile organic substances which enter the composition of unburnt hydrocarbons emitted in exhaust gases. Unfortunately, as the detailed composition of car tailpipe HC (VOC) emissions is generally unknown, the specific contribution of BTX is not singled out. These substance emissions will therefore be considered with the VOC emissions.

When considering particulate matter emissions which are also known to be a critical issue, fine particulates of below 2.5 micron diameter were considered. In 2000, mobile sources emitted 323 kt $PM_{2.5}$ (25% of the EU-25's total emissions) and 375 kt PM_{10} (12% of the EU-25's total emissions) (TNO, 2007)[8].

Two other impact categories, which were not considered in the EIPRO study, are important when dealing with passenger cars:

Land use is an important aspect. Land use associated with passenger cars related to road infrastructure (roads, motorways, parking) is still increasing in Europe and transport is continuously modifying the landscape and contributing to losses of biodiversity.

There are, however, serious limitations in considering land use as one impact category in the life cycle analysis framework, since the LCA community has, so far, not reached any consensus on how to measure this impact.

Nevertheless, the omission of the land use impact category in this project does not entail any bias in the analysis of the majority of the improvement options considered in this project (see section 2.4) as most

b For energy, total primary energy over the car life is calculated. However, the fact that the well-to-tank (WTT) and tank-to-wheel (TTW) parts have been considered separately means that the distribution of primary energy is not strictly calculated. For the WTT part, the energy accounted for is the energy used to produce one unit of final energy (petrol or diesel), from the oil extraction to the refinery process.

of them are neutral regarding land use intensity. The only exception relates to biofuels that require land for their production. This aspect will be discussed separately when this option is analysed.

The impact of **noise** is another category that was excluded from the analysis despite the fact that noise produced by cars is far from negligible. Some work is being done in the framework of UNEP/SETAC. Noise is measured during the standard type approval tests. However, data would be lacking when considering improvement options and for undertaking a comprehensive assessment, on-site conditions would need to be considered which is not possible within this project.

In summary, this project has considered the following impact categories (midpoint indicators):

- climate change (GWP)
- acidification (AP)
- eutrophication (EP)
- ozone depletion (ODP)
- photochemical oxidation (POCP)
- consumption of primary energy resources (PE)
- abiotic depletion (excluding primary energy depletion) (AD)
- solid waste (BW)
- particulate matters with a diameter lower than 2.5 microns (PM2.5) .

2.4. Approach for analysing improvement options

2.4.1. Objective and scope definition

The project aimed at identifying the main environmental improvement options related to passenger cars, addressing all the different life cycle stages and at estimating the size of the environmental improvement potentials.

In the assessment of the improvement options, the following questions were addressed:

- What could be achieved at the various life cycle stages and what would be the overall environmental benefit of these various options?
- What are the potential trade-offs between the different options and between the different types of environmental benefits?
- What are the different barriers (economic, social, market, etc.)? What are the costs?

Improvement options for passenger cars can be broadly classified as follows:

- options consisting of improving **car efficiency** through a change in its design (engine, car design, material composition)
- options consisting of a change in **car usage patterns**, resulting in fewer environmental impacts
- options consisting of **infrastructure changes** like dynamic traffic lights, road rolling resistance, etc.
- options consisting of **more systemic changes** such as the shift from private cars to collective transport, the reduction in mobility needs through changes in urban and land use planning of the different human activities.

Although representing a significant potential, the third and fourth options are of lower relevance for a Product Policy. The focus was therefore made on options one and two.

2.4.2. Environmental benefits

Once identified, the options were analysed with regard to their environmental benefits. To this end, the generic car models initially defined and used to estimate the different life environmental impacts of representative cars of the new EU-25 car fleet were used to simulate the effect of the options considered on their life cycle environmental performance. In practice, this meant that the same system definition, impact categories and functional units were used both to evaluate the baseline car models and the improved ones.

This also meant that the environmental benefits of the different options were not analysed and quantified for the EU-25 car fleet as a whole, but, instead in terms of impact reduction at car level. This was made in reference to the functional unit defined to implement the process-chain analysis (100 km). When reviewing the different improvement options consisting of a change of the car efficiency, and identifying the most technically and socio-economically feasible ones, it appeared that most of them were applicable to the new and future car fleet. Options consisting of a change in car use efficiency would obviously be applicable whatever the age of the car.

Providing a comprehensive quantification of the environmental benefits of the different options studied would have required applying more comprehensive and prospective modelling tools regarding the car fleet of today and that of the future along with their various impacts. Different European transport models exist (TREMOVE, TRANSTOOLS, ASTRA) which could potentially be used in such a future step.

In addition, some of the improvement options analysed in this project were, to a large extent, assessed together with related policy options and review processes. Impact assessments were, for instance, produced by the European Commission about the following:

- the formulation of new air pollution standards (EURO5 and EURO6)
- the review of the Community's strategy to reduce CO_2 emissions and improve fuel efficiency from passenger cars and light commercial vehicles
- the proposal for a new Directive regarding the fuel quality
- the targets contained in the Directive on end-of-life vehicles
- the review of the progress made in the use of biofuels.

2.4.3. Socio-economic barriers and costs

When analysing the options for the environmental improvement of passenger cars, their socio-economic impacts have to be considered in order to derive realistic estimates of potentials and environmental benefits.

In many cases, the implementation of the improvement options beyond any autonomous development requires new policy interventions with instruments selected amongst different possibilities and whose expected effects are assessed ex-ante. The social and economic impacts of the options will depend on the supporting policy that is put in place and on how this policy interacts with the economic agents (industries, consumers, institutions). For example, one new technology can be supported by push or pull incentives (taxes, subsidies, regulations and trainings are all possible examples) that may have different direct and indirect impacts on society.

A complete analysis of the socio-economic effects would require the use of a quantitative model that looks at how economic agents respond to new policy interventions. And, as already noted, this is beyond the scope of this project that is restricted to the analysis of the technically feasible options and does not consider the policy options aimed at supporting their market diffusion. On the other hand, this study provides preliminary indications regarding the socio-economic barriers and possible impacts associated with the options. Most of these socio-economic aspects can only be identified and qualitatively described. When quantification is made, this has to be considered as a first input for a broader impact assessment to be undertaken later in case policy options are subsequently envisaged.

The list of criteria established in the European Commission's guidelines for impact assessment[c] represents an initial reference to define the most relevant socio-economic impacts within this project and also to select those for which a meaningful quantification could be made. This list was considered in order to address two key questions:

1. Is the socio-economic impact relevant for the product group considered?
2. Can the potential impact be assessed disregarding the possible policy which would support the implementation of the option?

Regarding the **economic impacts**, all the categories considered in the impact assessment guidelines are relevant when considering passenger cars. Conversely, only a small number of these impacts can be assessed disregarding the policy options envisaged. This is why the quantification of economic impacts in this project is restricted to the **costs** induced by the different options analysed in this project (Table 1). Appendix I describes how these costs were quantified.

These costs will be considered together with the quantified environmental impacts of the different improvement options in order to assess the efficiency of the different options.

Table 1: Impact assessment criteria and quantification in the project

Economic impact	Quantification in the project
Competitiveness, trade and investment flows: Does the option have an impact on the competitive position of EU firms when compared with their non-EU rivals?	No
Operating costs and conduct of business: Does the option affect the cost or availability of essential input (raw materials, machinery, labour, energy, etc.)?	Yes
Does it impact on the investment cycle? Will it entail the withdrawal of certain products from the market? Is the marketing of products limited or prohibited?	No
Consumers and households: Does the option affect the prices consumers pay?	Yes
Specific regions or sectors: Does the option have significant effects on certain sectors?	No

Regarding the **social impacts** (see the matrix in Appendix I), employment and health aspects are the most relevant impact categories when considering improvement options for passenger cars. However, the scale and distribution of impacts on employment highly depend on the policy option envisaged. The project cannot thus provide any assessment regarding this question.

c IQ Tools: Supporting impact assessment in the European Commission. Available at: http://iqtools.jrc.es.

Health aspects as considered in the impact assessment guidelines, when transposed to the specific passenger car case, are mostly related to energy use and polluting substances which are explicitly analysed in the project. These aspects are therefore considered when analysing the environmental benefits and avoided damages.

Other aspects such as health and life loss related to **road safety** are obviously relevant. **In the study, when considering the different options, the options that would entail less safety for passengers and for other road and urban infrastructures were not considered (pedestrians, cyclists, etc.).**

The **environmental domain** is the central topic for this project and as the project implements the life-cycle approach, the most important impact categories are inherently considered and quantified. As explained in section 2.3, some impact categories are not considered for quantification due to the lack of data or agreed methodologies in the LCA community. However, due to the relevance of these impact categories, a qualitative assessment has been carried out.

Generally, the different impact assessments produced by the European Commission to assess the various new proposed policies should be considered along with this project.

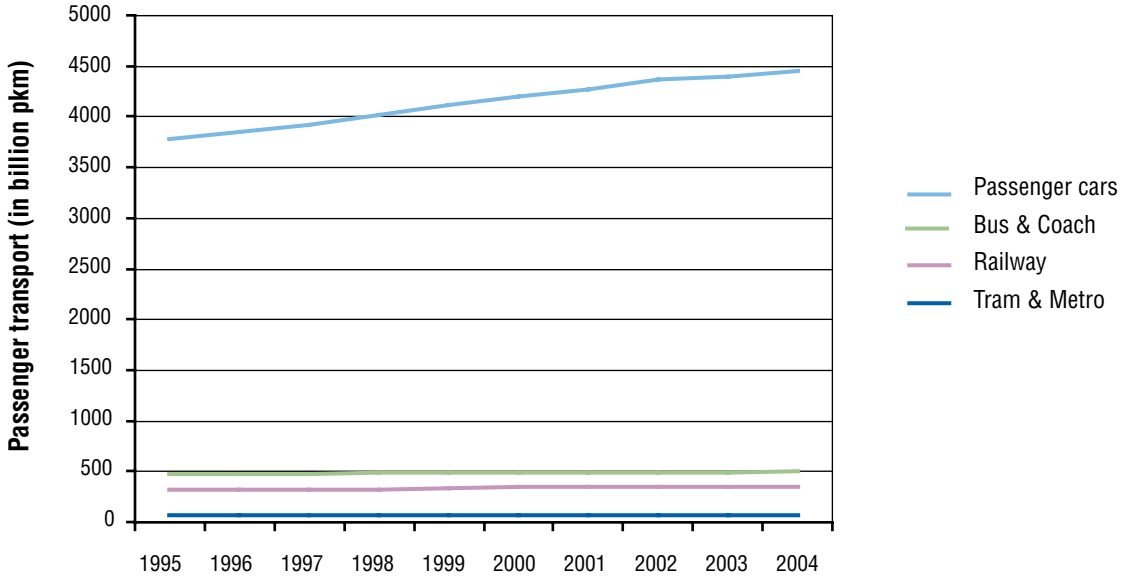
3. General overview of passenger cars in the EU-25

3.1. Introduction

Mobility of people plays an important and growing role in our economies. Over the period 1990 – 2000, it grew by 20% in the EU-15. The growth was also important between 1995 and 2005 in the enlarged European Union (by more than 15%). By far, road mobility needs are primarily met with passenger cars (see Figure 2).

In 2004, passenger cars accounted for around 83% of the total EU-25 land transport demand (in passenger-km)[9] with an annual growth rate of 1.8% between 1995 and 2005. For the year 2005, the modal split of transport modes estimated with TREMOVE is shown in Figure 3 (for the EU-19+2)[d].

Figure 2: Evolution of passenger transport per mode in the EU-25 from 1995 to 2004



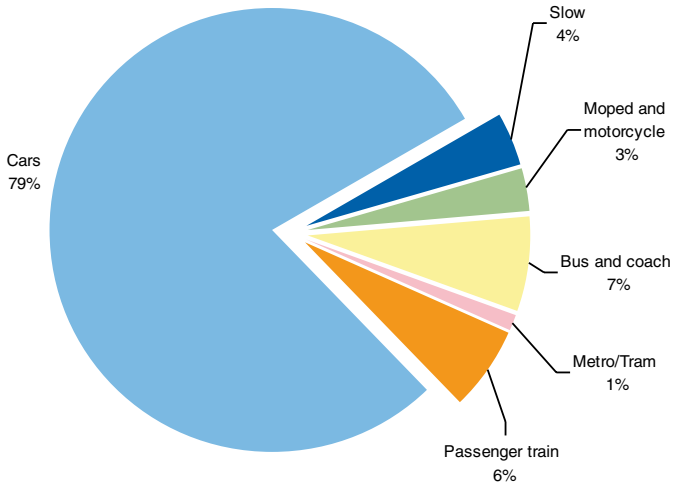
Source: European Union Road Federation[e]

There were 418 cars per 1 000 inhabitants on average in the EU-25 in 2005 and 404 in the EU-27 (see Figure 4). Also, between 7 000 and 13 000 km where travelled per car in 2000.

d All EU-25 Member States except Malta, Cyprus, Slovakia, Estonia, Lithuania and Latvia plus two non-EU countries (Norway and Switzerland).

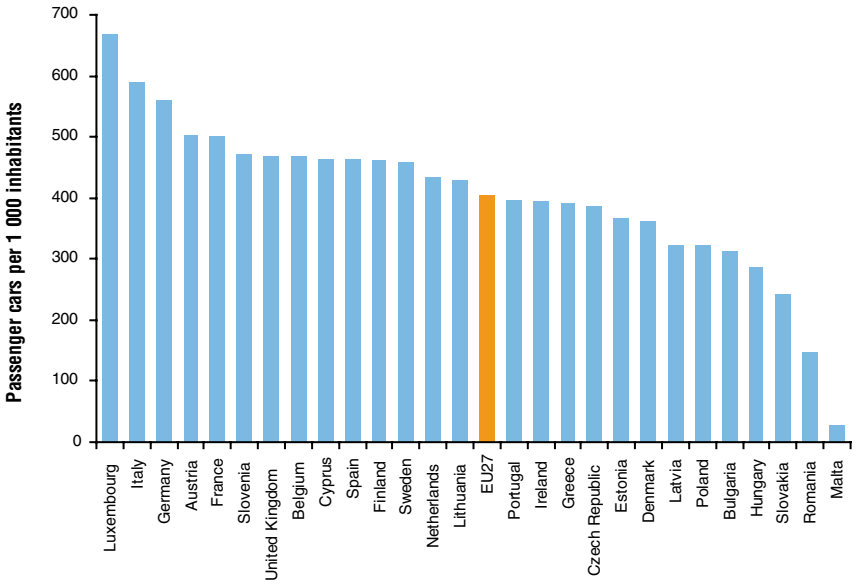
e European Union Road Federation: 2007 Road Statistics. Available at: http://www.erf.be/section/statistics.

Figure 3: Distribution of transport mode in total mobility



Percentages based on 2005 estimates in TREMOVE in the EU-19+2

Figure 4: Density of passenger cars by country in the EU-27 in 2005



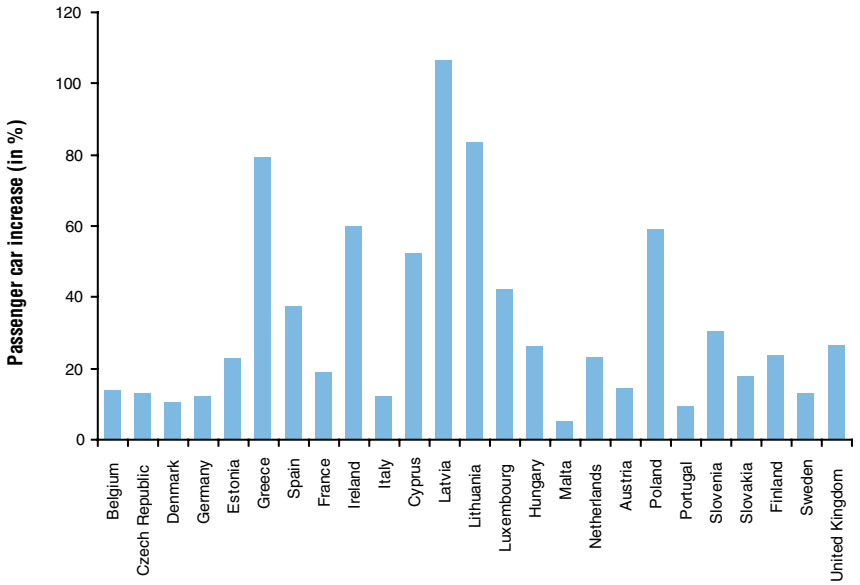
Source: Derived from the European Union Road Federatione

3.2. The EU passenger car fleet

3.2.1. Overview

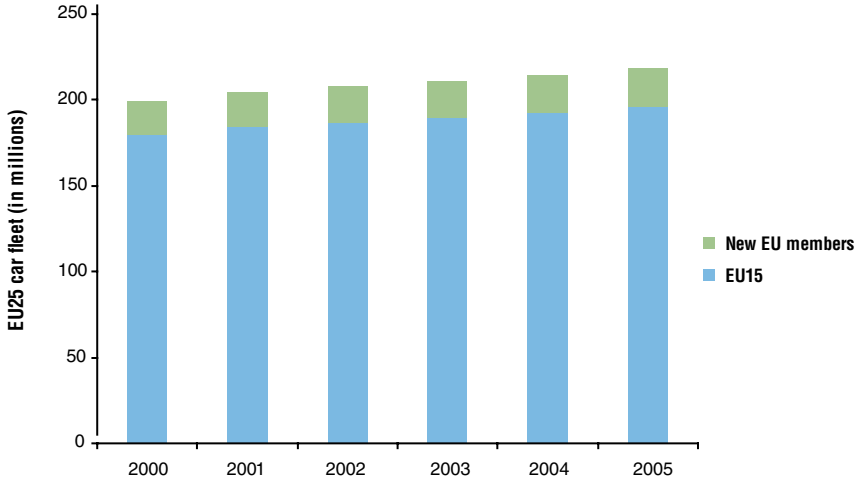
The number of passenger cars increased by nearly 40% between 1990 and 2004. The largest increases were recorded in Lithuania (+167%), Latvia (+142%), Portugal (+135%), Poland (+128%) and Greece (+121%). On the other hand, Sweden (+14%), Denmark (+20%) and Finland (+21%) registered the smallest increases. As shown in Figure 5 and Figure 6, the number of passenger cars in use in the EU-25 has grown continuously, reaching 213 million in 2005 compared to around 194 million in 2000.

Figure 5: Passenger car fleet evolution in the Member States from 1995 to 2004



Source: Eurostat + ACEA

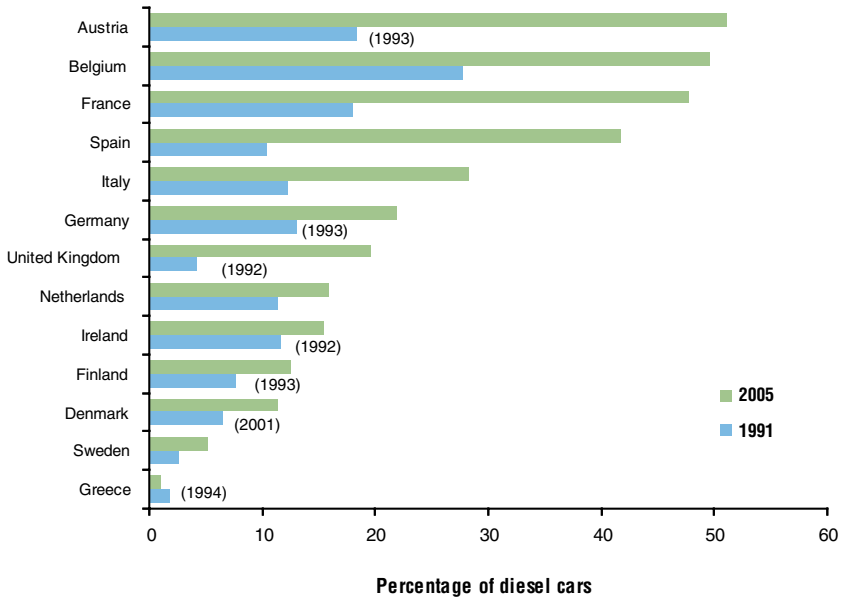
Figure 6: EU-25 car fleet (in million)



Source: Derived from ACEA

The share of diesel cars in the entire passenger car fleet is increasing in most Member States. Overall, the ACEA reported that around **30% of the European car fleet in 2005 was diesel powered** (in EU-25). Also, results from TREMOVE (version 2.32b) showed an increase of the total share of diesel vehicles from 13.5% to 23.5% over the period 1995 – 2005 in the countries covered (EU-19+2). Figure 7 illustrates this dieselisation phenomenon in some EU countries over a significant period of time.

Figure 7: Evolution of the share of diesel cars in the passenger car fleet in some EU Member States



Source: Derived from ACEA

The average size of car engines also changed since 1995. The share of medium and big cars (>1 400 cm^3) has increased from 50% to 59%. Table 2 shows that the share of medium/big cars is dominant for diesel cars in the existing car fleet which is not the case for petrol cars. Only a small share of the vehicle stock consists of LPG cars and natural gas compressed cars.

Table 2: Composition of the vehicle stock in the EU-25

	1995	2000	2005
Petrol small <1.4l	48%	44%	38%
Petrol medium 1.4l – 2.0l	31%	31%	28%
Petrol big > 2.0l	6%	5%	5%
Petrol cars	**85%**	**80%**	**71%**
Diesel small <1.4l	0%	0%	1%
Diesel medium 1.4l – 2.0l	8%	13%	20%
Diesel big > 2.0l	5%	5%	6%
Diesel cars	**13%**	**18%**	**27%**
Total cars	**100%**	**100%**	**100%**

Source: Based on preliminary estimations from TREMOVE 2.50 in EU-19+2

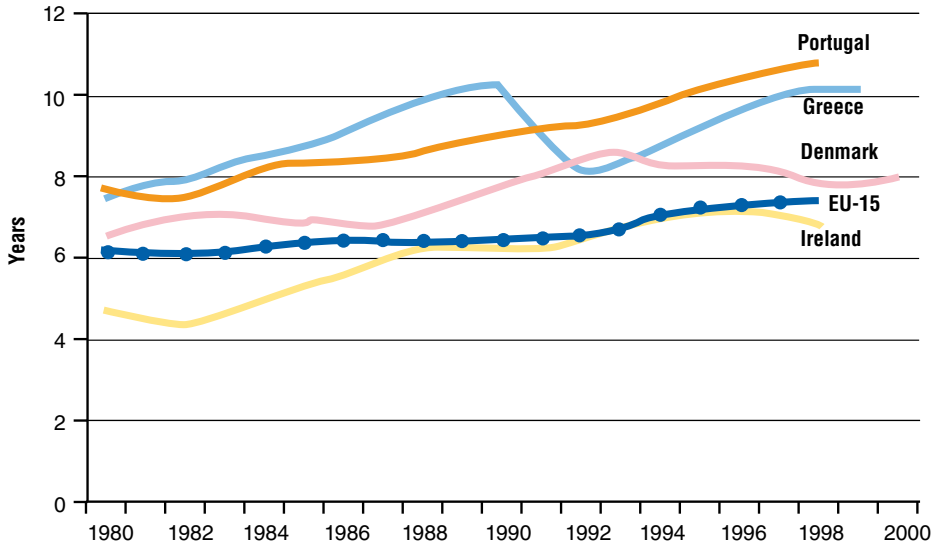
3.2.2. Average age of the car fleet

The average age of driven passenger cars in the EU-15 increased from 6.1 in 1980 to 7.6 years in 1999[10,f] (see Figure 8). This average age can vary widely between countries depending on their general

f The ACEA reported an average age of the car fleet of about 8 years in 2005.

economic conditions. For instance, the effects from scrappage schemes implemented in Greece and Denmark in the 1990s can be seen in Figure 8.

Figure 8: Average age of the car fleet in the EU-15



Source: EEA, 200310

3.2.3. Decomposition by age categories of the car fleet

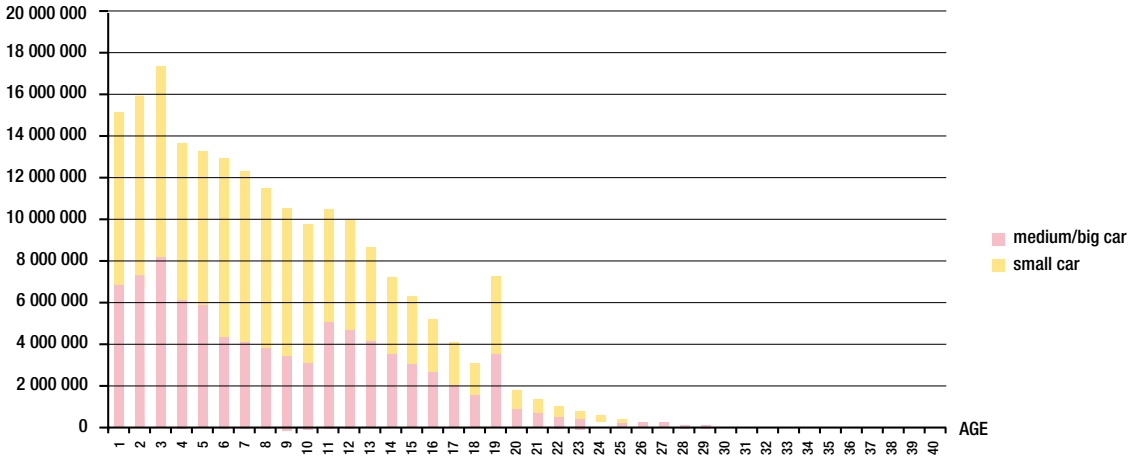
Figure 9 displays the composition of the car fleet in 2005. The statistics show that in 2004 cars more than 10 years old were generally more prominent in the new Member States than in the EU-15 (see Table 3).

Table 3: Composition of the car fleet in terms of age

	Less or equal to 2 years	Between 2 and 5 years	Between 5 and 10 years	10 years and older
Austria	14%	20%	32%	33%
Belgium	14%	25%	32%	29%
Finland	12%	16%	24%	47%
Ireland	17%	32%	37%	14%
Netherlands	14%	22%	33%	31%
Spain	15%	22%	24%	39%
Sweden	12%	19%	29%	41%
United Kingdom	18%	26%	33%	20%
Cyprus	9%	12%	34%	45%
Estonia	7%	8%	16%	69%
Hungary	20%	16%	18%	46%
Latvia	3%	4%	9%	85%
Poland	7%	12%	25%	56%

Source: ANFAC/ACEA11

Figure 9: Total number of small and medium/big cars by age in 2005 in the EU-19+2



Source: TREMOVE

The most up-to-date data (ACEA) indicate that almost 11.4 million cars are deregistered annually in the EU-15. Data for the enlarged EU are not known. Figures for Hungary suggest that 220 000 cars were deregistered in 2004. Only a fraction of these deregistered cars are scrapped.

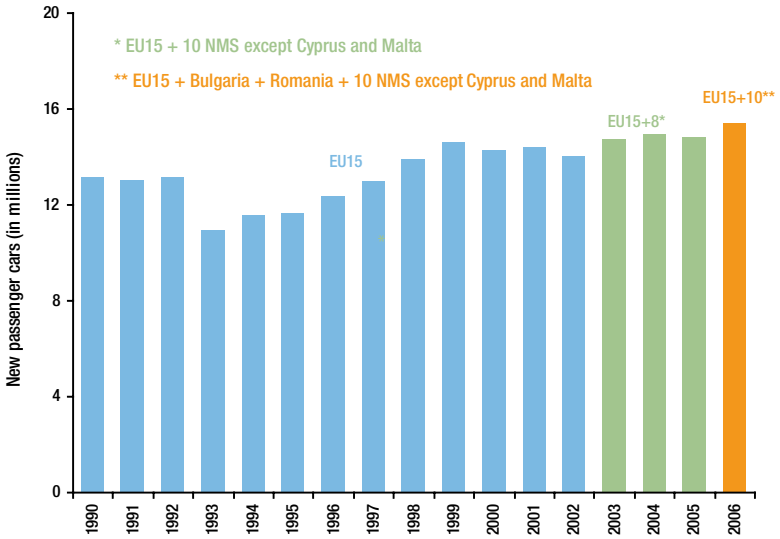
3.3. New car registrations and characteristics

3.3.1. New car registrations

Figure 10 depicts the evolution of new passenger car registrations between 1990 and 2006 in Europe. In 2006, the total number of new registrations was 15.42 million in the EU-27 (excluding Malta and Cyprus) which is slightly lower than in 2005. If the EU-15 only is considered, the total number has slightly increased from 14.32 million in 2000 to 14.36 million in 2006, but still remains lower than the record year of 1999.

The causes of these fluctuations are very diverse like, e.g. fuel price fluctuations, rising interest rates or lack of new models. A more detailed analysis of these factors is given in the ACEA Industry Report 07/08[12].

Figure 10: Evolution of new passenger car registrations in Europe

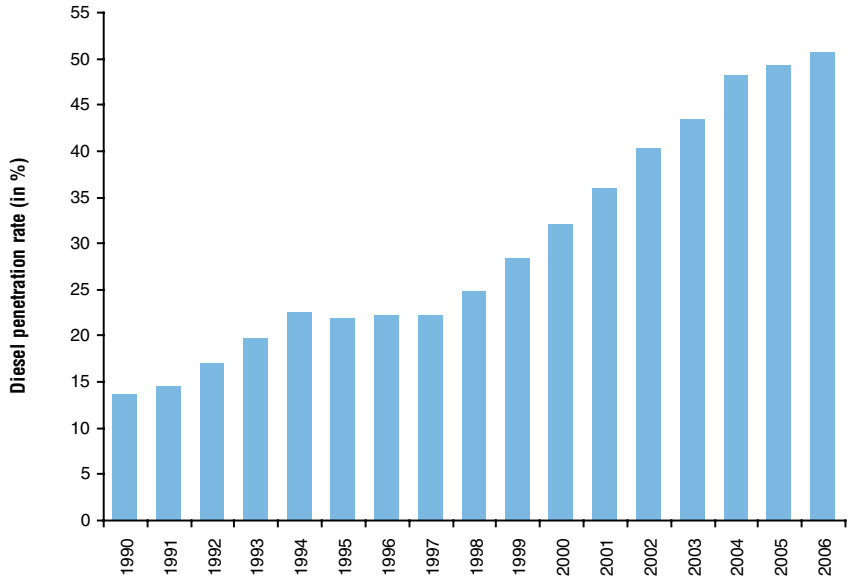


Source: Derived from ACEA

3.3.2. Penetration of diesel cars keeps on growing

As shown in Figure 11, the share of diesel cars has been continually increasing. The shift from petrol to diesel corresponds to more than 15% between 2000 and 2004. In 2006, the percentage of new diesel cars in the EU-15 + EFTA countries reached 50.8%. Great differences among the EU countries remain however due to tax regimes (e.g. in 2006 more than 70% of new registrations in Luxembourg, Belgium and France were diesel-powered cars. On the other hand, Greece (<4%) or Sweden (<20%) present much lower penetration rates).

Figure 11: Diesel penetration rates in Western Europe (EU-15 + EFTA)



Source: ACEA Industry Report 07/0812

3.3.3. Characteristics of new cars

A large share of the EU-15 new sales makes it possible to use the related information to derive the main characteristics of the new car fleet. This is made by using the data and information reported by the European Commission in the last report on the Community strategy to reduce CO_2 emissions from cars[13]. Based on these data, both the average power and the average cubic capacity were estimated to be 80 kW and 1 743 cm^3 respectively in 2004. It is worth mentioning that even though the average cubic capacity continuously increased from 2000 to 2004 (see Table 4), the following years 2005 – 2006 showed a slight decrease to reach 1 732 cm^3 in 2005 and 1 728 cm^3 in 2006. On the other hand, the average power has increased from 80 kW to 85 kW between 2004 and 2006.

Table 4: New vehicle characteristics in the EU-15 (2000 – 2006)

		2000	2001	2002	2003	2004	2005	2006
Power (kW)	**Average**	**72**	**75**	**77**	**78**	**80**	**82**	**84**
	Min	61 (PT)	64 (PT)	66 (PT)	66 (PT)	69 (PT)	72 (PT/IT)	64 (PT/IT)
	Max	95 (SW)	101 (SW)	101 (SW)	103 (SW)	104 (SW)	103 (SW)	104 (SW)
Capacity (cm^3)	**Average**	**1 698**	**1 723**	**1 736**	**1 738**	**1 740**	**1 732**	**1 728**
	Min	1 432 (PT)	1 482 (PT)	1 490 (PT)	1 496 (GR)	1 523 (PT)	1 524 (PT)	1 537 (PT/GR)
	Max	1 912 (SW/LU)	1 967 (SW)	1 972 (SW)	1 984 (SW)	1 999 (SW)	1 990 (SW)	1 972 (SW)

Source: ACEA
Initials in the brackets indicate the country

Table 5 presents a general view of technical characteristics of new cars in 2004. As expected the diesel cars have greater technical parameters than petrol cars. For instance, the average diesel capacity is roughly 1.9 l compared to 1.6 l for petrol.

Table 5: Average technical characteristics of new cars in the EU-15 (2004)

	Petrol				Diesel				Petrol + Diesel
	ACEA	JAMA	KAMA	All	ACEA	JAMA	KAMA	All	
Weight (kg)	1 249	1 234	1 113	1 240	1 453	1 486	1 741	1 462	1 349
Capacity (cm^3)	1 604	1 581	1 351	1 585	1 892	1 987	2 130	1 905	1 743
Power (kW)	79	80	62	78	83	81	85	83	80
Total sales	5 375 334	1 209 135	409 508	6 993 977	6 061 452	569 151	155 884	6 786 487	13 780 464

Source: European Commission

It thus appears that the medium car category (i.e. with a cylinder capacity of between 1.4 l and 2 l) dominates the new cars sales in Europe. The range of power and capacities has also been widening with the rapidly increasing penetration of big cars and SUV models (see Table 6). According to ACEA data, the share of SUVs in new car sales in Western Europe was almost constant over the period 1990 – 1997 and suddenly increased from 2.9% in 1997 to 8.2% in 2006.

Table 6: Breakdown of new passenger car registrations in Western Europe (EU-15 + EFTA) by bodies

Year	Saloons	Estates	Coupes	Convertibles	Monospaces*	Others	Unknown
2006	57.3%	13.0%	1.2%	2.7%	18.3%	7.4%	0.2%
2005	57.3%	13.0%	1.1%	2.8%	18.9%	6.6%	0.2%
2004	57.3%	13.1%	1.1%	2.8%	18.9%	6.6%	0.2%
2003	62.2%	13.2%	1.4%	2.5%	14.5%	5.4%	0.7%
2002	65.9%	12.5%	1.7%	2.0%	12.7%	5.2%	0.1%
2001	66.2%	12.1%	1.9%	1.9%	2.3%	15.6%	0.1%
2000	67.5%	12.6%	2.2%	1.5%	2.3%	13.8%	0.1%

** In 2002 there was a change in the definition of the monospace segment. This category now includes 'classic' monospaces, 'compact' monospaces and minispaces.*
Source: ACEA

4. Life cycle impacts of passenger cars

4.1. Introduction

The EIPRO study concluded that the contribution of passenger transport to the total environmental impacts of private consumption in the year 2000 ranged from 15% to 35%, depending on the impact category. Despite important improvements in car technologies, passenger cars have a high contribution to these impacts.

In this chapter, we further quantify the environmental impacts in more detail in order to both estimate the size of the different impacts and analyse the different life cycle stage contribution to the various impacts. This is made by applying the two complementary perspectives mentioned in section 2.2:

1. The application of the **process-chain approach** to some generic passenger cars. General characteristics were derived from the existing statistics about the new car fleet discussed in Chapter 3. In this first case, the environmental impacts generated over the full life cycle of individual cars were quantified. These impacts were then normalised to a unit distance driven with the car (100 km).
2. The estimation of the annual environmental impacts associated with the activities related to the current **EU-25 car fleet**, including the manufacturing of the cars purchased, the car use and the scrappage of end-of-life cars.

4.2. Life cycle impacts of generic passenger cars

4.2.1. Goal and scope definition

The goal of this analysis is to quantify the different environmental impacts generated over the life cycle of some typical cars that are marketed today in the EU-25.

The full life cycle of a car includes all transformation processes from the extraction of raw material and their transformation, through car component manufacturing with different materials, the car assembling, the car usage and upstream fuel chain, up to the car disposal. These transformation processes can be classified in stages.

The first main stages the production phase and it is of interest for policy purposes only when considering new cars. In fact, it is of very little interest to policy makers to know that a car produced 10 years ago generated a certain amount of air pollution.

This is one of the reasons why the application of a process-chain analysis was made for a new car.

It is also of little interest, and also possibly misleading to consider one very specific car case as the topic for a LCA analysis within this project: IPP will not seek to reduce the environmental impacts from one specific car model. Instead, it would foster improvement options that are applicable to as many cars as possible.

For this reason, two car models that best represented "average" new petrol and diesel cars were developed. These selected cars were also used as a reference case against which different improvement options are formulated and analysed in terms of environmental benefits (see Chapter 6). In a subsequent step, the costs of these different improvements were also assessed.

4.2.2. Definition of generic products and functional units

This study has considered two car base case models and has assessed their life cycle environmental impacts. These two cases were defined as those corresponding to the average characteristics of new cars sold in Europe, which primarily concern power, cylinder size and weight. These average characteristics were defined upon the most up-to-date statistics analysed and discussed in Chapter 3. These characteristics (e.g. cylinder size, power, weight, body model, lifetime, etc.) are summarised in Table 7.

The functional unit considered refers to the primary service of the car, namely the distance driven and was defined as a 100 km distance driven. This means that the overall life cycle impacts of the car are normalised to that functional unit. This enabled the effects of different mileages between the two car cases to be ignored.

By definition, the base case car models defined and considered differ in terms of weight and power. The two car models do not have identical performances (for instance in terms of acceleration[g]).

The two car models may also differ in terms of comfort and space.

This means that the environmental impacts estimated within this project cannot provide an accurate comparison regarding the respective environmental performance between a petrol car and a diesel car. However, as will be shown in section 4.5, the estimates derived remain in line with what the WTW project suggested.

In addition, the definition of car case models does not entail any serious bias when considering the improvement analysed. Also, the options do not suppose any change regarding comfort and safety.

Table 7: Main characteristics of the car models considered

	Petrol	Diesel
Average lifespan (years)	12.5	12.5
Air emission standard	EURO4	EURO4
Average annual distance (km)	16 900	19 100
Average total mileage (km)	211 250	238 750
Average cylinder capacity (cm^3)	1 585	1 905
Average power (kW)	78	83
Average weight (kg)	1 240	1 463
Body model	Saloon	Saloon

** Type approval value*

Both the petrol and the diesel car reference cases are assumed to comply with the **EURO4** standard regarding their tailpipe air pollutant emissions.

g This is a difference with the WTW study where several cars were defined by considering minimum performance criteria (time lags – for respectively 0 - 50 km/h, 0 - 100 km/h, 80 - 120 km/h – gradeability at 1 km/h, top speed, acceleration and range). The car models derived had similar – but not equal - performances. The engine displacement derived was respectively 1.6 l and 1.9 l for the petrol car and the diesel car, i.e. the same levels assumed in this project. Regarding the weight, the levels are assumed lower in the WTW study (1 181 kg and 1 248 kg) and the difference between the two cars is lower than what was assumed in this project (60 kg and 120 kg respectively).

4.2.2.1. Average car lifetime and annual distance

Overall, the average lifespan of a car in Europe is between 12 and 15 years. In a wide range of studies, car lifetime is assumed to be 12 years. Obviously, the life span varies between countries and vehicle technologies. In this study, an average life span of 12.5 years was assumed[h].

The average annual distance in Europe is around 15 000 km/year[i]. However, this value highly depends on the fuel type used since diesel cars are expected to total a higher annual mileage than petrol cars. In order to better estimate the annual distance for both types of cars, this parameter was calculated on traffic volume figures taken from TREMOVE for the year 2000 (in vkm) and the average annual mileage of petrol and diesel cars. This results in an average annual mileage of 16 900 km and 19 100 km respectively (medium/big car category).

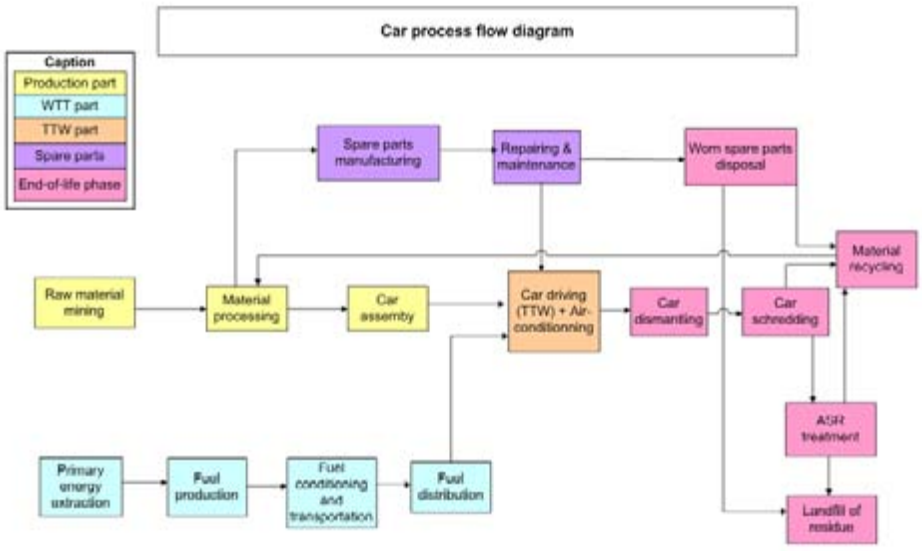
4.2.3. Product system definition and environmental categories

Figure 12 presents the major life cycle stages from cradle-to-grave for an automobile. Extraction and processing of raw materials, basic material production, assembling process, use of the car (WTT and TTW) and material recovery, recycling and disposal are the main phases included.

There are five main process groups:

1. Car production (including material production and car assembly).
2. Spare parts production (tyres, batteries, lubricants and refrigerants).
3. All fuel transformation process upstream to fuel consumption (WTT).
4. Fuel consumption for car driving (TTW).
5. Car disposal and waste treatment (EOL).

Figure 12: Process flow diagram of a car



Colours highlight the main life cycle stages in which accounted processes are allocated

h This value is derived from the scrappage function considered in TREMOVE.
i http://www.acea.be/.

The WTT and TTW together correspond to the well-to-wheel (WTW), i.e. the complete fuel chain.

Some processes are not dealt with in this study:

1. Transport of materials, car components and cars to the show room. The Ecotra study[14] has estimated the energy use per car transported to be about 100 litre fuel/ton transported, corresponding to about 4 GJ/car, which is negligible compared to the life cycle primary energy use of a car.
2. The EIPRO study suggests that road infrastructures represent a significant fraction of the life cycle impacts from transport (5% to 10%). These impacts are not included in the following calculations as none of the improvement options considered would affect the need for road infrastructures.
3. Road and motorway lighting. The study made by VHK (2005)[15] provides estimates regarding the impacts of street lighting in 2005 for the different impact categories. Even if these impacts are fully allocated to passenger cars (which overestimates the contribution from private road transport), the estimated impacts per 100 km remain low compared with those associated with the fuel consumption[j].
4. Car washing.

Omissions also concern:

- the manufacturing of cars – energy consumption during hydroforming, manufacturing of electronics, capital goods, etc.
- impacts generated during the car driving due to tyres and brake friction –according to the most recent Copert report[k], fine particles emitted from tyre/brake/road abrasion represent a small fraction of total suspended particles emitted by these processes. Furthermore, when considering $PM_{2.5}$ only, these emissions represent only 7% of the total road transport emissions[l].

The project has quantified the midpoint indicators as listed in section 2.3.2.

4.2.4. Assigning a monetary value to the various impacts

In order to provide an overall picture of the environmental impacts, the monetary values of the different impacts have been calculated and summed to an aggregated total. To this end, the coefficients detailed in Appendix I were used.

The caveats discussed in section 2.3.1 should be borne in mind when deriving the overall indications regarding the environmental impacts induced and also when appraising the cost effectiveness of improvement options.

4.3. Modelling approach

The environmental impact for the two reference cases was estimated by adopting the well established life cycle or process-chain approach that consists in analysing the two product systems 'diesel car' or 'petrol

j The primary energy is by far less than 1 GJ/100 km.
k Emission Inventory Guidebook, 2006, Road transport.
l The scale of the emission factors for fine particulates in relation to tyres and brake pads have been assessed by IIASA for the RAIN model, showing that the corresponding fraction of fine particulates is negligible when compared with tailpipe emissions (http://www.iiasa.ac.at/rains/).

car' by including, as far as possible, all the industrial or economic activities directly or indirectly linked to the production, use and end of life of the product itself (e.g. from cradle to grave). By encompassing all the life cycle stages of a product, this holistic approach permits a quantification of the overall and product-related environmental impacts that (in this study) are expressed in terms of aggregated midpoint indicators (i.e. t CO_2-eq for GWP, kg Sb-eq[m] for abiotic depletion, etc.). The overall and necessarily stylised structure of the analysed product system is shown in Figure 12.

For this purpose different data and information have been combined, such as:

- environmental impacts associated with the production of a certain unit (kg, MJ, etc.) of material or energy
- use of materials and energy in the manufacturing of a car as a function of its size or weight
- use of spare parts (e.g. batteries, tyres, lube oil, etc.) as a function of mileage
- fuel consumption and emission of pollutants related to the use of the car under average or more specific driving conditions (e.g. urban, non urban, etc.)
- functional relationship between the car's weight and fuel consumption
- recovery and recycling rate for metals and plastics.

Modelling the interaction of these parameters and variables made it necessary to devote effort into setting up a model flexible enough to allow for parameterisation and specification of functional forms other than linearly (e.g. a non linear functional specification has been applied in the case of cost assessment for the improvement options). Moreover, the parameterised set up of the model has proved to be very useful in the assessment of the improvement options, since in those cases, the parameters offer a way to proxy the technical and non technical options and compare their environmental profiles to those of the baseline models.

For this purpose, a specific tool has been developed in Matlab that offers a flexible modelling environment and allows for the specification of a parameterised model under different functional forms. Furthermore, the possibility of a contemporary assessment of both the environmental and economic impacts for all the tested improvement options has revealed an additional advantage of using this modelling framework.

By virtue of this modelling set up, a further analysis has been performed in a quite straightforward and integrated way. A Monte Carlo type of approach and variance based decomposition methods have been used to carry out an uncertainty and sensitivity analysis.

4.4. Key assumptions for the reference cases

4.4.1. Production phase

The production phase includes:

- the **extraction and processing of raw materials** into the different materials that compose the car and its spare parts
- the **car manufacturing and the assembling** of the different car components.

m In this entire report, the abbreviation "-eq" to refer to equivalent (CO_2-eq) is used.

4.4.1.1. Extraction and processing of materials

For the first step, life cycle data about the **extraction and processing of raw materials,** and **material production** were obtained from the Ecoinvent[16] database. All the selected Ecoinvent processes refer to the average Western European context (indicated with the acronym RER/U in Ecoinvent), except where otherwise specified. One exception is for iron and steel. The data for these processes were obtained from datasets provided by the International Iron and Steel Institute (IISI). The car's material composition was defined on the basis of what the existing literature suggests[17, 18].

Table 8 lists the material composition of the two baseline cars (diesel and petrol), and also the assumptions regarding the different materials (e.g. recycling rate, alloys).

Due to the lack of detailed information, the material composition for diesel and petrol cars was separated only for their relative content of iron, steel and aluminium, while the content of other non-ferrous metals, plastics and other materials is assumed to be the same.

The following notes refer to Table 8:

- the plastic category "other" is assumed to correspond to PP which is the most common plastic in car manufacturing
- textiles are assumed to be mainly polyethylene terephthalate (PET) and polypropylene (PP)
- other and miscellaneous materials have been excluded for the life cycle inventory
- polyethylene (PE) has been assumed to be high density polyethylene (HDPE)
- all fluids except fuels, refrigerants and lubricants, are excluded from the material composition. A study conducted by the University of Michigan[19] has been used as the data source for the fluids' percentage on the car's total weight. Therefore, their environmental impact is not assessed, but their contribution to the total car's weight, which entails larger fuel consumption per km, is considered
- paint is assumed to be alkyd paint with a 60% solvent content
- platinum (Pt), rhodium (Rh) and palladium (Pl), as used in converter catalysts, are included in the material composition according to what is indicated by an existing study (BIOIS 2006)[n]. Unavailability of detailed information meant that a distinction between the material composition of the catalyst in diesel and petrol cars could not be made.

4.4.1.2. Car assembling

Regarding car manufacturing and assembling, a lack of data limits the analysis to the environmental impacts in two ways:

- **energy** consumed during the assembly of the various components and
- **VOC emissions** due to painting operations.

Energy used (and fuel mix) for the assembly phase was derived from a study published by VW[20] :

n This study provides the following quantities per end-of-life vehicle: platinum 1.2 g, palladium 0.176 g, rhodium 0.274 g.

Table 8: Material composition for a petrol car and a diesel car

Materials (kg)	Petrol	Diesel
Total content of ferrous and non-ferrous metals	**819**	**1 040**
Steel BOF	500	633
Steel EAF	242	326
Total content of iron and steel	**742**	**959**
Aluminium primary	42	43
Aluminium secondary	26	29
Total content of aluminium	**68**	**72**
Cu	9	9
Mg	0.5	0.5
Pt	0.001	0.001
Pl	0.0003	0.0003
Rh	0.0002	0.0002
Glass	**40**	**40**
Paint	**36**	**36**
Total content of plastics		
PP	114	114
PE	37	37
PU	30	30
ABS	9	9
PA	6	6
PET	4	4
Other	**27**	**27**
Miscellaneous (textile, etc.)	**23**	**23**
Tyres		
Rubber	4	4
Carbon black	2	2
Steel	1	1
Textiles	0.4	0.4
Zinc oxide	0.1	0.1
Sulphur	0.1	0.1
Additives	1	1
Sub-total (4 units)	31	31
Battery		
Lead	9	9
PP	0.7	0.7
Sulphuric acid	4	4
PVC	0.3	0.3
Sub-total	14	14
Fluids		
Transmission fluid	7	7
Engine coolant	12	12
Engine oil	3	3
Petrol/diesel	23	25
Brake fluid	1	1
Refrigerant	0.9	0.9
Water	2	2
Windscreen cleaning agent	0.5	0.5
Sub-total	50	52
Total weight	**1 240**	**1 463**

Table 9: Energy consumption related to the assembling phase

Year: 2004	5.093.000 cars produced			
VW Europe	MWh	GJ	MJ/car	kWh/car
Gas and coal	5 680 000	20 448 000	4 015	1 115
Electricity	7 210 000	25 956 000	5 096	1 416
District heating	3 020 000	10 872 000	2 135	593
Total	15 910 000	57 276 000	11 246	3 124

Source: VW20

It was assumed that natural gas was the primary energy source used for district heating and that it was converted into final heat demand with a 70% efficiency so that the fuel consumption for heating was 3 050 MJ/car.

The energy demand for the production and processing of components was not included in this analysis. Compared to the VW Golf IV study[21], the total primary energy demand for car production including the production of materials (see Table 17) calculated in this study is lower. However, the underestimation due to the omitted component production does not exceed 10% of the overall energy consumption during the production phase and is not of great relevance compared to the primary energy demand from the use phase.

According to a study made by the Berkeley National Laboratory[22], electricity is primarily consumed in paint shops, lighting and HVAC. Fuels are mainly consumed in space heating, drying, and paint lines.

For paints, the figures considered in the new best available technique reference document (BREF) on surface treatments using solvents[o] (36 kg paint per car) were used, which is of the same order of magnitude as suggested by the VW Golf IV[21] study (41.6 kg). According to these two sources, NMVOC emissions are 4.8 kg/car and 3.2 kg/car respectively.

4.4.2. Spare parts production

Tyres, batteries, lubricants, and refrigerants are considered whereas transmission fluid, engine coolant, brake fluid, water and windscreen cleaning agent are not considered due to the lack of information.

4.4.2.1. Composition

The material composition of a battery (see Table 10) is derived from existing literature (GHK and BIOIS, 2006)[23].

Table 10: Battery material composition

Materials	% on total weight
Components containing lead	64
PP components	5
Sulphuric acid	29
Separators (PP, PVC, cellulose)	3
Total weight	**13 - 14 kg**

o http://eippcb.jrc.es/pages/FActivities.htm.

The material composition of a generic tyre with an average weight of 7.75 kg for a passenger car is reported by GHK and BIOIS (see Table 11). Due to a lack of data, textiles and additives are not accounted for and for the same reason, energy consumption for the manufacturing of tyres is not included.

Table 11: Material composition of a tyre for a passenger car

Materials	% on total weight
Rubber/elastomers	48
Carbon black	22
Metal	15
Textile	5
Zinc oxide	1
Sulphur	1
Additives	8
Total weight	**7.8 kg**

4.4.2.2. Average consumption of spare parts

The spare parts and their rate of consumption are shown in Table 12.

Table 12: Consumption rate for spare parts

Spare parts	Travelled distance (km)
Tyres	40 000
Batteries	80 000
Lubricants	10 000 (density 0.9 kg/l)
Refrigerants (R134a)	100 000 (density 0.000464 kg/l)
Brakes	40 000 (materials not quantified)

4.4.3. Tank-to-wheel (including mobile air conditioning)

The driving phase consists of driving the vehicle for a total distance of 211 250 km and 238 750 km respectively for the petrol and the diesel car (annual mileage times average lifespan).

The fuels considered are unleaded petrol and low sulphur diesel (50 ppm sulphur), produced and distributed in the EU-25.

In order to assess the environmental impacts generated by the full life cycle of cars including their actual use on roads by the final consumer, existing data about real world emissions due to car driving were considered, especially those from the ARTEMIS project[24]. This project has produced a very comprehensive database with measured emission levels form a large set of vehicles and different **real world driving cycles** (including sub-cycles, urban, rural and motorway)[p]. This is particularly relevant when considering options that assume a change in driving behaviour (see, e.g. eco-driving).

Unfortunately, this database provides real world emission data for very few EURO4 vehicles (three petrol cars and one diesel car). For this reason, type approval emission values were used for the regulated

p Considering real world emission factors in the framework of such a project should not be interpreted as a recommendation to substitute the NEDC driving cycle with another one for type approval purposes.

pollutants (CO, HC, NO_x, PM) as measured under the New European Driving Cycle (NEDC)[q]. Such measurements are made by the different Member States. Testing measurements carried out in the UK are made available on the internet by the Vehicle Certification Agency[25] and will be used as reference values in this study.

In order to derive an average emission value consistent with the car models considered, a selection criterion regarding the car cylinder of the cars measured in the UK sample was applied:

- for the petrol cars, a cylinder capacity between 1 450 and 1 700 cm^3
- for diesel cars, a cylinder capacity between 1 700 and 2 000 cm^3.

The average emission factors for CO_2 and regulated pollutants are presented in Table 13. It is worth noting that CO_2 emissions are close to the average NEDC CO_2 emission levels measured over the whole new car fleet in the EU-25 (169 g/km and 155 g/km for petrol and diesel cars respectively)[13].

Table 13: Average emission values derived from the test approval emission values reported in the UK

		Engine Capacity	CO_2	CO	HC	NO_x	PM
		cm^3			g/km		
Petrol cars	average	1 592	173	0.41	0.053	0.026	-
	min	*1 468*	*139*	*0.06*	*0.010*	*0.005*	-
	max	*1 699*	*221*	*0.78*	*0.096*	*0.071*	-
			-	*1.00*	*0.100*	*0.080*	-
Diesel cars	average	1 944	160	0.14	0.027	0.204	0.014
	min	*1 753*	*120*	*0.01*	*0.000*	*0.126*	*0.000*
	max	*1 998*	*205*	*0.48*	*0.377*	*0.245*	*0.025*
			-	*0.50*		*0.250*	*0.025*

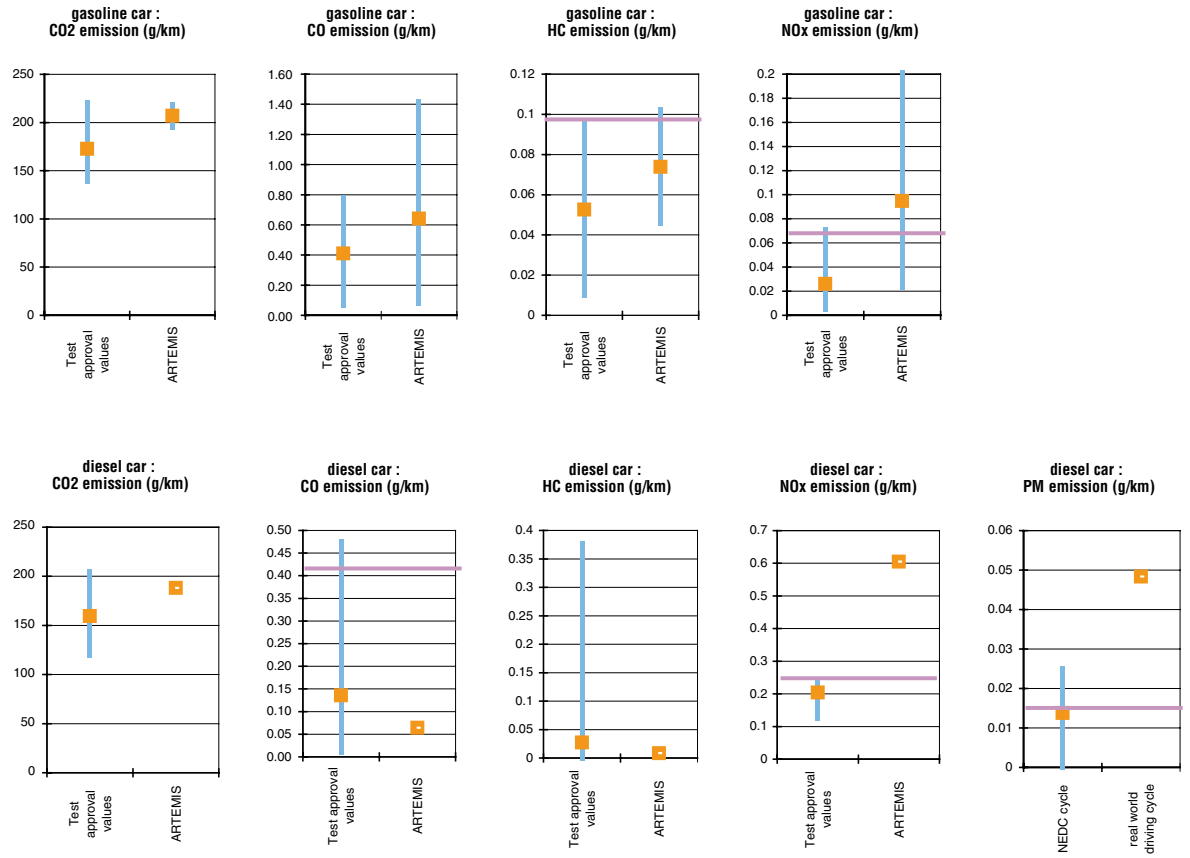
(EURO4 cars approved in the UK. Update Dec 2005, http://www.vcacarfueldata.org.uk/index.asp)

For the illustration of how test approval measurement can differ from real world emission values[r], the graphs shown in Figure 13 are presented which compare the two types of measurements. The comparison is of course not sufficient to derive the accurate effect of real world conditions on air pollutant emissions. It however does give a first indication of the direction and the order of magnitude. They for instance suggest that the gap is the highest for HC and NO_x emissions in the case of petrol cars and for NO_x and PM in the case of diesel cars.

q A combined chassis dynamometer test used for emissions testing and certification in Europe. It is composed of four Urban Driving Cycles, simulating city driving, and one Extra Urban Driving Cycle (EUDC), simulating highway driving conditions. The cold-start version of the test, introduced in 2000, is also referred to as the New European Driving Cycle (NEDC).

r Another aspect is the fact that type approval data include cold-start emissions, which is not the case in the ARTEMIS measures considered here.

Figure 13: Comparison of test approval measurements with real world emission levels



Source: type approval data: ***http://www.vcacarfueldata.org.uk/index.asp*** *and currently available data in ARTEMIS.*
The horizontal lines indicate the emission standards levels

CO_2 emissions and energy use present different levels under real world conditions when compared with NEDC measured values. Also, NO_X emissions under real world driving conditions lie well above those from type approval measurements. These differences were confirmed by the literature (see, e.g. Pelkmans (2006)[26], TNO et al.[148], Soltic et al.(2004)[27], Samuel et al.(2005)[28] and May and Gense (2006)[s]). Generally, it was underlined that fuel consumption and CO_2 emissions are underestimated by 10% - 20% in the NEDC compared to real world conditions (see, e.g. Pelkmans[26]). This effect is much better measured and documented for CO_2 than for other air pollutants.

In this study, an average of **14% additional energy use and** CO_2 **emissions** related to the various factors like occupancy rate, tyre deflation and driving behaviour are considered but still without including the air conditioning.

In order to add the MAC contribution, it is assumed that the two base case car models are equipped with the most common MAC system, i.e. based on HFC-134a as a working fluid (HFC-134a is not an ozone destructive gas but it is a greenhouse gas).

Correction factors were applied to the above emission levels to simulate the effects of MAC. These effects include the direct emissions of refrigerant (due to refrigerant leakages at the different life cycle stages)

s See presentations made during the EU level workshop on the impact of direct emissions of NO_2 from road vehicles on NO_2 concentrations (European Commission – DG ENV – 19 September 2006).

and the indirect effects resulting from additional energy consumption resulting from the operating air conditioning system (see also section 6.4). These corrections are described in the following paragraphs:

Correction on direct emissions: direct emissions are produced from refrigerant losses in the system occurring in rubber hoses and connections and also during servicing and charging, end-of-life treatment and accidents. From studies carried out by Ecole des Mines de Paris for ADEME, these average emissions correspond to a total of 70 g HFC-134a/year[29]. Considering the global warming potential of HFC-134a (1 300), the CO_2 emissions due to the total leakages was found to be around 5 g CO_2-eq/km from the assumptions made. It should be noted that this correction factor does not depend on the use level of MAC over the year, since leakages can occur when the system is on or not.

Corrections on fuel consumption and air pollutants: in the EU, the fuel used for automotive air conditioning is estimated to represent 3.2% of the automotive fuel consumption which, in turn entails additional CO_2 emissions and modified air pollutant emissions. The effect strongly depends on climate and driving conditions. Most of the assumptions made in this project are derived from ADEME information:

- **Over fuel consumption:** test campaigns conducted by ADEME[30,t] reported a 20% and 6% over fuel consumption for the **urban cycle** and the **extra-urban cycle** respectively, whatever the fuel considered. Higher values were measured in the case of extreme temperatures[u], with a more limited number of vehicles. The same percentage increase applied to CO_2 emissions
- **Air pollutants:** the corrections regarding pollutant emissions during the 2006 measurement campaign conducted by ADEME are summarised in Table 14.

Assumptions about the use of MAC: the intensity of the use of MAC of course depends on the climatic conditions. The IPCC[31] reported that MAC systems operate during 24% of the year in northern EU and 60% in the south of Spain. Figure 14 depicts the percentage range of MAC use (both cooling and demisting) for some countries, ranging from 20% in northern EU countries to 60% in South of Europe. The level of MAC use can also vary significantly within the same country. As an example, in France, the ADEME generally considers a 24% MAC use for Paris and 39.5% for Nice[v]. In the rest of this study, an intermediate average yearly value of 33% of MAC use is assumed.

Table 14: Average pollutant emissions in % spread between A/C on and off

		CO	HC	NO_x	PM
Diesel	Urban	-43%	-28%	37%	32%
	Extra-urban	-26%	8%	11%	1%
Petrol	Urban	39%	39%	43%	-
	Extra-urban	-4%	21%	-2%	-

Source: ADEME32
($T_{outside}$ = 25°C, Solar radiation ϕ = 550 W/m² and T_{set} = 20°C)

t In 2006, the ADEME carried out a test campaign with 16 vehicles (10 diesel cars and 6 petrol cars). Measurements were carried out under artificial sunshine of 550 W/m², an outside temperature of 25 °C and 50% relative humidity. The temperature within the saloon was set at 20 °C. The fuel consumption was measured for urban (average between 4 ECE 'cold' and 4 ECE 'hot') and extra-urban conditions (EUDC cycle).

u $T_{outside}$ = 35°C; T_{set} = 26°C; 60% relative humidity and without artificial sunshine, i.e. roughly similar to 30°C with a lot of sun.

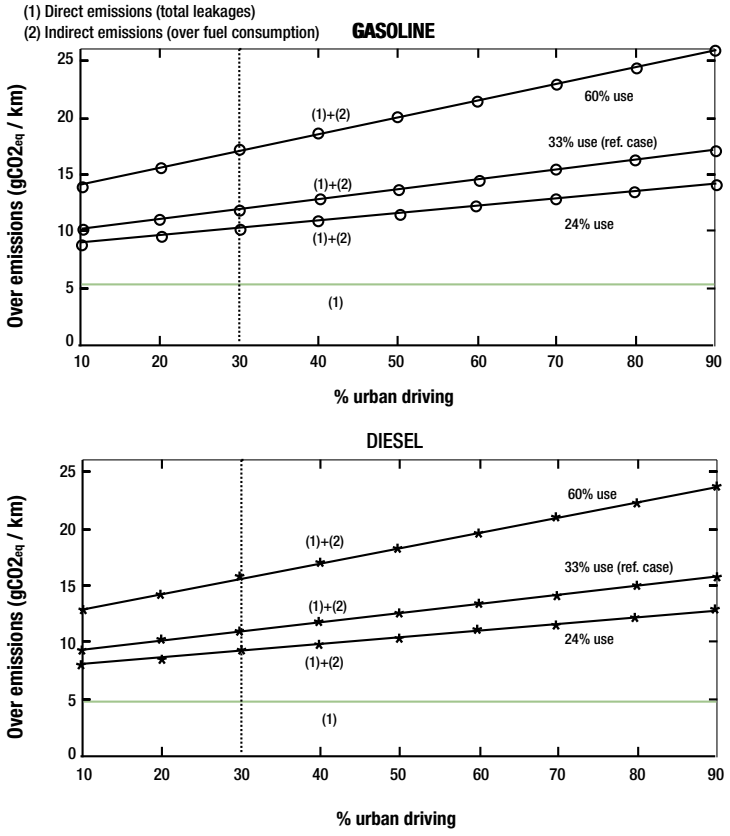
v Etude ARMINES/CRF, convention ADEME n°01 66 067, 2003.

Figure 14: The use of MAC in Europe

Source: Rugh, 200433

Finally, from the assumptions, the over fuel consumption due to the air conditioning system was around **3%** of the annual energy use (see section 6.4). This means that the total additional energy use and CO_2 emissions due to real world driving that were considered here is roughly **17%**[w]**.**

Figure 15: Influence of driving conditions on total CO_2-eq emissions for different MAC use



w As an example, TNO et al.[148] considered an overall factor of 1.195 between real world driving and NEDC.

(assuming direct emissions of 70g HFC-134a/year and indirect emissions of 20% urban and 6% extra urban)

Influence of driving conditions and use rate of MAC on total CO_2 emissions: In order to illustrate both the influence of MAC use and driving conditions on CO_2 emissions, Figure 15 plots the **total CO_2-eq emissions** (direct and indirect) obtained for different percentages of MAC use (ranging from 24% in Paris to 60% in Seville) and urban driving shares. As expected, the influence of the driving cycle increases when the MAC is more frequently used.

The conditions assumed in this study, i.e. 33% MAC use and around 30% of urban driving corresponds to 12 g CO_2-eq/km for petrol and 10.9 g CO_2-eq/km for diesel. Assuming a 30% urban driving share, the additional CO_2 emissions can vary from 10.2 g/km to 17.1 g/km for petrol and from 9.2 g/km to 15.6 g/km for diesel, while considering a MAC use range of 24% to 60% throughout the year (see Figure 15).

4.4.4. Well-to-tank (WTT)

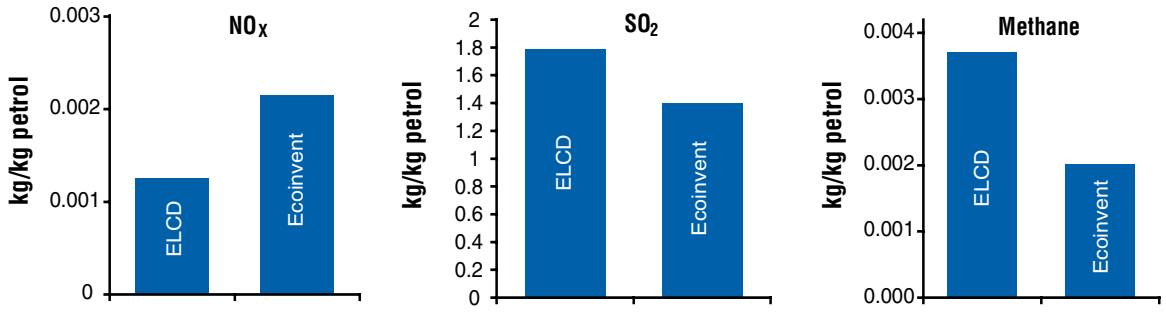
This phase includes crude oil extraction, refinery and distribution of the fuel.

The WTW study produced by the JRC(IES)/CONCAWE/EUCAR[34] is the most comprehensive and up-to-date study for the EU-25 providing detailed data about the primary energy use and greenhouse gas emissions associated with the fuel chain. These data were used to quantify these two impact categories.

For the other impact categories, the Ecoinvent database[35] was used which contains data about all the processes involved in the WTT at the European level. These impacts are, however, subject to important uncertainties. These uncertainties are illustrated by comparing the data taken from the Ecoinvent database and those reported in the European Life Cycle Data Set (ELCD)[x]. Published methane emissions, NO_x and SO_x emissions for instance very much depend on the assumptions regarding the different processes[y] (see Figure 16):

- methane: the amount of gas flared and in particular vented on oil production sites decreased in the past years. This might be a reason for higher CH_4 emissions in the ELCD dataset
- nitrogen oxides: lower emission factors (g/MJ, g/tkm) in refinery boilers and crude oil tankers might be a reason for lower values in the ELCD dataset
- sulphur dioxide: lower sulphur content of the liquid fuels used in the refinery (heavy fuel oil) and in the crude oil tanker (bunker oil: 3.5% average actual sulphur content) might be a reason for lower values in the ELCD dataset.

Figure 16: Comparison of the emissions in air of SO2, NOX and methane from the production of low sulphur petrol as reported in the ELCD dataset and Ecoinvent (kg/kg petrol)



x See the European platform on LCA managed by the JRC (IES): http://lca.jrc.ec.europa.eu.
y Personal communication with Rolf Frischknecht (Ecoinvent Centre – Empa).

This uncertainty must be kept in mind when interpreting the LCA results.

Another critical issue is the approach used to **allocate impacts** associated with crude oil transformation processes (from extraction to refinery) to the different oil products.

The combination of these data with the WTW study estimates for CO_2 and energy entails a certain degree of inconsistency due to the fact that the original data sources are different and also because the allocation of impacts from the refinery process to its different products is made differently:

- the WTW study used a marginal approach to allocate impacts to diesel and petrol
- the Ecoinvent database applies the "average" allocation approach, using the economic value of the different products.

The first approach is the most meaningful. As applied in the WTW study, it suggests that the refinery process entails more energy use and CO_2 emissions per MJ of diesel produced whereas the Ecoinvent database suggests that the other impacts are higher per MJ of petrol than per MJ of diesel. Based on this average approach, diesel is suggested to score better for the impacts other than CO_2 and primary energy (see Table 15).

Table 15: Environmental impacts per GJ petrol and diesel

	Petrol	Diesel	Unit	Source
Abiotic depletion (AD)	0.037	0.032	kg Sb-eq/GJ	Ecoinvent
Global warming (GW)	13	14	kg CO_2-eq/GJ	WTW study
Ozone layer depletion (ODP)	0.011	0.011	kg CFC-11-eq/GJ	Ecoinvent
Photochemical oxidation (POCP)	0.051	0.043	kg C_2H_4/GJ	Ecoinvent
Acidification (AP)	0.19	0.14	kg SO_2-eq/GJ	Ecoinvent
Eutrophication (EP)	0.015	0.014	kg PO_4-eq/GJ	Ecoinvent
Particles (PM2.5)	0.0048	0.0040	kg/GJ	Ecoinvent
Primary energy (PE)	0.14	0.16	GJ/GJ	WTW study

4.4.5. End-of-life (EOL)

The EOL baseline scenario assumed for the main basic material consumed is displayed in Table 16 and is based on estimates from GHK and BIOIS (2006)[23]. For the EOL of tyres, there is however a strong discrepancy between the figures reported by GHK and BIOIS (16.6% of tyres recovery) and other statistics (see, for instance, data produced by the European Tyre and Rubber Manufacturers Association http://www.etrma.org/) suggesting a recovery rate of around 60% in the EU-25.

This scenario assumes 100% landfilling of plastics. Specific data about the landfilling of plastics are available only for PE, PP and PU. The rest of plastics are treated as plastic mixtures. Paint and glass are assumed to be 100% landfilled.

As explained in the following paragraph, all waste treatment processes but recycling activities are accounted as part of the end-of-life.

One inherent difficulty in LCA studies is the accounting of the effects of activities taking place at the end-of-life of the products that involve materials reprocessing as recycling and reuse of materials or energy recovery. For instance, recycling materials from a disposed car supplies material that can be used in a new product (a new car or another new product) which therefore avoids using virgin material. There is no universally accepted approach for allocating either the physical impacts associated with the reprocessing

activity – which still requires using energy for instance – or the 'potential benefits' deriving from recycling that correspond to the difference between the impacts of the reprocessed materials and the virgin ones.

Table 16: End-of-life baseline scenario under market driven conditions (percentages)

	Reuse (%)	Recycling (%)	Recovery (%)	Landfill (%)
Ferrous	5	94	0	1
Non-ferrous (PGM not included)	10	87	0	3
Plastics + polymers	1	0	0	99
Tyres	21	0	66	13
Glass	0	0	0	100
Batteries	8	92	0	0
Fluids	29	71	0	0
Textiles	0	0	0	100
Rubber	0	0	0	100
Other	0	0	0	100

In this study the rules proposed by Koltun et al.[36] for recycling and recovery were used, which are:

- all materials and components of a product are produced for the life of that product
- the environmental impacts due to the disposal of materials and components that do not undergo any reprocessing are assigned to the product system they belong to
- the environmental impacts of the reprocessing activity (i.e. recycling, reuse, energy recovery, etc.) are ascribed to the process that makes use of the reprocessed materials.

In this approach, any advantage of using recycled material, for example in the production phase, is analytically captured in the lower environmental burdens associated with recycling compared to the primary route.

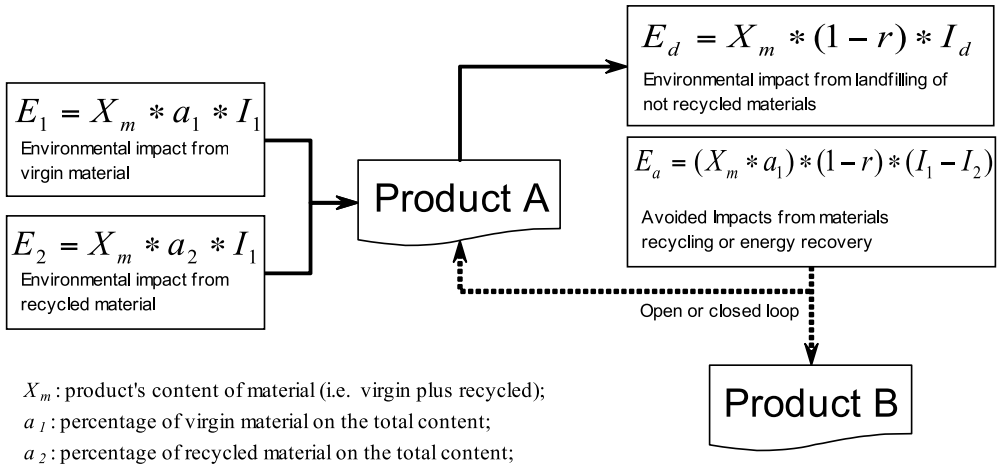
This methodological approach generates "uncredited" impacts, which means that in this study when accounting for recycling or recovery, although the potential benefits linked to the reprocessing of the end-of-life materials is quantified (e.g. using recycled materials compared to virgin ones), they are not subtracted from the overall impact of the product. The avoided impacts are presented separately to give an order of magnitude of the potential benefit associated with recycling and should always be interpreted cautiously as their scale strongly depends on the assumptions made regarding the material which is assumed to be substituted, the degree of quality of the recycled material and the new product which will potentially be made with this recycled material.

The approach used to calculate these potential avoided impacts is illustrated in Figure 17. The dashed lines refer to the two possible uses of the reprocessed material and allocation of the benefits or avoided impacts. In the same product system A of origin thus following a closed loop, or in a new product system B in this case with an open loop.

The approach used to deal with end-of-life recycling of materials does not double count any impact, since the 'avoided impacts' are calculated on the basis of the virgin material content of the product in the case of a closed loop or of the new product supposed to use the recycled material (especially relevant when discussing plastics recycling). For example, the potential benefits associated with the recycling of the car's steel content refer only to the metal which initially enters the production phase as primary and

they are calculated as the difference between the environmental impacts of the production of metals with the secondary process and the primary one respectively.

Figure 17: Schematic flow chart describing the approach adopted for the recycling of materials



X_m : product's content of material (i.e. virgin plus recycled);
a_1 : percentage of virgin material on the total content;
a_2 : percentage of recycled material on the total content;
I_1 : environmental impact for the production of one unit of virgin material;
I_2 : environmental impact for the production of one unit of recycled material;
E_1 : total environmental impact from production of virgin material;
E_2 : total environmental impact from production of recycled material;
r: recovery rate;
E_d: environmental impact from landfilling;
E_a : 'avoided' environmental impacts;

For **steel, aluminium, magnesium** and **lead**[z] a recycling rate of 95% (suggested by IISI for the automotive sector), 90%, 95% and 92%[aa] respectively has been assumed. For platinum, palladium and rhodium embedded in the catalyst, a recovery rate of 95%, 97% and 85% respectively is assumed.

4.5. Life cycle assessment results

This section discusses the overall contribution of the different life cycle stages of the two reference product systems "petrol" and "diesel" to the selected environmental impact categories. The results are presented both on a percentage basis (see Figure 18 and Figure 19) and in absolute values (see Table 17 and Table 18). The avoided impacts resulting from the recovery and recycling of part of the metal fraction (steel, aluminium and lead from batteries) are reported separately in the relevant tables. Figure 18 depicts characterisation results for the petrol car.

z Only lead components of the battery have been assumed to be recycled.
aa This rate refers to the recovery of the entire battery, as proposed in the GHK-BIOS End of Life study, and it has been applied to lead.

Figure 18: Life cycle impacts for the base case petrol car

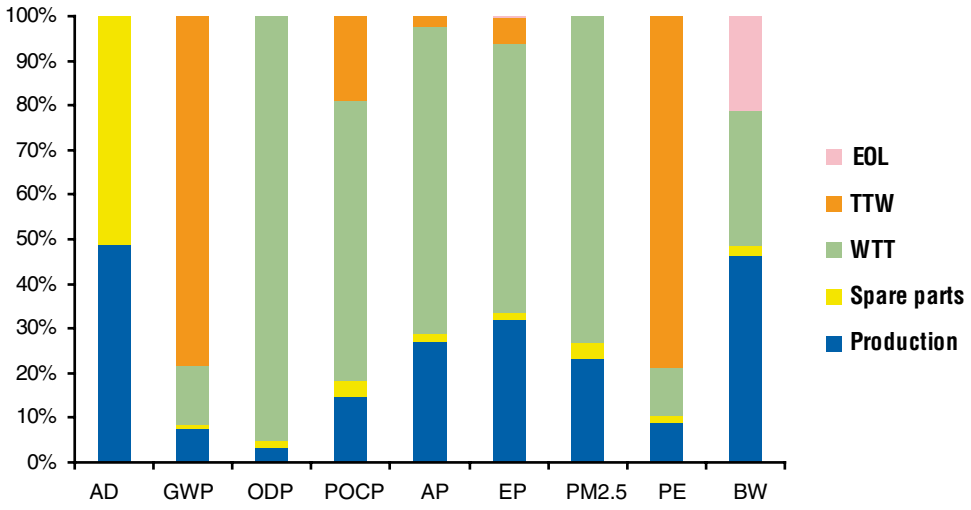


Table 17: Life cycle impacts for the base case petrol car

Impact categories	Units	Production	Spare Parts	WTT	TTW	EOL	Total
Abiotic depletion	kg Sb-eq	0.153	0.162	0.001	0.000	0.000	0.315
Global warming	t CO_2-eq	4.3	0.4	7.4	43.9	0.1	56.2
Ozone depletion	kg CFC-11-eq	0.0002	0.0001	0.0064	0.0000	0.0000	0.0067
Photochemical pollution	kg C_2H_4	7.0	1.8	30.2	9.0	0.02	48.0
Acidification	kg SO_2-eq	44.5	2.4	113.3	3.6	0.1	163.8
Eutrophication	kg PO_4-eq	4.8	0.2	8.9	0.9	0.03	14.8
PM2.5	kg	0.9	0.1	2.9	0.0	0.0	3.9
Primary energy	GJ	65.8	12.7	82.8	595.5	0.05	756.8
Bulk waste	kg	332.5	15.8	216.5	0.0	286.7	851.7

The contribution from the **production phase** is shown to be the most significant for bulk waste. The production phase determines significant impacts on abiotic depletion, eutrophication, particle emissions and acidification.

The high contribution to the abiotic depletion of the **spare parts production** results from lead which is assigned very high nominal values in the CML characterisation factors, compared to the other materials[ab].

The **WTT phase,** is shown to have high contribution to ozone depletion, acidification, photochemical oxidation, eutrophication and PM2.5. Contributions to greenhouse gas emissions and to primary energy are also significant. The actual scale of these contributions is subject to uncertainty to the two reasons mentioned in paragraph 3.

TTW phase has the largest contribution to greenhouse gas emissions and to primary energy. Its contribution is also relevant for photochemical oxidation and eutrophication.

ab These AD values (kg SB/kg) are as follows: aluminium: 1E-08, copper: 0.00194, iron: 8.43E-08, lead: 0.0135, magnesium: 3.73E-09, zinc 9%: 0.000992.

Some of these general patterns are also found for the **diesel car** (Table 18 and Figure 19). However there are also noticeable differences as compared with the petrol car:

- The contribution of the TTW is much higher for particulates, acidification, eutrophication and photochemical pollution. In the last three cases this is due to higher NO_x emissions.
- The difference of impacts between diesel and petrol for the WTT has to be considered cautiously as they are very much influenced by the data source used and also by the rules applied when allocating the emissions to the different products of refineries (see paragraph 3).

The low contribution from the EOL part (except for waste) was also one of the conclusions drawn also by the LIRECAR project[17].

Figure 19: Life cycle impacts for the base case diesel car

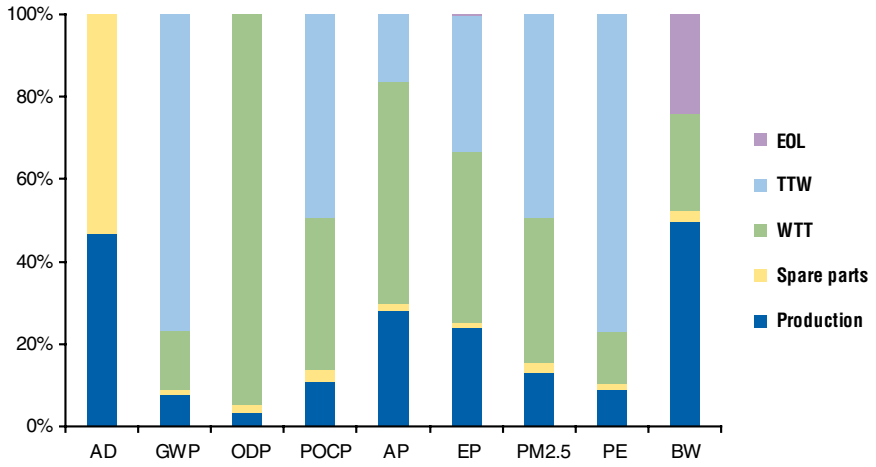


Table 18: Life cycle impacts for the base case diesel car

Impact categories	Units	Production	Spare Parts	WTT	TTW	EOL	Total
Abiotic depletion	kg Sb-eq	0.162	0.183	0.000	0.000	0.000	0.345
Global warming	t CO_2-eq	4.7	0.5	8.7	46.2	0.1	60.1
Ozone depletion	kg CFC-11-eq	0.0002	0.0001	0.0065	0.0000	0.0000	0.0069
Photochemical pollution	kg C_2H_4	7.6	2.0	26.1	34.9	0.02	70.7
Acidification	kg SO_2-eq	45.4	2.7	87.7	26.3	0.1	162.3
Eutrophication	kg PO_4-eq	4.9	0.3	8.5	6.8	0.03	20.6
PM2.5	kg	0.9	0.2	2.5	3.5	0.0	7.0
Primary energy	GJ	69.2	14.4	97.4	609.0	0.05	790.2
Bulk waste	kg	374.3	17.9	178.1	0.0	300.1	870.4

Table 19 and Table 20 show the impacts potentially avoided by metals recovery and recycling at a detailed level. The credits relate to the recycling of steel, aluminium, lead and the precious metals Pt, Pl and Rh and are the most significant for abiotic depletion, particles acidification and bulk waste.

Table 19: Credits for the petrol car system

Impact categories	Units	Steel	Lead	Aluminum	Pt	Rh	Pl	% production	% total
Abiotic depletion	kg Sb-eq	-0.0001	-0.14	-0.001	-0.002	-0.01	-0.0001	-48.3	-48.3
Global warming	t CO_2-eq	-0.78	-0.005	-0.38	-0.02	-0.01	-0.003	-25.3	-2.1
Ozone depletion	kg CFC-11-eq	0.0	-0.00012	-0.020	-0.0013	-0.0004	-0.0003	-6.6	-0.3
Photochemical pollution	kg C_2H_4	-1.5	-0.032	-0.5	-0.028	-0.008	-0.003	-23.7	-4.3
Acidification	kg SO_2-eq	-2.1	-0.19	-1.9	-5.6	-1.8	-2.4	-29.8	-8.5
Eutrophication	kg PO_4-eq	-0.26	-0.06	-0.17	-0.01	-0.003	-0.002	-9.9	-3.4
PM2.5	kg	0.0	-0.02	-0.17	-0.01	-0.003	-0.001	-18.8	-5.0
Primary energy	GJ	-0.77	-0.04	-5.25	-0.33	-0.1	-0.05	-8.3	-0.9
Bulk waste	kg	-172.6	-2.5	-63.6	-7.5	-2.5	-3.0	-23.5	-9.3

Table 20: Credits for the diesel car system

Impact categories	Units	Steel	Lead	Aluminum	Pt	Rh	Pl	% production	% total
Abiotic depletion	kg Sb-eq	-0.0001	-0.16	-0.001	-0.002	-0.01	-0.0001	-49.7	-49.6
Global warming	t CO_2-eq	-0.99	-0.005	-0.39	-0.02	-0.01	-0.003	-27.0	-2.3
Ozone depletion	kg CFC-11-eq	0.0	-0.00013	-0.021	-0.0013	-0.0004	-0.0003	-6.4	-0.3
Photochemical pollution	kg C_2H_4	-1.9	-0.036	-0.5	-0.028	-0.008	-0.003	-25.9	-3.5
Acidification	kg SO_2-eq	-2.6	-0.21	-1.9	-5.6	-1.8	-2.4	-30.3	-9.0
Eutrophication	kg PO_4-eq	-0.32	-0.07	-0.17	-0.01	-0.003	-0.002	-11.2	-2.8
PM2.5	kg	0.0	-0.02	-0.17	-0.01	-0.003	-0.001	-18.8	-2.9
Primary energy	GJ	-0.98	-0.05	-5.38	-0.33	-0.1	-0.05	-8.2	-0.9
Bulk waste	kg	-176.4	-2.8	-65.1	-7.5	-2.5	-3.0	-20.7	-9.3

An interesting result is that the primary energy avoided impact is larger for aluminium than for steel, despite the latter being used and recycled in much larger quantities. This result depends on the great differences in energy intensity existing between the primary routes of the two metals and their respective recycling processes.

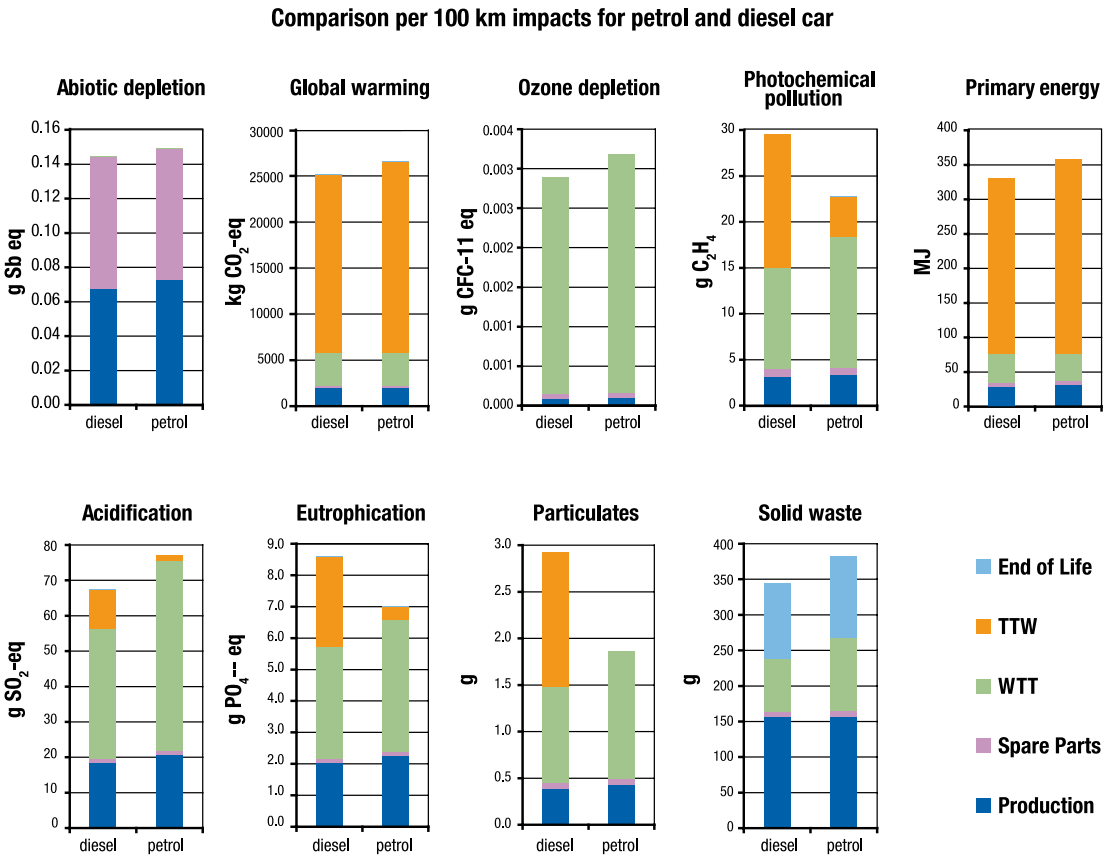
Figure 20 compares the results **normalised to a 100 km driven distance**[ac] obtained from the two systems for each impact category.

When comparing the results for the two base cases, their differences in terms of weight, power, and possibly in terms of comfort have to be noted. This means that the environmental impacts which are estimated within this project cannot be used to make an accurate comparison regarding their respective environmental performance. However, as far as energy and GHG emissions are concerned, the estimations are in line with what the WTW project showed, namely that diesel has slightly lower GHG emissions per

ac The estimated life cycle impacts (as measured in terms of midpoint indicators) were divided by the total mileage and multiplied by 100.

km than petrol (for the same car performance in terms of acceleration and comfort), in spite of higher emissions at the refinery.

Figure 20: Comparison of the two car systems (impacts per 100 km)



The petrol and diesel systems differ mainly at the level of the TTW phase.

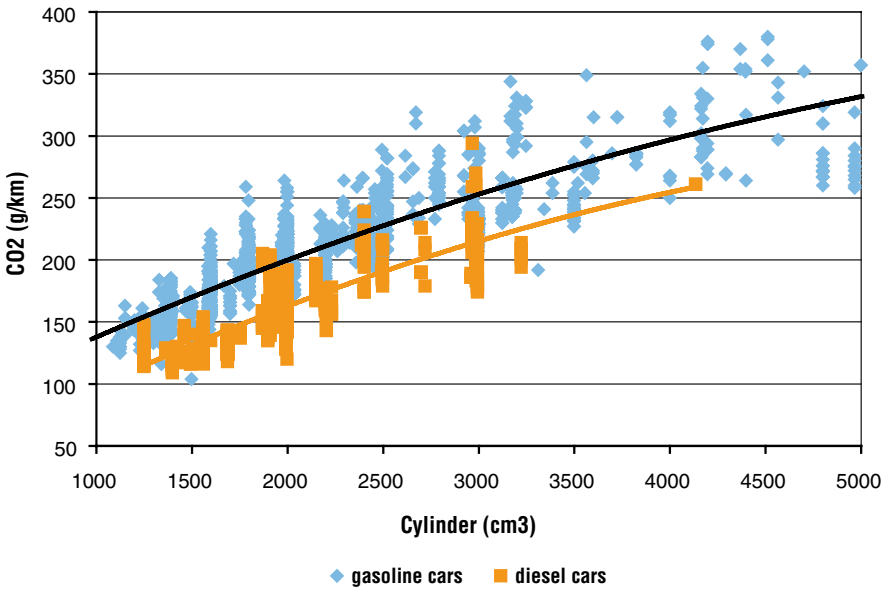
Regarding GHG and primary energy, the comparison suggests that the diesel car offers a higher performance than the petrol car. This comparison may, to some extent, be biased by the fact that the two base cases are not strictly comparable (e.g. performance, comfort). However, the conclusion is also supported by a comparison of type approval data for new cars. In Figure 21, a comparison is made between the CO_2 emissions from the petrol and diesel cars as derived from type approval data adjusted with the emissions increment derived from the WTW study[34].

The curve shows that, statistically, for a given cylinder, the petrol car emits more CO_2.

In the WTW study where several cars were defined by considering minimum performance criteria (time lags – for 0 - 50 km/h, 0 - 100 km/h, 80 - 120 km/h respectively – gradeability at 1 km/h, top speed, acceleration and range), the car models derived had similar performances. The engine displacement was 1.6 l and 1.9 l respectively for the petrol car and the diesel car, i.e. the same levels assumed in this project. Regarding the weight, the levels are lower in the WTW study (1 181 kg and 1 248 kg) and the difference between the two cars was lower than what was assumed in this project (60 kg and 120 kg respectively).

If there is a general 0.3 l to 0.5 l engine displacement gap between petrol and diesel cars of similar performances, this means that the conclusion about the higher performance of the diesel car remains valid.

Figure 21: Comparison of well-to-tank CO_2 emissions associated with new cars (petrol and diesel)



Source: derived from type approval data (EURO 4 cars approved in the UK. Dec 2005, ***http://www.vcacarfueldata.org.uk/index.asp****), adjusted with the WTT emissions*

The results are discussed in more detail in Appendix II, with a focus on the contribution of the respective lifecycle phases to the final environmental impact.

4.6. Sensitivity and uncertainty analysis

The exact size of the impacts and the contribution of the different phases is obviously subject to a certain degree of uncertainty. There are also different sources of uncertainty regarding the data that underpinned the analysis made in this study (environmental eco-profiles of the materials involved, impacts from refinery processes, etc.). The fact that there is indeed a degree of variation met in the new car fleet regarding car weight, engine efficiency also has to be borne in mind.

A sensitivity and uncertainty analysis was carried out in order to calculate the overall level of robustness of the results. These analyses were conducted by using the SimLab tool[37].

Various methods can be used to assess this sensitivity and uncertainty. The Monte Carlo method is the most commonly used procedure for performing an uncertainty analysis, in which the model is used repeatedly for combinations of the parameter values sampled within specified probability distributions. The main steps are the followings:

- select the function and input parameters of the model to be analysed
- define a probability density function for the selected input parameters (uniform, triangular, normal, log-normal, etc.)
- generate a matrix of input parameters, which are randomly chosen from the defined distributions
- run the model using the input matrix computed in the previous step
- calculate a statistic or an indicator to assess the relative influence of the input parameters on the outcome of the model or equation.

The sensitivity of the LCA's model parameters[ad] were measured, although for reasons of synthesis only the most relevant are shown in Table 21. Only the characterisation factors remain untested due to a lack of information regarding their distribution. Two different types of distribution have been used: log-normal for those parameters for which information about the probability distribution function are available and normal for cases where no additional information about the probability density function (PDF) are available. Table 21 lists the parameters tested and the assumed distribution.

Table 21: Assumption about distribution for the tested parameters

Impact categories	Lead in battery (production)	WTT	TTW	Weight	Mileage
AD	0.27	0.4	--	0.3	0.15
GWP	0.15	0.12	0.1		
ODP	0.28	0.35	--		
POCP	0.29	0.57	0.27		
AP	0.09	0.5	0.3		
EP	0.2	0.31	0.1		
PM2.5	0.39	0.47	0.2		
PE	0.32	0.14	--		
BW	0.45	0.62	--		
Distribution	Log-normal	Log-normal	Normal	Normal	Normal
Source	Ecoinvent	Ecoinvent	Copert	O.A.	O.A.

The values indicate the coefficient of variation calculated as the ratio of the standard deviation over the mean
O.A.: Own assumption

For the sake of synthesis, only the coefficients of variation for the environmental profile of lead are reported in Table 21; indeed, lead is the only parameter belonging to the production phase showing a significant sensitivity.

The uncertainty range for the **WTT** phase has been extracted from the Ecoinvent database and a normal distribution has been applied. For the **TTW** phase emissions the distribution derives from an uncertainty study made on the Copert model[38].

Altogether, 1000 Monte Carlo runs were applied with a latin hypercube sampling procedure and the sensitivity of each parameter was assessed by using the Smirnov index that indicates the correlation existing between each input factor or variable and the output of the model.

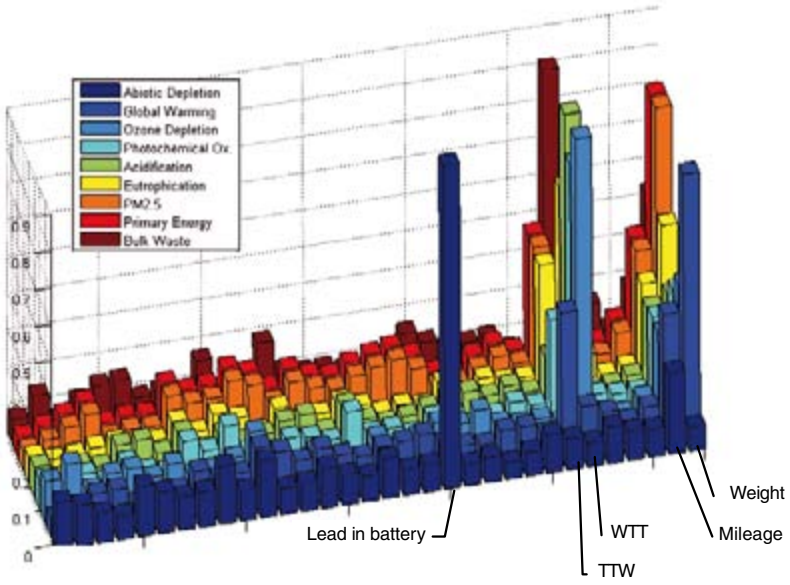
The sensitivity index does not differ so much from 0 when the parameter has a very small influence on the output, but it is close to 1 when the opposite is true. This measure indicates where the effort should be directed to have a more accurate estimation of the parameters and to reduce the overall model's uncertainty[39].

Figure 22 shows the Smirnov index for the analysed model's parameters. In all the impact categories (except abiotic depletion), WTT, weight, TTW and mileage are very sensitive parameters.

Among the remaining parameters, the overall influence from the environmental profile of the material and energy is negligible. The exception concerns the impact category "abiotic depletion" where the lead consumed by batteries is very sensitive.

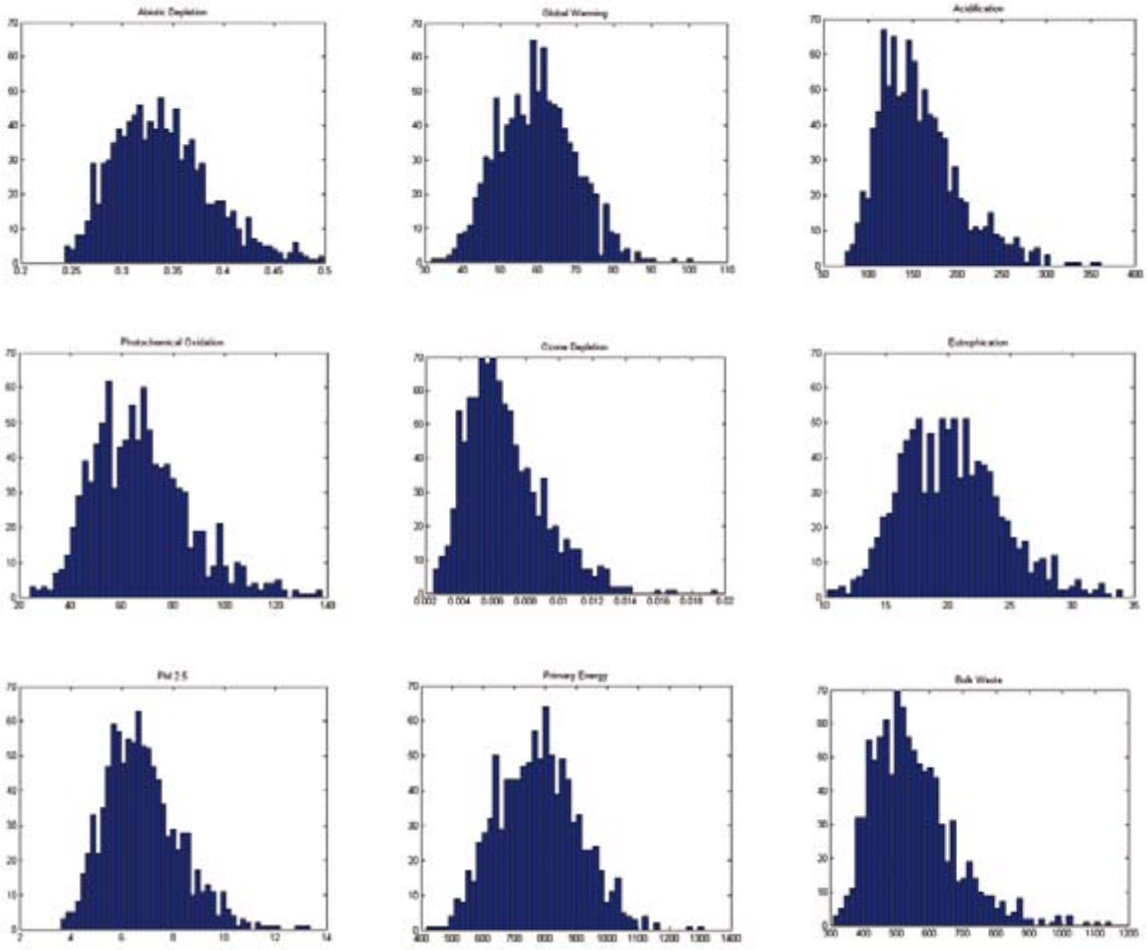
ad In total there are 32 parameters comprising the environmental profile of all the materials and energy source assumed in the car composition and manufacturing.

Figure 22: Sensitivity of model's parameters by impact categories



After performing a sensitivity analysis, the uncertainty underlying the life cycle results is shown in Figure 23 as empirical histograms and in Table 22 as standard deviations from average values.

Figure 23: Overall uncertainty per impact category



The fitting[ae] of the Monte Carlo results to all the continuous probability distributions was tested and Table 22 displays some relevant statistics as well as the parameters for the fitted distribution of all the impact categories.

Table 22: Empirical distribution and main statistics for the overall life cycle results

Impact categories	Mean	Median	Std. dev.	Coeff. of var.	Emp. distribution	Parameters
AD	0.34	0.33	0.05	0.14	Beta	Minimum=0.234;
						Maximum=0.691;
						Alpha=3.541;
						Beta=11.823;
GWP	59.56	59.62	10.1	0.17	Weibull	Location=27.084;
						Scale=36.065;
						Shape=3.563;
ODP	0.007	0.006	0.002	0.34	Log-Normal	Mean=0.007;
						Std. Dev.=0.002;
POCP	67.61	65.52	18.87	0.28	Gamma	Location=11.078;
						Scale=6.297;
						Shape=8.978;
AP	158.32	150.05	45.32	0.29	Beta	Minimum=82.597;
						Maximum=782.284;
						Alpha=2.382;
						Beta=19.626;
EP	20.23	19.9	4.02	0.2	Log-Normal	Mean=20.231;
						Std. Dev.=4.064;
PM2.5	6.81	6.66	1.46	0.21	Log-Normal	Mean=6.806;
						Std. Dev.=1.457;
PE	775.05	775.05	134.3	0.17	Student	Midpoint=775.049;
						Scale=129.725;
						Deg. Freedom=29.999;
BW	548.42	528.17	123.2	0.22	Gamma	Location=283.679;
						Scale=55.942;
						Shape=4.738;

The coefficient of variation in Table 22 is calculated as the ratio of the standard deviation over the mean and provides a dimensionless indication of the dispersion of the values around the mean.

The statistics shown in Table 22 indicate that the results obtained for GWP and PE are quite robust. For AD, EP and PM2.5 the uncertainty remains at an acceptable level. There is a greater uncertainty for the categories AP, POCP and especially ODP and this indicates a less robust result. The result for ODP depends on the uncertainty underlying the emissions of bromotrifluoromethane occurring during the

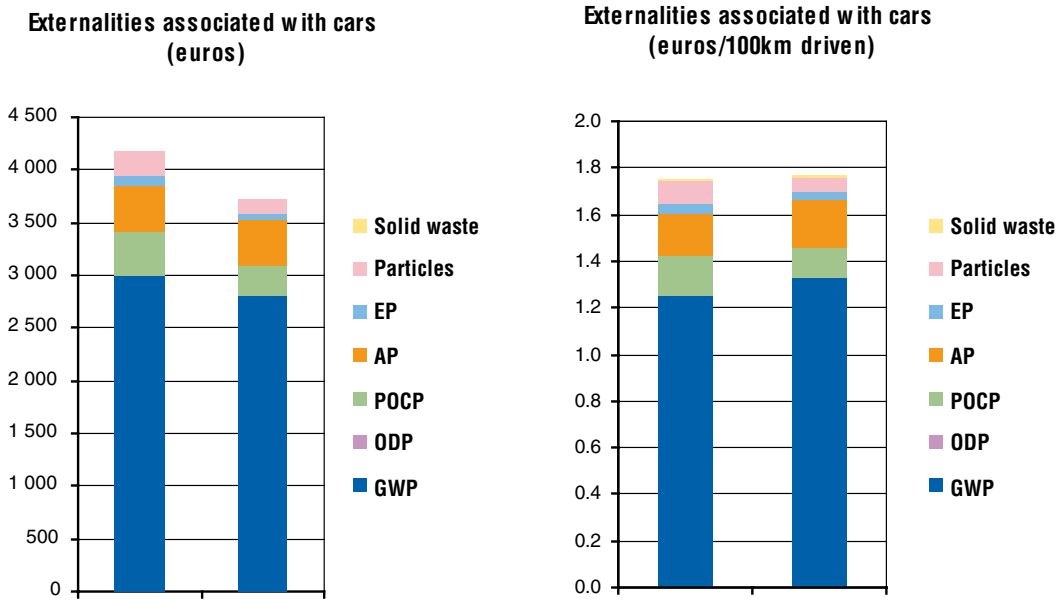
ae The fitting test used was the Kolmogorov-Smirnov test.

extraction of crude oil. Finally the result for AP depends to a very great extent on the SO_2 emissions range which occurs in the refinery process.

4.7 Monetary value of the life cycle impacts

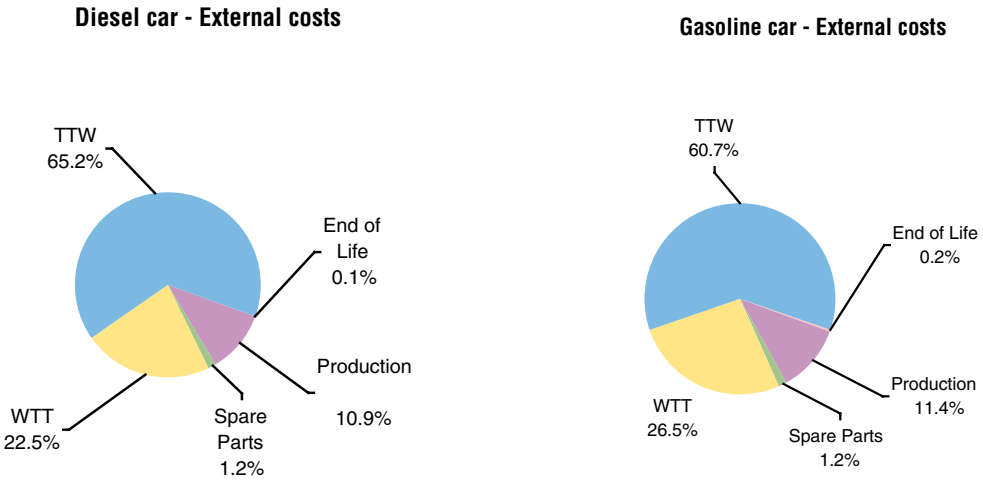
In the following, the monetary value of the impacts quantified for the reference petrol car and diesel car are given (see Appendix I for methodological details). Figure 24 displays the important role of greenhouse gas emissions, followed by photochemical pollution, acidification and particulates.

Figure 24: Monetary values of the impacts estimated for the two base case car models



When looking at the distribution of the estimated external costs, the pattern is the same for both cases as shown in Figure 25.

Figure 25: Contribution of the life cycle stages to the aggregated impacts as expressed by their monetary value



In total, the life cycle impacts estimated for the two base cases correspond to an average monetary value of 4 200 Euro and 3 700 Euro for the diesel and the petrol car respectively. When expressed per 100 km, this corresponds to about 1.75 Euro/100 km in both cases.

These monetary values are obviously subject to considerable uncertainty: taking into account the uncertainty range for each impact category, the total monetary value is expected to range from 1 175 Euro to 7 793 Euro for the diesel car and 890 to 7 000 Euro for the petrol car.

4.8 Environmental impacts of the current EU car fleet

To complement the life cycle environmental impacts quantified for the two base case car models in the previous section, the environmental impacts associated with the activities related to the EU-25 car fleet was also quantified.

The impacts were calculated for the reference year 2005 by including the impacts associated with the different activities induced by passenger cars:

- impacts induced by the manufacturing of the cars that are purchased in 2005, also including the impacts produced by all the upstream processes (raw material extraction, production of the materials that enter their composition)
- impacts associated with the process-chain of the fuel used by the existing car fleet, thus including the WTT and the TTW parts
- impacts associated with the spare parts used for the existing car fleet
- impacts associated with the end-of-life cars waste treatment.

4.8.1 Environmental impacts induced by new car production

For the calculation of this contribution, the number of new cars purchased in 2004 was used. The petrol and diesel car purchases were 7 534 910 and 6 956 118 respectively (EC, 2006)[13].

It was then assumed that the impacts previously quantified for the production phase of the two base case cars are representative of the average new car fleet. This is justified by the fact that the weight of the two car models is assumed to correspond to the average weight of new cars. Based on that an estimation was made on the overall impacts associated with the new cars (see Table 23).

Table 23: Impacts associated with the manufacturing of new cars in the EU-25

		Impacts new petrol car production		Impacts new diesel car production		All new car fleet
		Per petrol car	New petrol car fleet	Per diesel car	Diesel car fleet	
AD	kg Sb-eq	0.15	$1{,}15 \cdot 10^{6}$	0.16	$1{,}13 \cdot 10^{6}$	$2{,}28 \cdot 10^{6}$
GWP	t CO_2-eq	4.28	$3{,}22 \cdot 10^{7}$	4.73	$3{,}29 \cdot 10^{7}$	$6{,}51 \cdot 10^{7}$
ODP	kg CFC-11-eq	0.000213	$1{,}61 \cdot 10^{3}$	0.000214	$1{,}49 \cdot 10^{3}$	$3{,}10 \cdot 10^{3}$
POCP	kg C_2H_4	6.98	$5{,}26 \cdot 10^{7}$	7.62	$5{,}30 \cdot 10^{7}$	$1{,}06 \cdot 10^{8}$
AP	kg SO2-eq	43.6	$3{,}28 \cdot 10^{8}$	44.3	$3{,}08 \cdot 10^{8}$	$6{,}37 \cdot 10^{8}$
EP	kg PO_4-eq	4.8	$3{,}59 \cdot 10^{7}$	4.9	$3{,}40 \cdot 10^{7}$	$7{,}00 \cdot 10^{7}$
PM2.5	kg	0.91	$6{,}83 \cdot 10^{6}$	0.92	$6{,}37 \cdot 10^{6}$	$1{,}32 \cdot 10^{7}$
PE	GJ	65.8	$4{,}96 \cdot 10^{8}$	69.2	$4{,}82 \cdot 10^{8}$	$9{,}77 \cdot 10^{8}$
BW	kg	333	$2{,}51 \cdot 10^{9}$	374	$2{,}60 \cdot 10^{9}$	$5{,}11 \cdot 10^{9}$

4.8.2 Fuel chain related impacts

In order to calculate these impacts, use was made of the TREMOVE output results for the most recent baseline scenario (version 2.44), which includes emission estimates for all transport modes and especially for passenger cars for both TTW and WTT and for different substances (NO_X, CO, N_2O, CO_2, CH_4, VOC, PM2.5, etc.). Based on the emissions for 2005, and using the same characterisation factors as those used in the life cycle analysis made in section 4.2, these different emission levels were aggregated into the relevant midpoint indicators. This is given in Table 24.

Table 24: Impacts associated with the WTT and TTW emissions induced by the existing car driving

		WTT	TTW	WTW
GWP	t CO_2-eq	$1{,}04 \cdot 10^8$	$6{,}01 \cdot 10^8$	$7{,}05 \cdot 10^8$
POCP	t C_2H_4	$3{,}43 \cdot 10^5$	$1{,}63 \cdot 10^6$	$1{,}97 \cdot 10^6$
AP	t SO_2-eq	$1{,}47 \cdot 10^6$	$8{,}99 \cdot 10^5$	$2{,}37 \cdot 10^6$
EP	t PO_4-eq	$5{,}61 \cdot 10^4$	$2{,}29 \cdot 10^5$	$2{,}85 \cdot 10^5$
PM2.5	t	$6{,}76 \cdot 10^4$	$5{,}10 \cdot 10^4$	$1{,}19 \cdot 10^5$
PE	PJ	$1{,}19 \cdot 10^3$	$6{,}91 \cdot 10^3$	$8{,}10 \cdot 10^3$

Regarding PM2.5, the values only include the exhaust gas emissions. TREMOVE also estimates the non-exhaust gas particulate emissions. However, according to the most recent Copert report[af], fine particles emitted from tyre/brake/road abrasion represents a small fraction of total suspended particles emitted by these processes. Furthermore, when considering PM2.5 only, these emissions represent only 7% of the total road transport emissions.

4.8.3 Environmental impacts induced by spare parts

The life cycle analysis of the two base-case cars made in section 4.2 provided an estimation of the impacts associated with the different spare parts. These impacts, as expressed per 100 km, are used here for their extrapolation for the EU car fleet. This is made possible by considering the transport volume associated with passenger cars in 2005 which was estimated by TREMOVE (baseline, version 2.44) to be 2.93 10^{12} vkm. The resulting estimated car fleet impacts are given in Table 25.

Table 25: Car fleet impacts associated with the spare parts

		Spare parts	
		Per 100 vkm	Car fleet
AD	g Sb-eq	0.08	$2 \cdot 10^9$
GWP	g CO_2-eq	207.5	$6 \cdot 10^{12}$
ODP	g CFC-11-eq	0.0001	$2 \cdot 10^6$
POCP	g C_2H_4	0.85	$2 \cdot 10^{10}$
AP	g SO_2-eq	1.14	$3 \cdot 10^{10}$
EP	g PO_4-eq	0.11	$3 \cdot 10^9$
PM2.5	g	0.07	$2 \cdot 10^9$
PE	MJ	6.03	$2 \cdot 10^{11}$
BW	g	7.50	$2 \cdot 10^{11}$

af Emission Inventory Guidebook, 2006, Road transport.

4.8.4 Environmental impacts associated with car disposal

The impacts associated with the end-of-life car disposal has to take into account the annual amount of cars disposed in the EU-25 and an average estimate of the impacts of the waste treatment of these disposed cars.

Accurate statistics about car disposal are not available, especially when considering the EU-10 countries. According to ACEA, 11.4 million cars were deregistered in the EU-15 in 2004. A total of 130 000 vehicles are suggested to have been deregistered in the most important EU-10 countries except Hungary. In Hungary, 220 000 vehicles were deregistered, but only a fraction of these vehicles was treated. It is assumed that this fraction was lower than 50%. Therefore, the assumption is that in total 240 000 vehicles were disposed of in the EU-10 in 2004. In total for the EU-25, 11.64 million vehicles were treated. The quantified impacts produced for the two base cases were then used to calculate a EU-wide estimation of the environmental impacts induced by the end-life vehicle treatment (see Table 26). This slightly overestimates the impacts as the older cars had a lower weight than the new ones. As will be seen in section 4.8.5, this only biases the results related to waste.

Table 26: Impacts associated with the end-of-life vehicles

		End of Life	
		Per car	All car fleet
AD	kg Sb-eq	0.0	0.0
GWP	t CO_2-eq	0.059	$6.88 \cdot 10^5$
ODP	kg CFC-11-eq	0.0	0.0
POCP	kg C_2H_4	0.018	$2.11 \cdot 10^5$
AP	kg SO_2-eq	0.077	$9.00 \cdot 10^5$
EP	kg PO_4-eq	0.04	$4.17 \cdot 10^5$
PM2.5	kg	0.0	0.0
PE	GJ	0.049	$5.68 \cdot 10^5$
BW	kg	243.7	$2.84 \cdot 10^9$

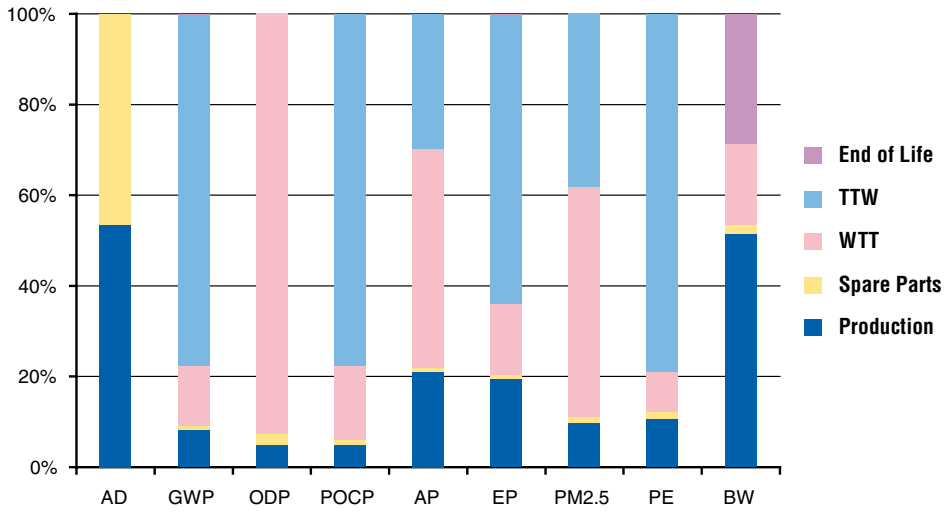
4.8.4 Total environmental impacts

Summing up the previous estimates, the overall impacts associated with the EU-25 car fleet can be calculated (see Table 27 and Figure 26).

Table 27: Total environmental impacts generated by the EU-25 car fleet

		Production	Spare Parts	WTT	TTW	EOL	Total
AD	t Sb-eq	2 279	2 246	4	0	0	4 530
GWP	Mt CO_2-eq	65	6	104	601	1	777
ODP	t CFC-11-eq	3	2	58	0	0	63
POCP	kt C_2H_4	106	25	343	1 628	0	2 102
AP	kt SO_2-eq	637	33	1 468	899	1	3 038
EP	kt PO_4-eq	70	3	56	229	0	359
PM2.5	kt	13	2	68	51	0	134
PE	PJ	977	177	810	7 294	1	9 259
BW	kt	5 109	220	1 774	0	2 837	9 941

Figure 26: Total environmental impacts generated by the EU-25 car fleet



For the WTT and TTW emissions, the upper values do not include the ADP, ODP and waste impact categories. The Ecoinvent database was used to quantify these impact categories.

The distribution of these different impacts into the different activities contribution is also shown in Figure 26. This can be compared to the impact breakdown derived for the two base cases (new petrol car and new diesel car). As far as abiotic depletion and waste categories, primary energy and greenhouse gases are concerned, the distributions are similar.

The pattern is dramatically different when considering POCP, AP, EP and PM2.5 and the TTW emissions have a much higher contribution when considering the car fleet than when considering new cars, even considering new diesel cars. This illustrates the fact that the car fleet is composed of different age categories. Older cars have much lower performances regarding the different pollutants (NO_X, CO, PM, VOC) than the EURO4 cars that are sold today.

This aspect is illustrated in Figure 27, which displays the past and projected emission levels for NO_X as modelled with TREMOVE under the baseline scenario[ag]. It illustrates the gradual penetration of new abatement technologies as implied by the successive air emission limits introduced by European legislation. In the ten years from 1995 to 2005, NO_X emissions were halved.

It also shows the effect of gradually introducing more diesel cars: whereas the NO_X emissions were largely associated with petrol cars in 1995 and 2000, these emissions rapidly declined with the introduction of TWCs on petrol cars. So both the growing penetration of diesel cars and lower performance regarding NO_X emissions compared to petrol cars has resulted in growing NO_X emissions of these cars. According to this baseline scenario, the emissions related to diesel cars are expected to be kept constant in the future as a result of the EURO4 emission limits, despite a still growing diesel car fleet.

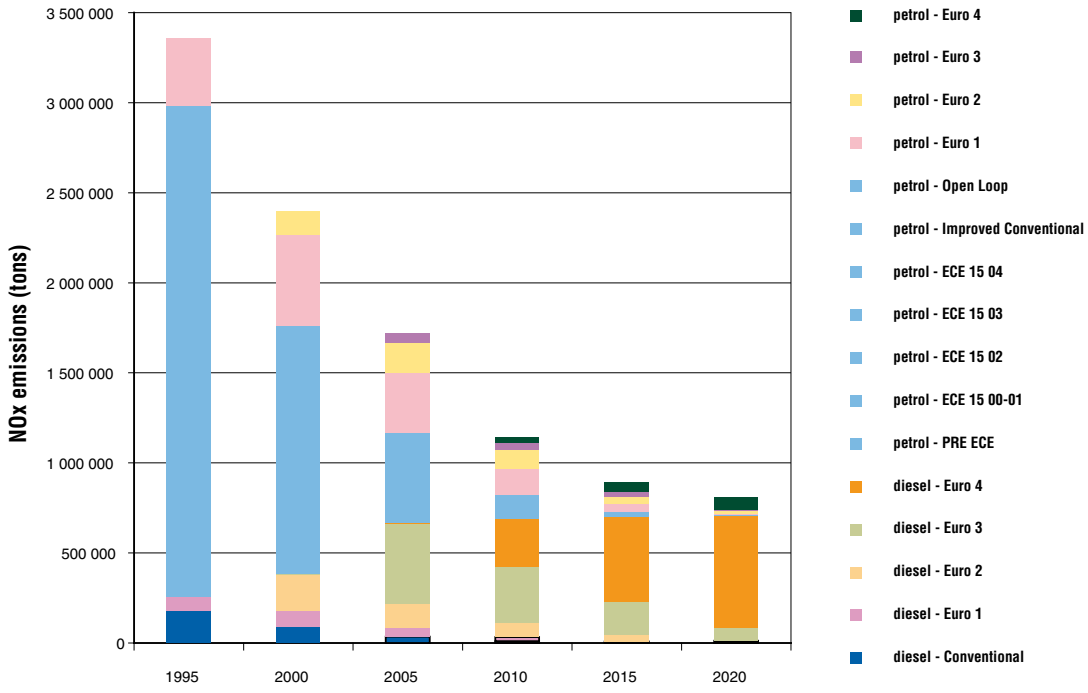
It has to be emphasised that while the concentrations of ambient NO_X are on a downward trend, concentrations of NO_2 have often been static or even rising. The development of ambient NO_2 concentrations as observed near roadsides can be explained by an increasing contribution of direct emissions of NO_2 specifically from diesel-fuelled vehicles. Instead of a 5% share of NO_2 in the emitted

ag Note that the NO_X emissions modelled in TREMOVE are based on emission factors (COPERT) that aim to reflect real world emissions.

NO_X typically assumed in standard atmospheric pollution models, modern diesel cars can be as high as 30% to 80%[ah].

This baseline scenario does not, however, include the effect of the new air standards EURO5 and EURO6 which will result in lower emissions.

Figure 27: NOX emissions projected with TREMOVE (2.44) for the EU-19+2 countries



4.9 Conclusions

The life cycle analysis made for the new car models showed that for some impact categories the two systems exhibited a similar impact in terms of both size and life cycle phases breakdown, while for others substantial differences were found.

In both analysed cases, **primary energy** and **GHG emissions** were dominated by the tank-to-wheel phase, followed by the well-to-tank and the production phase. A similar impact was estimated for the categories **ozone depletion** (which in both cases depended almost entirely on the emissions occurring during the WTT phase), and for **abiotic depletion** that was dominated by the production phase and spare parts (lead). A similar conclusion was drawn for the generation of **solid waste** that was shared between the production, WTT and EOL phases in both systems.

The size and breakdown of the other impacts, namely **photochemical oxidation, eutrophication, acidification** and **particles** substantially differ from one case to the other.

In the petrol system and for all these remaining categories, the well-to-tank phase produced the largest impacts followed by the production phase. However, for the diesel system, the higher emissions of NO_X

ah The EU level workshop on the impact of direct emissions of NO_2 from road vehicles on NO_2 concentrations, Brussels, 19 September 2006, Summary meeting notes.

and particulates occurring during the TTW phase radically changed the size and breakdown of the life cycle impacts for these impact categories.

The exact size of impacts and the contribution of the different phases can vary as a result of the different specific car cases considered. There was indeed a degree of variation met in the new car fleet regarding car weight and engine efficiency.

Moreover, there were also different sources of uncertainty regarding the data that underpinned the analysis (e.g. environmental eco-profiles of materials involved, impacts from refinery processes).

The uncertainty underlying these different variables was analysed and their impacts on the final results were estimated. There is obviously room for refining the results. However, overall, it should be noted that the above conclusions are robust.

The analysis indicated that, per 100 km driven, the petrol system was less environmentally friendly in respect to ozone depletion, bulk waste, abiotic depletion, global warming and primary energy. Despite the fact that the two car models did not have the same characteristics in terms of acceleration and comfort – which tended to lead to higher impacts for the diesel car, these results were in line with those from the WTW study, as far as energy and GHG emissions are concerned.

When considering the aggregated impacts as proxied by the monetary value of the different impacts, the two cars performed similarly. What differs was the relative contribution of the different impact categories.

When considering the overall car fleet, the exhaust gas emissions of substances associated with POCP, AP, EP and PM2.5 make a much higher contribution than for new cars, even for diesel cars because the older cars have much lower performances regarding the different pollutants (NO_x, CO, PM, VOC) than the EURO4 cars that are sold today.

5. Identification of the improvement options

5.1. Introduction

When considering improvement options, different types of improvements are relevant:

- options consisting of improving **car efficiency** through a change in design (engine, car design, composition)
- options consisting of a **change in the car use pattern**, resulting in less environmental impacts
- options consisting of **more systemic changes** like the shift from private cars to collective transport, the reduction in mobility needs through changes in urban and land use planning of the different human activities.

The options consisting of more systemic changes are undoubtedly of high relevance and offers an important potential. However, considering their lower relevance for a product policy, we focused on the two first series of options only. Furthermore, their assessment definitively requires the use of comprehensive transport models to capture the whole complexity of changes implied in such options.

The literature dealing with passenger cars and with different energy and environmental improvement options was systematically reviewed. Based on that, a long list of options technically proven and likely to be on the market within the next 30 years was put together. This list is displayed in Table 28 where the options are classified according to the stage of the life cycle in which they could be implemented. A list of reference is also given especially if the specific literature is not quoted in this document.

This does not systematically mean that the environmental effect likely to be induced by the option is restricted to this process. The effects can be produced at other stages of the life cycle. For instance, the improvement of the car's aerodynamics entails changes in the car body and its shape (thus possible changes in the production phase's environmental impacts), together with effects on the environmental performance of the use phase.

For each option, the literature covering the technical and analytical background related to each improvement option was reviewed. This included the different technical and scientific data and studies that underpinned the existing or developing **environmental legislation** regarding cars (see section 2.4.2).

For the sake of comprehensiveness when using such data, results and reports, it was essential to take the existing or new legislation in the framework of this project into account. The environmental benefits associated with some of the options are already being reaped, either fully or partially by existing legislation or are expected to be exploited to a certain degree by new or developing legislation.

Most of the options considered are of a technical nature. Options that mostly depend on behavioural and consumption changes also need to be considered. The concept of "technical" potential is here much less meaningful. In this case, it is somehow more difficult to assess a potential for improvement as it will, to a large extent, depend on consumer behaviour. In this case, the estimated potential should be considered as a theoretical potential.

Table 28: List of improvement options considered in the literature review

Life cycle phase	Process	Option			References considered in this project that are not necessarily mentioned in this report
Production phase	Raw material mining	Improving process		T	
	Material processing	Improving process		T	
	Car design and assembling	Improving energy efficiency		T	
		Improving the application of solvents, paints and adhesive		T	40, 41, 42, 43
		Design for better dismantling		T	44, 45, 46
		Material substitution	Choosing recycled / renewable / recyclable/ low environmental profile materials	T	47, 48, 49, 50, 51, 52, 19, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69
			Optimising the design and choosing light materials	T	
		Improving the aerodynamics (car body and tyres)		T	70, 71 72 73, 74, 75, 76
		Higher MAC efficiency	Improving the efficiency of climate control systems	T	34, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87,88, 89, 90, 91, 92, 93, 94
			Substitute refrigerant	T	
Well-to-tank	Primary energy extraction	Improve the efficiency of the process		T	
	Fuel production	Improve the efficiency of the process	Improving the refinery process	T	95, 96, 97, 98, 99 100, 101, 102
			Design the process for cleaner fuel production	T	
	Fuel distribution	Improving technical equipment for fuel distribution		T	
Use phase	Car driving	Reducing the fuel consumption and air pollution from car driving	Emission control systems for current engines	T	103, 104, 105,106, 107, 108, 109, 110, 91, 88, 89, 90, 87, 92
			More efficient power trains	T	102, 90, 111, 112, 113, 114, 115
		Alternative fuels		T	
		Properly inflate tyres		T	See “Improving the car body aerodynamics”
		Adapt vehicle speed		B	
		Driving behaviour		B	
		Optimise the use of air-conditioning		B	See “Higher MAC efficiency”
	Worn spare parts disposal	Increase recovery and recycling of tyres		T	116, 117, 118, 119, 120, 121, 122
		Increase recovery and recycling of batteries		T	93, 123, 124, 125, 126, 127, 128
		Increase recovery and recycling of lubricants		T	
End-of-life	Waste treatment	Increase recycling and recovery		T	23, 129, 130, 131, 132, 133, 134, 135, 136, 17, 137, 138, 139, 140, 141, 142, 143

T: Technical, B: Behavioural

5.2. Justification regarding options not considered for further analysis

Not all of the options listed in Table 28 above were selected for further assessment within this project. The selection was made using the following criteria:

1. Is the option likely to be eligible for IPP?
2. Is the option likely to improve processes that generate significant impacts?
3. Is there evidence that the existing technical potential is already covered by existing legislation?
4. Are there any reliable data and information to quantify the environmental impacts? Is the quantification feasible under the methodological approach used in the project?

Having addressed these questions, it was concluded that some options do not need or could not be further assessed. The explanations are given later.

It should be noted, however, that excluding options from quantification does not automatically mean that the options are not relevant at all.

5.2.1 Options related to industrial process improvements

Technical options can be implemented in the different industry sectors that supply materials involved in car production (e.g. metals, plastics, glass, etc.) in order to improve the eco-balance of these materials and therefore reduce the life cycle environmental impacts associated with the car production phase. These industry sectors produce goods that are used in many different final products, thus not specifically in cars.

Such improvements are, to a large extent considered in the environmental legislation for industry (e.g. IPPC Directive, ETS, LCP, etc.). (Re)-considering these processes and their improvement in a IPP framework is less relevant. Therefore, neither the improvements that are stimulated by the existing regulation (applying for instance BAT in the sectors concerned), nor the autonomous improvements that could be implemented by industry in the short and in the longer term, are considered in this project.

This has to be kept in mind when analysing the different life cycle performances and possible improvements. The process-chain approach (see section 2.4) applied in this project, does not provide the dynamic perspective needed to reflect the improvements expected to occur in the different sectors. As a result, it may introduce a bias regarding the environmental improvements achievable over the life of the car. This may have some consequences when analysing some improvement options such as weight reduction (see section 6.2).

5.2.2. Design for better dismantling

As will be discussed in section 6.9, the achievement of high mechanical recycling rates at the EOL phase is challenged by several technical and economic barriers, especially regarding the non metallic fraction. One of these barriers is the cost entailed by car dismantling aimed at a high level of separation of different components (including plastic components).

In this regard a dismantling and recycling-oriented design of the car may play an important role by lowering the costs of dismantling and by increasing the value of the recycled material, and consequently increase the net revenue obtained by their recovery. The main objectives of a design for disassembly and recycling strategy can be summarised as follows:

Improving the joining technology: the use of snap fits and nut/bolt may allow the avoidance of adhesive and may reduce the contamination of components by the adhesives. Therefore, they have a higher recycling rate. This may also facilitate the maintenance and reparability of a car thus reducing the replacement of parts during its life cycle. Most of the practices concern the adoption of fastener techniques and are adopted by many automotive companies.

Reducing the diversity of materials used: this can be achieved through a series of practices such as:

- mark plastic parts to facilitate recycling and repair
- reduce the number of parts used during assembly
- select materials that do not need to be separated for recycling
- design parts/assemblies to minimise the need for packaging and select packaging that is reusable, has a recycled content, and/or is recyclable
- reduce the amount of paint used.

These options can contribute to achieving higher mechanical recycling rates.

In this project, these options are, however, only implicitly taken into account when considering the options consisting of the increase of mechanical recycling at the car end-of life.

The SEES project has, however, shown some limitations regarding the impact of design for dismantling in the case of electric and electronic systems[ai].

5.2.3. Options related to the primary energy extraction and fuel production

Conversion processes occurring from oil extraction to the fuel supply are often dealt with in literature and are referred to as part of the well-to tank (WTT) chain, whereas the processes that occur from the fuel supply to car driving are referred to the tank-to wheel chain (TTW). The life cycle impact analysis presented in Chapter 4 has shown that the WTT impacts are an important contribution to impacts in the life cycle of a car. This part thus devises a lot of attention when considering the life cycle car performance.

These impacts can be subdivided into two important components:

- impacts induced upstream to the oil transformation in refineries
- impacts induced during the oil transformation in refineries.

Regarding the first component there is a clear potential to reduce some of the major environmental impacts stemming from oil extraction, the high diversity of oil fields[aj] and crude oil quality and crude oil production processes. Improvement options would concern the gas as by-product from oilfields, waste water treatment of oil exploitation, diffuse losses, etc. An analysis of such options could be an own topic and study however. Within this project, it would be impossible to derive generalised conclusions about the applicability and scale of environmental benefits from the different improvement.

The conversion of crude oil into different products consumed in the various sectors (transportation, heating, electricity, industry) is operated in more than 104 refineries in the EU25. One typical refinery is now characterized by a crude oil processing capacity higher than 3 billion (thousand million) tonnes/year.

ai http://www.sees-project.net/index.php.

aj It has to be underlined for instance that the exploitation of unconventional oil reserves (oil sands, oil shale) that are currently under development generate higher GHG emissions than the exploitation of conventional oil reserves.

The refinery is a complex chemical process which entails different types of emissions (air, water soil) and wastes. The process inherently requires energy use (refineries use part of their intake as fuel, however part of this oil consumption is being replaced by natural gas) and generates CO_2 emissions.

Best available technologies are described in a BREF and improvement options exist to reduce these impacts.

These options, again are more likely to be addressed under existing legislation (IPPC, ETS, etc.) and not under the IPP framework.

Two aspects regarding WTT and, more specifically regarding refineries are however worth to be considered within this project. Over the past years, refineries have adapted their installations and production mix to two main trends characterizing the automotive sector, and, especially passenger cars:

- Petrol and diesel are the two typical fuels for road transport. Over the last years diesel cars represent an increasing importance in the EU25 car fleet (see Chapter 3). The refineries have adjusted their production mix and products accordingly[ak].
- Increasing requirement for cleaner fuels as a result of the environmental legislation (unleaded and low aromatic content petrol, low sulphur content fuel – 10 ppm since 2005).

Car fleet dieselisation

The first issue was particularly investigated during the literature review: how is the refinery activity in EU25 likely to adapt to the evolving EU car fleet, especially the growing importance of diesel in fuel consumption? Different sub-questions relate to this issue:

1. what are the likely environmental consequences, especially regarding CO_2 emissions?
2. what are the likely consequences in terms of energy security supply?

What are the likely environmental consequences, especially regarding CO_2 emissions?

One major difficulty to answer this question is that there is no unequivocal way of allocating energy consumption from refineries to the different products, especially to diesel and petrol respectively[al]. One possible calculation is the marginal approach, which was used in the WTW study[34]. This approach estimates the energy use and CO_2 emissions associated with, respectively, an increased diesel production, and an increased petrol production, by the EU refineries.

The calculation made in that study for the horizon 2010 led to the conclusion that 1 MJ diesel produced implies 0.1 MJ energy use and 8.6 g CO_2. For petrol, the estimations are respectively 0.08 MJ and 6.5 g CO_2 per MJ produced[am]. Thus these figures indicate that **diesel turns out to produce slightly more WTT GHG per MJ produced**.

The characteristics of the refinery process suggest that, provided that the energy efficiency is likely to be reduced and that CO_2 emissions would increase is additional hydro-cracking processes are needed. The impacts of such energy and CO_2 emission increase is however unknown due to the lack of data and modelling where the WTT and TTW chains would be considered together to capture the dynamic

ak CO_2 emissions of the EU25 refinery sector represented 3.1% of total CO_2 emissions in 1990, and 3.35% in 2002.
al the same problem also arises when discussing about other environmental impacts
am These figures have been used in this project when quantifying the car life cycle impacts and improvement options

evolution of both the car fleet size and the car engines (diesel and petrol) evolution. This project cannot obviously solve this question.

What are the likely consequences in terms of security of energy supply?

Higher demand for diesel in EU, accompanied with an increasing surplus of petrol may accentuate the dependence on third countries (diesel imports) whereas increasing quantity of petrol would need to be exported.

Most of the surplus of petrol produced in EU is exported to US. The possibilities for further export in the future might need to be reconsidered as a consequence of the voluntary policy in US to substitute petrol with ethanol.

Fuel quality

Technically, fuel can be produced with lower content in substances like sulphur or PAH. This project did not quantify the effects of reducing these substance contents in fuels:

The need for low sulphur content (below 10 ppm) fuels is less related to lower SO_x emissions than to the fact that new cars is highly recommended for cars fitted with catalytic converters (see sub-chapter 6.5). It is also contributing to higher engine efficiency. The marketing of low sulphur content fuel (petrol and diesel) is already an obligation in the EU. The average sulphur content of fuels in Europe is currently around 50 ppm but lower concentrations are already achieved in some countries (Germany). The 10 ppm upper limit is also provided by the Directive 2003/17/EC[144] for diesel by 2009.

Whereas producing low sulphur content requires more energy during the WTT, the benefit achieved in the TTW largely outweigh this energy surplus. Assessing the overall balance would need a more comprehensive approach than the one followed in this project, namely considering both the car fleet and refinery processes.

PAH emissions in exhaust gases are responsible for health damages, especially in urban areas. There is no reliable data available to quantify the impacts of lower PAH content. There is even not evidence that these emissions are correlated with the PAH content of fuels. In addition petrol vehicles fitted with catalysts are shown to emit much less than older cars.

5.2.4 Fuel distribution

The storage and the distribution of motor fuels in service stations cause a number of environmental impacts. The main environmental key issue still concerns the emissions of volatile organic compounds released during the filling of the petrol storage and petrol car tanks.

Potential contamination of soil and groundwater due to fuel spills are also to be considered.

Regarding VOC emissions, options can be implemented at two levels:

- The stage I vapour recovery of petrol (vapour recovery during storage tank filling).
- The stage II vapour recovery of petrol (vapour recovery during car tank filling).

The first category is already subject to regulation since 2004 by the Directive 94/63/EC[145] which allowed reducing VOC emissions during petrol refuelling by 80%.

The second category is made possible with best available technologies[an] consists of a number of measures that improve the environmental performance of the service stations without putting an unreasonable financial burden on the companies involved. *"The selected BAT are among others vapour recovery to reduce refuelling emissions and several techniques to prevent soil and groundwater pollution like leak detection and cathodic protection of storage tanks, waterproof floorings, leakproof nozzles."*

Stage II vapour recovery techniques enable to reduce the VOC emissions by 75%. It is not a cheap technique (average additional cost per litre petrol is 0,04 to 0,09 former Belgian Francs – about 0.1 to 0.225 euro cents). The investment in itself is nevertheless feasible, provided a number of preconditions within the sector are fulfilled. This does not mean however that this additional effort cannot be fatal for some station operators."

A draft 2003 EPTC survey indicates that Stage II vapour recovery is already installed in 85% to 100% of service stations in Austria, Denmark, Germany, Hungary, Italy, Luxemburg, Netherlands, Sweden, and Switzerland.

A EU regulation covering stage II vapour recovery of petrol could be proposed by the Commission. Measures are envisaged in some countries (UK for instance).

5.2.5. Reuse, recovery and recycling of lubricants

Some 75% to 95% of a typical engine lubricant is made up of a base oil - a mineral oil that comes directly from a refinery[ao]. These base oils can naturally contain straight or branched chains of hydrocarbons, hydrocarbon molecules with aromatic rings attached, or these chains can be produced by further chemical reactions of the base oils. The remainder of the lubricant comprises a variety of additives, which are used to improve performance.

Waste oils are classified as hazardous waste and represent a risk for human health and ecosystems if they are discharged to water or soils.

Through their use, lubricants lose their initial properties, due to contamination and, at some point, they cease to be fit for the use they were originally intended. These used oils are then replaced by fresh lubricating oils and then some waste oils remain. Some 50% of what is purchased will become waste oils (the rest is lost during use, or through leakages, etc.) Therefore approximately 2 500 kt of waste oil needs to be managed every year in the EU (of which about 1 600 kt from automotive applications). It is also worth mentioning that **leakages from cars** are still significant which means that improved control would be needed (at technical car control for instance). Car manufacturers should improve the sealing in cars.

The used lubricant/waste oil is partly collected by different organisations. The collected ratio may range between 20% and 86% in the different EU-25 Member States[ap].

The average collection rate in the EU-15 was around 81%. It can be further improved. This would be made possible if consumers, garages and do-it-yourselfers would refrain from dumping these precious liquids but hand them to authorised collectors that will ensure their adequate recovery[aq]. In the EU-25, it can be estimated that the unrecorded amount of lubricant associated with traffic can be as high as 100 000

an http://www.emis.vito.be/EMIS/Media/BAT_abstract_service_stations.pdf

ao Producing lubricants from biodegradable material is also an option (based on rape seeds for instance). Advantages are to be seen in saving fossil energy and diminishing the greenhouse effect. Disadvantageous are the potentials of acidification, eutrophication, and ozone depletion. A final objective valuation on the basis of these aspects is not possible.

ap http://www.total.com/static/en/medias/topic103/Total_2003_fs09_Used_lubricant_disposal.pdf.

aq http://europa.eu.int/comm/environment/waste/oil_index.htm.

tonnes/year, or even more. This huge volume of waste oil goes into the nature, water, and soil, and creates a pollution that could be avoided with organised waste oil collections and higher discipline in this area.

The Waste Oil Directive 75/439/EEC, as amended by Directive 2000/76/EC, is designed to create a harmonised system for the collection, storage, recovery and disposal of waste oils, such as lubricant oils for vehicles, turbines, gearboxes and engines, hydraulic oils, etc. The Directive also aims at protecting the environment against the harmful effects of illegal dumping and of treatment operations.

It sets a priority for the regeneration of waste oil that dates from the seventies. However, recent scientific information does not provide evidence that regeneration is more environmentally advantageous than other treatment recovery options. For this reason, the European Commission's proposal for a Directive on waste (COM(2005) 667 final) proposes to repeal the Waste Oil Directive. On the other hand, considering that the separate collection of waste oils remains crucial to waste oil management and that the prevention of damage to the environment from their improper disposal, it proposes to make obligatory the collection of waste oils.

The impacts associated with waste oil – such as being hazardous waste – cannot be addressed in this project as eco- and human-toxicity impacts are not quantified in a comprehensive way.

5.2.6 Reuse, recovery and recycling of batteries

Each year, approximately 800 000 tonnes of automotive batteries are placed on the Community's market[128].

According to the Directive about the end-of-life of vehicles (2000/53/EC), batteries must be stripped before any end-of-life car treatment. The Directive, which applies to both automotive lead-acid batteries and nickel-cadmium batteries, also required the substitution of mercury, lead, hexavalent chromium and cadmium in vehicles by 1 July 2003. However, a series of exemptions are provided by Annex II of the legislation. The use of lead in batteries is exempted without a time limit. The Annex II has been amended by a Commission Decision (2002/525/EC), granting an exemption for the use of cadmium in batteries for electric vehicles.

Batteries, including batteries for automotive applications are also subject to specific environmental legislation. Directive 91/157/EEC as amended by 98/101/EC and supplemented by 93/86/EEC was aimed at avoiding dangerous materials getting into the environment, at minimising their use, and at encouraging the reuse of components which are suitable for reuse, the recovery of components which cannot be reused, and giving preference to recycling when environmentally viable. It does not prescribe measurable and verifiable instruments preventing the uncontrolled disposal of batteries and accumulators into the environment.

A new Directive was adopted recently (2006/66/EC) that repeals the previous one. This Directive requires the separate collection of automotive batteries (25% by September 2012 and 45% by 26 September 2016), so that these batteries are not collected on the basis of the schemes set up under Directive 2000/53/EC. Their landfilling and incineration are also prohibited.

It also requires the recycling of 65% by average weight of lead-acid batteries and accumulators, including the recycling of the lead content to the highest degree that is technically feasible while avoiding excessive costs.

The Directive does not specifically address the new nickel-metal hydride (Ni-MH) batteries whose use is expected to grow in the future, notably in hybrid cars. The growing penetration of these new batteries will require the development of appropriate recycling technologies. Such technologies are emerging today.

The impacts associated with batteries – such as being hazardous waste – are not fully addressed within this project as eco- and human-toxicity impacts are not quantified on a comprehensive way.

5.2.7. Recycling and recovery of tyres

In the last decade, the disposition routes adopted in Europe for waste tyres has shifted from the landfilling of about 65% to the recovery of more than 65% by reuse (part worn), retrading and mainly energy recovery or material recycling. However, despite the positive change, more than 26% of tyres were still landfilled in the EU-25 in 2004. Therefore the specified target in Directive 1999/31/EC, which imposes the complete ban of the landfilling option for waste tyres by 2006, is still far from being achieved. Different end-of-life options are already available and practically adopted. A brief description of these options is given below:

- **reuse as products** is a currently adopted option especially in maritime application such as coastal protection, artificial reefs, erosion barriers, sea-walls and off-coast breakwaters, boat fenders**.** Other types of reuse of used tyres that need a mechanical pre-treatment (grinding, shredding, etc.) include road surface, porous bitumen additive, and additive material for sound barriers, thermal and sound insulation barriers, animal mattresses and shoe soles. The main disadvantage of these processes is the high energy requirements due to the mechanical pre-treatment processes
- **material recovery processes,** such as reclaim-devulcanisation, gasification, pyrolysis or microwave treatment, represent interesting options which enable the recovery of valuable products and raw materials like rubber, gas, oil, carbon char, carbon black and steel. However, these processes are currently applied on a small scale because of the lower economic convenience. This is an obstacle which might be overcome through pushing R&D expenditure in this direction
- **incineration with energy recovery** does not seem to be an interesting option, despite the high calorific value of tyres. This disposal route encounters public opposition and has to face stricter emission limits imposed by the currently adopted legislation in Europe (2000/76/EC). Moreover, incineration treatment requires a high capital investment and it is competitive only on a large scale. The combustion residues generated by tyre incineration does not have a potential for being reused; for example the steel recovered from tyres incineration plants is carbonised and contains high concentrations of sulphur, thus it is unsuitable for recycling. The residues require high costs for final disposal
- **co-combustion of tyres in cement kilns**, at present is by far the leading thermal technology used for scrap tyre management. The main advantage of using tyres consists of their high calorific value and cheapness as fuel, which displaces coal, as well as the good quality of the cement obtained. However, there are many concerns about the health impact of this process as well as for the presence of contaminants in the cement that is produced.

Some of the options discussed above would have deserved to be analysed in more detail. This is notably true for the co-combustion in cement kilns and material recovery processes, due to the resources displacement potential that they entail. However, an almost complete absence of data for the energy and material balance and for costs has prevented such an indepth analysis from being conducted. Moreover, additional impacts on human health that can result from the co-combustion in cement kilns cannot be quantified as the toxicity impact categories have not been included among the selected impact categories.

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6. Assessment of the most promising options

6.1. Introduction

In this chapter, we consider the short list of options drawn from the literature review and criteria discussed in the previous chapter. For each of the options selected, the following key issues are discussed: What is the current situation and main trends? What are the technical options and technical potential? What is the existing legislation and what are the current policy developments? What are the main social and economic barriers and drivers for the implementation of the technical potential?

The environmental benefits and costs associated with the technical options were then quantified. To this end, assumptions regarding the relevant parameters used to calculate the benefits and costs were made. Finally the petrol and the diesel car model analyses (see section 4.2) were used as a benchmark against which the options were examined.

For the sake of consistency, some of the options listed in Table 28 have been regrouped which led to the following list of options:

- car weight reduction
- car body and tyres
- air conditioning
- power train improvements
- tailpipe air emission abatement systems
- hybrid cars
- biofuels
- end-of-life vehicle recycling and recovery
- speed control
- driving behaviour.

Some of these options actually include several sub-options and, in total 16 options were quantified.

The two last options represent non purely technical options as they depend to a large extent on a change in consumer behaviour.

6.2. Car weight reduction

6.2.1. Description of the options

The use of light materials to reduce the total weight of a car might prove to be a successful strategy for reducing fuel consumption. High strength steel (HSS), aluminium, magnesium and composites are the available technical options that can be adopted in the short to medium term. A literature review concerning the use of these materials in car manufacturing and the main findings are summarised below:

- **high strength steel** has a competitive price (if compared to other lighter materials), a relevant displacement potential and a high tensile strength. It does not require a radical change of car manufacturing production lines and can be easily recycled

- **aluminium** as pure element has a low tensile strength, thus its use in the automotive industry is completely in the forms of alloys. Depending on the alloying elements, wrought, stamped and casted aluminium can be used for structural, non structural and engine components like for example: bumper reinforcements, seat tracks, lorry bumpers, body panels, inner body panels, wheels, fuel delivery systems. Aluminium can be used for car body manufacturing, but with a significant increase in the production costs and increased difficulty for the repairing: damage to aluminium requires specific tools if not a complete replacement
- **magnesium**: an extensive use of magnesium alloys is strictly connected with a lower price of the metal and improved resistance to corrosion, the latter would enable the use of this material for exterior and structural applications that are more exposed to oxidising agents. The SF_6 treatment applied to casted magnesium is an environmental hot spot of this product's life cycle. It is the lightest engineering material and is characterised by low energy consumption in recycling due to its low melting point if compared to steel and aluminium. The current applications of Mg alloys in the automotive industry are based on the use of high pressure die castings (HPDC) products
- **composites**: there are barriers, at least in the short and medium term, to the use of composites for structural applications, mainly consisting of manufacturing and raw material costs. Moreover, the extensive use of composites for structural parts, which would enable substantial weight reductions to be achieved without decreasing crash resistance of the car, requires a radical change of the currently adopted production lines. Plus composite materials are much more difficult to recycle if compared to metals[146]

The substitution potential among different materials depends on their specific density and mechanical properties (stiffness, tensile strength, ductility, etc.). Table 29 shows possible pathways towards lighter car components with a gradual penetration of aluminium, magnesium[147] and composites.

Table 29: Summary table of possible material substitutions and expected achievement

	Currently used	Short term: t< 5 years	Medium term: 5<t<10 years	Long term: t>10 years
Engine and drive train	Iron or aluminium	Iron, aluminium	Aluminium, magnesium	Aluminium, magnesium
Transmission apparatus (inc. suspensions, wheels, brakes, etc.)	Iron and steel	HSS	HSS and aluminium	HSS and aluminium and magnesium
Body	Steel sheet	HSS	HSS, Aluminium	Aluminium, magnesium, C-fiber composites
Closures	Steel	HSS (weight red: 22 – 47%)[1]	HSS, aluminium,	HSS, aluminium, composites
Interior components	PVC	Polyethylene terephthalate	Polyethylene, polypropylene	Bio-based polymers

[1] ULSA Closures

Despite weight saving targets per component adopted by the automotive industry rather successfully, the average weight of cars has increased, thus compensating any possible net fuel saving. The request for

additional components to increase a car's safety and comfort (e.g. air bags, door supports, anti-lock braking system, air conditioning), or to reduce its environmental impact (e.g. noise insulation panels, catalysts) has determined this upward trend. The list below gives a concise overview of the current material composition of a medium sized car and of the possible technical development and material substitution that might occur:

- **iron and steel** are the most extensively used materials (up to 75% - 80%). Their use is expected to remain constant or slightly decrease in the medium to long term. However in the short term, the use of HSS is the most promising for many car components, for its technical properties and lower price, if compared to aluminium or magnesium alloys
- **aluminium** currently accounts for 5% to 8% of an average European car's total weight, but its use is expected to increase within this decade although its higher market price might present an obstacle
- **magnesium** alloys are currently used in small quantities in European car manufacturing (0.5% - 1%), but they can provide substantial additional weight savings. As for aluminium alloys, the high market price, if compared to steel, and the additional change in the production line constitute an obstacle for its large scale use
- the use of **composites** remains limited because of the high costs of the material and unfamiliarity of manufacturing methods among the car manufacturers. Its limited recyclability presents a further impediment.

6.2.1.1. Existing legislation and current developments

So far, lightweight cars are not concerned by legislation. This option is however concerned by the new proposed strategy regarding CO_2 emissions reduction from cars (see section 6.6.3).

6.2.1.2. Social and economic barriers and drivers

Economic and environmental barriers have to be considered when envisaging an extensive use of lighter materials. Lighter materials have a higher market price depending on the raw materials and manufacturing costs, and need changes to be made to the production lines needing additional investments in technology. Therefore, the risk is that of producing a car which is not affordable by consumers.

Moreover, legislative development in the recycling of cars might represent a further obstacle for those materials that are less recyclable than metals (i.e. composites) and where the infrastructure for recycling is not in place.

Finally, additional safety requirements might offset the weight reduction obtained by using lighter materials.

6.2.2. Environmental benefits of the option

6.2.2.1. Assumptions

The weight reduction targets that are considered in this study are those already analysed by TNO et al.[148]: -5%, -12% and -30%. The car´s material compositions that allow the weight reduction options to be achieved, are listed in Table 30 were used.

The changes in the material composition are based on the following assumptions:

- -5%: displacement of conventional ferrous metals for high strength steel (the declining use of ferrous metals results from the application of less HSS to achieve the same resistance performances)
- -12%: displacement of ferrous materials with aluminium
- -30% Al: intensive displacement of ferrous materials with aluminium
- -30% Mg: intensive substitution of ferrous materials with magnesium.

An unchanged amount of plastics is assumed to be used in all the options; this assumption results in an increasing percentage content of plastics.

Figure 28 and Table 30 display the material composition for the base case and the improvement options implemented in the current set up of the model.

Figure 28: Car's material composition applied in the different improvement alternatives

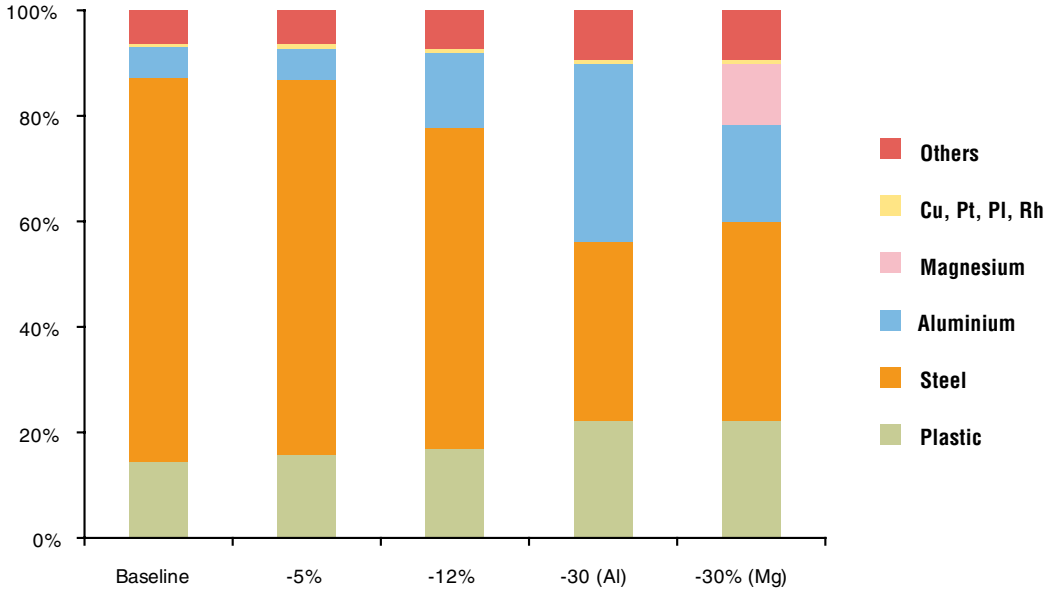


Table 30: Weight improvement options for the two systems: 'diesel' and 'petrol'

	Baseline		-5%		-12%		-30 (Al)		-30% (Mg)	
Materials	**Diesel**	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Petrol**
Plastics	193	193	193	193	193	193	193	193	193	193
Steel	959	742	886	680	695	519	300	184	333	212
Aluminium	72	68	72	68	160	142	291	254	160	142
Magnesium	0	0	0	0	0	0	0	0	99	84
Cu, Pt, Pl, Rh	9	9	9	9	9	9	9	9	9	9
Glass and paint	82	82	82	82	82	82	82	82	82	82
Other materials and fluids	147	145	147	145	147	145	147	145	147	145
Total weight	**1 463**	**1 240**	**1 390**	**1 178**	**1 287**	**1 091**	**1 024**	**868**	**1 024**	**868**

A reduction of weight affects the driving phase. In practice, there might be some differentiation between the different driving cycles, with a lower environmental benefit under motorway driving conditions. The effect of these weight reductions on CO_2 emissions and on fuel consumption is estimated as follows (see TNO et al.[148]):

$$\frac{\Delta CO_2}{CO_2} \approx -0.65 * \frac{\Delta M}{M}$$

where $\Delta M/M$ refers to the percentage weight change. This equation means that 100 kg additional weight roughly results in 0.3 - 0.4 l/100 km additional fuel consumption, depending on the vehicle type. (Estimations can only be made for fuel consumption and CO_2 emissions). It has to be noted that a wide range of studies/references propose lower or higher potentials. For instance, the European Aluminium Association considers that a 100 kg weight reduction corresponds to a cut of 0.3 to 0.6 litres per 100 km in fuel consumption leading to 20% lower exhaust gas emissions and proportionally reduced operating costs[ar]. In the calculations it was assumed that the air pollutant emission values were unchanged although a reduction in the air pollution emission level should be expected.

6.2.2.2. Environmental benefits of the option

The environmental benefits obtained through the weight reduction options are discussed in this section and displayed in the following tables that show the ratio of the improvement option results over the baseline. For all the analysed options, except the '-5%', the main result is the trade-off between the improvements obtained in the use phase (WTW) thanks to a lower weight and the worsening of the production phase due to the use of materials with a worse environmental profile (i.e. aluminium and magnesium). The results obtained for the two systems 'petrol' and 'diesel' do not present differences that deserve further comparison. Therefore, the following discussion of the results is restricted to the 'diesel system'.

Table 31 shows the results for the '-5%' option. Due to the underlying assumption (e.g. the high strength steel has the same environmental profile as the conventional one) the results indicated an improvement in all the life cycle phases and for all of the impact categories.

Table 31: Life cycle impacts for the '-5%' improvement option – diesel car

	Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)					
	Production	**Spare Parts**	**WTT**	**TTW**	**EOL**	**Total**
AD	98.2	100	96.9			99.2
GWP	96.8	100	96.9	97.0	100	97.0
ODP	100.0	100	96.9			97.0
POCP	97.3	100	96.9	100	100	98.6
AP	99.4	100	96.9	100	100	98.1
EP	99.3	100	96.9	100	100	98.5
PM2.5	100.0	100	96.9	100		98.9
PE	98.5	100	96.9	96.9	100	97.1
BW	96.4	100	96.9		98.5	97.3

ar See: http://www.azom.com/details.asp?ArticleID=1964 and http://www.eaa.net/eaa/downloads/Aluminium_in_cars_Sept2007.pdf.

As previously mentioned, a larger impact in the production phase was detected for the '-12%' option and these results are shown in Table 32.

Table 32: Life cycle impacts for the '-12%' improvement option – diesel car

Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)						
	Production	Spare Parts	WTT	TTW	EOL	Total
AD	96,4	100	92,5			98,3
GWP	102,6	100	92,5	92,8	100	93,6
ODP	118,2	100	92,5			93,5
POCP	101,1	100	92,5	100	100	97,3
AP	104,8	100	92,5	100	100	97,3
EP	103,2	100	92,5	100	100	97,6
PM2.5	129,8	100	92,5	100		101,3
PE	108,0	100	92,5	92,5	100	94
BW	114,3	100	92,5		98,5	104,1

With the exception of abiotic depletion, this option has a larger impact on all the categories for the production phase. The overall environmental profile that is shown in the 'Total' column is worse than the baseline only for the PM2.5 emissions and bulk waste produced. In both the cases, these depend on the use of aluminium and the absence of any improvement for these categories obtained during the WTW.

The same considerations are valid for the next option which is the '-30%' option (see Table 33). In this case the use of aluminium is more intensive and the environmental performance of the production phase is worse than before. Again, the overall results are better than the baseline in all the impact categories but PM2.5 and bulk waste.

Table 33: Life cycle impacts for the '-30%' improvement option – diesel car

Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)						
	Production	Spare Parts	WTT	TTW	EOL	Total
AD	91,0	100	81,3			95,8
GWP	106,6	100	81,3	81,9	100,0	83,9
ODP	145,5	100	81,3			83,6
POCP	102,8	100	81,3	100	100,0	93,4
AP	112,1	100	81,3	100	100,0	93,2
EP	107,9	100	81,3	100	100,0	94,1
PM2.5	174,6	100	81,3	100		103,2
PE	120,1	100	81,3	81,3	100,0	85,0
BW	135,7	100	81,3		96,34	110,3

Table 34 displays the results for the last of the analysed options which was the '-30%-Mg' option.

Table 34: Life cycle impacts for the '-30%-Mg' improvement option – diesel car

Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)						
	Production	Spare Parts	WTT	TTW	EOL	Total
AD	90,0	100	81,3			95,3
GWP	232,1	100	81,3	81,9	100	93,8
ODP	142,6	100	81,3			83,5
POCP	99,7	100	81,3	100	100	93,0
AP	106,2	100	81,3	100	100	91,6
EP	109,2	100	81,3	100	100	94,4
PM2.5	155,8	100	81,3	100		100,7
PE	120,6	100	81,3	81,3	100	85,0
BW	121,8	100	81,3		91,3	102,5

With the exception of POCP and AD, the use of magnesium determines a larger impact for all the impact categories in the production phase compared to the baseline. The largest difference is found for GWP and is due to the emissions of a large amount of SF_6 used as a cover gas in foundries to prevent oxidation. The emissions factor for SF_6 that is used in this study corresponds to the one proposed by the International Panel of Climate Change[149] (i.e. 0.001 kg/t Mg). Alternative treatments of the metal that substitutes SF_6 with other gases with a much lower impact on GWP are available but not considered in this work since they currently do not represent a common procedure in the magnesium industry and there is not much information available. However, these alternative treatments might be largely available by 2010 and an extensive use of magnesium in car manufacturing has to be supported by an initiative aiming at the phase out of SF_6 from the magnesium production process[150].

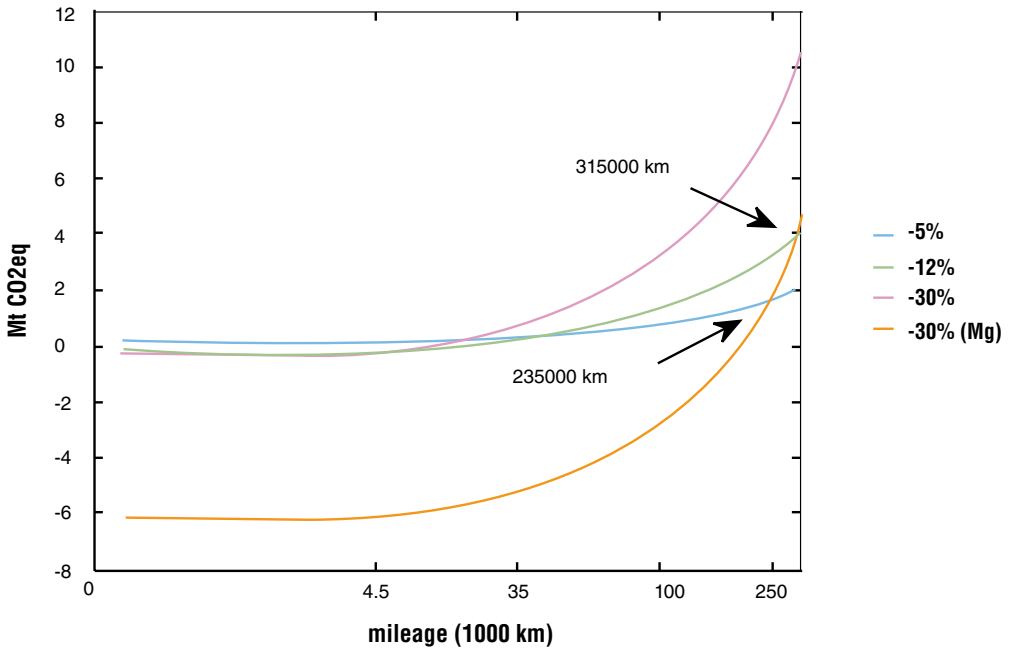
These results show that options to reduce the vehicle weight generate substantial environmental gains regarding energy and GHG emissions and air pollution. They also show the existence of trade-offs between GHG emissions reduction and waste reduction. This was also a conclusion made in the LIRECAR project[17].

When considering these results, it should be noted that no improvement was assumed regarding the different material processes concerned whereas, within the time horizon of these options such improvements can be expected, such as energy efficiency, CO_2 emission reductions and air pollution emissions.

Sensitivity to mileage

Due to the higher energy intensity of 'light metals', the environmental benefits obtained by virtue of a car's weight reduction highly depend on the mileage. That is to say, an actual environmental benefit is achieved only when the cumulative fuel saving is enough to compensate for the larger energy consumption occurring during the production phase. Figure 29 shows the correlation of mileage and GWP reductions for the three technical options analysed in this study. The *y* axis depicts the cumulative difference between the baseline and each improvement option as a function of the mileage that is depicted on the x-axis.

Figure 29: Breakeven points estimated for the weight reduction improvement options for GWP



The -30% weight reduction expected by using magnesium alloys and by displacing steel appears as the least convenient. An actual improvement is reached only after 235 000 and 315 000 km travelled if compared to the two alternative options -5% and -12%. The results shown in Figure 29 do not take recycling into account. However, the results remain basically unchanged even with recycling of the metal fraction.

6.2.2.3. Direct costs

For the cost analysis, a cost curve that associates a cost per each kg of weight reduction has been estimated by using the data provided by TNO et al.[148]. On the basis of this cost curve, the following direct manufacturing costs have been estimated:

- -5%: 168 Euro and 135 Euro for the diesel and the petrol system respectively
- -12%: 544 Euro and 425 Euro for the diesel and the petrol system respectively
- -30% Al and -30% Mg: 2 185 Euro and 1 619 Euro for the diesel and the petrol system respectively.

6.3. Car body and tyres

6.3.1. Description of the options

Both the aerodynamic and rolling resistances have major influences on vehicle fuel economy.

In a simplified problem of a vehicle at constant speed on a horizontal road, the net power P(W) transmitted to the wheels that compensates losses due to aerodynamic and rolling drag is given by:

$$P = \eta P_{engine} = \frac{1}{2}\rho C_D A V^3 + C_{RR} M g V$$

η: *gear box and rotating parts efficiency*

V: vehicle speed (m/s)

ρ: *density of air* (≈ 1.2 *kg/m*^{3})

M: total vehicle mass (kg)

A: frontal area (m^2)

C_D: *aerodynamic drag coefficient*

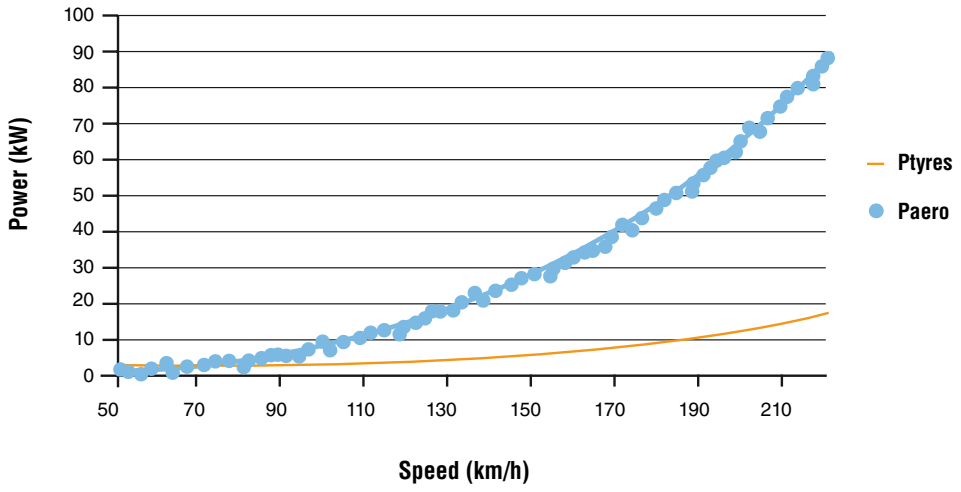
C_{RR}: *rolling resistance coefficient*

g: gravitational acceleration (9.81m/s^2)

where the quantities $\frac{1}{2}\rho C_D A V^3$ and $C_R\ MgV$ are the power lost due to aerodynamic and rolling drags (in W) respectively.

As shown in Figure 30, the effect of the aerodynamic drag dramatically increases with speed due to the cubic dependence V^3 of the power term (the aerodynamic forces are not really important up to 60 km/h).

Figure 30: Power lost while driving

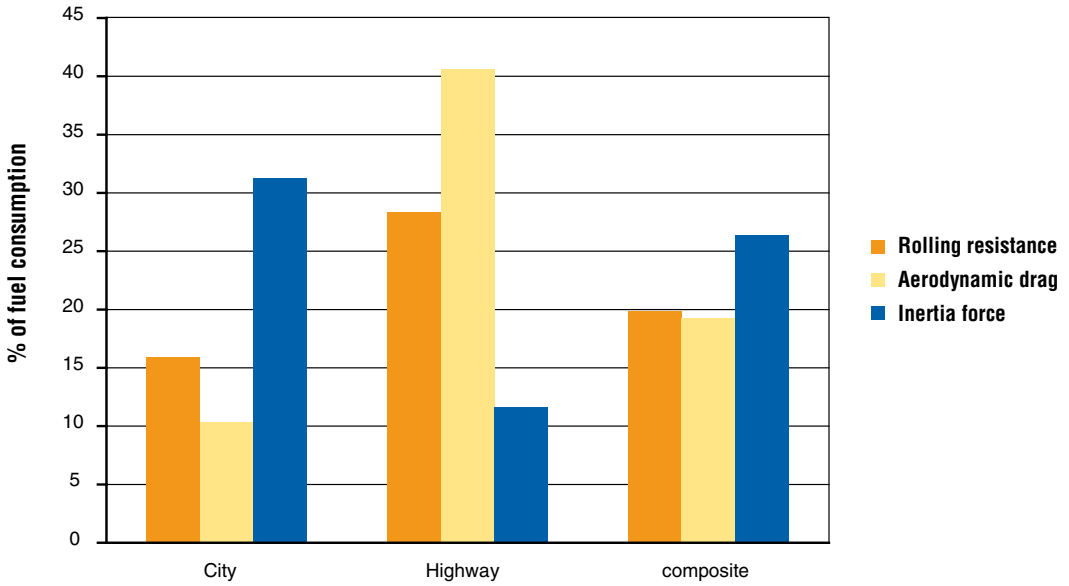


*Source: (Elena, 2001)*70

Figure 31 illustrates the contribution of the rolling resistance (associated with the deformation of the tyres), the aerodynamic drag[as] and the inertia force on fuel consumption for three driving conditions[at]. Whereas the inertia force is predominant in the city, it is no longer the case for the motorway cycle where drag forces (aerodynamic and rolling resistance) account for about 70% of the total fuel consumption.

as Resistance applied to a body as it passes through the air, caused by pressure and friction.
at Note that the sum is less than 100% since it is part of the tractive energy only.

Figure 31: Influence of driving conditions on aerodynamic drag, rolling resistance and inertia contributions to fuel consumption



Remark: ***Indicative values only, derived from Duleep****151*

Therefore, speed, weight and drag coefficients (C_D or rather the drag area (C_DA)[au] for aerodynamic drag and C_{RR} for rolling resistance) are the physical parameters that mainly influence the drag forces. The following sections describe the options for improving these coefficients. The vehicle speed and weight are treated as separate options.

6.3.2. Current situation and main trends

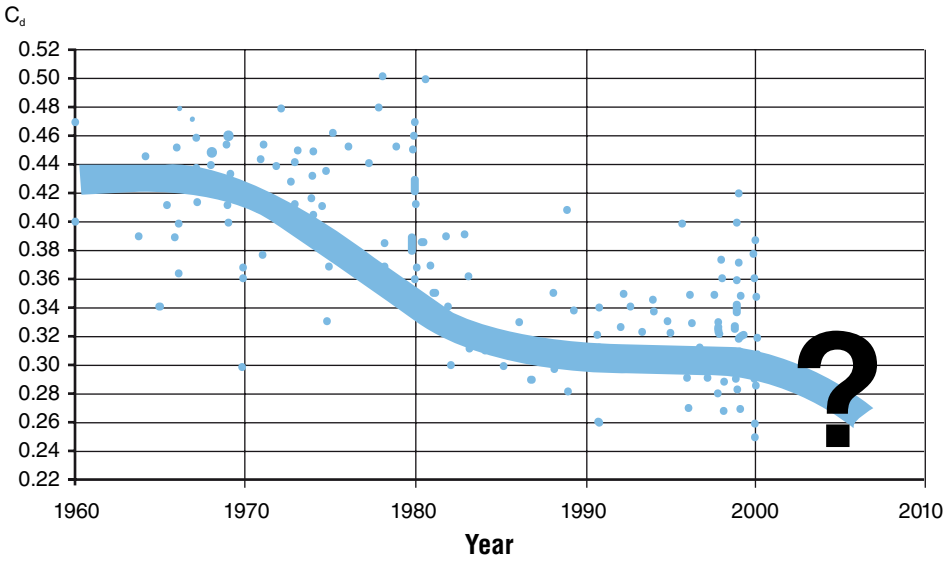
Typical modern cars have an aerodynamic drag coefficient C_D in the range of 0.3 to 0.4 or even less. The lowest level (0.25) is currently achieved in the Audi A2 3L TDI introduced in 2001 (aluminium body technology with 825 kg vehicle weight) and the Honda Insight.

As shown in Figure 32, the aerodynamic drag follows a decreasing trend, especially after the oil crisis of 1973. The figure displays 3% to 5% less consumption per car between 1980 and 1985 thanks to aerodynamic improvements.

At the same time, the EU vehicle fleet is constantly evolving with different types of vehicles, especially including spacious and more comfortable cars (e.g. SUVs), making aerodynamic optimisation (reducing drag area) more challenging for these new cars with higher frontal areas. Moreover, other parameters, e.g., the increasing size of the population (height, weight and age) must be taken into consideration for the design of new cars.

au The product of the frontal area by the drag coefficient is called the drag area (m^2). This value is widely used as it enables comparisons to be made in terms of the aerodynamic efficiency of different cars. For instance, the drag area of the Peugeot 206 is around 0.65 m^2 (C_D = 0.32; A = 2.03m^2).

Figure 32: Drag coefficient (CD) of European vehicles since 1960



Source: (Elena, 2001)70

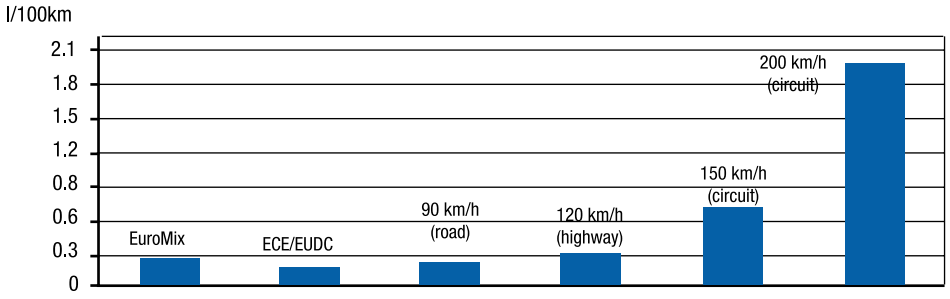
6.3.3. Technical potential

There is a significant technical potential related to the two types of options. Both are associated with significant environmental benefits.

6.3.3.1. Aerodynamics

The sensitivity of the fuel consumption on the aerodynamic drag coefficient C_D is highlighted in Figure 33. Elena[70] assumed that a 10% decrease in C_D could lead to fuel savings of about 0.2 to 0.3 l/100 km depending on the driving cycle (excluding the so-called "circuit" cycle).

Figure 33: Fuel consumption savings for a 10% decrease in C_D for different road types



Source: (Elena, 2001)70

The goal is to achieve an optimum drag area taking into account the consumer's choice and the environmental constraints. In the short to medium term, evolution is expected to carry on but not as spectacularly as during the 1980s.

Aerodynamic engineers seek to reduce the aerodynamic drag area (C_DA). For this purpose, they still rely on experimental studies (wind tunnel testing) but they mostly use simulation tools (e.g. CFD software) and optimisation methods to design the car shape.

There are several ways to reduce aerodynamic drag. Even if the overall shape of the car has the biggest influence on the drag coefficient, many improvements regarding the car underbody, cooling systems, rear view mirrors, etc. may contribute to drive the drag coefficient down. However, many of the improvement options listed below will most probably face design conflicts with customers' desires for comfort and safety issues. Examples are:

- lower the engine hood, rake the windscreen ⇒ conflict with engine size, but better forward visibility
- changes in the rear end ⇒ conflict backward visibility and boot space
- smoothing underbody and covering the engine compartment ⇒ conflict with needed engine airflow
- reduce distance between body and ground ⇒ conflict with easy entry and off-road capability
- reduce internal airflow, etc.

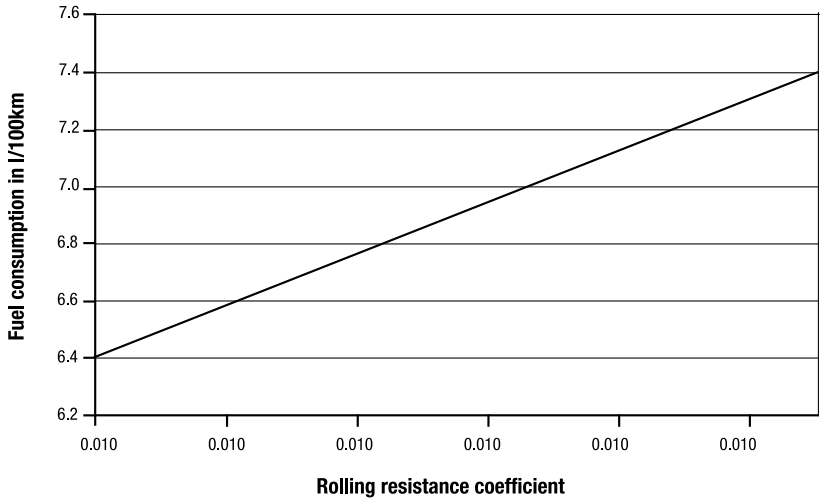
As a result, these changes are not expected to entail substantial improvements and it is likely that the remaining options for further improvements will be incorporated in the new vehicles as part of an autonomous and continuous development[av]. A slow evolution in the short and mid-term is therefore expected.

6.3.3.2. Rolling resistance

As explained previously, tyres have a non-negligible impact on a car's fuel economy since they are directly responsible for about 15% to 30% of typical fuel consumption, depending on driving conditions.

Figure 34 shows the relationship between the rolling resistance coefficient and fuel consumption.

Figure 34: Fuel consumption/rolling resistance coefficient correlation for a passenger car at 60 km/h



Source: Danish Road Institute71

av Note that the most important efforts for drag reduction concern heavy vehicles which have the largest aerodynamic drag levels.

It is generally considered[aw] that a 10% reduction in tyre rolling resistance yields a fuel saving of 1% to 2.5%, depending on driving conditions, road surface, driving style, etc. Tyre rolling resistance depends on many parameters like:

- tyre design: shape, composition, etc.
- tyre pressure
- vehicle weight[ax]
- road surface
- ambient temperature (affecting tyre pressure)
- driving behaviour, driving cycle, etc.

In literature, a wide range of studies have been carried out in this area. Examples are:

- Europe: EU projects like SILVIA (see, e.g. technical note from the Danish Road Institute[71]), TÜV[76], the CARS 21 final report[152], the European Tyre School[74], etc.
- North America: California Energy Commission[72], ATVP[73], the special report of the Transportation Research Board[153], etc.

Obviously, there is a significant technical potential related to fuel savings from tyres by acting on the factors described previously, e.g. tyre design, road surface and pressure control.

Two of these options are particularly promising:

- the use of low rolling resistance tyres (LRRT)
- the regular control of their pressure through the tyre pressure monitoring system (TPMS).

The combination of these two technical options might lead to a very significant economy of fuel (around 5%) while changes in road surface would effect the whole existing vehicle fleet but will not be considered in this study.

Low rolling resistance tyres (LRRT)

The use of silica in tyre's tread composition can result in a reduction in rolling resistance up to 20% while maintaining the wet grip performance. According to the range defined before, it could save up to 5% of fuel. According to the tyre manufacturer Pirelli, the potential of rolling resistance reduction thanks to silica reaches 22% with a 100% silica composition and 9% with a 50% silica composition (see, e.g. Calwell[154]).

Using tyres with low rolling resistance (LRRT) could thus reduce fuel consumption within the range of 2% - 5%.

aw As an example, the California Air Resources Board (CARB) estimates that a 10% reduction in rolling resistance would result in 2% CO_2 reduction (http://www.arb.ca.gov/cc/042004workshop/final-draft-4-17-04.pdf).

ax The use of light materials instead of iron and steel can significantly reduce the rolling resistance by not pressing down so hard on the tyres.

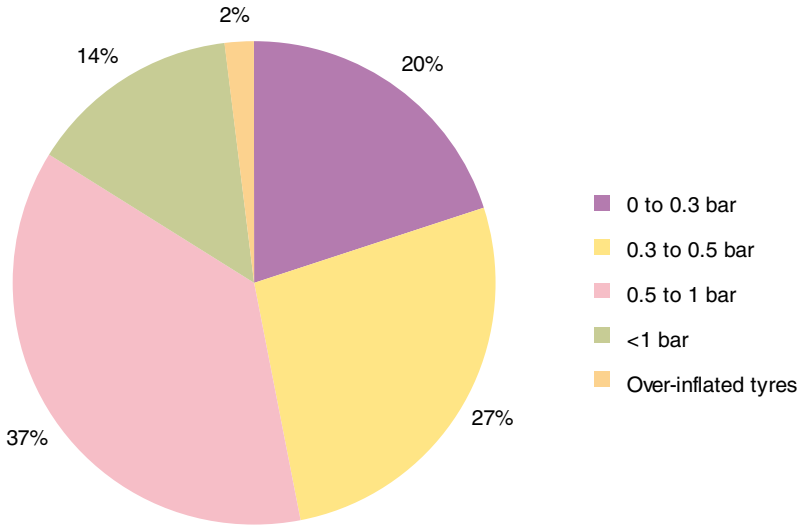
Tyre pressure monitoring system (TPMS)

Tyre pressure is modified due to air escaping (about -0.07 bars per month) and ambient temperature (± 0.06 bars/10 °C). Driving with under-inflated tyres increases the rolling resistance and then increases tyre wear (reducing lifespan) and fuel consumption[155].

The importance of under pressure tyres can be illustrated by the results of the 'fill up with air' campaigns held in summer 2003[ay] in France (see Figure 35).

According to these results, the over fuel consumption range due to under pressure tyres in France is estimated to 4%. Although it is only an example, it shows the high influence of tyre pressure on fuel consumption (along with reduction in injuries and deaths, and thus cost savings, etc.).

Figure 35: Percentage of under pressure tyres



(derived from the French campaign "fill up with air")

The tyre pressure monitoring system (TPMS) is a promising technical solution to cope with this problem[az]. Globally, there are two main types of TPMS: the direct and indirect systems[ba]. In the first case, the tyre pressure is directly measured, while in the second case, the system estimates differences in pressure by comparing the rotational speed of the wheels. In both cases, the driver is informed when the pressure in one (or more) tyre falls below a pre-determined level. Unless the TPMS is connected to a self-inflation system, the driver should stop the vehicle and inflate the tyre. This system is about to be launched on a retrofitting market and is expected to be standard equipment in the next few years (5 - 10 years).

An ideal maintenance would lead to a fuel consumption reduction (and CO_2 emission) of 1% to 2.5% in Europe[156]. The introduction of an accurate TPMS on all new vehicles from 2008 would significantly increase fuel economy (by 3% - 4% for 30% - 40% of the fleet). Table 35 summarises the fuel saving potentials expected from the LRRT and TPMS improvement options.

ay http://www.michelin.com.
az This problem can also be addressed through non-technical means like information to consumer.
ba Hybrid systems also exist that combine direct and indirect technologies.

Table 35: Synthesis of potential related to the LRRT and TPMS options

Potential improvements	Impact on rolling resistance	Average impact on fuel consumption (1)
LRRT (shift from 'black' to 'green' tyres)	From 10% to 20% reduction	2% - 5% fuel savings (depending on driving conditions) (e.g. 3.2% for the urban and 5.1% for driving on major/ minor roads, from http://www.michelin.com)
TPMS (monitoring/self-inflation systems)	-0.3 bar → +6% -0.5 bar → +15% -1 bar → +30%	If tyre pressure is regularly checked, potential fuel savings of at least 2% (own estimates in line with the literature).

(1) assuming that 10% reduction in rolling resistance leads to 1% to 2.5% of fuel savings

6.3.4. Existing legislation and current developments

For the time being, there is no European legislation fostering such improvement options. These options are, however, currently being considered in the framework of the strategy regarding CO_2 emission reductions from transport (see section 6.6.3).

The United States recently proposed regulations to require low pressure sensing. It is expected that "California will soon require tyre manufacturers to report rolling resistances of replacement tyres sold in that state. Based on a review of these and other data, California may establish minimum efficiencies for replacement tyres. Other states in the United States are likely to follow California's example. The European Union and Canada are also investigating policy options"[bb].

6.3.5. Environmental benefits and direct costs quantification

6.3.5.1. Assumptions

There is a high degree of uncertainty about the scale of environmental benefits partially due to a lack of data for both tyres and aerodynamics.

Aerodynamics

Even if it is widely recognised that improved aerodynamics will result in important energy savings, it is difficult to anticipate the development of new technologies for this option and there is a lack of technical description of new technologies. The literature reviewed suggests that most of the improvements will be realised autonomously.

As a rough estimation, it was concluded that aerodynamics could reduce fuel consumption from 1% to 4% in the coming years. In this study, a 1.5% reduction was assumed as reported by TNO et al.[148]. This result would, however, be achieved through important R&D efforts in aerodynamic design but still limited due to the design constraints described previously. It is only an average value that highly depends on driving conditions (vehicle speed).

bb http://www.iea.org/Textbase/work/2005/EnerEffTyre/summary.pdf.
http://www.ciwmb.ca.gov/agendas/mtgdocs/2003/08/00012317.pdf.

Tyres

Tyres offer a higher potential. As described before, tyre improvements are likely to mainly occur by using LRR tyres and TPMS. According to the literature review carried out, the shift from "black" tyres to low rolling resistance tyres (the so-called "green tyres") can decrease fuel consumption by approximately 2% - 5%, depending on driving conditions. In this study the same average value (2%) as reported by TNO et al.[148] was considered. Regarding the TPMS option, a 2.5% reduction potential is assumed (see Table 36).

Overall, both options would then enable an average fuel consumption reduction (and thus CO_2 emission reduction) of 4.5% to be achieved.

Reduction of pollutant emissions is expected but it was impossible to quantify these reductions. Moreover, the influence of the driving cycle is not considered.

Table 36: Improvement potential for tyres and aerodynamics

Improvement option	Assumption	Average fuel savings/ CO_2 reduction	Air emissions	Source
Aerodynamic	Continuous development	1,50%	n.a.	TNO et al.[182]
Tyres	LRRT	2%	n.a.	TNO et al.[182]
	TPMS	2,50%	n.a.	TNO et al.[182]

6.3.5.2. Environmental benefits of the option

Table 37 and Table 38 show the environmental benefits obtained through aerodynamic improvements for petrol and diesel cars. Only the WTT and TTW impact categories are positively affected by this option where climate change and primary energy will be reduced by about 1.5%. Acidification is very slightly reduced due to fewer sulphur emissions (because of less energy consumed).

Table 37: Life cycle impacts for the improved car body aerodynamics option – petrol car

	Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)					
	Production	Spare Parts	WTT	TTW	EOL	Total
AD	100	100	98.5			100
GWP	100	100	98.5	98.6	100	98.7
ODP	100	100	98.5			98.6
POCP	100	100	98.5	100	100	99.1
AP	100	100	98.5	100	100	99.0
EP	100	100	98.5	100	100	99.1
PM2.5	100	100	98.5			98.9
PE	100	100	98.5	98.5	100	98.7
BW	100	100	98.5		100	99.6

Table 38: Life cycle impacts for the improved car body aerodynamics option – diesel car

	Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)					
	Production	**Spare Parts**	**WTT**	**TTW**	**EOL**	**Total**
AD	100	100	98.5			100
GWP	100	100	98.5	98.6	100	98.7
ODP	100	100	98.5			98.6
POCP	100	100	98.5	100	100	99.5
AP	100	100	98.5	100	100	99.2
EP	100	100	98.5	100	100	99.4
PM2.5	100	100	98.5	100		99.5
PE	100	100	98.5	98.5	100	98.7
BW	100	100	98.5		100	99.7

The "tyres" improvement option combining LRRT/TPMS presents higher impacts (see Table 39 and Table 40).

Table 39: Life cycle impacts for the improved tyres (LRRT + TPMS) option – petrol car

	Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)					
	Production	**Spare Parts**	**WTT**	**TTW**	**EOL**	**Total**
AD	100	100	95.6			100
GWP	100	100	95.6	95.7	100	96.0
ODP	100	100	95.6			95.9
POCP	100	100	95.6	100	100	97.3
AP	100	100	95.6	99.9	100	97.0
EP	100	100	95.6	100	100	97.4
PM2.5	100	100	95.6			96.8
PE	100	100	95.6	95.6	100	96.1
BW	100	100	95.6		100	98.9

Table 40: Life cycle impacts for the improved tyres (LRRT + TPMS) option – diesel car

	Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)					
	Production	**Spare Parts**	**WTT**	**TTW**	**EOL**	**Total**
AD	100	100	95.6			100
GWP	100	100	95.6	95.7	100	96.1
ODP	100	100	95.6			95.9
POCP	100	100	95.6	100	100	98.4
AP	100	100	95.6	100	100	97.6
EP	100	100	95.6	100	100	98.2
PM2.5	100	100	95.6	100		98.5
PE	100	100	95.6	95.6	100	96.1
BW	100	100	95.6		100	99.1

6.3.5.3, Direct costs

It is very difficult to estimate additional costs for improvements in aerodynamics. The CARB[158] estimated that reducing fuel consumption by 1.5% to 2% through aerodynamic improvements would cost between 0 USD to 125 USD RPE[bc] (i.e. from 0 Euro to 105 Euro). TNO et al.[148] assessed an average manufacturer cost of 75 Euro for a 1.5% fuel reduction, whatever the vehicle type. In this study, we will assume the same additional cost namely 75 Euro (Table 41).

Contrary to aerodynamics, many cost figures are available for tyres. For this option, we need to define additional costs for tyres with Low Rolling Resistance as well as for the Tyre Pressure Monitoring System. As for aerodynamics, our assumptions are derived from the deep literature review carried out by TNO et al.[148]:

- LRRT: the typical range of costs is within the range (35 Euro - 55 Euro) per set of tyres. We will assume an average cost of 50 Euro (TNO et al.[148]).
- TPMS: TNO et al.[148] reported important costs variation between different TPMS technologies. They however estimated that additional costs of TPMS would vary between 40 Euro and 65 Euro depending whether the system is direct (65 Euro) or indirect (40 Euro). Despite its higher cost, the direct system is more likely to enter the EU market in early years (they are more accurate and reliable than indirect systems). We will assume an incremental cost of 65 Euro as reported by TNO et al.[148].

Table 41: Costs estimates for aerodynamic and tyres

Improvement option	Assumption	Average fuel savings/CO_2 reduction	Average additional cost (€)
Aerodynamics	Continuous development	1.5%	75
Tyres	LRRT	2%	50
	TPMS	2.5%	65

Source: TNO et al.148

6.4. Mobile air conditioning (MAC)

6.4.1. Description of the options

The main environmental effect of MAC consists of additional energy use, GHG emissions and air emissions. These are "direct" GHG emissions resulting from refrigerant losses (at the level of the rubber hoses and connections, and at the level of servicing and charge and at the end-of-life) and "indirect" GHG and air emissions resulting from the additional energy use associated with the operating air conditioning system.

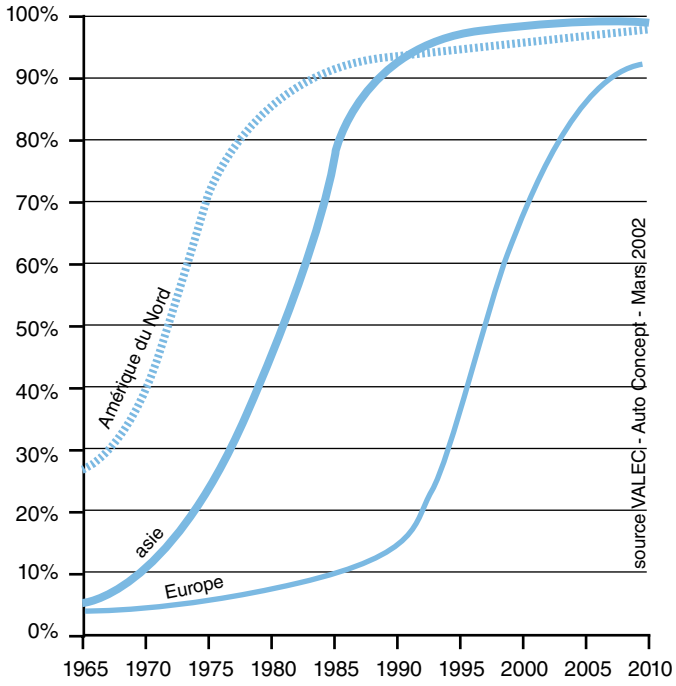
Both the environmental impacts and potential improvements of mobile air conditioning systems have been widely studied in literature. Results from the studies carried out by ADEME[bd] will be the main references in this section, completed by further data, e.g. from the IPCC Special report[31] or the SAE[be].

bc Retail Price Equivalent.
bd Agence de l'Environnement et de la Maitrise de l'Energie (http://www2.ademe.fr).
be See the Improved Mobile Air Conditioning Cooperative Research Program - IMAC (http://www.sae.org/altrefrigerant/ and http://www.sae.org/events/vtm/).

6.4.1.1. Current situation and main trends

The percentage of new vehicles equipped with air conditioning systems has significantly increased over the last years (see Figure 36). Almost half of the EU automotive fleet was equipped with an air conditioning system in 2003[78]. On a worldwide level, this rate was reached in 2000 as a result of high rates in the US and in other industrial countries. It is expected that 90% of cars will be equipped with AC in 2010 in the EU-25.

Figure 36: The evolving percentage of new vehicles equipped with air conditioning



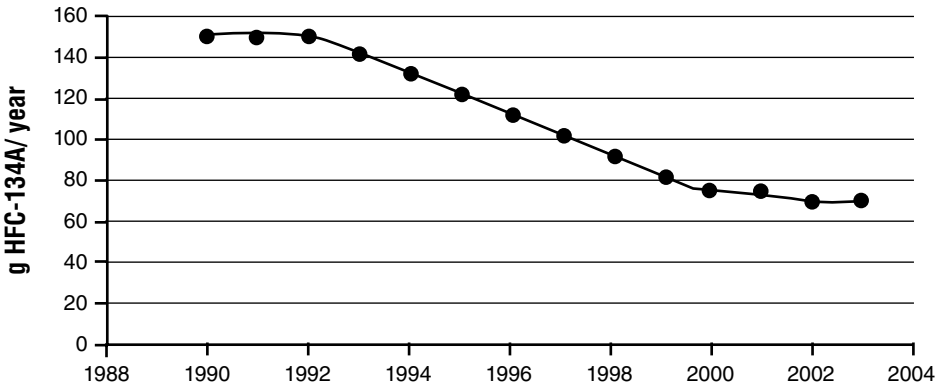
Source: ADEME77

The most common AC systems in recent and new cars use **HFC-134a** as a working fluid. HFC-134a has been used for several years now to replace CFC-12 which was completely forbidden in 1994. HFC-134a is not an ozone destructive gas but it is a greenhouse gas with a global warming potential (GWP) of 1 300.

Direct emissions: in 2003, the total leakage emissions (i.e. leakage rates, loss at servicing, accident and EOL) were around 70 g HFC-134a/year[29] (see Figure 37). This represents roughly 5g CO_2 eq./km (see Chapter 5). It is worth mentioning that overall leakages due only to refrigerant losses lie around 10 g HFC-134a/year[30, bf].

bf In 2004 - 2005, the ADEME funded a study undertaken by Ecole des Mines de Paris which measured refrigerant losses. The figures obtained from three MAC systems were lower than 10 g HFC-134a/year, taking into account that most of the leakages occur when a MAC is on. This was confirmed in another study from Ecole des Mines de Paris (for ACEA) in 2005, where 37 different MAC systems were measured.

Figure 37: Evolution of the total leakage rate in g HFC-134a/year (accidents included)



Source: ADEME29

It has to be noted that refrigerant leakages may substantially depend on system design, vehicle age, maintenance practice, model year, and operating environment. Little is known about the effects of these variables (for further information, see e.g. the study carried out by Schwarz et al.[79] for the EC).

Indirect emissions: the indirect impacts of MAC systems highly depend on climatic conditions and engine type. On a national level, the impacts of air conditioning are growing and represent a significant fraction of the fuel consumption by cars in industrialised countries. The additional energy use has consequences it terms of additional CO_2 emissions and also additional air pollutant emissions. However, it is still hard to derive converging figures from literature. In this study, the average over fuel consumption due to MAC was found to be around 3.3% over the year, that fits well into the range of 1% - 7% reported by ADEME[30].

Total emissions (TEWI): the sum of direct and indirect additional GHG emissions induced by the air conditioning is generally called the total equivalent warming impact (TEWI). According to the assumptions made, the TEWI was found to lie between 11 g CO_2 eq./km to 12 g CO_2 eq./km depending on the vehicle type (see Chapter 5).

Again, it should be kept in mind that this range is very rough since it depends on several parameters such as climatic conditions and technology type.

6.4.2. Technical potential

Four technical options and one non-technical option can help reduce the environmental impacts of MAC:

- reducing the leakages of refrigerants
- using refrigerants with a lower global warming potential
- improving the energy efficiency of MAC systems
- reducing the thermal load of passenger compartments
- non-technical option, e.g. by reducing the cooling demand in the car.

6.4.2.1 Reducing the leakages of refrigerants

The first group includes the improvement of leak tightness or recovery at servicing, resulting in the reduction of direct emissions. It is estimated that the leakage rates could be reduced by 50% or even more thanks to better leakage tightness and recovery.

Both flexible hose (high and low pressure) and system component connections (type and number) account for 25% of leakage emissions[bg]. The remaining 50% are due to compressor shaft seals[85]. In the US, manufacturers agree that existing systems can be improved to achieve up to 50% reduction in refrigerant leakage[85]. These improvements could be done through the use of low-permeability hoses and improved elastomer seals and connections. A certification method will certainly need to be developed for each component (e.g. heat exchangers, compressor). However, while low cost improvements to current HFC-134a systems to reduce leakage are feasible, the benefits for climate change are modest compared to the other alternatives such as the use of new working fluids.

Another efficient way to reduce service-related emissions of refrigerant would be to train technicians to use recovery and recharge systems with near zero emissions as a standard procedure. The use of high sensitive leak detectors as well as a sufficient knowledge to fix the leaks would also contribute to the reduction of emissions. However, the availability of recovery/recycling equipment is still a problem, even if the phase out of CFC-12 had a positive effect.

Another major source of emissions is related to the availability of disposable cans for end-users who want to recharge their own AC system. The global emissions related to these practices seem to be important.

6.4.2.2. Using refrigerants with a lower global warming potential

The second group of improvement options seeks to use **new working fluids** with lower global warming potential, thus reducing direct emissions (95% or 100% reduction).

New working fluids are expected to be used after the phase out of HFC-134a. However, it is still difficult to estimate which refrigerant will penetrate the market the most and disadvantages could arise depending on the refrigerant used.

HFC-152a: this refrigerant is considered a candidate substitute of HFC-134a. Its GWP is much lower than that of HFC-134a (140 instead of 1 300). Due to its very low GWP (but still much higher than CO_2) it is not affected by the EU legislation and may be used after 2012. Its main drawback is that it is a flammable substance (but not as flammable as propane or most other hydrocarbon-based refrigerants), introducing additional safety considerations with respect to the system design, operation, and maintenance. Mainly for these reasons, HFC-152a is not expected to enter the EU market.

The literature assumes an average potential reduction of indirect emission of 10% compared to the HFC-134a reference case (see, e.g. IPCC[31], TNO et al.[148]).

R-744 (CO_2): carbon dioxide CO_2 (designated R-744) has a much lower GWP than other refrigerant candidates. CO_2 is non-toxic in small doses but concentrations over 5% can be lethal. It is also cheap and non-flammable. The principal difference of a CO_2 system is the much higher operational pressures required[84], around five times those of a baseline HFC-134a system (transcritical cycle). Consequently, all components and connecting flow tubing must withstand not only these pressures but also incorporate a

bg Without considering operation at servicing, accidents and EOL.

safety factor of four to five times the expected maximum. Hence, this refrigerant will require new designs and new components[bh] which represent a challenge in terms of cost, occupant safety, and efficiency to the manufacturers. The schedule on which CO_2 systems could be deployed is very uncertain.

Apart from direct emissions, a few improvements are expected regarding fuel consumption from a CO_2-based AC system. The comparison with HFC-134a-based systems is difficult to assess as it clearly depends on climate conditions. Under hot temperatures (e.g. in the USA or in the south of EU), the over fuel consumption can even be higher for CO_2 than for HFC-134a.

Other candidate working fluids: another option would be to use hydrocarbons (e.g. propane, isobutene). Indeed, these gases are widely used in industry and their thermodynamic properties are mildly better than HFC-134a. However, hydrocarbon systems present an important drawback in terms of security. These systems are not considered as a leading alternative for MAC refrigerant technology and there is no support from car manufacturers.

Recently, Honeywell, Dupont de Nemours and others have developed new refrigerants with a low GWP (<150) that are still being tested. These new fluids are in line with EU legislation and might become the future refrigerants[bi].

6.4.2.3 Improving the energy efficiency of MAC systems

Use of more efficient Variable Displacement Compressors (VDC)

Compared to the on/off cycling associated with traditional fixed displacement compressors (FDCs) that considerably impacts on the performance of smaller engines[bj], the use of variable displacement compressors (VDC)[bk] presents the following main advantages:

- smooth continuous compressor operation
- dynamic system response, allowing the refrigerant flow to be modulated in accordance with cooling demand resulting in a significant efficiency improvement for most cooling demands
- can eliminate air reheating when associated with automatic climate controls
- can provide better thermal comfort.

For instance, the annual over-consumption in France dropped from 0.55 l/100 km for the Renault Laguna 1 to 0.3 l/100 km for the Laguna 2, by using a variable displacement compressor (VDC) and the control automation[81]. VDCs are currently available technology. In the EU, where the average engine displacement is less than 2 l, VDCs can provide significant improvements to engine performance.

bh New compressors capable of operation at high pressure (>50 bars) need to be developed.
bi http://www.sae.org/congress/2006/showdaily/tuesday1.pdf
http://rtitech.com/2006%20Refrigerant/Future%20of%20Refrigerant.pdf.
http://www.afce.asso.fr/ , http://refrigerants.dupont.com/Suva/en_US/science/soc_sustainable.html
http://www.dehon.com/fr/index_fr.php?menu=actu&idm=&action=3&deroul=0&idn3=76
http://www.dehon.com/fr/index_fr.php?menu=actu&idm=&action=3&deroul=0&idn3=226.
bj Under mild conditions, FDCs tend to overcool the cabin and then reheat the air to provide a moderate level of cooled air.
bk The infinitely-variable displacement wobble-plate compressor (VDC) changes the piston-stroke length (or wobble-plate angle) and the displacement consequently to exactly match the vehicle's air conditioning demand.

Improved heat exchangers and climate control

Further efficiency gains can be achieved through improvements in heat exchanger designs (evaporators and condensers) and better control systems such as improved heat transfer and enhanced air recirculation. That would result in better airflow management and consequently better energy efficiency.

Furthermore, progress can be made in standardising the measurement of energy consumption due to AC operation (in order to facilitate the comparison of technical proposals), the use of active or passive pre-conditioning at a stop, etc. When the AC is on, the use of an automatic climate control enables the saving of more energy than with the manual system. However, it should be noted that the automatic control is generally more widely used (mode by default) than the manual control, which partially reduces the expected advantages[30, 161].

Future MAC technologies

Several candidate technologies are likely to replace conventional air conditioning systems. Examples are metal hydrides, absorption systems, thermo-acoustic refrigerators, zeolite systems, magneto caloric heat pumps, ejector refrigeration, etc. However, these systems need further research and are not efficient enough to replace the conventional technology in the short term[82].

6.4.2.4. Reducing the thermal load of passenger compartments

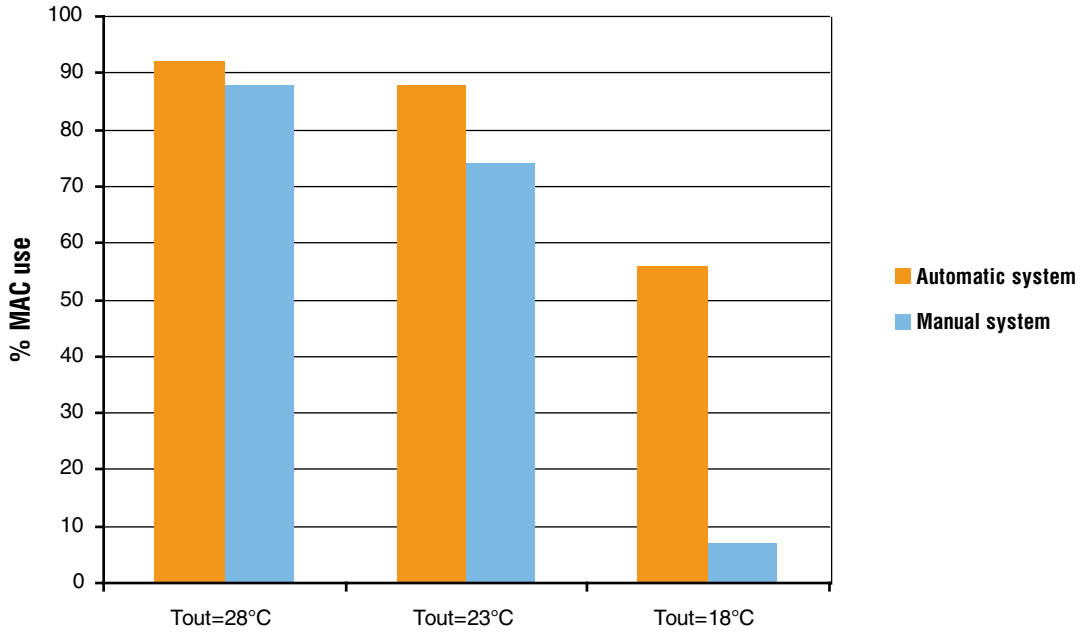
A better design of the cabin will result in a sensible reduction[bl] of requested cooling capacity leading to low energy consumption. Examples are insulation of doors and roof, limitation of window size, use of solar reflective glazing[83]. It is also recognised that the colour of the car influences the thermal load since surfaces that are less absorbent (e.g. white colour) transmit less heat inside the compartment resulting in a temperature decrease[159]. Even though these options could significantly reduce the heat load within the cabin, they will face some design constraints such as extra weight, safety issues (e.g. driver visibility), additional costs, etc. The use of ventilated seats is also expected to have a significant impact on fuel consumption reduction[160] (ranging from 0.3% to 0.5% fuel savings when the AC system is on).

6.4.2.5. Non-technical option: reducing the cooling demand

Although there is no doubt that a more efficient HFC-134a-based system can reduce fuel consumption (e.g. through VDC use or new components) it is expected that automatic control will be longer used over the year[30, 161]. As shown in Figure 38, the percentage of MAC use in outside temperatures of 28 °C, 23 °C and 18 °C are 92%, 88% and 56% respectively with automatic control and 88 %, 74 % and 7 % with manual control. Therefore, the annual over fuel consumption is not expected to decrease when using an automatic AC system.

bl A heat-load reduction of about 30% was estimated by the National Renewable Energy Laboratory (NREL).

Figure 38: Difference between automatic and manual AC control with regard to MAC use



Source: derived from ADEME161

The ADEME[32] launched a test campaign to assess the impact of the set temperature on fuel consumption. In 28 °C and without artificial sunshine (roughly similar to 25 °C in clear weather) setting the cabin temperature to 23 °C instead of 20 °C ensures a 2% - 5% gain of fuel consumption in the city and 1% - 2% for extra-urban driving.

In 35 °C and without artificial sunshine, shifting the set temperature from 20 °C to 23 °C leads to a 5% - 8% fuel saving for urban driving and 2% - 6% on extra-urban cycle. The gain can go up to 7% - 10% on urban cycle and 4% - 7% on extra-rural cycle when the air temperature is fixed at 26 °C instead of 20 °C initially.

6.4.3. Existing legislation and current developments

The regulations on certain fluorinated greenhouse gases[162] ("F-gases": HFCs, PFC and SF_6) and the Directive 2006/40/EC on mobile air conditioning systems[163] are the two main policy measures used to reduce the direct emissions from air conditioning systems.

As far as MAC systems are concerned, the main elements of the regulation[162] deal with the containment of fluorinated gases - including a general obligation to take all practicable measures to prevent and minimise leakage and some maximum leakage standards; certain installations will have to be inspected at least once per year.

After a long negotiation process launched in 2003 between the European Parliament and the European Council, Directive 2006/40/EC[163] was approved in May 2006 establishing emission limits for air conditioning systems in motor vehicles, namely:

- **as of 2011**: ban for F-gases with a global warming potential (GWP) of more than 150 for new models coming out of factories. This effectively rules out the use of HFC-134a but allows the less potent HFC-152a, which has a global warming potential of 140
- **as of 2017**: ban on F-gases with GWP of more than 150 for all cars.

Leakage rates will also be limited. Before phase out starts, maximum leakage rates of HFC-134a from mobile air conditioning should not exceed 40 g HFC-134a/year for vehicles with a single evaporator and 60 g HFC-134a/year for vehicles with two evaporators (e.g. minivans).

Note that the recent Commission's proposal regarding the reduction of CO_2 emissions from cars[164] includes minimum efficiency requirements for air conditioning systems.

6.4.4. Environmental benefits and direct costs quantification

In the following assessment, the following assumptions are made:

- regarding the total direct emissions the trend of total leakages can be seen in Figure 37. A total leakage rate of 50 g HFC-134a/year[32] is likely to be achieved in the short term (2010 - 2015) thanks to improvements in leakages, loss at servicing, accidents and EOL[bm]. It would represent a 20 g HFC-134a/year reduction compared to the 70 g HFC-134a/year defined as the reference
- no technical improvements with regard to new HFC-134-based systems were assumed. As explained previously, it was considered that the automatic regulation is generally more widely used (mode by default) over the year than the manual control that would partially reduce the expected benefits of this technology.
- due to great uncertainties about their technical/market potentials, the use of CO_2 and HFC-152 as new working fluids is not taken into account in this assessment. New refrigerants that are more efficient have been developed recently and might represent a better alternative
- therefore, no impacts from new MAC technologies on fuel savings will be estimated in this study. However, the impact of a non technical option that consists of changing the required air temperature in the compartment to a reasonable level (by increasing the set temperature from 20 °C to 23 °C) will be assessed. The maximum potential reduction given by ADEME is assumed, i.e. 5% fuel savings for urban driving and 2% for extra urban (see Table 42).

Table 42: Potential improvements expected from improved MAC leakages and more efficient MAC use

Improvement option	Assumption	Fuel savings	Source
Improved total HFC-134a leakages	From 70 g/year to 50 g/year	CO_2 only	ADEME[30]
MAC efficient use	The driver shifts the set temperature from 20 °C to 23 °C (outside temperature is 25 °C)	2% - 5% (urban) 1% - 2% (extra-urban)	ADEME[30]

6.4.4.1. Environmental benefits of the option

Table 43 shows the life cycle impacts related to the reduction of the total HFC-134a leakages (petrol cars). The impacts are very modest since only GHG emissions during the TTW phase are affected and at a very low level (around 0.7% of CO_2 reduction). The results for the diesel car are very similar.

bm Remark: Leakages during EOL are allocated to the TTW part in these quantifications.

Table 43: Life cycle impacts for the improved total HFC-134a leakages option – petrol car

	Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)					
	Production	**Spare Parts**	**WTT**	**TTW**	**EOL**	**Total**
AD	100	100	100			100
GWP	100	100	100	99.3	100	99.4
ODP	100	100	100			100
POCP	100	100	100	100	100	100
AP	100	100	100	100	100	100
EP	100	100	100	100	100	100
PM2.5	100	100	100			100
PE	100	100	100	100	100	100
BW	100	100	100		100	100

On the other hand, the non-technical option "MAC efficient use" enables a higher climate change/ primary energy reduction and can be considered as a substantial cost-effective option. Results are shown in Table 44 and Table 45.

Table 44: Life cycle impacts for the MAC efficient use option – petrol car

	Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)					
	Production	**Spare Parts**	**WTT**	**TTW**	**EOL**	**Total**
AD	100	100	99.1			100
GWP	100	100	99.1	99.1	100	99.2
ODP	100	100	99.1			99.1
POCP	100	100	99.1	100	100	99.4
AP	100	100	99.1	100	100	99.3
EP	100	100	99.1	100	100	99.4
PM2.5	100	100	99.1			99.3
PE	100	100	99.1	99.1	100	99.1
BW	100	100	99.1		100	99.8

Table 45: Life cycle impacts for the MAC efficient use option – diesel car

	Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)					
	Production	**Spare Parts**	**WTT**	**TTW**	**EOL**	**Total**
AD	100	100	99.1			100
GWP	100	100	99.1	99.1	100	99.2
ODP	100	100	99.1			99.1
POCP	100	100	99.1	100	100	99.6
AP	100	100	99.1	100	100	99.5
EP	100	100	99.1	100	100	99.6
PM2.5	100	100	99.1	100		99.7
PE	100	100	99.1	99.1	100	99.2
BW	100	100	99.1		100	99.8

6.4.4.2. Direct costs

The incremental cost of total leakage emissions are derived from TNO et al.[148]. They estimated an average cost of 25 Euro per 10g of HFC-134a. Considering a 20 g HFC-134a reduction, the cost will therefore be 50 Euro.

6.5. Tailpipe air emission abatement systems

6.5.1. Description of the options

Besides CO_2 emissions, energy use by car driving generates air pollution and contributes to impacts such as acidification, photochemical oxidation and respiratory effects directly induced by fine particles (e.g. PM2.5). The main substances involved are NO_X, PM, SO_X, CO and VOC.

6.5.1.1. Current situation and main trends

Continuous efforts have been made by the car industry to reduce these impacts by introducing and implementing technical solutions to reduce tailpipe emissions from cars.

This has resulted in significant reductions of air pollution by passenger cars and other road transport: emissions of particulate matters, acidifying substances and ozone precursors declined by 30%, 34% and 40% respectively from 1990 to 2003[165]. This was achieved despite the growing mobility demand, thanks to catalytic converters and other technical options to control fuel combustion and exhaust gases.

Since the early 1990s petrol cars have progressively been equipped with three-way catalysts (TWC).

Technical solutions have also been – more recently – introduced in order to address the most critical emissions associated with diesel cars, namely NO_X and fine particles (PM2.5). The most common option implemented today to tackle NO_X emissions is exhaust gas recirculation (EGR) and all diesel engine cars sold in Europe are fitted with a diesel oxidation catalyst (DOC) which also partly reduces PM emissions.

Despite these improvements, the contamination of air in urban areas close to traffic zones remains and new or more advanced technical options have been researched and developed with a view to further reduce these emissions.

For instance, limits for NO_2 concentrations set by European legislation[bn] for 2010 are exceeded in many places in Europe, particularly at roadside stations.

It should also be noted that while the concentrations of ambient NO_X are on a downward trend, concentrations of NO_2 have often been static or even rising. The development of ambient NO_2 concentrations as observed near roadsides can be explained by an increasing contribution of direct emissions of NO_2 specifically from diesel-powered vehicles. Instead of a 5% share of NO_2 in the emitted NO_X typically assumed in standard atmospheric pollution models, modern diesel cars can be as high as 30% to 80%[bo].

bn Directive 1999/30/EC about limit values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air of 22 April 1999 (JOC L 163).

bo EU level workshop on the impact of direct emissions of NO_2 from road vehicles on NO_2 concentrations, Brussels, 19 September 2006, Summary meeting notes.

6.5.1.2. Technical potential

Each available technical option to reduce the air emission levels of new cars is characterised by a certain degree of involvement and combination of three types of innovations:

- new engines (or power trains)
- engine management options
- after-treatment equipments.

These three groups of innovations are being developed for the two main types of combustion engines, petrol and diesel.

For indirect injection engine **petrol cars** the TWC remains the dominant improvement option available, with higher performance achieved today to reduce cold start emissions, through new coated materials.

Lean NO_x trap (LNT) are also developed in order to fit with the emerging **direct injection petrol** engine, which operates under lean combustion conditions characterised by higher NO_x emission levels.

NO_x emission reductions are also achieved with the **exhaust gas recirculation (EGR)**, which allows the inert exhaust gas to be recirculated in controlled amounts into the intake of the engine. In the first system developed, the EGR was ensured with a circuit external to the engine. The further developed solution is the internal EGR where the recirculation is induced by a pressure difference between the inlet and exhaust manifolds. This difference is generated by the simultaneous opening of the inlet and exhaust valves. This requires variable valve timing (VVT). EGR can be implemented on naturally or boosted aspired engines.

For **diesel cars**, two types of after-treatments have been developed which aim at reducing NO_x emissions on the one hand, and, on the other hand, particulate matters (PM) emissions, alongside HC and CO emissions reductions.

The current **diesel oxygen catalysts (DOC)** do not represent a satisfactory solution to reduce PM. The number of solid particles is unchanged and issues associated with ultra fine particulates remain unresolved.

These two objectives can be met with **diesel particulate filter (DPF)** that removes PM by physical filtration (ceramic honeycomb monolith, ceramic fibre or sinter metal plates). The removal of PM from the trapped soot is based on either oxygen or NO_2, which implies raising the temperature up to 550 °C and 250 °C respectively, and entails energy surplus (1.5% to 2% additional energy use). NO_2 is also emitted during regeneration and ash is accumulated.

Other technical challenges concern the durability (which can be better ensured below 50 ppm sulphur and – even 15 ppm is recommended) and the cost entailed by the use of PGM (platinum group metals).

Various improvements are being achieved such as the development of new filter materials, of coating processes and concepts. Some new DPF catalyst formulations are, for instance, dropping the required PGM levels and durability is getting better.

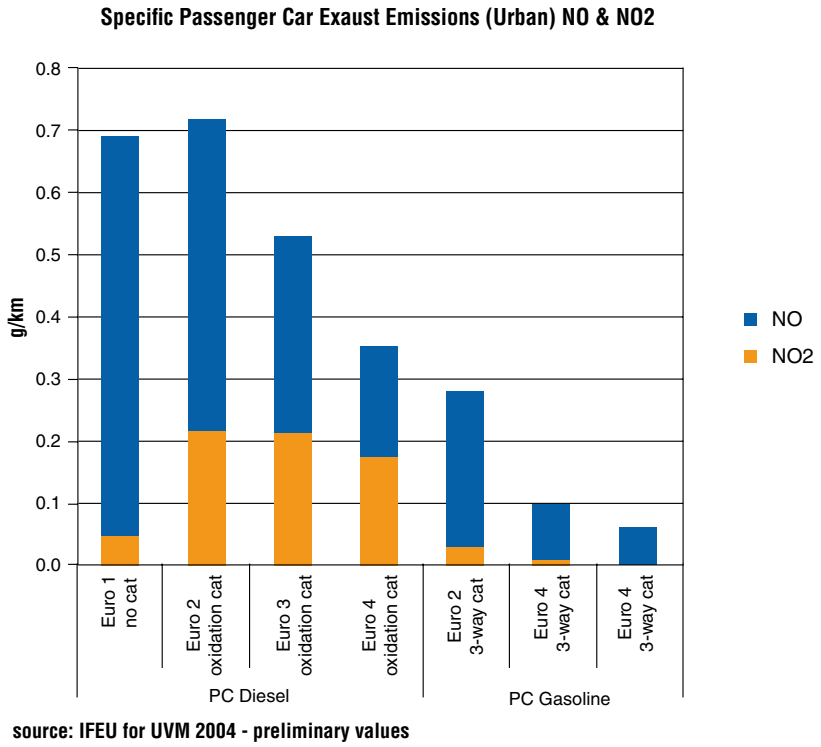
The **diesel oxidation catalyst (DOC)** is further developed with new coating options (increased noble metal loading, increased size of close coupled oxidation catalyst, new coating options (Pd)) that improve the performance regarding HC and CO conversion.

The introduction of the DOC has contributed to reducing NO_x emissions from diesel cars. However, whereas these emission levels decreased over time, it has been observed that the NO_2 fraction remained almost constant (see Figure 39). This is one of the main explanations for the fact that air quality measurements in urban zones (London and North Rhine-Westphalia, for instance) show that NO_2 concentrations were

almost constant since the early 1990s, thus not following the downward trends observed for total NO_X concentrations.

As a consequence, the contribution from road transport to NO_2 concentration is estimated to be almost half (Gense R., 2006) [bp].

Figure 39: NOX emissions levels for the different car technologies



Further NO_X emission reductions are achievable with new catalytic converters such as the **selective catalytic reduction (SCR)**, the **lean NO_X catalyst (LNC)** and, the **lean NO_X traps (LNT)**. This last case operates with the adsorption (trapping) of NO_X from lean exhaust followed by the release and catalytic reduction under rich conditions NO_X, CO, HC. NO_X adsorbers employ precious metal catalyst sites to carry out the NO to NO_2 conversion step. The NO_2 is then chemically stored in alkaline-earth oxide as a nitrate. The stored NO_X is removed in a two-step reduction process by temporarily inducing a rich exhaust condition using a pulsed charge when fuelling. Both LNT and SCR catalyst systems benefit from an appropriate NO_2:NO_X ratio. Options regarding diesel engine management include cooled exhaust gas recirculation (EGR), reduced compression ratio and turbo charging. In summary, technical options are developed or are being further developed to reduce air pollution:

- for petrol cars, the options available for the indirect injection engine consist of a combination of EGR with the most advanced TWC, whereas the direct injection engine will require the more costly LNT
- for diesel car, DPF already drastically limits the emissions of particulate matter. DOC, combined with EGR help reducing NO_X emissions. LNC, SCR and LNT offer higher reduction performances.

bp See presentations made during the EU level workshop on the impact of direct emissions of NO_2 from road vehicles on NO_2 concentrations (September 2006).

These well identified options have however several ancillary implications:

- higher manufacturing and maintenance costs, especially for diesel cars
- environmental burden shifts, especially in terms of energy penalty (up to 1.5% with DPF and LNT)
- higher requirements regarding the sulphur content.

Future improvements of combustion engines and power trains will also help to reduce air pollution from cars. The hybrid car is also an option that could contribute to reducing air pollutants in addition to reducing CO_2 emissions (see section 6.7).

Other new car engine developments also look promising regarding air emission limits. This is the case with the newly investigated engines such as the **controlled auto ignition (CAI)** for petrol cars and **HCCI** engine for diesel cars. The HCCI engine is shown to have much lower NO_x emission levels[166].

However, these engines do not offer competitive performances regarding CO_2 and energy performance.

6.5.1.3. Existing legislation and current developments

Some of the above technical options are already on the market, to a large extent driven by European legislation regarding air emissions by cars. New cars now have to comply with the EURO4 standard.

Lower emission limits (EURO5 and EURO6) were recently adopted (see Table 46).

Table 46: Emission limits provided by the EU legislation

				g/km		
Petrol	**EURO1**	**EURO2**	**EURO3**	**EURO4**	**EURO5**	**EURO6**
Period	1992 - 1995	1996 - 1999	2000 - 2004	2005 - 2009	Sept 2009	Sept 2014
CO	3.160	2.200	2.300	1.000	1.000	1.000
HC(**)			0.200	0.100	0.068	0.068
Nox			0.150	0.080	0.060	0.060
HC+Nox	1.130	0.500				
PM					0.005 (*)	0.005(*)
Diesel	**EURO1**	**EURO2**	**EURO3**	**EURO4**	**EURO5**	**EURO6**
Period	1992 - 1995	1996 - 1999	2000 - 2004	2005 - 2009	Sept 2009	Sept 2014
CO	3.160	1.000	0.640	0.500	0.500	
HC						
Nox			0.500	0.250	0.180	0.080
HC+Nox	1.130	0.700	0.560	0.300	0.230	
PM	0.180	0.080	0.050	0.025	0.005	0.005

(*) only for direct injection engines that operate partially or wholly in lean burn mode
(**) for Euro 1 to Euro 4, HC refers to total hydrocarbons; for Euro 5 and Euro 6, HC refers to non-methane hydrocarbons

The implementation of EURO5 will further drive developments in terms of engine control systems and catalysts (to abate NO_x and, for higher swept volumes, PM). The emission limits will require petrol cars equipped with upgraded catalytic converters. Diesel cars – at least medium and large classes – will have to be equipped with EGR systems and DPF filters to achieve the required NO_x and PM reductions. The

implementation of EURO6 will entail a further reduction of NO_x emissions from diesel cars. This would entail the introduction of LNT or SCR.

6.5.2. Environmental benefits and direct costs quantification

6.5.2.1. Assumptions

Quantifying the environmental benefit of the technical options described previously cannot be made for each individual technology (distinguishing for instance EGR from TWC or SCR from LNT).

When reviewing the relevant literature, information was available on the efficiency of the different systems. The quantitative information generally expresses this efficiency as a percentage of the unabated emission levels. These percentages cannot be used to derive an improvement of the environmental performance for one specific car, or from the car models defined in this project, notably because it is not known what the level of unabated emissions from these cars are.

In the following a very simplified method was used to simulate the effect of achieving the EURO5 emission levels and the EURO6 emission levels for diesel cars.

To this end, the sample of type approval data from the UK used in section 4.2 to derive emission factors for the base case car models was used.

In order to simulate the effect of achieving the EURO5 and EURO6 emission levels for this car model, it was assumed that the effect of the proposed standards would consist of applying caps to each type approval data measurement. These caps would correspond to the different air pollution limits. Average, minimum and maximum emission levels were then calculated.

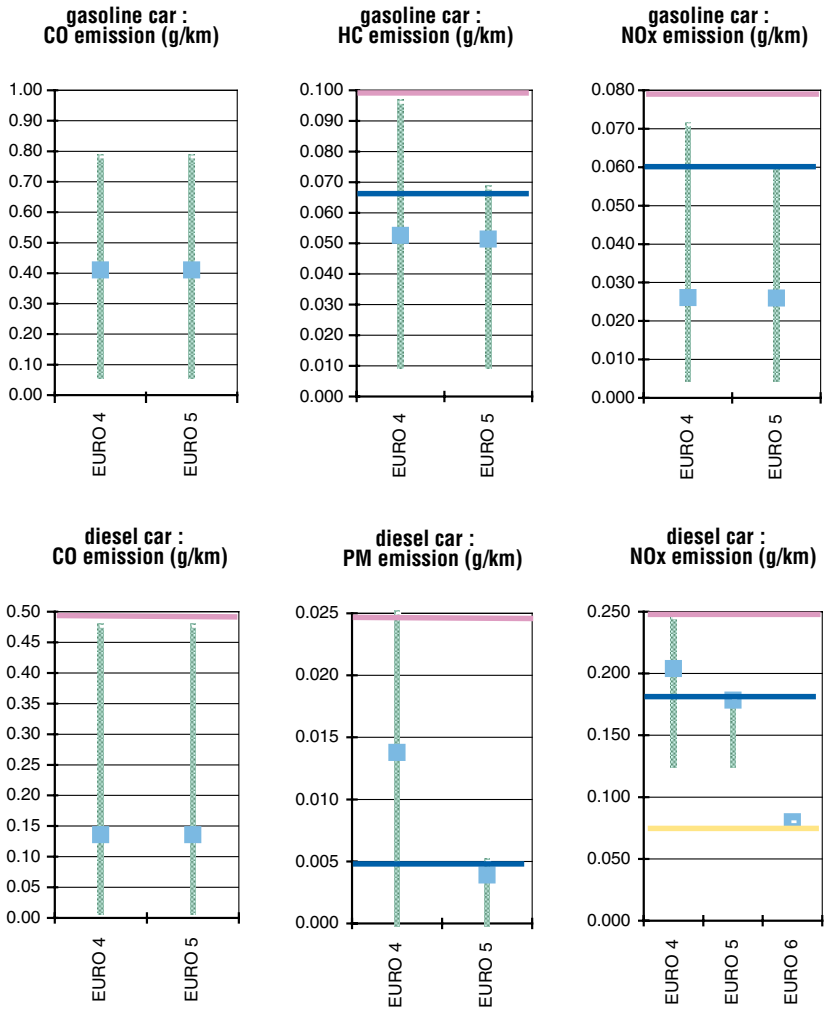
6.5.2.2. Environmental benefits of the option

The results of the above approach are shown in Table 47 and in Figure 40.

Table 47: Emission levels assumed

EURO 5		**Engine Capacity**	**CO_2**	**CO**	**HC**	**NO_x**	**PM**
		cm³			**g/km**		
Petrol cars	Average	1 592	173	0.41	0.051	0.026	-
	Min	1 468	139	0.06	0.010	0.005	-
	Max	1 699	221	0.78	0.068	0.060	-
	EURO5 emission limits			*1.00*	*0.068*	*0.080*	-
Diesel cars	Average	1 944	160	0.14	0.027	0.178	0.004
	Min	1 753	120	0.01	0.000	0.126	0.000
	Max	1 998	205	0.48	0.377	0.180	0.005
	EURO5 emission limits			*0.50*		*0.180*	*0.005*
EURO 6		**Engine Capacity**	**CO_2**	**CO**	**HC**	**NO_x**	**PM**
		cm³			**g/km**		
Diesel cars	Average	1 944	160	0.14	0.027	0.080	0.004
	Min	1 753	120	0.01	0.000	0.080	0.000
	Max	1 998	205	0.48	0.377	0.080	0.005
	EURO6 emission limits			*0.50*		*0.080*	*0.005*

Figure 40: Emission level ranges expected with the introduction of EURO5 and EURO6



The horizontal red, blue and brown lines correspond to the EURO4, EURO5 and EURO6 levels respectively

These figures surprisingly suggest that, for petrol cars, the best estimated emission levels (lower bounds) for CO, HC and NO_x would not change. The change concerns the distribution of emission levels around this unchanged average level. This is explained by the fact that, today, many new petrol cars already comply with the EURO5 emission limits.

For diesel cars, the effect is significant for PM, and, to a lower extent for NO_x emissions. This is because for NO_x emissions, the differences are more significant under EURO6 because it requires more drastic technology changes (LNT or SCR combined with EGR).

These effects are reflected in the following tables that show the impacts on the overall car life (Table 48 – Table 50). The changes are only significant for the diesel car when substantial emission reductions are achieved regarding PM and even more when NO_x emissions are reduced.

Table 48: Life cycle impacts for the air abatement I option – petrol car

Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)						
	Production	**Spare Parts**	**WTT**	**TTW**	**EOL**	**Total**
AD	100	100	100	-	-	100
GWP	100	100	100	100	100	100
ODP	100	100	100	-	-	100
POCP	100	100	100	99.3	100	99.9
AP	100	100	100	100	100	100
EP	100	100	100	100	100	100
PM2.5	100	100	100	-	-	100
PE	100	100	100	100	100	100
BW	100	100	100	-	100	100

Table 49: Life cycle impacts for the air abatement I option – diesel car

Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)						
	Production	**Spare Parts**	**WTT**	**TTW**	**EOL**	**Total**
AD	100	100	100			100
GWP	100	100	100	100	100	100
ODP	100	100	100			100
POCP	100	100	100	88.9	100	94.5
AP	100	100	100	88.2	100	98.1
EP	100	100	100	88.1	100	96.1
PM2.5	100	100	100	30.9		65.8
PE	100	100	100	100	100	100
BW	100	100	100		100	100

Table 50: Life cycle impacts for the air abatement II option – diesel car

Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)						
	Production	**Spare Parts**	**WTT**	**TTW**	**EOL**	**Total**
AD	100	100	100			100
GWP	100	100	100	100	100	100
ODP	100	100	100			100
POCP	100	100	100	44.7	100	72.7
AP	100	100	100	41.4	100	90.5
EP	100	100	100	41.2	100	80.5
PM2.5	100	100	100	30.9		65.8
PE	100	100	100	100	100	100
BW	100	100	100		100	100

6.5.2.3. Direct costs

In this study, the cost data from the "Independent Panel" as summarised by TNO[104] was considered.

Based on this consideration, it was assumed that an additional 50 Euro per petrol car will result from EURO5. This corresponds to the upgrade of the capacity of the catalytic converter (no new technique needed).For diesel cars, the cost data from the expert panel report was used which corresponds the most to the emission limit values adopted for EURO5 and EURO6. As shown in Table 51, the emission levels for PM (2.5 mg/km) were lower than what was prescribed by the two air emission standards. For NO_x emissions, the emission values (150 mg/km) assumed to represent EURO5 were also lower than what was actually requested by EURO5.

This means that the average cost data (respectively 745 Euro and 920 Euro per car) may somehow be overestimated (see Table 51). These costs were subjected to uncertainty related to the price of PGM (notably platinum) and also to the possible effects of mass production.

Table 51: Costs data for the air emission reductions for diesel cars

Diesel cars	EURO5	EURO6
PM (mg/km)	2.5	2.5
NO_x (mg/km)	150	150
Min cost (Euro)	517	920
Max cost (Euro)	974	920
Average cost (Euro)	746	920
Technology involved	EGR, DPFs	EGR, DPFs + SCR or LNT

6.6. Power train improvements

There is no doubt that the efficiency of internal combustion engines (ICEs) has been considerably improved since their introduction. The question is therefore to identify areas where further progress can be carried out. Generally, energy losses from ICEs are classified within three main categories:

- energy losses at the exhaust (due to released hot gases)
- energy losses due to heat transfer through surfaces
- energy losses due to friction (i.e. moving parts) especially the piston within the cylinder (pumping losses belong to this category).

The objectives are then to reduce these losses by using new power trains[bq] i.e. more **efficient engines and transmissions**. In this section, promising options regarding the improvements of engine efficiency and transmission of current vehicles are analysed. These options are very likely to enter the market in the short term (2010). It should be noted that hybrid technologies are covered in section 6.7.

Table 52 presents a list of high-potential technical options that were inventoried by TNO et al.[148].

bq In the broad sense, the 'power train' refers to all the components of a vehicle's drive system (engine, transmission, differential, etc.). But it is sometimes used to refer to only the engine and transmission.

Table 52: Technical options to improve fuel economy and reduce CO_2 emissions of passenger cars

	Petrol vehicles	Diesel vehicles
ENGINE	Reduced engine friction losses	Reduced engine friction losses
	DI/homogeneous charge (stoichiometric)	Four valves per cylinder
	DI/stratified charge (stoichiometric)	Piezo injectors
	DI/stratified charge (lean burn/complex strategies)	
	Mild downsizing with turbocharging	Mild downsizing
	Medium downsizing with turbocharging	Medium downsizing
	Strong downsizing with turbocharging	Strong downsizing
	Variable valve timing	
	Variable valve control	
	Cylinder deactivation	Cylinder deactivation
	Variable compression ratio	
	Optimised cooling circuit	Optimised cooling circuit
	Advanced cooling circuit and electric water pump	Advanced cooling circuit and electric water pump
		Exhaust heat recovery
TRANSMISSION	Optimised gearbox ratios	6-speed manual/automatic gearbox
	Piloted gearbox	Piloted gearbox
	Continuous variable transmission	Continuous variable transmission
	Dual-clutch	Dual-clutch

Source: TNO et al.148
Mild downsizing with turbocharging: -10% cylinder content reduction
Medium downsizing with turbocharging: -20% cylinder content reduction
Strong downsizing with turbocharging: -30% cylinder content reduction

6.6.1. Engine

Reduced engine friction losses (petrol/diesel): this includes low friction engine and gearbox lubricants.

Variable valve timing (VVT) technologies: the objective is to reduce pumping losses (work required to draw air into the cylinder under part-load operation) by controlling the flow of air/fuel into the cylinders and exhaust out of them. The question is therefore to determine when and how long the intake and/or exhaust valves open. The optimum timing and lift settings depend on the engine speeds. This results in optimised torque and power leading to fuel savings and air emissions reduction (allowing control of NO_x emissions produced during combustion). Overall, fuel consumption improvements of 6% - 8% are achievable. It should be noted that there are many type of VVT technologies under countless denomination available, e.g. variable valve control (VVC), continuous variable valve timing (CVVT), variable valve timing with intelligence (VVTi), variable valve timing and lift electronic control

(VTEC), variable valve event and lift (VVEL) system that could reduce CO_2 emissions up to 10%[br]. Note that VVTs can also be combined with direct injection engines. Moreover, the combination of VVT systems with internal exhaust gas recirculation (EGR) is seen as a very efficient technology (it can help reduce NO_x emissions when burning ultra lean mixtures[bs]).

Gasoline direct injection (GDI): gasoline direct injection (GDI) is a variant of fuel injection employed in modern four stroke petrol engines. The petrol is injected right into the combustion chamber of each cylinder, as opposed to conventional multi point fuel injection that happens in the intake manifold. The major advantages of a GDI engine are increased fuel efficiency and high power output. This is achieved by the precise control over the amount of fuel and injection timings, which are varied according to the load conditions. Moreover, the direct injection of fuel enables homogeneous operation (similar to port injected engines but with about 3% fuel economy benefit) or stratified lean burn operation with a combustion more comparable to a diesel engine. This mode reduces the pumping losses of the 4-stroke engine and provides a fuel consumption reduction by up to 15% compared to a conventional engine. These engines are likely to be more important than conventional port fuel injection engines by 2020[93]. Such engines could cost 10% - 30% more than conventional spark ignition engines because they use advanced injection technology and additional NO_x after-treatment necessitated by lean burning[bt]. Fuel consumption could be reduced by up to 15% compared to a conventional engine, depending on the technology used (homogeneous or stratified charge, etc.). Stratified charge lean operation of a direct injection engine cannot reasonably be combined with VVT since both technologies are aiming for the same kind of loss reduction.

Petrol engine downsizing with turbocharging: in the near future, downsizing of petrol engine is seen as a promising way of energy saving. The principle is to reduce the engine swept volume ("mild", "medium" and "strong" downsizing respectively reduce cylinder content by 10%, 20% and 30%) while maintaining the same performance in terms of torque and power. The advantage relates to the fact that, with the car driving at similar engine torque demand, the engine runs at higher internal load which means improved efficiency. The benefit in fuel consumption/CO_2 emissions is expected to achieve up to 20%. Downsizing can also be combined in a second step with pumping loss reduction technologies like stratified lean operation. These technologies will then not provide the same amount of fuel economy as for a standard naturally aspirated engine but for further tightened CO_2 reduction targets they can be an attractive option.

Injection control systems for diesel: controlling the timing of the start of injection of fuel into the cylinder is the key to minimise the emissions and maximise the fuel economy (efficiency) of the engine. The exact timing of starting this fuel injection into the cylinder is controlled electronically in most of today's modern engines. In older diesel engines, a distributor-type injection pump, regulated by the engine, supplies bursts of fuel to injectors which are simply nozzles through which the diesel is sprayed into the engine's combustion chamber. As the fuel is at low pressure and there cannot be precise control of fuel delivery, the spray is relatively coarse and the combustion process is relatively crude and inefficient[bu].

Cylinder deactivation: pumping losses at part load operation can also be reduced by switching off some of the cylinders (less air required increasing the engine efficiency). The intake and exhaust valves of the target cylinders are closed thanks to electronically controlled systems. For instance, an eight-cylinder engine could be operated on six or four cylinders during low power demand (e.g. cylinders 1, 4, 6 and 7 for a V8). The net effect of cylinder deactivation is an improvement in fuel economy and

br http://www.greencarcongress.com/2007/03/nissan_to_intro.html.
bs http://en.wikipedia.org/wiki/Fuel_injection.
bt One of the main concerns of GDI is over NO_x emissions. The use of EGR can partly solve this problem.
bu http://en.wikipedia.org/wiki/Diesel_engine.

likewise a reduction in exhaust emissions. Overall, fuel consumption could be reduced by 7% - 10%. This technology (although not new) is seen as a very attractive option for both diesel and petrol engines to be applied especially on larger displacement 6- and 8-cylinders engines.

Variable compression ratio: this modifies the compression ratio as a function of the vehicle performance needs (in terms of acceleration, speed and load). The compression ratio is lowered at high power demand and increased for low power demands. It is however difficult to assess the potential even if improvements in fuel consumption of up to 30% are claimed.

Exhaust heat recovery (modern direct injection diesel cars): the available heat in the exhaust gas behind the catalyst is sufficient to support the warm-up adequately for most of the ambient conditions at no fuel consumption penalty[167].

6.6.2. Transmission

Continuous variable transmission (CVT)[bv]**:** the ratio of the rotational speeds of two shafts, as the input shaft and output shaft of a vehicle or other machine, can be varied continuously within a given range, providing an infinite number of possible ratios. The CVT has an infinite number of ratios available within a finite range, so it enables the relationship between the speed of a vehicle engine and the driven speed of the wheels to be selected within a continuous range. Since adding more gears improves fuel consumption performance, this system can provide better fuel economy than other transmissions by enabling the engine to run at its most efficient speeds within a narrow range (up to 10% CO_2 reduction is expected). Already integrated in some hybrid vehicles (e.g. the Honda Civic and the Toyota Prius), the CVT is considered as the new generation transmission.

Piloted gearbox: this technology is a sort of automatic gearbox but at lower cost. The principle of the piloted gearbox is to electronically handle gear changes and clutch control. The clutch pedal is then removed and the gear shift does not have any mechanical connections with the gearbox. This system provides better comfort to the driver while reducing fuel consumption (up to 5%). It is well suited to small cars (e.g. the Citroen C3 Pluriel) for urban driving conditions. The PSA group expects a sharp increase of vehicles equipped with piloted gearbox starting from the end of 2006.

Dual-Clutch: this technology is very similar to the piloted gearbox but it has two clutches (one for pair gear ratios and the other for impair gear ratios). In this way, the next gear ratio is pre-selected even before the gear change avoiding an interruption to the engine-transmission connection. The continuity of power transmission reduces energy losses (kinetic energy) while gear changing and therefore reduces fuel consumption (up to 10% for extra-urban cycle). However, this technology is very complex and more expensive than the piloted gearbox.

Note that these technical solutions are often classified in the category of "automatic" or rather "semi-automatic" gearboxes.

6.6.3. Existing legislation and current developments

CO_2 emissions reduction from passenger cars is one important strategy of the Community. In June 2006, the European Council reconfirmed that "in line with the EU strategy on CO_2 emissions from light duty vehicles, the average new car fleet should achieve CO_2 emissions of 140 g CO_2/km (2008/2009) and

bv See http://en.wikipedia.org/wiki/Continuously_variable_transmission.

120 g CO_2/km (2012)". The European Parliament called for even more ambitious targets (80 - 100 g/km) for new vehicles in the medium term.

The Community's strategy is based on three pillars (1) commitments of the automotive industry on fuel economy improvement (2) the fuel economy labelling of cars and (3) the promotion of car fuel efficiency by fiscal measures.

Commitments have been made by the European (ACEA), the Japanese (JAMA) and the Korean (KAMA) automobile manufacturers associations. These commitments are designed to achieve total EU-15 new passenger car fleet average CO_2 emissions of 140 g/km by 2008 (ACEA) and 2009 (JAMA and KAMA) by technological developments affecting different characteristics and market changes linked to these developments. The progress made until 2004 was reviewed by the Commission and the main conclusions were as follows:[bw]

- "In 2004, the average specific new car fleet CO_2 emissions were 161 g/km for ACEA which remains the frontrunner, and 168 g CO_2/km for KAMA and 170 g CO_2/km for JAMA. Compared to 1995, the average specific CO_2 emissions have been reduced by 24 g CO_2/km or 13% for ACEA, 26 g CO_2/km or 13.3% for JAMA, and 29 g CO_2/km or 14.7% for KAMA;
- Compared to 2003 all three associations reduced, in 2004, the average specific CO_2 emissions of their cars registered for the first time on the EU market: ACEA by about %, JAMA by about 1.2 % and KAMA by about 6.1 %. Since 1995, fuel efficiency improvements in diesel passenger cars have been greater than in gasoline vehicles and, along with the sustained increase in the share of diesel vehicles in the EU15 new passenger car market, this has made an important contribution to the overall progress achieved so far (see Table 3)9. This trend calls for further improving the performance of diesel passenger cars regarding the emissions of atmospheric pollutants, as proposed by the Commission in the recent EURO5 proposal10;
- ACEA and JAMA have pursued in 2004 an unbroken trend of CO_2 emissions reduction although their recent performance is lower than annual reductions in the first years of their commitments. ACEA already reached in 2000 the intermediate target range envisaged for 2003 and is since 2003 below the lower end of this range. JAMA is inside the intermediate target range since 2002. KAMA made a very significant progress and met its 2004 intermediate target range of 165-170 g CO_2/km;
- In order to meet the final target of 140 g CO_2/km major additional efforts are necessary, as the average annual reduction rates of all three associations need to be increased. Assuming a constant rate of improvement over the full period 1995-2008/9, the reduction would be some 3.5 CO_2/km per year, or around 2 % per year. In the years remaining until 2008/9 the annual reduction rates must now reach an average of 3.3 % for ACEA, 3.5 % for JAMA and 3.3 % for KAMA. It was anticipated from the beginning that the average reduction rates would be higher in the later years. However, it is noted that the gaps to be closed, expressed in required annual performance, have further increased in 2004 (see Table 2). This is a cause of concern. The Commission will pursue its close monitoring of the Associations' achievements under their Commitments."

bw EC Commission, 2006, Communication from the Commission to the Council and the European Parliament – Implementation of the Community Strategy to reduce CO_2 Emissions from cars: Sixth annual Communication on the effectiveness of the strategy (COM(2006)463 final).

A legislative approach is currently being discussed in order to ensure that the 120 g CO_2/km target is achieved by 2012. In February 2007, the Commission published the results of the review of the Community strategy[164], where it proposes policy means. These include:

- compulsory requirements aimed at gradual decarbonisation of road fuels, through an amendment of the fuel quality directive, and a proposal for a revision of the biofuel directive
- proposed measures on the vehicle side, that include stricter fuel efficiency levels for passenger cars and other technological improvements
- demand/behaviour oriented measures.

A legislative framework is planned to be proposed to the Council and the EP by end of 2007 or by mid-2008 to achieve the EU objective of 120 g CO_2/km.

The objective of 130 g CO_2/km is proposed to be mandatory and to be achieved by vehicle motor technologies.

The further reduction (up to 120 g/km) would be achieved by other technical improvements considered in this proposal concern:

- setting minimum efficiency requirements for air conditioning systems
- the compulsory fitting of accurate tyre pressure monitoring systems
- setting maximum tyre rolling resistance limits in the EU for tyres fitted on passenger cars and light commercial vehicles
- the use of gear shift indicators, taking into account the extent to which such devices are used by consumers in real driving conditions
- increased use of biofuels maximising environmental performance.

Demand/behaviour oriented proposed measures are also considered, including informed choice as a buyer and responsible driving behaviour of the consumer.

6.6.4. Environmental benefits and direct costs quantification

The figures used are based on the outcome from TNO et al.[148] providing CO_2 reduction potential as well as additional manufacturer costs for some of the technical options described previously, for both petrol (Table 53) and diesel passenger cars (Table 54). It should be noted that these values are estimates only and are subject to some uncertainties, e.g. type of reference car considered.

In order to explore different combinations and define an overall potential emerging from these technical solutions, several possible combinations of engine/transmission technologies were assumed, 16 combinations for petrol cars and 8 for diesel cars. For each combination, both total CO_2 reduction potential and additional costs are estimated from the values given in Table 53 and Table 54. One route can combine more or less options depending on their compatibility. For instance, the option “reduced engine friction losses” could be combined with all the other options. On the other hand, “piloted gearbox” and “dual-clutch” cannot be combined since they belong to the same technology group (“semi-automatic” gearbox). The results are presented in Table 55 and Table 56.

Table 53: Potential powertrain improvements for medium petrol cars

	Petrol vehicles (medium)	Average CO_2 reduction (%)	Costs (Euro)
ENGINE	Reduced engine friction losses	4	50
	DI/homogeneous charge (stoichiometric)	3 (1.5-3)	150
	DI/stratified charge (lean burn, complex strategies)	10	400
	Mild downsizing with turbocharging	(5)	(260)
	Medium downsizing with turbocharging	10 (9-10)	300
	Strong downsizing with turbocharging	12	450
	Variable valve timing	3 (3-3.5)	150
	Variable valve control	7 (7-8)	350
	Cylinder deactivation		
	Variable compression ratio	(6)	
	Optimized cooling circuit (E-thermostat, oil-water heat exchanger, split cooling)	1.5 (1.5-1.7)	35
	Advanced cooling circuit + electric water pump + heat storage	3 (3-3.5)	120
TRANSMISSION	Optimised gearbox ratios	1.5	60
	Piloted gearbox	4	350
	Continuous variable transmission		
	Dual-clutch	5	700

Source: derived from TNO et al.148
In parenthesis: indicative values or range (communicated by ACEA)

Table 54: Potential powertrain improvements for medium diesel cars

	Diesel vehicles (medium)	Average CO_2 reduction (%)	Costs (Euro)
ENGINE	Reduced engine friction losses	4	50
	4 valves per cylinder		
	Piezo injectors		
	Mild downsizing with turbocharging	3	150
	Medium downsizing with turbocharging	5	200
	Strong downsizing with turbocharging	7	300
	Cylinder deactivation		
	Optimized cooling circuit	1.5	35
	Advanced cooling circuit + electric pump water	3	120
	Exhaust heat recovery	1.5	45
TRANSMISSION	6-speed manual/automatic gearbox		
	Piloted gearbox	4	350
	Continuous variable transmission		
	Dual-clutch	5	700

Source: TNO et al.148

Table 55: Potential CO_2 reduction and additional costs for different technology routes (medium petrol cars)

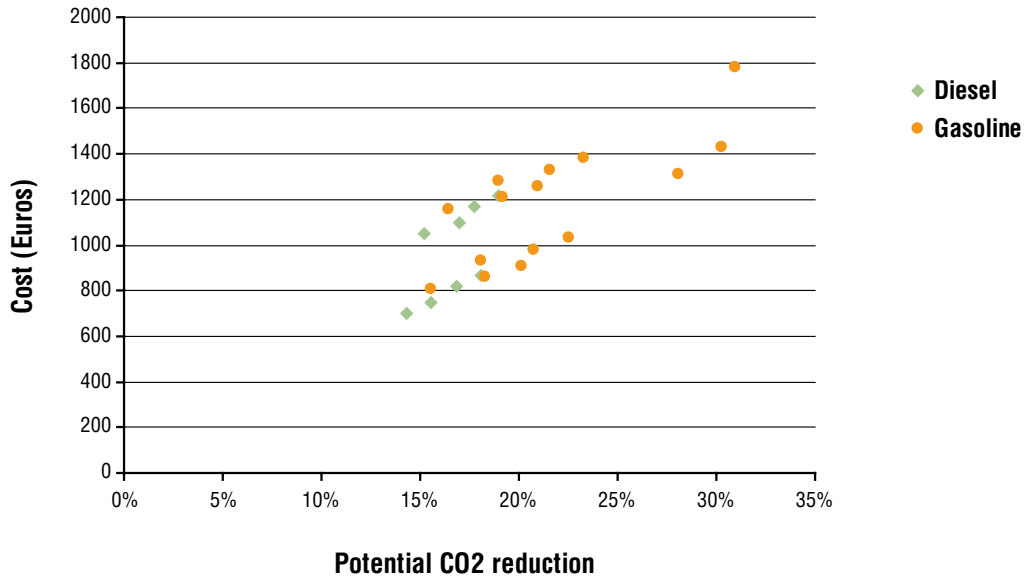
Combination	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
ENGINE																
Reduced engine friction losses	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
DI/stratified charge (lean burn/complex strategies)			•	•			•	•			•	•			•	•
Strong downsizing with turbocharging		•		•		•		•		•		•		•		•
Variable valve control	•				•				•							
Advanced cooling circuit + electric water pump									•	•	•	•	•	•	•	•
TRANSMISSION																
Optimised gearbox ratios	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Piloted gearbox	•	•	•	•									•	•	•	•
Dual-clutch					•	•	•	•	•	•	•	•				
Total CO_2 reduction (%)	15.6	20.1	18.3	28.1	16.5	20.9	19.2	28.9	19.0	23.3	21.6	31.0	18.1	22.5	20.8	30.3
Total cost (Euro)	810	910	860	1310	1160	1260	1210	1660	1280	1380	1330	1780	930	1030	980	1430

Table 56: Potential CO_2 reduction and additional costs for different technology routes (medium diesel cars)

Combination	C1	C2	C3	C4	C5	C6	C7	C8
ENGINE								
Reduced engine friction losses	•	•	•	•	•	•	•	•
Strong downsizing	•	•	•	•	•	•	•	•
Advanced cooling circuit + electric water pump	•	•			•	•		
Exhaust heat recovery	•		•		•		•	
TRANSMISSION								
Piloted gearbox	•	•	•	•				
Dual-clutch					•	•	•	•
Total CO_2 reduction (%)	18.1	16.9	15.6	14.3	19.0	17.7	16.5	15.2
Total cost (Euro)	865	820	745	700	1 215	1 170	1 095	1 050

Figure 41 plots the CO_2 reduction and additional costs for each of the technical routes. As expected, the options for diesel cars are more aggregated and offer less potential than petrol in term of CO_2 reduction (but at lower costs). There is also a gap in additional costs for both cars due to the low cost-effectiveness of the dual-clutch option compared to the piloted gearbox (only 1% CO_2 reduction added for 350 Euro more).

Figure 41: Additional costs versus CO_2 reduction potential for all the technical solution considered



The potential CO_2 reductions for medium sized petrol cars lie within the range 15.6 - 31% while the additional costs vary from 810 to 1 780 Euro. On average, a 22.1% CO_2 reduction potential combined with an average cost of 1 207 Euro was obtained.

For medium sized diesel cars, the range was 14.3 - 19% of CO_2 reduction combined with 700 – 1 215 Euro of additional costs. The total potential was then given by 16.7% of CO_2 reduction at the average additional cost of 958 Euro (Table 57).

Table 57: Average fuel/CO_2 reduction and costs for improved power trains

Option	Average fuel/CO_2 reduction (%)	Average additional costs (€)
New power trains (petrol cars)	22.1	1 207
New power trains (diesel cars)	16.7	958

Precise potential reductions regarding the air pollutants could not be established, although they are expected to be highly affected by these new technologies (positively or negatively).

6.6.4.1. Environmental benefits of the option

The "new power train" option will therefore considerably affect both climate change and primary energy of the TTW and WTT phases because of their important potential reduction (see Table 58 and Table 59). The highest improvements were obtained for the petrol cars.

Table 58: Life cycle impacts for the power train improvements option – petrol car

	Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)					
	Production	**Spare Parts**	**WTT**	**TTW**	**EOL**	**Total**
AD	100	100	78.6			100
GWP	100	100	78.6	78.7	100	80.5
ODP	100	100	78.6			79.7
POCP	100	100	78.6	100	100	86.6
AP	100	100	78.6	99.6	100	85.2
EP	100	100	78.6	100	100	87.2
PM2.5	100	100	78.6			84.3
PE	100	100	78.6	78.6	100	80.9
BW	100	100	78.6		100	94.6

Table 59: Life cycle impacts for the power train improvements option – diesel car

	Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)					
	Production	**Spare Parts**	**WTT**	**TTW**	**EOL**	**Total**
AD	100	100	83.9			100
GWP	100	100	83.9	84.0	100	85.3
ODP	100	100	83.9			84.7
POCP	100	100	83.9	100	100	94.0
AP	100	100	83.9	100	100	91.3
EP	100	100	83.9	100	100	93.3
PM2.5	100	100	83.9	100		94.3
PE	100	100	83.9	83.9	100	85.6
BW	100	100	83.9		100	96.7

6.7. Hybrid cars

6.7.1. Description of the options

Contrary to conventional ICE engines, in hybrid electric vehicles (HEVs) one power source delivers electrical energy. There are HEV configurations that differ regarding the capacity of the electric motor, the cost, the performance and other benefits. The type depends on how the electric motor contributes to the propulsion of the vehicle and in what proportion (see, e.g. Maggetto[169]). There are usually four primary types of hybrid electric vehicles[168] (see Figure 42):

- **micro hybrid:** no driving power is supplied by the electric motor. The electric motor provides functions such as auxiliary power, starter/generator, managing engine stop/start and the use of regenerative braking to charge the battery. Fuel savings can range from 4 - 10% (or even more), depending on the driver usage profile, and vehicle/engine combination. The stop/start functionality can also be provided by using conventional starter and advanced control strategy in combination with classical alternators which will also deliver regenerative braking functionality, i.e. additional electric motor not necessary for all applications. As an example, the PSA Citroen C3 Stop & Start can save around 6% over a standard combined cycle and up to 10% in the city[bx].

  Examples of micro hybrid vehicles include: PSA Citroen C2, C3, BMW 1 and 3 series petrol and diesel

bx http://www.citroen.com/CWW/en-US/TECHNOLOGIES/ENVIRONMENT/STOPANDSTART/.

- **mild hybrid:** the electric motor can provide modest assistance under acceleration to the ICE, but is never the sole source of driving power. The system also supports features such as regenerative breaking, stop/start and others. Fuel savings for mild hybrids usually lie between 10% and 20% depending of the driving cycle.

  Examples of mild hybrid vehicles include: Honda Civic Hybrid, Honda Accord Hybrid

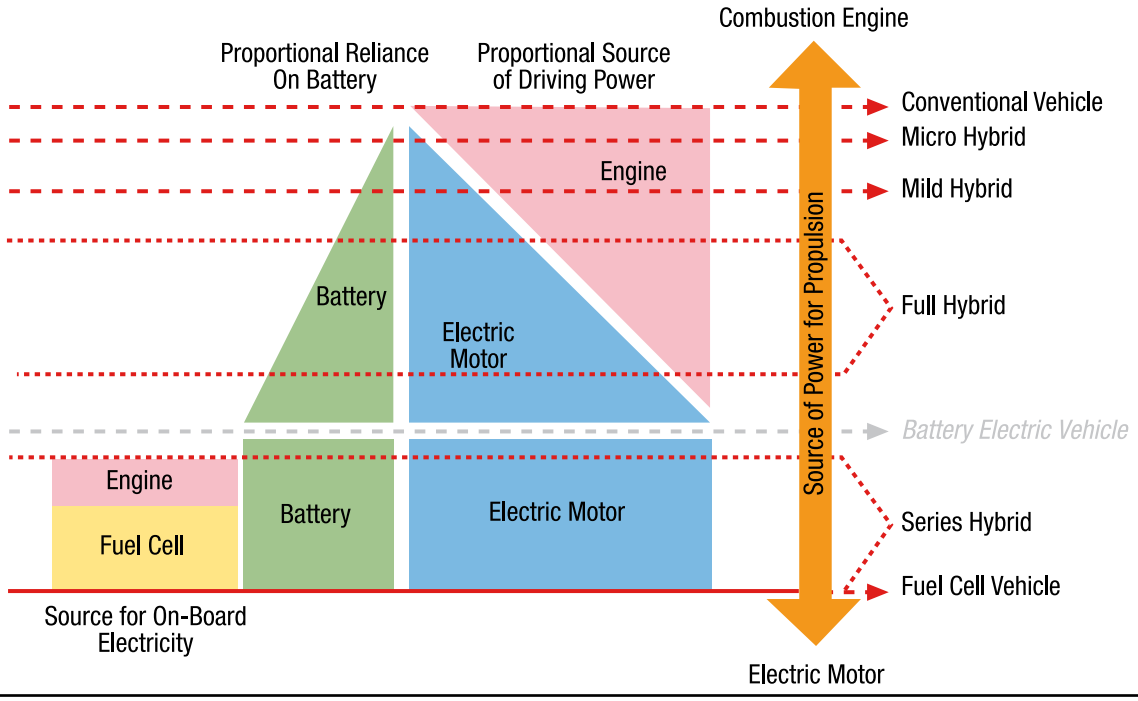
- **full hybrid (or strong hybrid):** the full HEV can be driven by the electric motor or the engine independently or together. The electric motor and the ICE provide different levels of power (a full hybrid electric motor typically provides around 40% of the maximum engine power as additional torque). The electric motor can be used as the sole source of propulsion for low speed, low acceleration driving, such as in stop-and-go traffic or for backing up. Batteries on full hybrids are larger and more powerful than those on mild hybrids. The most common types of full hybrid electric vehicle systems are 1) parallel hybrid, 2) series hybrid, and 3) power-split hybrids, depending on the configuration of the electric machine, the combustion engine and the transmission. **Parallel hybrids** means the electric motor and the engine are hooked up in parallel to the same transmission. For the **series hybrid**, the traction is given by only one central electric motor or by wheelbulb motors. Finally, the power-split hybrid or **combined hybrid**[169] is a combination of a series and a parallel hybrid powertrain. This technology is the one used by Toyota (Prius model) that benefits from both the parallel and series hybrid concepts.

  On average, fuel savings with a full hybrid can range from 15% to 25% depending on the technology type and the driving conditions. TNO et al.[148] reported that full hybrids can reduce fuel consumption by 22% and 18% respectively for petrol and diesel hybrids.

  Examples of full hybrid vehicles include: Toyota Prius, Toyota Lexus, Ford Escape Hybrid

- **Others:** Fuel cell electric vehicles (see, e.g. Maggetto[169]).

Figure 42: Different hybrid types and configurations



Source: http://www.greencarcongress.com/2004/08/a_short_field_g.html

6.7.2. Current situation and main trends

The European market sales for HEVs increased by 91% in 2006, mainly driven by Toyota and its full HEVs that accounted for around 78% of total HEV sales in Europe in 2006 (12% for mild and only 10% for micro HEVs). The sales of the Toyota Prius have increased from around 20.000 units in 2005 to 30.000 units in 2006. Honda sold around 5 000 mild HEVs in 2006.

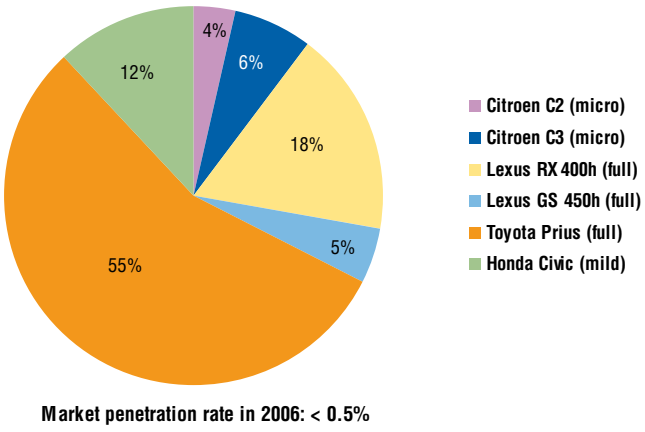
However in the international context, these results are very low compared to North America and Japan, mainly due to:

- A higher penetration of diesel vehicles in the EU
- extra cost to be paid by the consumers
- lack of models in the EU.

Therefore, the HEV market still remains a niche market in Europe (less than 0.5% penetration in 2006). European vehicle manufacturers are still not confident about introducing hybrid vehicles, with most manufacturers like Ford, Opel, and VW delaying their plans to launch HEVs in 2006.

As shown in Figure 43, Toyota with its full HEVs (Toyota Prius and Lexus), PSA Peugeot Citroen with its micro HEVs (Citroen C2/C3), and Honda with its mild HEVs (Honda Civic) were the only players in the European HEV market in 2006.

Figure 43: Composition of the EU hybrid market in 2006



Source: http://www.greencarcongress.com/2007/03/hybrid_electric.html
Note that total sales of HEVs in 2006 were around 54000 i.e. less than 0.5% of the EU vehicle market

Micro hybrids: in 2006, PSA sold more than 5 000 units of its Citroen C2/C3 models using the stop and start system. Even if there is a high potential market for micro hybrids in the EU, car manufacturers are still hesitant due to the high extra costs of this technology (500 - 700 Euro) compared to conventional petrol vehicles. However, Ford, General Motors and BMW expect to enter the EU market of micro hybrids in the next few years (2008 - 2009 for Ford and Opel and 2010 - 2015 for BMW).

Full hybrids: it is considered that the market will be dominated by full hybrids in the next few years, mainly due to their high potential in environmental protection. According to some experts, the volume sales of full hybrids might be multiplied by 5 in 2012. However, this depends on a multitude of factors influencing these sales.

Mild hybrids: the uptake rates of mild hybrids might be limited due to their low cost-effectiveness compared to full hybrids.

6.7.3. Technical potential

As described previously, HEVs can offer an interesting solution for reducing emissions considerably, compared to other candidate technologies such as gasoline direct injection, automated manual transmissions (AMTs), and so on.

Some research is being made to develop the **diesel hybrid car** (PSA group, Toyota, VW[by]). For this reason it is still difficult to gather large samples of measurements and make a full comparison of both cars. The diesel hybrid car is expected to result in even higher benefits (20 - 30%) when compared with the current conventional diesel car[bz].

PSA Peugeot Citroen is the first manufacturer to seize the 'diesel hybrids' opportunity and they plan to market the first diesel hybrid by 2010 - 2015. Their challenge is to develop diesel hybrid vehicles to be much more fuel efficient than current hybrid-petrol cars. At the beginning of 2006, PSA unveiled two demonstrators featuring a diesel-electric hybrid powertrain, the Peugeot 307 and the Citroën C4 Hybrid HDi. The objective is to cut CO_2 emissions and reduce fuel consumption by as much as 25% through combined powertrain and vehicle actions.

One technical aspect to be considered concerns electric energy storage (battery) and the special characteristics required for hybrid cars. Because of insufficient charge acceptance and limited charging times, lead-acid batteries do not have the performance required by hybrid cars. Indeed, hybrid cars require fast charging batteries with stable cycling performance, high power and energy density[170]. These conditions can be fulfilled by using nickel metal hydride (NiMH) or Li-ion batteries. The future market of HEVs will highly depend on the development progress of these batteries.

Technical, economical and environmental properties of batteries have been analysed in the European project[ca] SUBAT (Matheys et al., 2005)[171]. NiMH batteries present a good energy to weight ratio[cb]. The disadvantage is that high current operation during charging (exothermic reaction), makes thermal management and cooling of these batteries essential (which may explain why higher A/C efficiency is sought in hybrid cars).

The issue of NiMH and NiCd battery recycling has been analysed by D. Noréus[172]: "NiMH batteries don't require any special recovery system needs to be established, as in the case of NiCd which has to be kept separate from other recovery systems due to handling precautions with cadmium. This, in combination with a valuable metal content mainly from nickel and cobalt, gives NiMH scrap already today a positive value. NiMH producers can conveniently get rid of this production scrap and faulty cells through ordinary scrap merchants and recover a positive value. At present the recycling is practically made by recycling the cells together with steel scrap for the steel industry."

by http://www.greencarcongress.com/2006/11/report_toyotais.html.

bz It should be kept in mind that different parameters may influence the actual gain such as the driving type (urban versus non urban), temperature, etc. Investigations are also ongoing in order to develop further test measurements that are better adapted to these new power trains.

ca See also the US programme to develop advanced batteries for HEVs under the FreedomCAR Partnership (http://www1.eere.energy.gov/vehiclesandfuels/).

cb The specific energy and specific power of NiCd batteries are 55 Wh/kg and 1 500 W/kg respectively (25 Wh/kg and 350 W/kg for the lead-acid battery).

6.7.4. Existing legislation and current developments

There is no specific policy tool to stimulate the development and diffusion of HEVs in the market[cc]. However, they are concerned by the existing and developing legislation regarding CO_2 emissions together with any other improvements of power trains (see section 6.6.3).

6.7.5. Socio-economic barriers and drivers

The main barrier today concerns the cost and therefore the price of the hybrid cars compared to the current conventional power train (see section 6.7.6).

Another barrier might be the lack of information to the public regarding this new technology, and potentially, the lack of trust regarding its reliability. No clear evidence regarding this point was found.

More investigation regarding the public acceptance towards hybrid cars was made in the US where the market is developed.

More information regarding batteries, including their efficiency, durability and environmental performances also needs further investigation (see section 6.7.6).

6.7.6. Environmental benefits and direct costs quantification

6.7.6.1. Assumptions

The clear advantage of hybrid cars is the higher energy performance (and lower CO_2 emissions) when compared with the current common car. The advantage is the highest in urban and rural driving conditions. For urban driving, HEVs can reduce CO_2 emissions in the range of 5 - 8% for micro hybrids (e.g. stop and start system), 20 - 30% for mild hybrids and 30 - 40% for full hybrids.

Full hybrid cars are expected to offer the highest environmental performance and to gain the most significant market shares in the short term in Europe. Therefore, this analysis is based on full hybrid car technology.

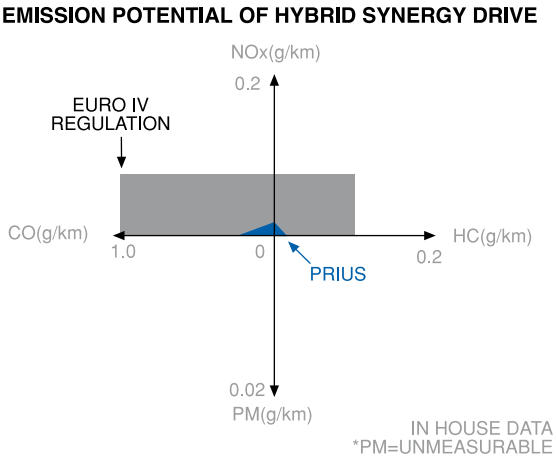
Full hybrid petrol cars

A significant market penetration of full hybrid petrol cars is expected to start in 2010.

In Europe, the Toyota Prius is the only marketed case where type approval data are available regarding emissions levels. These test approval measurements show a high performance of both CO_2 emission and regulated air pollutants (see Figure 44).

cc In Greece, however, hybrids are exempted from the annual circulation tax paid by conventional vehicles and are not subject to certain circulation restrictions in Athens city centre.

Figure 44: Pollutant emissions reduction of the Toyota Prius



Source: http://www.hybridsynergydrive.com/en/prius_emissions.html

As previously mentioned, the performances are the highest under urban cycle and much lower on motorways. Jeanneret et al.[90] measured the performances of the Toyota Prius for different regulatory driving cycles (NEDC 10-15 modes, HYZEM cycles, including urban, road, motorway). They also compared 13 conventional petrol cars equipped with a TWC. The dispersion of the emission levels was important:

- regarding air pollutants (CO, HC, NO_x), the Toyota Prius scores better than most of the vehicles compared. Regarding the respective means, the emission reductions range from 60 - 90% for CO, 50 - 90% for HC and 20 - 60% for NO_x
- regarding CO_2, the reduction is very important for the NEDC cycle (-20%). The benefit is particularly important for the urban cycle (-28%) and for the road driving cycle (-15%) and is much lower on motorways (-3%). These figures have to be considered as orders of magnitudes because the dispersion of the different measurements was important.

When looking at the CO_2 type approval data, the Toyota Prius is shown to have up to 40% improvement compared to the average petrol car sold today. This is higher than what the different literature sources report regarding the fuel economy of the hybrid petrol car. For instance, the WTW study[34] and also the study made by TNO et al.[148] consider a 20 - 25% improvement.

One important aspect to be noted when considering performance is the fact that the Toyota Prius combines different innovations, including the hybrid power train, improved ICE, a low aerodynamic drag coefficient and a high performance air conditioning system.

In this project, a 25% improvement for CO_2 and for energy is assumed. For the regulated pollutants, the type approval measures for the Toyota Prius were considered (Table 60). These emission levels are much lower than the EURO4 emission limits. These low emission levels may be attributed together to the hybrid technology and the air abatement system implemented.

Table 60: Potential reduction of CO_2/fuel consumption and regulated pollutants for hybrid petrol cars

FC (l/100km)	CO_2 (g/km)	CO (g/km)	NO_x (g/km)	HC (g/km)	PM (g/km)
25% improvement compared to the base case	25% improvement compared to the base case	0.18	0.01	0.02	0

Full hybrid diesel cars

Hybrid diesel is likely to enter the market in around 2015, even though PSA Peugeot Citroen announced by 2010.

Some research is still being made in development of the diesel hybrid. For this reason it is still difficult to gather large samples of measurements and make a full comparison of both cars. The diesel hybrid car is expected to result in even higher benefits (around 30%) when compared with the current conventional diesel car.

The objectives stated by PSA Peugeot Citroen with the two demonstrators featuring a diesel-electric hybrid power train, the Peugeot 307 and the Citroën C4 Hybrid HDi, is to cut CO_2 emissions and reduce fuel consumption by as much as 25%. The PSA hybrid technology combines the HDi diesel engine 1.6 l (and also particulate filter) with the stop and start system (STT), an electric motor, an inverter and high voltage batteries.

Table 61 summarises the potential fuel consumption reduction predicted by PSA Peugeot Citroen. The overall potential reduction of CO_2 and fuel consumption is around 30% (45% for the urban cycle) compared to conventional diesel. For hybrid petrol cars, this potential reduction includes the effect of combined vehicle and power train improvements.

Table 61: Performance and fuel consumption of hybrid HDi

VEHICLE	CONVENTIONAL C4/307	HYBRIDE HDi
Engine	Diesel 1.6 litres (80 kW)	Diesel 1.6 litres (66 kW)
Transmission type	Manual 5 gears	Robotised 6 gears
Speed max (km/h)	192	181
From stop to 100 km/h From stop to 400 m From stop to 1 000 m	12.4" 18.5" 33.7"	12.4" 18.4" 33.9"
KD: 30 to 60 km/h KD: 80 to 120 km/h	5.8" 13.0"	3.5" 10.6"
NEDC Cycle Std CEE 1999-100		
Fuel consumption (l/100 km) CO_2 emissions (g/km)	4,7 125	3,4 90
Fuel savings vs HDi in %	-	**-28%**
Urban Cycle		
Fuel consumption (l/100 km) CO_2 emissions (g/km)	5,4 145	3,0 80
Fuel savings vs HDi in %	-	-45%

Source: http://www.psa-peugeot-citroen.com/document/presse_dossier/DP_Hybride_HDi_EN1138701208.pdf

The figures provided by PSA Peugeot Citroen will be used in these assumptions (see Table 62). Unfortunately, there is little indication about the pollutant emission levela. As this new car is expected to be marketed later than 2010, the emission levels will have to comply with the future EURO5 standard for diesel cars. Therefore, the TA emission values will be lower than these EURO5 limits.

Table 62: Potential reduction of fuel consumption/CO_2 and regulated pollutants for hybrid diesel

	Fuel savings	CO_2	CO	NO_x	HC	PM
Full diesel hybrid	45% urban 28% NEDC (extra urban)	45% urban 28% NEDC (extra urban)	< EURO4 emission level			

Batteries

In order to take into account the environmental impacts associated with NiMH batteries, information regarding the weight and longevity of the battery for the Toyota Prius has been used (39 kg, and 8 years lifespan corresponding to the warranty offered by Toyota[cd]).

See Table 63 which shows the composition of a NiMH battery. The first column would, in principle, better fit with the case considered (full hybrid). However, the second column seems more consistent with the overall weight characteristics. For this reason, the second column composition was used.

Table 63: HEV power train materials, NiMH battery option

		Full Hybrid	Mild Hybrid
aluminium	kg	9.6	3.9
iron	kg	37.9	6.6
steel	kg	1.7	0.7
copper	kg	20.7	5.2
plastics, all	kg	13.7	4.4
nickel	kg	20.1	4.8
carbon	kg	1.8	0.7
silica	kg	9.5	3.6
other ( )	kg	2.1	0.5
manganese	kg		
zirconium	kg	2.3	0.6
(n/a)	kg	8.4	2.0
total	kg	128	33
Long-term perspective*: lead	kg	-13.0	n/a
total	kg	115	33

** lead-acid battery may be omitted from the system*

Source: Christidis et al.111

6.7.6.2. Environmental benefits of the option

The environmental benefits obtained by using full hybrid cars (petrol and diesel) are displayed in Table 64 and Table 65 showing the ratio of the improvement options' results over the baseline.

Regarding the petrol hybrid car, overall, the life cycle impacts are shown to be significantly improved when compared with the baseline. The only exception relates to waste. This obviously results from the substantial improvements at the TTW level (fuel saving and air emissions reduction). The high gains regarding fuel also entail important reductions in primary energy demand, thus reflecting in lower WTT impacts.

The other striking changes relate to spare parts for which all impacts, but abiotic depletion, are made worse. This results from the battery and its different material requirement. Both the higher weight of NiMH batteries used in hybrid car and the environmental profile of Nickel[ce] are the main explanations for these increased impacts.

cd The SUBAT project made the same assumption that the battery will not have to be replaced during the lifetime of the vehicle/
ce The LCA data Nickel used in these calculations were comparable with those reported by the Nickel Institute.

In these results, waste is suggested to be worse than in the baseline case. This is partly due to the large amount of primary nickel used for the production of this type of battery .

No comprehensive study on batteries which could have been compared was found. The only one found was made by Matheys et al.[171] which only considered energy and GHG emissions. The results of this study contradicts that study as Matheys suggested that their life cycle performances are not worse than lead batteries but even better.

The hybrid diesel is shown to have somehow higher environmental benefits compared to its base case (due to the assumptions made regarding the fuel economy).

Table 64: Life cycle impacts for the "full hybrid" improvement option – petrol car

	Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)					
	Production	**Spare Parts**	**WTT**	**TTW**	**EOL**	**Total**
AD	100	12.5	75.8			55.1
GWP	100	158.7	75.8	75.9	100	78.4
ODP	100	106.2	75.8			77.2
POCP	100	126.7	75.8	42.5	100	75.0
AP	100	670.9	75.8	52.4	100	90.6
EP	100	135.7	75.8	50.5	100	83.1
PM2.5	100	258.2	75.8			88.0
PE	100	116.3	75.8	75.8	100	78.6
BW	100	664.0	75.8		100	104.3

Table 65: Life cycle impacts for the "full hybrid" improvement option – diesel car

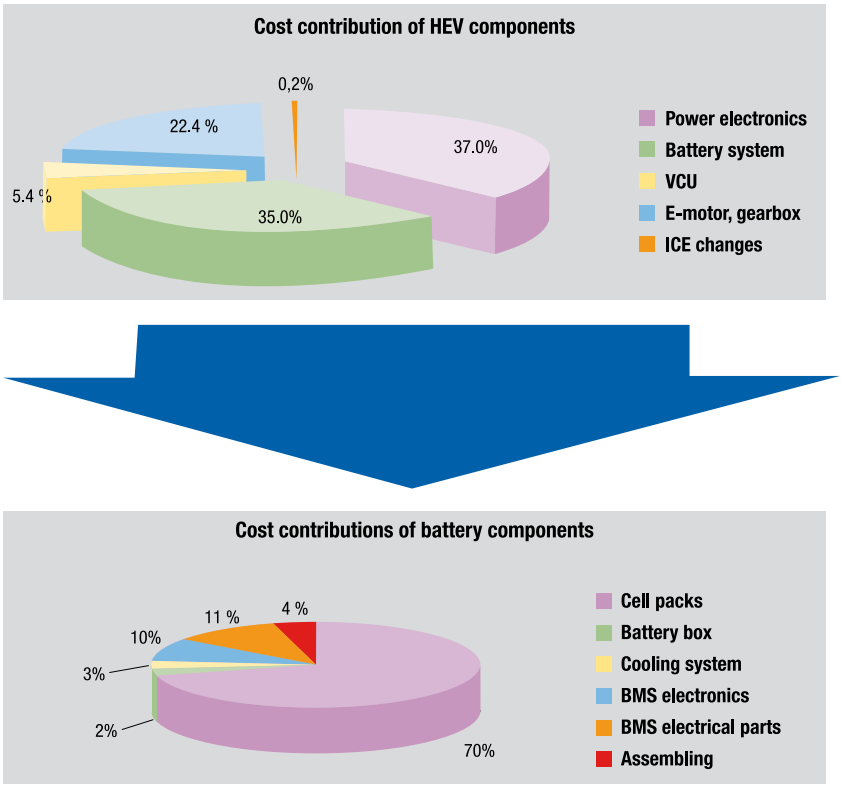
	Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)					
	Production	**Spare Parts**	**WTT**	**TTW**	**EOL**	**Total**
AD	100	11.4	68.1			53.0
GWP	100	151.3	68.1	68.3	100	71.5
ODP	100	105.4	68.1			69.9
POCP	100	123.1	68.1	100	100	88.9
AP	100	601.5	68.1	99.9	100	91.2
EP	100	127.7	68.1	100	100	87.1
PM2.5	100	238.2	68.1	100		92.0
PE	100	114.1	68.1	68.1	100	71.8
BW	100	596.0	68.1		100	103.7

6.7.6.3. Direct costs

Globally, the cost of hybridisation corresponds to the additional energy storage device (e.g. battery, supercapacitor), electric motor/generator, and motor controllers. For hybrid vehicles already on the market, their average price lies around 3 000 - 5 000 Euro higher than that of a comparable conventional

model. Frost and Sullivan[cf] reported extra costs for full petrol hybrids in the range 2 000 - 2 500 USD and 5 000 - 5 500 USD for hybrid diesel. As illustrated in Figure 45, these additional costs mainly depend on costs of power electronics and the battery system (the battery usually accounts for 30% to 50% of the additional cost for HEVs).

Figure 45: Cost contributions of HEV and battery components



Source: Bitsche et al., 2004 173
(Example of 300V, 35kW NiMH battery system using air cooling; BMS = Battery Management System)

Currently the additional costs of diesel hybrids are too high (around 6 000 Euro per vehicle) to compete with conventional technologies. A diesel engine typically costs around 10% more than a petrol engine with similar power, even without the cost of adding an electric motor, batteries and the electronics to run them. This technology is promising only if the additional costs can be reduced. Much R&D is needed relating to the costly systems i.e. high voltage batteries, electric motors, inverters and regenerative braking. However, PSA Peugeot Citroen predicts that this additional cost will be driven down to 2 000 Euro by 2010; it does, however. depend on a large number of factors. For this purpose, PSA Peugeot Citroen has launched an important research programme but most of the critical decisions will be taken in the very short term.

It is therefore very difficult to anticipate the uptake of this technology and to assess the additional costs. Due to these uncertainties, the same average additional costs as those considered by TNO et al.[148] are assumed, namely 3 500 Euro per vehicle, for both petrol and diesel hybrids (medium category).

An in depth analysis of economic aspects and market potential of hybrid vehicles was carried out by Christidis et al.[111].

cf http://www.automotive.frost.com.

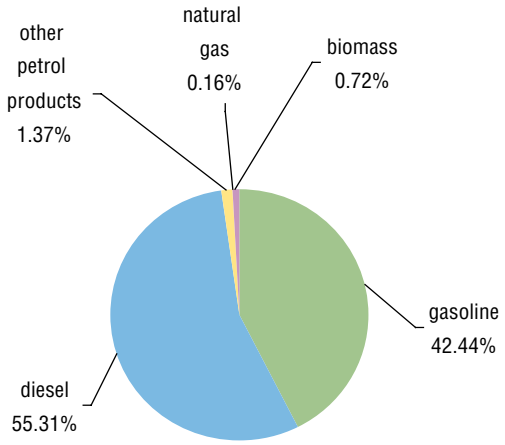
6.8. Biofuels

6.8.1. Description of the options

Conventional fossil fuels largely dominate the energy supply for road transport. Petrol and diesel are the two most important fuel products used for car driving (see Figure 46). Much smaller quantities (less than 1.5%) of other fuel products (especially LPG) are used. Other fossil products consist of natural gas.

Besides fossil-based fuels, renewable energy is also supplying a very small part of the final energy consumption by road transport. This energy is produced with the conversion of biomass energy into fuel (biofuels). Although remaining low, the contribution of biofuels in the road transport energy supply has grown (from 0.3% in 2001 to 0.7% in 2003 and 1% in 2005).

Figure 46: Share of energy demand of the different fuels for road transport



Source: Eurostat

Currently, biofuels can be produced in two distinct forms: biodiesel and bioethanol.

Conventional biofuels

For biodiesel, two important pathways are based on oilseeds from crops such as rapeseed and sunflowers. Oilseeds are crushed to produce vegetable oil and oil cake, a by-product used for animal feed. Vegetable oil is combined with alcohol (methanol or ethanol) and transformed into biodiesel, with glycerine as a by-product. Biodiesel can either be distributed by road tanker or ship to refineries or depots to be blended with diesel fuel or sold in its pure form at fuel stations.

For bioethanol, the main raw materials used to date are sugar cane (Brazil), corn (US), sugarbeet and wheat (Europe), which are processed by traditional fermentation[cg]. Ethanol from sugarbeet and wheat produce DDGS (dried distillers grains with solubles) and pulp for animal feed as well as electricity for the production process.

cg Bioethanol can be produced from any biological feedstock containing sugar or that can be converted into sugar such as starch or lignocellulose.

Advanced biofuels

A second generation of biofuels (or "advanced" biofuels) is currently at a developing stage.

Advanced biodiesel (or synthetic diesel) uses the biomass-to-liquid process (BTL). It consists of a pretreated biomass gasification route followed by a cleaning process, the Fischer-Tropsch synthesis, producing a variety of chemical products and fuels (most commonly FT diesel, kerosene, naphtha, etc.). The biomass to liquids routes are considered as an extension application from the gas to liquids and coal to liquids technologies that are already commercially available.

Advanced or lignocellulosic ethanol is based on the lignocellulosic biomass which is treated with enzymes and hydrolysis in order to remove lignin for ethanol production from the cellulose after the hydrolysis of sugars. This process is still in its research and development phase.

The importance of the BTL concept for future alternative fuels is the potential to use a wider range of biomass feedstock to produce them, as well as the quality obtained for the research and development plants demonstrates high quality fuels with also lower GHG emissions when compared to fossil diesel or petrol options or even to existing conventional biofuels in spite of their high energy intensive processes. It should be noted that these saving potentials are obtained when using by-products for self energy sufficiency of the processes.

Furthermore, industries like the pulp and paper industry are developing BTL options from residual production material such as "black liquor" to produce synthetic gas as well as possible synthetic fuels.

Renewable material used for this new generation of biofuels include short rotation crops (e.g. miscanthus, poplar, willow) as well as straw and residual wood. These options can either be pretreated in various ways including fine wood particle chippings, torrefaction and flash pyrolysis. The pyrolysis and fine wood particles are considered as feasible pathways more possibly pyrolysis than fine wood chippings. The corresponding option follows a gasification step that results in hydrogen and carbon monoxide rich gas. In order to obtain liquid fuels, this gas is then conducted to the synthesis step (Fischer-Tropsch synthesis) after cleaning and conditioning where a variety of chemicals and fuels are obtained including FT diesel, naphtha and others. A by-product with the remaining off-gas is the subsequent generation of power used in the production process and also available for the electricity network through a combined cycle.

Second generation biofuels are expected to be commercially available between 2010 and 2015 and are likely to be more expensive than conventional biofuels (see JRC-CONCAWE WTW study[34]) in the early years, but are expected to decrease afterwards. Furthermore, the feedstock of an increased demand on the feedstock price is considered to be much more limited for second generation biofuels than first generation. When considering all of these facts together, and taking technology developments into account, it is likely that the production costs of first and second generation biofuels will converge over time.

6.8.2. Current situation and main trends

Increasing the share of biofuels in the total fuel consumption from road transport is considered as a means to both reduce CO_2 emissions from transport and increase the energy security supply of the EU. It has been an objective for the EU with the EU Directive on the promotion of the use of biofuels or other renewable fuels for transport[ch]. The Directive states that "Member States should ensure that a minimum

ch JO L/123, Directive 2003/30/EC.

proportion of biofuels and other renewable fuels is placed on their markets, and, to that effect, shall set national indicative targets" and that "a reference value for these targets shall be 2%, calculated on the basis of the energy content of all petrol and diesel for transport purposes placed on their markets by 31 December 2005." A target was also set for 2010 (5.75%). However, there is no legal obligation for Member States to achieve it.

Biofuels are currently one important topic in the policy debate regarding both energy security supply and CO_2 emission reduction from cars. The recent report made by the European Commission on the progress made in this direction[ci] has shown that the interim target was not achieved and that the progress made was very uneven within the Member States. The Commission then concluded that the target of the biofuels Directive for 2010 is not likely to be achieved.

It proposed a series of steps to be followed in order to achieve a share of 10%. This 10% is expected to be achievable in 2020 with limited reliance on the second generation biofuels. The development of these new biofuels is, however, seen as an important condition to improve GHG and the security of supply impacts of achieving this target.

In its report, the Commission announced a proposal for the revision of the Directive in order to:

- send a signal showing the EU's determination to reduce its dependence on oil use in transport and to move towards a low carbon economy
- set minimum standards for the share of biofuels in 2020 (10%)
- ensure that the use of poorly performing biofuels is discouraged while the use of biofuels with good environmental and security of supply performance is encouraged.

In connection with this, the Commission also proposed amending the Directive on the fuel quality[cj], where, amongst other things, it proposed a mandatory monitoring (by suppliers for road transport) of life cycle GHG to be introduced from 2009. From 2011, these emissions are proposed to be reduced by 1% per year. In its conclusion from 15 February 2007[ck], the Council endorsed "a 10 % binding minimum target to be achieved by all Member States for the share of biofuels in overall EU transport petrol and diesel consumption by 2020, to be introduced in a cost-efficient way. The binding character of this target is appropriate subject to production being sustainable, second-generation biofuels becoming commercially available and the Fuel Quality Directive being amended accordingly to allow for adequate levels of blending".

One main means to achieve this progressive reduction is to increase the share of bio fuels in road transport by also ensuring that the most efficient biofuel routes from a GHG perspective are used.

6.8.3. Socio-economic barriers and drivers

Social and economic barriers being discussed in the impact assessments made by the Commission for the two new proposals discussed above.

6.8.4. Environmental benefits and direct costs quantification

ci EC Commission, 2007, Communication from the Commission to the Council and the European Parliament: Biofuels Progress Report – Report on the progress made in the use of biofuels and other renewable fuels in the Member States of the European Union (COM(2006)845 final).

cj EC Commission, 2007, Proposal for a Directive amending Directive 98/70/EC regarding the specification of petrol, diesel and gasoil and the introduction of a mechanism to monitor and reduce GHG emissions from the use of road transport fuels and amending Council Directive 1999/32/EC regarding the specification of fuel used by inland waterways vessels and repealing Directive 93/12/EC (COM(2007)18).

ck http://www.consilium.europa.eu/ueDocs/cms_Data/docs/pressData/en/trans/92799.pdf.

6.8.4.1. Assumptions

Biofuels can be used either in low blends or in high concentrations (up to 100% for biodiesel, E85 or E95 for ethanol). For ethanol, a blend of 85% ethanol and 15% petrol (E85) is typically used in flexi-fuel-vehicles (FFVs)[cl]. The 15% petrol improves the cold startability by increasing the vapour pressure. Note that FFVs (e.g. Ford Focus/C-MAX, Saab 9-5, Volvo C30/S 40/V50) are already sold in different markets of the EU, particularly in Sweden.

Therefore, this means that when quantifying the impacts of using biofuels on the LCA impacts of a car, high biofuel shares could be considered. However, this would not be very realistic as such a high share is not achievable either for the whole car fleet today or for the new car fleet.

To make the assessment more realistic, two options regarding the blend assumptions were considered (namely 5% and 10% biofuel). WTW air emissions data for higher rates are also very limited.

In addition, the first generation of biofuels was also considered because advanced biofuels are not yet commercialised. In addition, whereas the WTW energy and GHG performance are relatively well documented in literature, information regarding all the other environmental impacts is very poor.

Therefore, making a full life cycle assessment would be very speculative. However, there are already evidences that second generation biofuels would generally provide better environmental performance than the first generation. This was shown for instance by Baitz et al. (2004) who compared the life cycle environmental performances of the Choren process to produce synthetic diesel[174].

In the following, the approach and information used to quantify some of the environmental impacts related to the use of biofuels under these conditions is described.

6.8.4.2. Well-to-tank related impacts

The JRC-CONCAWE WTW study[34] is the most recent and comprehensive study about life cycle impacts of automotive fuels. However, as it only concerns energy and GHG emissions, it had to be completed with other sources of information and data. To this end, the study report "Participative life cycle analysis" produced by SenterNovem[175] was used.

The study includes a life cycle analysis of ethanol and biodiesel use compared to their respective baseline (petrol/diesel). This recent study quantifies the life cycle impacts of both bioethanol and biodiesel. The results are presented in terms of "midpoint" indicators. The scope and main assumptions regarding the WTT part are given in Table 66.

cl These vehicles can operate on different ratios of ethanol and petrol.

Table 66: Scope and main assumptions regarding the WTT

	Biodiesel	Bioethanol
Geographical unit	**Netherlands**	**Netherlands**
Crop	Rapeseed (50% from WE, 25% eastern EU, 25% ROW)	Wheat from Western Europe
Co-products	Cake from biodiesel production applied as fodder for cattle Glycerine sold to the pharmaceutical industry	Straw: 33% ploughed in soil, 33% as bed-material for cattle, 33% CHP Cake from bioethanol: production applied as fodder for cattle Lignin residue not used for combustion
Variants considered	1. Amount of fertiliser applied 2. Soy replacement (no change as compared to the baseline)	1. Amount of fertiliser-N applied, accounting for the uncertainty in IPCC range for direct soil N-emissions 2. Use of straw for CHP
Allocation method	Economic allocation	Economic allocation

It is worth noting that the Netherlands was the geographical unit, which means that both production and consumption are assumed to take place in this country. Therefore, the transport of fuel is assumed to be restricted to this area.

Most of the final results are presented in relative terms, as a percentage of the impacts associated with the 100% diesel or petrol used. This means that they can be combined with the Ecoinvent data in order to derive the impacts associated with the WTT part of biofuels (see Table 67).

In order to match these figures with the CO_2-eq estimates from the JRC-CONCAWE WTW study[34], the different CO_2 estimates from the WTW study corresponding to wheat for ethanol and rapeseed for biodiesel were extracted. In these CO_2 estimates, credits to the different by-products (glycerine, animal fodder, heat production) are applied so that the net CO_2 emissions are negative.

Table 67: WTT impacts per MJ fuel for biofuels as compared with the reference case

WTT (kg/MJ)	Gasoline	Bioethanol neat				Diesel	Biodiesel neat		
		Base case	Low fertiliser	High fertiliser	Straw in CHP		Base case	Low yield	High yield
Eutrophication	0.015	0.050	0.053	0.054	0.014	0.014	0.29	0.2	0.083
Acidification	0.19	0.33	0.35	0.33	0.14	0.14	0.58	0.54	0.43
POCP	0.051	0.087	0.087	0.087	0.043	0.043	0.044	0.044	0.044
Climate change(1)	13	-4.0				14	-8.8		
Primary energy (MJ/MJf)(1)	140	1 500				160	1 100		

(1) based on WTW study

Table 67 does not provide estimates for ODP and for PM2.5, but these impacts are not expected to be larger than for the reference case. It was therefore assumed that these impacts are unchanged.

6.8.4.3. Tank-to-wheel related impacts

Tailpipe emissions associated with biofuels depend on different factors.

The air pollution standard that the car meets (EURO1 to EURO4): EURO4 cars are more energy efficient than older cars and are, in addition, equipped with catalysts. This means that the (scarce) measurements made about the effect of biofuels on unabated tailpipe emissions cannot just be extrapolated to abated

tailpipe emission. The effect would depend on the driving conditions: most of the measurements are made under "hot" start emissions. The "cold-start" emission levels are not so well tested.The blend rate considered: impacts would of course be different from 5% to 100% blend biodiesel.

In the different studies (see for instance the SenterNovem study, Niven (2005)[176], Lussis[177]), the effects of biofuels use are characterised as follows:

Petrol => ethanol

On a non-recalibrated engine (which is likely to be the case with E10), the following trends are generally reported:

- CO reduced
- PM reduced and of lower mutagenicity
- NO_x mostly unchanged (both increases and decreases are reported
- HC slightly increased. Profile also changed: more ethanol and aldehydes
- toxic substances:
  - o aldehyde emissions higher (huge increase reported in some studies – 100 - 200%. (It is likely that the three catalytic converters are efficient in converting the aldehydes, but insufficient information was obtained).
  - o increase of formaldehydes emissions
  - o decrease of benzene, toluene, xylene emissions
- CH_4 emissions higher.

On recalibrated engines (beyond E20), HC emissions would be reduced:

Diesel =>biodiesel

- CO reduced
- PM lower
- NO_x higher at some operating points
- HC reduced and aldehydes (but oxidation catalyst efficient in converting the aldehydes).

Table 68 presents the assumed emission levels for the two biofuel options.

Table 68: TTW emission profiles of cars using biofuels and compared with petrol/diesel

	EURO4		EURO4	
g/km	Gasoline	E10	Diesel	B10
CO	1.00	1.00	0.50	0.45
VOC	0.10	0.10	0.15	0.13
NOX	0.08	0.08	0.15	0.17
PM	0.00	0.00	0.03	0.01
Acidification	0.06	0.06	0.10	0.11
POCP	0.12	0.12	0.18	0.19
Eutrophication	0.01	0.01	0.02	0.02

6.8.4.4. Environmental benefits of the option

Based on the above assumptions and information, a comparison of the different environmental impacts associated with the use of biofuels compared to the pure fossil based case was made (see Table 69 and Table 70). The changes are incurred in the TTW and the WTT parts. In both cases (biodiesel and bioethanol), small positive impacts are suggested for abiotic depletion and waste, and more significant benefits regarding greenhouse gas emissions, ozone depleting substances and particulates.

Regarding ethanol, small benefits regarding photochemical pollution and acidification are expected. The opposite trend is expected for biodiesel. Eutrophication is expected to dramatically increase with biodiesel.

Regarding primary energy, both cases entail a higher increase of energy use by the TTW part, and also by the WTT part. When considering fossil fuels only, there is however a significant decrease of primary energy demand.

Table 69: Life cycle impacts for the bioethanol option (10% blend) – petrol car

	Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)					
	Production	**Spare Parts**	**WTT**	**TTW**	**EOL**	**Total**
AD	100	100	100	-	-	100
GWP	100	100	98.8	90.3	100	92.3
ODP	100	100	100	-	-	100
POCP	100	100	107.1	100	100	104.5
AP	100	100	108.7	100	100	106.0
EP	100	100	125.2	100	100	115.1
PM2.5	100	100	100	-	-	100
PE	100	100	197.9	100	100	110.7
BW	100	100	100	-	100	100

Table 70: Life cycle impacts for the biodiesel option (10% blend) – diesel car

	Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)					
	Production	**Spare Parts**	**WTT**	**TTW**	**EOL**	**Total**
AD	100	100	100	-	-	100
GWP	100	100	98.4	90.4	100	92.4
ODP	100	100	100	-	-	100
POCP	100	100	100.4	107.7	100	103.9
AP	100	100	130.3	109.3	100	117.9
EP	100	100	300.3	109.3	100	186.3
PM2.5	100	100	100	51.6	-	76.1
PE	100	100	158.8	100	100	107.2
BW	100	100	100	-	100	100

These results provide an indication of the expected changes regarding the different environmental aspects of cars partly fuelled with biofuels. It should be noted that biofuel options are numerous in terms

of crops and that these may have different environmental performances. It should also be remembered that the assessment does not consider the impacts on land which, in this case, may result in an overall over-estimation of the life cycle performance of biofuels. Energy yields can widely vary depending on the feedstock used (e.g. one hectare of rapeseed will produce 66 GJ compared to 27 GJ for sugarbeets[178].

6.8.4.5. Direct costs

The costs associated with biofuels are derived from the WTW study (see Table 71). Based on the cost estimates given in that report for the different biofuel pathways, an average value for the incremental costs for biodiesel and bioethanol when compared with the conventional fuel was calculated (diesel and petrol respectively), which depends on the oil price assumption (25 Euro per barrel or 50 Euro per barrel).

A similar mean value is derived for bioethanol and biodiesel (8.3 Euro/GJ to 8.4 Euro/GJ substituted).

Table 71: Additional costs of biodiesel and bioethanol compared to the respective conventional fuel

Euro/MJ	25 Euro/barrel	50 Euro/barrel	Average
Bioethanol	0.0107	0.0061	0.0084
Biodiesel	0.0107	0.0059	0.0083

Source: ***based on the WTW study****34*

6.9. End-of-life vehicle recycling and recovery

6.9.1. Current situation and main trends

According to ACEA, 11.4 million passenger cars were deregistered in the EU-15 in 2004, of which 7.7 million were treated in waste treatment facilities. About 130 000 vehicles were deregistered in the most important EU-10 countries but Hungary. In Hungary, 220 000 vehicles were deregistered, but only one fraction of these vehicles has been treated. In total, less than 70% of the deregistered cars were treated.

As shown in Chapter 4 and in existing studies, the share of the EOL phase in the life cycle impacts of a car is relatively small. Waste is the only significant impact. Scrapped cars represent less than 0.7% of the total amount of waste generated annually in the EU (EUROSTAT, 2005)[cm]. The current situation of EOL vehicles treatment is detailed below.

Pretreatment consists of draining the fluids and removing substances of concern from the EOL vehicle (battery, fluids and fuel). The pre-treatment is still failing to meet some of the requirements of the EOL Directive (pyrotechnic devices, HFC, airbags and lead are the most relevant). Insufficient de-pollution affects the efficiency of the subsequent treatment (contamination with undesired substances, including hazardous substances).

After depollution, some spare and core parts are removed. Some parts are required to be removed by the EOL Directive). Other are also removed if this is economically viable for the operator and depending on the infrastructures met in the different Member States.

After dismantling, the remaining body is fed into a **shredder**. The crushed fraction is separated through magnetic separation and air aspiration techniques into three main fractions. One fraction is predominantly

cm Eurostat, 2005, Waste Generation and Treatment in Europe.

composed of **iron** – recycled as steel scrap – representing about 70% of the total output[129]. A **light fraction** is composed of non-ferrous metals, and a **heavy fraction** is a mixture of non-ferrous metals and non-metallic materials.

Most of the **non-ferrous metal content** of the heavy fraction is separated from the rest after a series of manual and automatic processes. It then undergoes further processing and ultimately recycling operations.

The ultimate non-metallic residues constitute the **shredder refuse or automotive shredder residue (ASR)**. It currently represents about 20% to 25% of the average weight per vehicle.

Currently, ASR undergoes very little treatment and is mostly placed in **landfill sites**. A general characterisation of their chemical composition is difficult[cn]. In Daniels et al. (2004), the composition of two different samples from Europe is given[183]. It suggests a high share of foams and rubber. Plastics, in total, represent from 14% to 34%.

The importance of plastics with regard to EOL vehicle treatment is continuously growing due to the upward trend in plastic content: In vehicles currently reaching the end of their life, the plastic content ranges from 6% to 10% whereas, in new cars the percentage ranges from 10% to 15%.

One aspect related to ASR is also the fact that, despite the presence of some toxic components such as cadmium, arsenic, platinum, mercury and PCB, there is still a lack of clarity concerning ASR whereas it is classified as hazardous by the Basel Convention, it not the case in the EC legislation.

6.9.2. Technical potential

The level of materials recovery[179] from EOL vehicles can be technically increased along two broad options:

- enhancing the degree to which **car wrecks** are **dismantled** in order to reduce the volume to be shredded and the resulting amount of shredder residues. This, ultimately, contributes to the increasing degree of recycling, especially mechanical recycling
- developing new **post shredder technical options**.

There are also efforts to design cars with a view to making the dismantling operation more cost effective and to covering more parts of the car (see section 5.2.2).

Further dismantling: Optimal sequences for the dismantling operations have been identified both to limit the cumulative time for dismantling and the volume of removed parts (see Barbiroli, 2000[134]).

The increasing use and variety of plastic in cars is one of the main sources of complexity of car dismantling. This operation can be facilitated by the **marking of the different plastic components**.

cn This is due to the important composition variations from car to car and to the various degrees and types of treatment applied. In addition, waste streams stemming from other end-of-life products contained in the EOL vehicle, such as sand, gravel, bricks, concrete and other household and commercial waste, are sometimes illicitly introduced in the waste treatment facility (Ambrose, 2000).

The experience described by ARN (the Netherlands)[co] is one example of the most advanced dismantling operations[cp]. Achieving and going beyond this level of dismantling and mechanical recycling is, however, challenged by the incremental time consumption and costs entailed.

The recycling of materials and plastics in particular is subject to physical and chemical limitation – contamination of the material with some components may limit the possibilities for recycling and also the quality of the material recycled. These limitations were analysed by Reuter et al. (2005)[139] who came to the conclusion that a realistic maximum rate regarding recovery/recycling would together include feedstock, mechanical recycling and energy recovery in a range from 90% to 95%.

Post shredder treatment: Different post-shredder treatment (PST) options have been developed over the last years. These options include options to further separate the different ASR waste streams that are subsequently recycled or thermally processed (feedstock recycling and energy recovery[cq]). Although these developments are technically compatible with enhanced car dismantling, they are also seen as an alternative to the previous option. Gaiker (2007)[180] has reviewed the different technologies for plastic waste treatment.

One example is the **VW-SiCon** post-shredder technology[181] developed by SiCon GmbH in collaboration with Volkswagen (see Table 72). The shredder residue is sorted and separated on the basis of its physical properties, producing different streams. The process is sought to be developed and adapted to the growing diversity of plastics used in cars. In this sense the process design is market-driven, taking into account the product requirements, the expected destination of the outputs (for instance, plastic granulate being used in furnaces, what are their standards for combustibility). The technology allows continuous adaptation to the evolution of cars, from the currently processed cars produced fifteen years ago to the cars manufactured today. In this technology, the different outputs and market potentials are as follows (see Table 72):

Table 72: VW-SiCon: treatment of the different material flows and market potential

Recycled fraction	Market potential
Shredder granulate (plastic + low chlorine and metal content)	Reducing agent in blast furnaces as a substitute for heavy oil
Plastic fraction with a high PVC content	PVC in the Vinyloop process (developed by Solvay)
Shredder fibres (mixture of textile fibres and seat foam)	Sewage sludge dewatering as a dewatering agent of coal dust
Shredder sand (glass, fine iron particles, rust, fine copper, wires, dust containing lead, zinc and lacquer particles)	Glass, rust and lacquer particles: slag builder in non metallurgy and reducing agents Fine iron particles: reducing agents Copper wires, lead and zinc dust: introduced back in the metallurgic cycle
Further ferrous and non-ferrous metals	

Source: Report produced by the stakeholder group established by the Commission for the review of the EOL Directive

co Even in the Netherlands where very high levels of 83.4% reuse and recycling and 85.4% reuse and recovery were achieved in 2004 by ARN system, these drivers will see post-shredder technology installed in a new plant expected to come into operation in 2007 (stakeholder consultation).

cp Car parts and material concerned are for instance inner tubes, tyres, rubber strips, bumper, grill, PU foam, safety belts, tank, fuel, (see http://www.arn.nl/engels/2praktijk/222.php).

cq Feedstock recycling refers to any processes (pyrolysis, thermal cracking, hydrocracking, blast furnace, etc.) used to break down polymeric waste into simpler substances subsequently repolymerised to produce virgin materials. Energy recovery: Plastic waste can be used to generate energy by incineration or in several industry processes (in cement kilns for instance), ASR from cars, ASF (mixed shredded waste from cars, municipal and industrial waste).

An example of a thermal separation method is the one developed by the **Argonne National Laboratory** (US). A licensed agreement was signed with ELV **SALYP** Center and a full-scale demonstration plant (Belgium) combining the ANL technology with others has been operational since 2000. It is a multistage plastics separation plant (thermo plastic sorting). The process is fully continuous, minimising materials handling and labour costs. According to Salyp the initial 3.5 million USD necessary to process 40 000 tons/year can be recovered within just a few years[182]. The performance of the installation was assessed in 2004 in a project conducted in the US and headed by ANL (Daniel et al., 2004). The cost for separation of a mixed plastic stream is estimated to 0.26 USD/kg (Daniels et al., 2004)[183]. Salyp's near industrial sorting line was able to separate different material streams (metals, fibres, foam – using the ANL technology –, fines, plastic concentrates) and recover a mixed plastics fraction. Tests show, for instance, that the resulting polyurethane foam meets performance criteria for new material carpet padding and for reuse in automotive applications. However, sorting the mixed fraction into individual plastic streams could not be accomplished. A life cycle assessment of the process is being conducted in the framework of the "Automotive Lightweighting Materials Programme" headed by ANL (Daniel et al., 2004).

Other technologies include the THERMOSELECT process (Drost et al.[135]), TwinRec (Selinger et al.[136]) and SVZ in Germany (syngas production).

Energy recovery of plastics may also be limited in some cases because for blast furnaces, only plastics with high caloric values can be accepted. On the other hand, plastic granulates can be used in blast furnaces as the reducing agent (feedstock recycling).

6.9.3. Existing and developing environmental legislation

The Directive 2000/53/EC on end-of-life of vehicles[143], with its different amendments, is the main instrument dealing with the management of end-of-life vehicles, spare and replacement parts, dealing with the vehicle design and regarding the collection, storage and treatment of EOL vehicles.

It stipulates different requirements regarding the **vehicle design** including:

- endeavouring to reduce the use of hazardous substances when designing vehicles
- designing and producing vehicles which facilitate dismantling, re-use, recovery and recycling
- increasing the use of recycled materials in vehicle manufacture
- ensuring that components of vehicles placed on the market after 1 July 2003 do not contain mercury, hexavalent chromium, cadmium or lead, except in some car components.

Member States have to set up **collection systems** for EOL vehicles and for waste used parts. They have to ensure that all vehicles are transferred to authorised treatment facilities, and have to set up a system of deregistration upon presentation of a certificate of destruction.

The last holder of an end-of-life vehicle will be able to dispose it free of charge ("free take-back" principle). Producers have to meet all, or a significant part of the cost for applying this measure.

Undertakings carrying out treatment operations have to strip EOL vehicles before treatment and recover all environmentally hazardous components. Priority has to be given to the reuse and recycling of vehicle components (batteries, tyres, oil).

Member States have to ensure that producers use material coding standards which allow identification of the various materials during dismantling. These standards laid down in Decision 2003/138/EC are based on ISO coding standards (for plastics and rubbers).

Economic operators have to provide prospective purchasers of vehicles with information on the recovery and recycling of vehicle components, the treatment of end-of-life vehicles and progress with regard to re-use, recycling and recovery.

In 2005, it was estimated that 75% of materials contained in EOL vehicles were recycled (metal content) whereas the aim of the Directive is (article 7.2b):

- to increase **the rate of re-use and recovery** to 85% by average weight per vehicle and per year by 2006, and to 95% by 2015
- to increase **the rate of re-use and recycling** over the same period to at least 80% and 85% respectively by average weight per vehicle and per year.

Achieving the above quotas means that the most of the materials included in shredder residues have to be recovered/reused.

In January 2005, in view of this review process, the Commission established a stakeholder working group (SWG) who delivered a report on 4 November 2005[184].

The report expects that: "many Member States will report reuse, recycling and recovery performances more or less in line with the 2006 targets, based upon those ELVs captured and using their own definitions and interpretations"[184]. It points out different problems related to the Directive implementation:[184]

- the lack of robust monitoring systems needed to make a reliable assessment, partly due to the complexity of the process-chains, and to the numerous actors involved. The reports also points out the lack of harmonisation regarding waste fraction definitions and treatment methods
- available data suggest that many countries are facing difficulties in implementing the Directive
- the lack of legislative and economic drivers for change. The economic efficiency of ATFs is questioned for the longer term. Downstream applications for the recovered post shredder non metallic fraction are not widely available in all countries, but function well in a few
- adequate infrastructure is lacking in some countries (quality dismantlers, shredder capacity) and the number of ELV collection points have to increase. The percentage of ELVs that are not captured by the certified systems in place is high (at least 40%)
- a large fraction of cars are being sold and legally exported second hand, especially to the new Member States. This means that these countries will face an increasing need of ELV treatment facilities – and high investments – in order to comply with the reinforced targets for 2015 and beyond
- some of the new Member States may not, however, be able to develop their systems quickly enough to meet the 2006 targets on time.

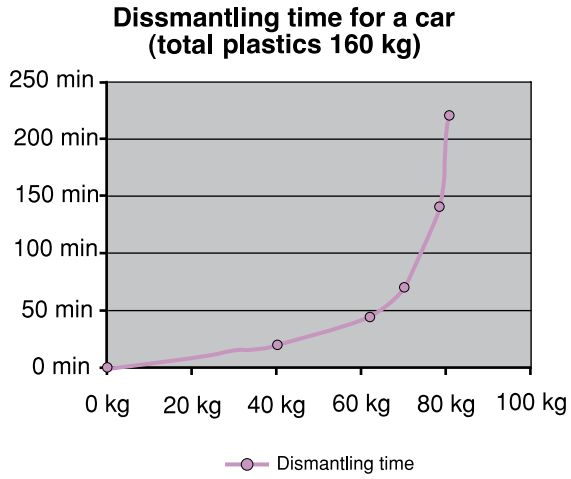
The Commission recently produced a report[185], on which basis these targets will be re-examined by the European Parliament and the Council, taking account of the material composition of vehicles and any other relevant environmental aspects related to vehicles.

6.9.4. Main barriers against non-metal recycling and recovery

Costs induced by the different technical options were considered by the SWG. One issue emphasised is the high cost associated with the dismantling operations which require man-hours to be spent per vehicle which consequently generates costs (see Figure 47). Globally, the total time required for depollution and dismantling, including administration, has been assessed at around 1 hour 30 minutes per vehicle.

An indicative overall extra cost to fulfil the requirements of Annex I to the Directive would be in the approximate range of 45 Euro to 80 Euro per ELV.

Figure 47: Marginal efforts required for increments in plastic recycling from EOL vehicles



Source: Plastics Europe, quoted by EPEC141

In most cases, non metallic wastes dismantled or sorted and separated post shredder cannot be reused for their original purpose but need to find other markets where they can displace materials from other sources. Data in Table 73 show that dismantling costs represent the highest contribution to the total cost from dismantling to the mechanical recycling of the parts recovered. This is particularly true beyond a certain amount of plastic concerned as these costs follow a similar trend as shown as in Table 73, including a dramatic increase for each plastic kg beyond ~70 kg.

It also shows that the sale of parts and granulates is sufficient to pay for transport and processing granulation processes but is far from sufficient to pay off the dismantling costs.

Table 73: Comparison of plastic recycling costs with income from the sale of recovered parts and granulates

	Euro/t plastic
Dismantling	333 - 4 137
Transport	250 - 300
Processing	150 - 250
Granulation	200 - 300
Total	**933 - 4 987**
Income from sale of parts	0 - 90
Income from sale of granulate	180 - 1 150

Source: Fraunhofer Institute

The **economic viability** of **post shredder** treatment and recycling is determined by the availability of economically sustainable applications. The amount of ASR from EOL vehicles has been estimated to be around 3 000 000 tonnes per year for the EU-25. Compliance with the EOL Directive targets up to 2006

and then to 2015 implies a doubling of the capacities of both reuse and/or material recycling and of energy recovery.

For the time being, the market opportunities for recycling are, however, too limited for the bulk of the materials, which can be recovered by post shredder treatment in any event, at much lower costs. There is no economic incentive to recycle materials other than steel and some valuable components because these materials have a negative market value and no market exists[141].

The VW-SiCon technology is an example where technology has been developed and designed in such a way as generating outputs where market potentials exist. Innovation is needed regarding such post-shredder technologies.

It should be noted that some new challenges like the increasing use of lightweight materials (plastics, magnesium), the development of hybrid cars (new types of batteries), the generalisation of catalysts, and, later, fuel cells. Schexnayder et al. (2001)[142] have for instance assessed the waste quantities related to a new generation vehicle (the so-called 3XV, referring to the fuel mileage which is three times better than the 1994 baseline vehicle). They estimated that aluminium will become a large contributor of total waste. Platinum will also increase due to the generalisation of catalytic converters which will induce a growing gross demand for platinum group metals (PGM) (potentially 75% of world production capacity in 2005). If recycling is taken into account, this share would be reduced to 30%, which is still significant in terms of smelting capacity needs.

However, the expected market penetration of fuel cells in ~2030 would tend to limit this growth as fuel cells do not need catalytic converters.

Additional hazardous waste will result from both batteries (160% increase of hazardous waste resulting from nickel metal hydride and 35% increase resulting from lithium ion batteries) and from plastics (26% to 41% increase).

6.9.5. Environmental benefits and costs quantification

6.9.5.1. Literature review

The assessment of the environmental impacts of the different waste treatment routes applied for EOL vehicles has been analysed in a few studies. The main findings from these studies has been summarised by considering two questions: Is ASR recycling/recovery more advantageous than landfilling? How do the different ASR treatment options compare?

Landfill versus other ASR treatment options:

All studies reviewed - except the LIRECAR project[17] (see below) - conclude that **both the mechanical recycling route and the thermal recycling route offer clear environmental benefits compared to the current situation where landfilling is the main destination for ASR residues**.

Another more surprising conclusion drawn from the comparison of the three EOL scenarios is that there is no significant difference for most of the environmental impact categories, including hazardous waste. The only exception is for total waste where the recycling scenario leads to a 25%-50% improvement. In addition, the improvement is linked to the production phase (mining of coal used in power plants and ore mining).

Comparison of the different ASR treatment options:

Some studies have analysed and compared the environmental performances of some EOL treatment options in particular. For instance, VW has performed a comparative LCA of two treatment options (Krinke et al., 2005)[132]:

- the **dismantling** of plastic components from EOL vehicles followed by **mechanical recycling**. The plastic fraction separated was supposed to be recycled into equivalent new product (with 1:1 ratio) and the fraction collected as a mixed plastic was supposed to substitute concrete
- the **VW-SiCon** process mainly based on **feedstock recycling** of material fractions that are specifically separated from the shredder residues of EOL vehicles after the shredder process (see above description).

For both options the EOL Directive's 2015 target was assumed to be achieved. The study considered four environmental impact categories (global warming, acidification, photochemical ozone creation, eutrophication) and sensitivity analyses were performed (regarding the substitution ratio for plastics).

The environmental burden of each of the two routes was reported to be reduced when compared with the current situation (landfilling); however, the benefits were not quantified. For each impact category, a lower performance was estimated for the first process (29%, 13%, 17%, 6% less reduction respectively for the dismantling route when compared with the VW-SiCon process for global warming, acidification, troposphere ozone, eutrophication).

The relative performance of the two compared technologies were shown to be sensitive to the substitution ratio of plastic materials into new plastics, to the transport distances implied, to the amount of plastics and light and non-ferrous metals and also to the assumed separation rate.

The study carried out for APME (Öko-Institut, 2003)[138] considered different plastic components. It compared the two main treatment routes to the current situation (bulk of ASR landfilled): dismantling followed by mechanical recycling on the one hand and thermal processing on the other hand (including incineration, cement kilns, SVZ gasification, blast furnace). The study showed that mechanical recycling is advantageous for the parts composed of PP (bumpers for instance) whereas the advantage was lower for others.

The LIRECAR project[17] analysed three sets of vehicle scenarios (1 000 kg reference and two lightweight scenarios – 900 kg and 750 kg respectively) and three EOL scenarios, including the current situation (reference), one scenario assuming 100% recycling and a third one with 100% energy recovery for ASR. The environmental impacts of the reference cars were based on the data from seven real cars. The study did not show any significant difference between three EOL scenarios (with the exception of solid waste where the recycling scenario leads to a 25%-50% improvement). In addition, the improvement was suggested to be linked to the production phase (mining of coal used in power plants and ore mining).

6.9.5.2. Assumptions for the study and quantification

The above-mentioned studies provided some indications regarding the environmental performance of particular PST and/or specific plastic waste treatments.

The recent study made by GHK and BIOIS[23] reviewed the different technologies and the existing LCA analysis about the environmental performance for the different plastic resins and came to the conclusion that about 80% of the resins currently used in cars are not covered by such studies. The data analysed in BIOIS provides a clear illustration of this wide range of variation both across technologies and across

plastic types. The minimum and maximum values for these data were given in the study (see Table 74). This suggests that comparing the different treatment routes under a generic approach is a delicate problem.

Table 74: Environmental impacts associated with plastic waste treatment as reported by GHK and BIOIS

		Mechanical recycling		Feedstock recovery				Energy recovery				Landfill	
				Blast furnace		Syngas production		Cement kiln		MSWI			
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Energy consumption	MJ	-105	13	-48	-20	-58	-17	-48	-19	-35	-13	0.2	0.6
GWP	kg CO_2-eq	-6.1	4.0	-0.3	0.1	-0.2	1.4	-1.7	-0.6	0.3	0.2	0.03	0.4
Acidification	g SO_2-eq	-45.6	3.1	-3.2	0.5	-11.4	2.7	-0.9	0.8	-4.1	0.3	0.01	1.5
POCP	g C_2H_4-eq	-36	10	-1	0.1	-5	0.3	-0.1	1	-0.44	0.28	0.0	0.1
Eutrophication	g PO_4-eq	-5.3	0.8	-0.14	0.11	-1.02	0.3	-0.03	0.1	-0.3	0.3	0.03	0.9
Bulk waste	g	-272	70	-10	30	-150	12	-390	0.0	-70	230	1 000	1 000
Hazardous waste	g	-30	11	0.1	10	-0.1	3	0.0	0.0	0.0	50	0.0	0.0
External costs	Euro	-158	208	-7	7	-11	73	-34	-26	4	109	5	40

One aspect to also have in mind is that the net impacts associated with the different technologies are all subject to some assumptions: in each assumptions have to be made regarding the energy substituted, the destination of the recycled material and the new product value.

In the present project, the primary goal when considering the EOL improvement options was therefore to derive a general indication of what further recycling/recovery plastic waste from cars entails in terms of changes of the car life cycle impacts. As most of the effort needed to fulfil the EOL Directive concerns plastics, focus was made on this fraction, which in the base case cars is assumed to represent 200 kg. A scenario where 50% plastic is mechanically recycled and 50% plastic is recovered was then considered (feedstock – blast furnace, syngas – or energy – cement kilns and incineration).

With a view to quantifying this scenario, the data produced by the Fraunhofer study[140] was used, which was one of the data sets reviewed in the BIOIS study. The advantage of these data is that detail is provided regarding the avoided impacts. Based on that, averages over the different technologies (recovery, recycling, landfilling) were calculated and the different resins covered[cr], which were then applied to the plastic fraction and respective streams assumed to be recycled and feedstock/energy recovered. This means that **plastics are considered as a mix of different types and the singling out of the impacts of recycling or recovering some of them was not sought.**

To a certain extent, this underestimates the potential and possible options to optimise the environmental performance of treating ASR. These results should be interpreted with this bias clearly in mind.

The results are presented in Table 75 which displays the estimated gross impact associated with the EOL phase. The impacts that are expected to be avoided are also presented with the total impacts and these avoided impacts given as a percentage of the total car life cycle impacts.

cr As provided in the GHK and BIOIS report in their Appendix 6.

These results show that, even if avoided impacts are not considered, the life cycle impacts are almost unchanged (very slight increase for GWP and POCP). When credits are considered, a net benefit is expected for all impact categories, but POCP.

Table 75: Life cycle impacts for the improved recycling/recovery option – diesel car

	Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)						
	Production	**Spare Parts**	**WTT**	**TTW**	**EOL**	**Total**	**avoided impacts**
AD	100	100	100			100	0.0000
GWP	100	100	100	100	208.4	100.1	-0.71
ODP	100	100	100			100	0.00
POCP	100	100	100	100	37.3	100	-0.09
AP	100	100	100	100	177.1	100	-0.77
EP	100	100	100	100	55.2	99.9	-0.17
PM2.5	100	100	100	100		100	0.00
PE	100	100	100	100	330.9	100	-1.31
BW	100	100	100		33.4	77.0	6.15

6.9.5.3. Direct costs

With a view to making the direct costs estimation consistent as much as possible with the estimated environmental benefits shown above, the GHK and BIOIS study was used which also made cost quantifications of the different technology options. This cost analysis covered the costs related to the two waste treatment routes (feedstock recovery/energy recovery and mechanical recycling of ASR) and the costs associated with landfilling (see Table 76).

Table 76: Costs for the three technical options for plastic waste treatment

	Euro/kg		
	Lower estimate	**Medium estimate**	**High estimate**
Mechanical treatment of ASR	0,020	0,075	0,100
Thermal treatment of ASR	0,075	0,120	0,200
Landfill costs	0,035	0,065	0,115

Source: GHK and BIOIS

Based on these figures, and considering 200 kg per ELV, the extra cost entailed per vehicle by the three scenarios was calculated and compared with the base case where all plastic wastes are assumed to be landfilled (see Table 77). The cost ranges from a net cost (+23 Euro/ELV) to a net benefit (-14 Euro/ELV). In this last case (the low cost scenario), the avoided costs related to landfill outweighed the costs entailed by the ASR treatment.

Table 77: Costs related to ELV treatment

	kg plastic/ ELV	High cost scenario		Medium cost scenario		Low cost scenario	
		Euro/kg	Euro/ELV	Euro/kg	Euro/ELV	Euro/kg	Euro/ELV
Mechanical treatment of ASR	100	0.10	10	0.08	7	0.02	2
Thermal treatment of ASR	100	0.20	20	0.12	12	0.08	7
Avoided disposal to landfill	200	-0.04	-7	-0.07	-13	-0.12	-23
Additional cost of baseline			**23**		**6**		**-14**

6.10. Reducing speed limits on motorways

6.10.1. Description of the options

In this section the option of reducing the speed limit is described. This type of measures is seen by some EU countries (e.g. France) as an efficient way to reduce, among others, fuel consumption/CO_2 emissions and improve local air quality.

Motorways are the focus here because at lower speeds (e.g. rural cycle), the expected potential reduction is more speculative due to the fact that lower speed limits may result in situations where it is more difficult to drive in top gear which would counterbalance the expected positive gain. Environmental impacts of lower speed limits have been examined by many studies and appear to be achievable at low cost.

For instance, ADEME[cs] carried out simulations to assess the environmental impact of three speed limit reductions. It was found that reducing speed limits on motorways from 130 km/h to 120 km/h would reduce fuel consumption by 14% or around 1 l/100km. Literature reports that reducing motorway cruising speed from 120 km/h to 110 km/h will reduce fuel consumption by about 20%.

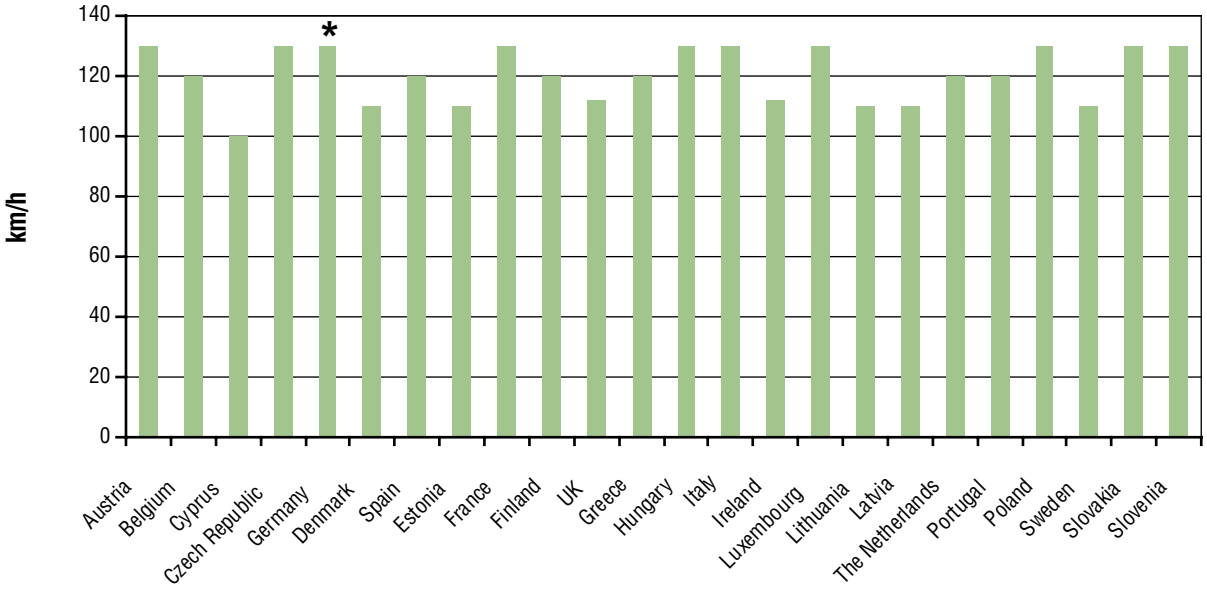
Alongside cutting CO_2 emissions, reducing the speed limits on motorways would obviously present indirect effects such as reducing the need for high-powered cars (which has shown to be increasing over the last years).

6.10.2. Existing legislation and current developments

In Europe, general speed limits for cars inside urban areas are relatively harmonised (50 km/h except Slovakia and Poland) but they vary widely outside urban areas (from 65 km/h to 100 km/h) and, to some extent, on motorways. Figure 48 highlights general maximum speed limits for cars on motorways in the EU-25 (except Malta). In some countries, speed limits are reduced in bad weather conditions or for newly qualified drivers.

cs http://www2.ademe.fr/servlet/getDoc?cid=96&m=3&id=19335&ref=13418&p1=B.

Figure 48: Maximum authorised speed on motorways in the EU (except Malta)



**130 km/h is the recommended maximum speed on motorways in Germany*

6.10.3. Socio-economic barriers and drivers

Benefits from speed limits concern safety, air quality, congestion and also reduce noise. It is obvious that vehicle speed is at the core of the road safety concerns. Higher speed increases both the risk of accidents and the consequences of a crash.

The implementation of such limits may, on the other hand entail resistance from the driver. Recent results from a SARTRE[ct] survey, however, indicate that 79.4% of the drivers would support the harmonisation of speed limits throughout Europe.

6.10.4. Environmental benefits and direct costs quantification

6.10.4.1. Assumptions

The improvement potentials of speed limits on fuel consumption and air emissions are derived from Copert IV[186] which is based on the work carried out by Samaras et al.[187] in the framework of the ARTEMIS project. This report presents speed dependent hot emission factors (EF) covering both air pollutants (CO, HC, NO_x and PM) and fuel consumption (FC) for cars.

The equations giving the evolution of the emission factors as a function of the vehicle speed as shown in Table 78 were used, considering petrol EURO4 and diesel EURO3 vehicles (unfortunately EURO4 equations are not available for diesel cars)[cu]. The relative impact of speed on fuel consumption and air emissions could then be assessed.

ct Social Attitudes to Road Traffic Risks in Europe (see http://sartre.inrets.fr/).
cu This is an assumption. As no results were available for diesel EURO4, the EURO3 results were used as a reference.

Table 78: Emission factors vs. speed for petrol and diesel cars

EF=(a+c*V+e*V2)/(1+b*V+d*V2)								
Gasoline car (EURO4)	**a**	**b**	**c**	**d**	**e**	**120 km**	**130 km**	**Ratio**
CO	0.14	-0.01	-0.0009	0.00005	0.0	1.09	1.96	0.56
HC	0.01180		-0.00003		0.000001	0.02	0.02	0.92
NOX	0.11		-0.002		0.00001	0.02	0.02	0.91
FC	0.02	0.07	0.36	-0.00027	0.009	32.50	37.40	0.87

EF=(a+c*V+e*V2)/(1+b*V+d*V2)+f/V									
Diesel car (EURO3)	**a**	**b**	**c**	**d**	**e**	**f**	**120 km**	**130 km**	**Ratio**
CO	0.17		-0.0029		0.0	1.10	132.00	143.00	0.92
HC	0.09650	0.10300	-0.00024	-0.00007	0.000002		0.01	0.01	1.04
NOX	2.82	0.19800	0.067	-0.00143	-0.00046		1.00	1.44	0.70
PM	0.05		0.00		0.000		0.06	0.07	0.85
FC	162.00	0.12	2.1800	-0.00078	0.0		52.18	59.11	0.88

Source: Samaras et al.187

6.10.4.2. Environmental benefits of the option

The above ratios are applied for the part of the driving cycle relevant to motorways. This results in an overall emission reduction as shown in Table 79.

Table 79: Potential emission factor reductions

	FC/CO_2	**CO**	**NOX**	**HC**	**PM**
Petrol (EURO4)	-5.70%	-4.30%	-8.80%	-8.40%	
Diesel (EURO3)	-11.30%	-13.10%	-28.20%	4.30%	-15.50%

The estimated impacts on the life cycle of the two base case models are presented in Table 80 and Table 81.

Table 80: Life cycle impacts for the speed limits on motorways option – petrol car

Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)						
	Production	**Spare Parts**	**WTT**	**TTW**	**EOL**	**Total**
AD	100	100	98.6			100
GWP	100	100	98.6	98.6	100	98.7
ODP	100	100	98.6			98.6
POCP	100	100	98.6	96.1	100	98.4
AP	100	100	98.6	98.2	100	99.0
EP	100	100	98.6	98.2	100	99.0
PM2.5	100	100	98.6			99.0
PE	100	100	98.6	98.6	100	98.7
BW	100	100	98.6		100	99.6

Table 81: Life cycle impacts for the speed limits on motorways option – diesel car

	Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)					
	Production	Spare Parts	WTT	TTW	EOL	Total
AD	100	100	97.2			100
GWP	100	100	97.2	97.3	100	97.5
ODP	100	100	97.2			97.3
POCP	100	100	97.2	93.6	100	95.8
AP	100	100	97.2	93.2	100	97.4
EP	100	100	97.2	93.2	100	96.6
PM2.5	100	100	97.2	96.1		97.1
PE	100	100	97.2	97.2	100	97.5
BW	100	100	97.2		100	99.4

6.10.4.3. Direct costs

Achieving speed limits would imply some measures such as information campaigns, changing road signs, etc. However, it is very difficult to assign a cost to these measures. Therefore the assumption was made that direct costs are negligible.

6.11. Driving behaviour

6.11.1. Description of the options

Like reducing speed limits on motorways, "eco-driving" is an example of a **cost-efficient option** for cutting CO_2 emissions, with beneficial psychological impacts on drivers, e.g. lowering stress or improving driving feeling. Further positive effects include increasing road safety, reducing traffic accidents, mind-opener for inter-modality, reducing wear on the powertrain, brakes, tyres, etc.

It is widely recognised that driving behaviour significantly affects fuel consumption and air emissions of vehicles. Many studies have compared vehicle emissions from the so-called "eco-driving style" on the one hand with the "normal average" style on the other. Generally speaking, eco-driving means that the driver should follow a long list of rules[cv] such as:

- shift from a higher gear below 2 500 rpm for petrol cars and 2 000 rpm for diesel cars
- maintain a steady speed in the highest gear possible
- look ahead and anticipate traffic flow
- no abrupt accelerating or breaking
- switch off the engine at short stops
- remove unnecessary loads from the vehicles as well as unused roof/rear racks
- check and adjust tyre pressure regularly
- etc.

cv See also http://www.ford.com/en/goodWorks/environment/airAndClimate/ecoDrivingTips.htm.

The four first rules are usually viewed as "basic" rules[cw].

The effect of eco-driving training on fuel consumption and CO_2 emission has assessed in depth by TNO et al.[148]. It is very important to distinguish between the short term and the long term achievable effects of eco-driving since the benefit tends to decrease over time.

6.11.1.1. Short term effects

Short term effects are the effects obtained directly after a training course. In this case, it is assumed that drivers may save between 5% and 25% of fuel, depending on their driving style. However, in practice, the average impact of eco-driving on fuel consumption is rather 10% (TNO et al.[148]). In literature, most of the studies assessed the impact of eco-driving just after instruction to the drivers.

An assessment of eco-drive courses conducted in 2000 and in 2001 by the Federal Office of Energy in Bern[cx] (Switzerland) considered eco-drive as a simple and extremely energy-efficient instrument. They estimated that eco-driving can reduce fuel consumption by 10-15%.

According to the US EPA's website[cy], practicing fuel efficient driving can improve fuel economy by more than 10%. Ford eco-driving[cz] showed a 25% reduction as a result of training courses when comparing the eco-driving style to "normal-average" driving behaviour (a potential fuel consumption reduction of up to 25% after training is also considered by the ACEA[da]).

In 2004, Van Mierlo et al.[188] carried out a measurement campaign to assess, among others, the influence of driving style on fuel consumption and vehicle emissions from 'on the-road' experiments with a wide range of vehicle classes. For this purpose, a group of people were instructed with eco-driving style tips namely:

1. Shift as soon as possible at a maximum of 2 500 rpm (2 000 rpm for diesel) to as high a gear as possible.
2. Press the throttle quickly and vigorously as much as it takes to keep up with the traffic.
3. Do not shift down to a lower gear too early and keep the car rolling without disengaging the clutch and in as high a gear as possible.

A certain drive cycle was driven before and after they received the driving tips, in order to measure the difference in driving behaviour (for urban and extra urban). Tests were made with 12 vehicles (seven petrol and five diesel) representative of the "modern" Flemish car fleet (in 2003). The speed data were measured by TNO. The impacts on fuel consumption and other pollutants are summarised in Table 82.

It should be noted that motorway profiles were not measured (the driving behaviour has less impact on motorways since the driving dynamics, i.e. acceleration/braking, are less important). Assuming the following driving shares (i.e. 29.2% urban, 44.9% extra urban and 25.9% motorway), the average effect of driving behaviour on fuel consumption and CO_2 emissions would be 12.4% for petrol and 12.2% for diesel cars. These figures lie well within the overall range defined by literature.

cw Tyre pressure control and better MAC use also belong to this list. These options are treated as independent options in our study.
cx http://www.eco-drive.ch/download/evalu_e.pdf.
cy www.fueleconomy.gov/feg/drive.shtml.
cz Ford eco-driving, the clever move (http://www.ford-eco-driving.de/download/Eco-Driving-Leaflet-ENG-5-2004.pdf).
da http://www.acea.be/node/423.

Table 82: Potential reductions on fuel consumption and air emissions due to changes in driving behaviour

		FC/CO_2 (%)	CO (%)	HC (%)	NO_x (%)	PM (%)
Petrol	Tips 1 and 3, urban	**-4**	n.c.	n.c.	-55	
	Tips 1 and 3, extra urban	**-25**	-59	-39	-47	
Diesel	Tips 1 and 3, urban	**-8**	n.c.	n.c.	n.c.	-27
	Tips 1 and 3, extra urban	**-22**	-37	-24	-29	-31

Source: derived from Van Mierlo et al.188
n.c. = non consistent

6.11.1.2. Long term effects

Due to the effectiveness and durability of training, the effects of eco-driving decrease over time. In practice, it is assumed that "long term effects" correspond to overall achieved effects about one year after training. TNO et al.[148] estimated these achievable effects to be about 3%, while literature gives a typical range of 2 - 3.5%. Other sources (e.g. ACEA) assume even higher long term effects (7% under every-day driving conditions[106]).

Work carried out in the framework of the European Climate Change Programme (ECCP) in 2001 calculated a reduction potential for driver education and eco-driving of at least 50 million tons of CO_2 emissions in Europe by 2010. This would mean savings for consumers of about 20 billion Euro per year.

Globally, "eco-driving" means small changes for the driver and high impacts on improving fuel economy and reducing air emissions.

6.11.2. Socio-economic barriers and drivers

Cost efficiency in terms of CO_2 reduction (without socio-economic effects) has already been demonstrated by the Dutch campaign 'Het Nieuwe Rijden' HNR ("New Driving Force")[db] is that some 7 Euro per ton CO_2 is reduced by eco-driving. Taking into account socio-economic effects, eco-driving comes out as a "profit centre" by generating financial value (i.e. avoidance of accident costs).

Overall, eco-driving can be seen as "sustainable mobility best practice", i.e. gaining economic, emotional, social and environmental benefits at the same time. The key is the high intrinsic motivation and acceptance of the drivers trained to apply eco-driving techniques under every day driving conditions. The didactic concept has to clearly convey the personal benefits of practicing Eco-driving for each individual driver. To train people the "right way" is essential for "positive emotions", intrinsic motivation and the integration of eco-driving techniques into the individual driving style. From many psychological studies[dc], the key principles of a "good" communication and training concepts are known to overcome scepticism. It is also important that the "don't dos" in a training session or communication are identified in detail. While this training is a massive psychological intervention, these key principles must be considered by the instructors to gain best and sustainable training results possible while avoiding the negative effects.

Many of the eco-driving practices differ from the driving style generally advocated a generation ago. With many new drivers being taught how to drive by their parents, Eco-Drive proponents suggest that

db https://www.senternovem.nl/mmfiles/Greenweek%202005_tcm24-122873.pdf.
dc Ford/DVR 1999 - 2007, internal surveys.

many people are driving new cars with an obsolete and inappropriate driving style. In a bid to counter faulty driving practices already learned and teaching novices the new 'correct' way to drive, eco-drive concepts are being used by driver trainers, are being taught in schools and are being instituted as part of fleet training programmes.

The effects of eco-drive training on safety have shown clear evidence in several studies. Johansson[189] referred to a long term study in Finland that found a significant decrease in fuel consumption and a reduction in costs associated with accidents in a government car fleet. Other studies have examined the effects of eco-driving both in terms of fuel consumption and crash risk.

Also, recent studies (German Road Safety Council - DVR) with two different German car fleets, and professional drivers identified Eco-driving behaviour as a strong business case. The impact and relevance of eco-driving trainings also under "worst case scenarios" are proven, noting the specific framework of professional driving, such as "time pressure"/"professional stress" without any benefit for the driver in terms of lower fuel costs/recognition. Finally, in both the fleets surveyed a long term effect (approx. 1 year after training) of fuel economy improvement of some 8% is gained from reliable fleet management system data under every day conditions. Also a significant improvement of road safety was identified with some 35% less accidents of eco-trained personnel compared to the untrained control groups.

6.11.2.1. Technical potential

A further 3% improvement can be expected from the introduction of an advanced, "intelligent" gear shift indicator system (GSI) targeting a high acceptance rate and perceived as a valuable driver assistance system (without supporting eco-driving training, just the GSI impact itself). In fact, the potential of eco-driving programmes (see, e.g. the Dutch HNR programme) is even higher, as demonstrated by other studies pointing to a long term reduction potential if combined with GSI of more than the above-stated long term 10 - 15%, depending on target groups, motivation and training concepts. In addition, the above-mentioned benefit of GSI is probably too low as it underestimates the percentage and extent of drivers following GSI. Another in-vehicle device that could support eco-driving is the econometer. In this context, drivers' training is important.

6.11.2.2. Existing legislation and current developments

There is a strong impetus in many European countries for drivers to improve their fuel economy through changes in their travel behaviour. The eco-driving concept includes advice for car manufacturers and policy changes for roads and infrastructure changes, but its primary thrust is a smoother driving style – gliding through the traffic. With respect to implementing eco-driving, the Netherlands has played a leading role in Europe with the most comprehensive and stringent nation wide eco-driving campaign 'Het Nieuwe Rijden' ("New Driving Force") since 1999 with a budget of more than 35 million Euro up to 2010 to continue this governmental programme. This continuing campaign is also impressive because of the cost-effectiveness of the entire programme, which is calculated to be about 7.6 Euro per ton CO_2 reduced – with the prognosis to be lowered further in the long term[190].

Yet, whilst eco-driving forms part of climate change policies in some European countries (such as Austria, Spain, the Netherlands) most governments have failed to make more use of this effective 'no

regrets' measure so far. Eco-driving is one of the options considered in the newly proposed measures aimed at reducing CO_2 emissions. Different national initiatives are also being considered[dd].

6.11.3. Environmental benefits and direct costs quantification

6.11.3.1. Assumptions

In the following, we only quantify the potential reduction of eco-driving on fuel consumption (and then CO_2 emissions) **in the long term** i.e. about one year after training, as defined previously (Table 83). Potential reductions in air pollutants are also likely, but measured with less accuracy[de]. Our assumptions stem from the conclusions of TNO et al.[148] on the combined effect of eco-driving and GSI in the long term. They indeed assume that long term effect of applying eco-driving with the aid of GSI can reduce fuel consumption by **4.5%** (3% from eco-driving lessons and 1.5% due to the sole effect of GSI).

Table 83: Long term effect of eco-driving

	Avg. reduction in fuel consumption/CO_2 emissions	Regulated pollutants	Source
Eco-driving	3.00%	n.a.	TNO et al.[149]
Use of GSI	1.50%	n.a.	TNO et al.[149]
Total long term reduction	**4.50%**	n.a.	TNO et al.[149]

6.11.3.2. Environmental benefits of the option

The estimated impacts on the life cycle of the two base case models are shown in Table 84 and Table 85.

Table 84: Life cycle impacts for the driving behaviour option – diesel car

	Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)					
	Production	Spare Parts	WTT	TTW	EOL	Total
AD	100	100	95.6			100
GWP	100	100	95.6	95.7	100	96.1
ODP	100	100	95.6			95.9
POCP	100	100	95.6	100	100	98.4
AP	100	100	95.6	100	100	97.6
EP	100	100	95.6	100	100	98.2
PM2.5	100	100	95.6	100		98.5
PE	100	100	95.6	95.6	100	96.1
BW	100	100	95.6		100	99.1

dd Netherlands: www.hetnieuwerijden.nl/ Austria: www.spritspar.at , Switzerland: www.eco-drive.ch , Germany: www.neues-fahren.de , Scandinavia: www.ecodriving.com. See also: http://www.observatoire-vehicule-entreprise.com/fre/developpement/3799/la_semaine_europeenne.html.

de A wide range of values regarding air emissions of CO, HC and NO_x can be found in literature (e.g. from 20% to 150% changes for NO_x).

Table 85: Life cycle impacts for the driving behaviour option – petrol car

	Life cycle impacts compared to the base case (all figures are expressed relative to the base case value)					
	Production	Spare Parts	WTT	TTW	EOL	Total
AD	100	100	95.6			100
GWP	100	100	95.6	95.7	100	96.0
ODP	100	100	95.6			95.9
POCP	100	100	95.6	100	100	97.3
AP	100	100	95.6	99.9	100	97.0
EP	100	100	95.6	100	100	97.4
PM2.5	100	100	95.6			96.8
PE	100	100	95.6	95.6	100	96.1
BW	100	100	95.6		100	98.9

6.11.3.3. Direct costs

The cost of eco-driving has also been accurately examined by TNO et al.[148]. They refer to the costs of dedicated eco-driving lessons, government campaigns and also the costs of GSI devices. The costs of lessons are set at 100 Euro whereas the additional manufacturer costs of GSI are 15 Euro (22 Euro additional retail price). Knowing that these 115 Euro can result in 4.5% fuel consumption reductions in the long term (assuming duration of the effect of 25 years, see TNO et al.[148]), there is no doubt that eco-driving can be a cost effective means of cutting CO_2 emissions of passenger cars.

6.12. Shifting to smaller cars

As shown in Chapter 3, the car fleet in Europe has evolved over the last years towards bigger cars. Even more striking is the rapid penetration of bigger car models, including SUVs. According to ACEA data, the share of SUVs in new car sales suddenly increased from 2.5% in 1997 to 7.5% in 2005. This, of course, has consequences on the overall performance of the car fleet both because of the higher material requirements for car manufacturing and because of the higher energy use required per km driven. Therefore, car downsizing could also be envisaged as one of the options technically feasible to reduce the environmental impacts from cars. The most relevant shift which could be envisaged would consist of a substitution of a big car to a medium sized one.

In this project, the different aspects of such an option have not been analysed in detail. Several aspects should indeed be analysed in detail with a view to obtaining realistic potentials regarding the application and effects (economic, social and environmental) of this measure. The following information is primarily aimed at illustrating the environmental advantage of such an option, with a comparison of the environmental impacts related to the base case diesel car model (the diesel case was considered) and of a lower car category (with a cylinder in the range of 1 250 to 1 400 cm^3).

To this end, the car weight was assumed to be 20% lower than the base case (i.e. 1 170 kg instead of 1 463 kg initially). Regarding the TTW impacts, type approval data have been used.

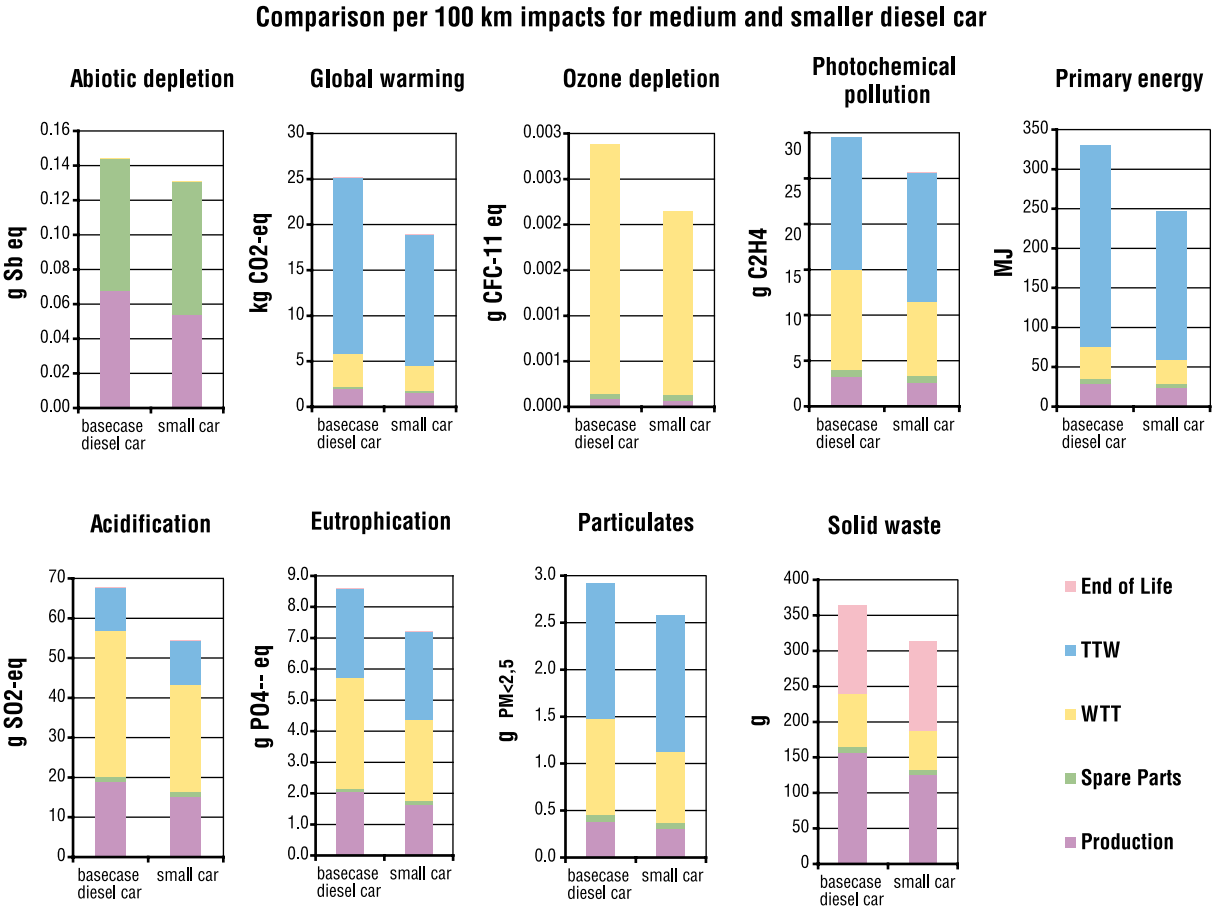
Table 86: Emission factors for smaller cars

		Engine capacity	CO_2	CO	$HC+NO_x$	HC	NO_x	PM
		cm^3	g/km					
Diesel cars	*Average*	1 280	122	0.17	0.220	0.019	0.201	0.018
	Min	1 248	109	0.05	0.165	0.010	0.145	0.002
	Max	1 399	148	0.32	0.280	0.060	0.240	0.023
	EURO4 emission limits			*0.50*	*0.300*		*0.250*	*0.025*

(1) EURO4 cars approved in UK (last update Dec 2005. http://www vcacarfueldata org uk/index asp)

In order to estimate the life cycle impacts of such a smaller car, the mileage was assumed to be the same as for the medium car. The impacts per 100 km are shown in Figure 49, when compared with the base case. These results show a reduction for all impact categories.

Figure 49: Environmental impacts of smaller cars compared to the base case (diesel car) according to life cycle phase per 100 km



The above comparison between a medium car and a smaller car should be complemented with a similar comparison including a SUV model. The recent study made by Ecolane[191] has shown that life cycle greenhouse gases and air pollutant emissions related to SUVs are higher than those from large family cars.

7. Overall assessment of the options and untapped potential

The groups of options (and sub-options) analysed in the previous chapter are listed in Table 87 with the main conclusions regarding the technological changes involved, the consumer change implied if any, the main barriers and the potential trade-offs identified.

Table 87: Summary of the improvement options assessed

Improvement option	Technological change	Consumer change	Barriers and benefits	Trade-off
1. Car weight reduction: • 5% reduction • 12% reduction • 30%reduction • Magnesium	High strength steel, aluminium Other (less promising): composites, magnesium	-	New investments in production lines; need for new safety and control equipment	More limitations for recycling (composites); impacts of production phase may increase and total life cycle impacts would highly depend on the actual car mileage
2. Car body and tyres • Aerodynamics • Tyres	Reducing the aerodynamic drag, low rolling resistance tyres (LRRT), tyre pressure monitoring system (TPMS)	-	Customer's desire for comfort; safety	-
3. Mobile air conditioning (MAC) • MAC imporvement • Efficient use of MAC	New refrigerants; leak tightness; recovery at servicing; better design of the cabin	Reducing cooling demand	-	-
4. Tailpipe air emission abatement systems • Air abatement option (I) (diesel car) • Air abatement option II (diesel and petrol car)	Engine management options (EGR); catalytic converters	-	Higher purchase costs and possible higher maintenance costs	Higher fuel consumption and CO_2 emissions; higher demand for PGM
5. Powertrain improvements	Various engine and transmission improvements	-	-	-
6. Hybrid cars	Micro hybrid; mild hybrid; full hybrid		Lack of information amongst the public; need for information regarding batteries	Could entail special development of recycling technologies (batteries)
7. Biofuels • Bioethanol • Biodiesel	First generation: biodiesel, bioethanol; second generation (Fischer-Tropsch synthesis)	-	Land availability; potential conflict with food supply	Land use and biodiversity; higher NO_x emissions
8. End-of-life vehicle recycling and recovery	To some extent design for dismantling and further dismantling post schredder technologies	-	Low value for waste plastics; dismantling is time consuming	Possible minor increase in GHG emissions for some recycling options
9. Speed control		Yes	Fewer accidents	-
10. Driving behaviour	Eco-driving behaviour assisted by gear shift indicator system (GSI)	Yes	Need eco-driving training; durability of effects of the training may vary a lot from one driver to the other; fewer accidents	-

In Table 88 and Table 89, the results regarding the different options analysed for the petrol car and diesel car have been summarised. The tables provide the total results for the different environmental categories first in absolute terms (per 100 km) and then as a percentage of the reference case. At the bottom of each table, the monetary value associated with the per 100 km impacts that are expected to be avoided by each option are given, together with the direct costs associated with the option. The improvement options analysed are ranked according to the time horizon frame in which they are assumed to be marketed.

All the options are shown to generate benefits regarding the majority of environmental impact categories. Four of the examined options are also expected to generate disbenefits for at least one of the impact categories. The main potential trade-offs suggested with these results concern the energy-related impacts (especially GHG) and waste (in the case of recycling/recovery, hybrid car, weight reduction option):

- **lightweight cars** are undoubtedly beneficial in reducing fuel consumption in the use phase. Depending on the weight reduction option, it is expected that the amount of waste due to the production phase will be increased along with increased PM emissions
- **hybrid cars** are shown to offer an overall high environmental performance. They may also entail particular problems resulting from the batteries used (NiMH). Definitive conclusions are, however, difficult to derive as only very few hybrid car models are currently marketed in Europe. The results derived in this project could not, however, be compared with similar detailed results from other studies. Further investigation would be needed regarding the available recycling technologies and also regarding the detailed characteristics (e.g. material breakdown, etc.) of the batteries
- **increasing recycling/recovery rates** have the benefit of significantly reducing ultimate waste (and landfilling). On the other hand, this is expected to generate very small increases in GHG emissions, acidifying substances and eutrophication. This, however, does not take into account the impacts that are potentially avoided by the substitution of primary fossil energy or raw material outside of the car system
- **in the case of biofuels**, as far as the first generation is concerned, additional eutrophication effects and slight PM emission increases are expected for the petrol car (using ethanol). Acidification is also expected to increase with biodiesel. Despite the fact that fossil fuel energy is reduced by using biofuel, it has to be stressed that primary energy is generally increased. On the other hand, the increased use of land entailed by biofuel production is not taken into account here. The second generation of biofuels was not analysed in this project. However, literature reports that such negative effects are not expected or likely to be significantly reduced.

In these different cases, it should be noted that there are many possible technological pathways which could not be singled out or quantified with a sufficient degree of detail. It cannot be excluded therefore that some of the particular pathways would lead to better environmental performance whereas some would entail worse performances than what these results suggest. There are also analytical gaps that entail uncertainties.

The various options have similar impacts (when compared with the reference) when comparing the diesel car and the petrol car. There are two main exceptions:

- the different improvements regarding the power train are shown to have higher potential and relative environmental benefit for the petrol car than for the diesel car
- when compared with the respective reference, the environmental benefit expected from air abatement systems is higher for the diesel car.

Table 88: Overview of the environmental benefits and costs associated with the different options (petrol car)

	Impacts normalised to a 100 km distance	Reference	2005				2010							2020	Car use efficiency		
			Weight reduction 5%	Weight reduction 12%	MAC improvement (HFC-134)	Hybrid car	Higher recovery / recycling rates	Bioethanol	Aerodynamics	Tyres	Weight reduction 30%	Power train improvements	Air abatement option I	Weight reduction Mg	Driving behaviour	Speed limitation	MAC efficient use
Absolute	AD (g Sb-eq)	0.149	0.148	0.147	0.149	0.082	0.149	0.149	0.149	0.149	0.143	0.149	0.149	0.143	0.149	0.149	0.149
	GWP (kg CO_2-eq)	26.6	25.8	25.0	26.4	20.8	26.6	24.5	26.2	25.5	22.5	21.4	26.6	24.9	25.5	26.2	26.4
	ODP (mg CFC-11-eq)	3.18	3.09	2.98	3.18	2.46	3.18	3.18	3.14	3.05	2.69	2.54	3.18	2.68	3.05	3.14	3.15
	POCP (g C_2H_4)	22.7	22.2*	21.7*	22.7	17.0	22.7	23.7	22.5*	22.1*	20.3*	19.7*	22.7	20.2*	22.1	22.3	22.6*
	AP (g SO_2-eq)	77.6	75.9*	74.7*	77.6	70.3	77.6	82.2	76.8*	75.2*	70.3*	66.1*	77.6	69.2*	75.2	76.8	77.0*
	EP (g PO_4-eq)	7.03	6.89	6.79	7.03	5.84	7.02	8.09	6.97	6.84	6.44	6.13	7.03	6.46	6.84	6.96	6.99
	PM2.5 (g)	1.86	1.82	1.88	1.86	1.64	1.86	1.86	1.84	1.80	1.90	1.57	1.86	1.83	1.80	1.84	1.85
	PE (MJ)	358.3	348.3	337.7	358.3	281.7	358.3	396.6	353.6	344.3	307.0	289.7	358.3	307.0	344.3	353.7	355.2
	BW (g)	403.1	392.9	416.6	403.1	420.7	308.5	403.1	401.7	398.7	436.9	381.2	403.1	408.2	398.7	401.7	402.2
	Aggegated impacts (Euro)	1.77	1.71	1.67	1.75	1.47	1.77	1.68	1.74	1.70	1.52	1.44	1.76	1.64	1.70	1.74	1.75

(*) For this option, the impact on TTW air emission levels was not quantified. One can expect some reduction

Relative (Reference = 100)	AD	100.0	99.2	98.4	100.0	55.1	100.0	100.0	100.0	100.0	96.0	100.0	100.0	95.6	100.0	100.0	100.0
	GWP	100.0	97.2	93.9	99.4	78.4	100.1	92.3	98.7	96.0	84.8	80.5	100.0	93.7	96.0	98.7	99.2
	ODP	100.0	97.2	93.7	100.0	77.2	100.0	100.0	98.6	95.9	84.4	79.7	100.0	84.3	95.9	98.6	99.1
	POCP	100.0	97.8	95.7	100.0	75.0	100.0	104.5	99.1	97.3	89.2	86.6	99.9	88.8	97.3	98.4	99.4
	AD	100.0	97.8	96.3	100.0	90.6	100.0	106.0	99.0	97.0	90.6	85.2	100.0	89.2	97.0	99.0	99.3
	EP	100.0	98.0	96.7	100.0	83.1	99.9	115.1	99.1	97.4	91.6	87.2	100.0	91.9	97.4	99.0	99.4
	PM2.5	100.0	97.8	100.8	100.0	88.0	100.0	100.0	98.9	96.8	102.1	84.3	100.0	98.1	96.8	99.0	99.3
	PE	100.0	97.2	94.3	100.0	78.6	100.0	110.7	98.7	96.1	85.7	80.9	100.0	85.7	96.1	98.7	99.1
	BW	100.0	97.5	103.3	100.0	104.3	77.0	100.0	99.6	98.9	108.4	94.6	100.0	101.2	98.9	99.6	99.8
	Aggregated impacts	100.0	97.1	94.4	99.3	83.1	100.0	95.3	98.5	96.0	86.3	81.5	99.7	92.7	96.0	98.5	99.0

94	lower than 95%
97	between 95% and 100%
101	higher than 100%

AD: Abiotic Depletion	POCP: Photochemical Pollution	PM2.5: Particulate Matters (<2.5 µ)
GWP: Global Warming Potential	AD: Acidification Potential	PE: Primary Energy
ODP: Ozone Depletion Potential	EU: Eutrophication Potential	BW: Bulk Watse

Avoided impacts (Euro)	0.05	0.10	0.01	0.30	0.00	0.08	0.03	0.07	0.24	0.33	0.00	0.13	0.07	0.03	0.02
Direct costs (Euro)	0.02	0.11	0.03	1.51	0.00	0.19	0.02	-0.01	0.59	0.30	0.03	0.59	-0.01	-0.02	-0.02

A comparison of the results for these two options illustrates the relevance of a life cycle approach. Although affecting one specific life cycle stage, options can reduce the impacts of other processes. In the case of the power train improvement options, a direct impact on GHG emissions is expected (although not quantified, some tailpipe air emission reductions can also be expected). Indirect positive impacts are also expected for the WTT part as less primary energy needs to be extracted and processed. This is not the case with air abatement options.

Table 89: Overview of the environmental benefits and costs associated with the different options (diesel car)

	Impacts normalised to a 100 km distance	Reference	2005			2010							2020			Car use efficiency		
			Weight reduction 5%	Weight reduction 12%	MAC improvement (HFC-134a)	Higher recovery/ recycling rates	Biodiesel	Aerodynamics	Tyres	Weight reduction 30%	Power train improvements	Air abatement option I	Air abatement option II	Hybrid car	Weight reduction Mg	Driving behaviour	Speed limitation	MAC efficient use
Absolute	AD (g Sb-eq)	0.145	0.143	0.142	0.145	0.145	0.145	0.145	0.145	0.138	0.145	0.145	0.145	0.077	0.138	0.145	0.145	0.145
	GWP (kg CO_2-eq)	25.2	24.4	23.6	25.0	25.2	23.3	24.9	24.2	21.1	21.5	25.2	25.2	18.0	23.6	24.2	24.6	25.0
	ODP (mg CFC-11-eq)	2.89	2.80	2.70	2.89	2.89	2.89	2.85	2.77	2.42	2.45	2.89	2.89	2.02	2.41	2.77	2.81	2.86
	POCP (g C_2H_4)	29.6	29.2*	28.8*	29.6	29.6	30.8	29.4*	29.1*	27.6*	27.8*	28.0	21.5	26.3	27.5*	29.1	28.4	29.5*
	AP (g SO_2-eq)	68.0	66.7*	66.1*	68.0	68.0	80.1	67.4*	66.4*	63.4*	62.0*	66.7	61.5	62.0	62.2*	66.4	66.2	67.6*
	EP (g PO_4-eq)	8.61	8.48	8.41	8.61	8.60	16.04	8.56	8.45	8.10	8.03	8.27	6.93	7.50	8.13	8.45	8.31	8.58
	$PM_{2.5}$ (g)	2.93	2.90	2.97	2.93	2.93	2.23	2.92	2.89	3.02	2.76	1.93	1.93	2.70	2.95	2.89	2.84	2.92
	PE (MJ)	331.0	321.3	311.1	331.0	331.0	354.9	326.7	318.1	281.3	283.2	331.0	331.0	237.5	281.5	318.1	322.6	328.2
	BW (g)	364.6	354.7	379.5	364.6	280.8	364.6	363.5	361.3	402.0	352.5	364.6	364.6	378.0	373.7	361.3	362.4	363.8
	Aggegated impacts (Euro)	1.75	1.70	1.66	1.74	1.75	1.70	1.73	1.69	1.52	1.53	1.70	1.64	1.41	1.64	1.69	1.70	1.74

(*) For this option, the impact on TTW air emission levels was not quantified. One can expect some reduction

Relative (Reference = 100)	AD	100	99.2	98.3	100	100	100	100	100	95.8	100	100	100	53.0	95.3	100	100	100
	GWP	100	97.0	93.6	99.5	100.1	92.4	98.7	96.1	83.9	85.3	100	100	71.5	93.8	96.1	97.5	99.2
	ODP	100	97.0	93.5	100	100	100	98.6	95.9	83.6	84.7	100	100	69.9	83.5	95.9	97.3	99.1
	POCP	100	98.6	97.3	100	100	103.9	99.5	98.4	93.4	94.0	94.5	72.7	88.9	93.0	98.4	95.8	99.6
	AD	100	98.1	97.3	100	100	117.9	99.2	97.6	93.2	91.3	98.1	90.5	91.2	91.6	97.6	97.4	99.5
	EP	100	98.5	97.6	100	99.9	186.3	99.4	98.2	94.1	93.3	96.1	80.5	87.1	94.4	98.2	96.6	99.6
	PM2.5	100	98.9	101.3	100	100	76.1	99.5	98.5	103.2	94.3	65.8	65.8	92.0	100.7	98.5	97.1	99.7
	PE	100	97.1	94.0	100	100	107.2	98.7	96.1	85.0	85.6	100	100	71.8	85.0	96.1	97.5	99.2
	BW	100	97.3	104.1	100	77.0	100	99.7	99.1	110.3	96.7	100	100	103.7	102.5	99.1	99.4	99.8
	monetarised aggregated impacts		97.2	94.6	99.4	100	97.2	98.7	96.4	86.9	87.3	97.1	93.8	80.2	93.7	96.4	97.0	99.1

94	lower than 95%
97	between 95% and 100%
101	higher than 100%

AD: Abiotic Depletion	POCP: Photochemical Pollution	PM2.5: Particulate Matters (<2.5 µ)
GWP: Global Warming Potential	AD: Acidification Potential	PE: Primary Energy
ODP: Ozone Depletion Potential	EU: Eutrophication Potential	BW: Bulk Watse

Avoided impacts (Euro)		0.05	0.09	0.01	0.00	0.05	0.02	0.06	0.23	0.22	0.05	0.11	0.35	0.11	0.06	0.05	0.02
Direct costs (Euro)		0.03	0.15	0.02	0.00	0.17	0.01	-0.01	0.77	0.22	0.36	0.45	1.21	0.77	-0.01	-0.04	-0.01

The results related to the different improvements of the power train (without hybrid) when compared with the hybrid case indicate that the latter would generate more environmental benefits. The actual gap between both types of power train improvements is, however, somewhat overestimated due to the fact that, in the first case, the possible improvements regarding air pollution from TTW (as a result of fuel saving) were neglected.

It should also be noted that the impacts on tailpipe air pollutant emissions – which are likely to be reduced – could not be quantified for other options (e.g. weight reduction, MAC, aerodynamics, tyres, driving behaviour, speed limits).

Besides the car efficiency options, those that would rely more on changes in driver behaviour are also shown to have environmental improvement potential. This is the case regarding eco-driving and speed limits.

As also noted earlier, parameters like the weight, the power or the car's volume all affect the life cycle's environmental impacts. These parameters are all subject to consumer decisions when a new car is purchased.

In terms of the overall environmental gain, the options with a very significant potential can be broadly distinguished from others where the benefits are of a lower magnitude. The first class is composed of the options where the energy use (and thus CO_2 emissions) from TTW (and indirectly from WTT) is substantially reduced.

Direct costs are displayed alongside the avoided environmental costs (as expressed by the monetary value of the different avoided environmental impacts) and are shown in Figure 50 and Figure 51. These figures provide an indication of the cost-effectiveness of the different options when compared to each other.

These figures should not be over-interpreted. The analysis made in Chapter 6 has largely shown the degree of uncertainty and variation to which the direct cost of the different options is subjected. Also, external costs are too highly uncertain for two main reasons :

- although assigning external costs to environmental damage is based on methods that have been extensively improved over the years, these can always be disputed and also their results highly depend on various assumptions and actual data
- external costs that could be estimated in this project do not cover all the estimated physical impacts. On the one hand, some physical impacts were omitted in the study because of lacking data and methods (eco-toxicity, land use). On the other hand, other impact categories could not be accounted for in the external cost calculations. This is the case for abiotic depletion and for energy resource depletion. In this last case, one proxy could have been the costs associated with energy supply security. For instance, in the framework of the review of the progress made in the use of biofuels, the IPTS[192] estimated that the maximum cost of energy security supply would be 0.097 Euro/litre fuel (about 3 Euro/GJ). If this value would have been used in this project, the resulting avoided costs would have been estimated to have been higher than what the figures show.

Therefore the main information that can be derived from these figures are the relative cost effectiveness of the options when compared with each other.

In terms of the overall environmental gain, the options with a very significant potential can be broadly distinguished from others that have benefits of a lower magnitude. The first class is composed of options where the energy use (and thus CO_2 emissions) from TTW (and indirectly from WTT) is substantially improved.

Generally, the higher the avoided environmental cost is, the higher the direct cost is. Some options are, however, suggested to be more cost-effective than others. The hybrid car is shown to be more costly than the other improvement options.

Options that are less reliant on technological changes such as driving behaviour are shown to be win-win options (see also speed limits and efficient use of MAC). The option reducing the rolling resistance of tyres is also shown to be a win-win option.

Figure 50: Avoided impacts and direct costs of the different improvement options per 100 km (petrol car)

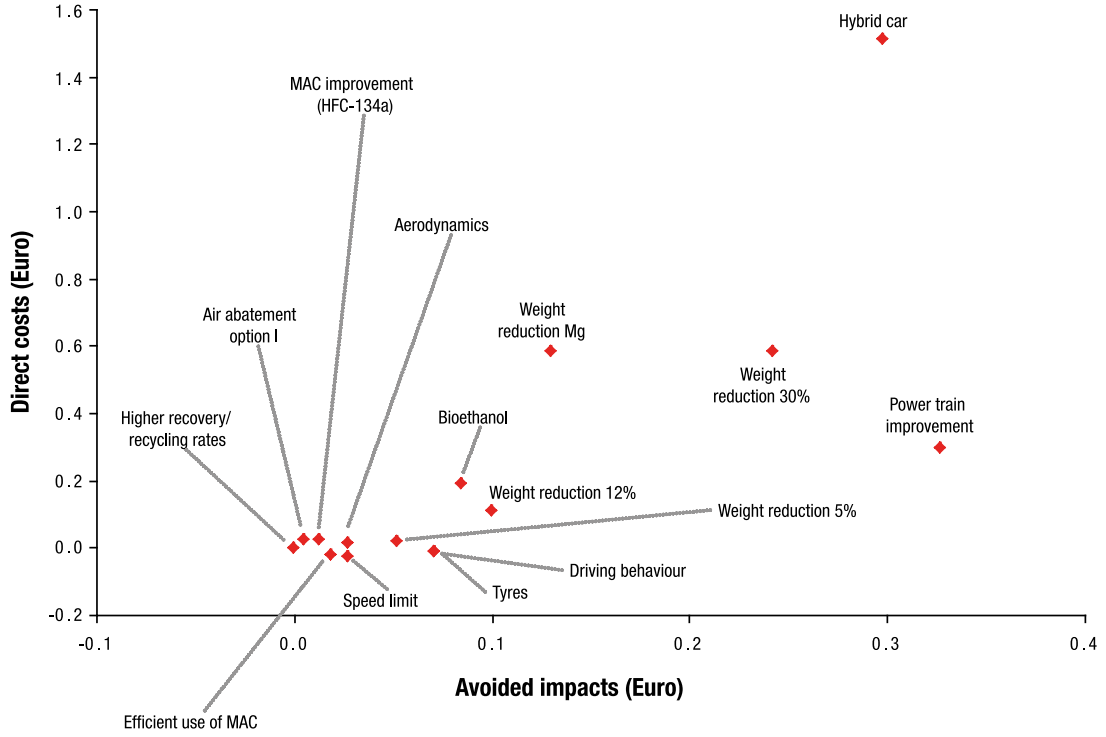
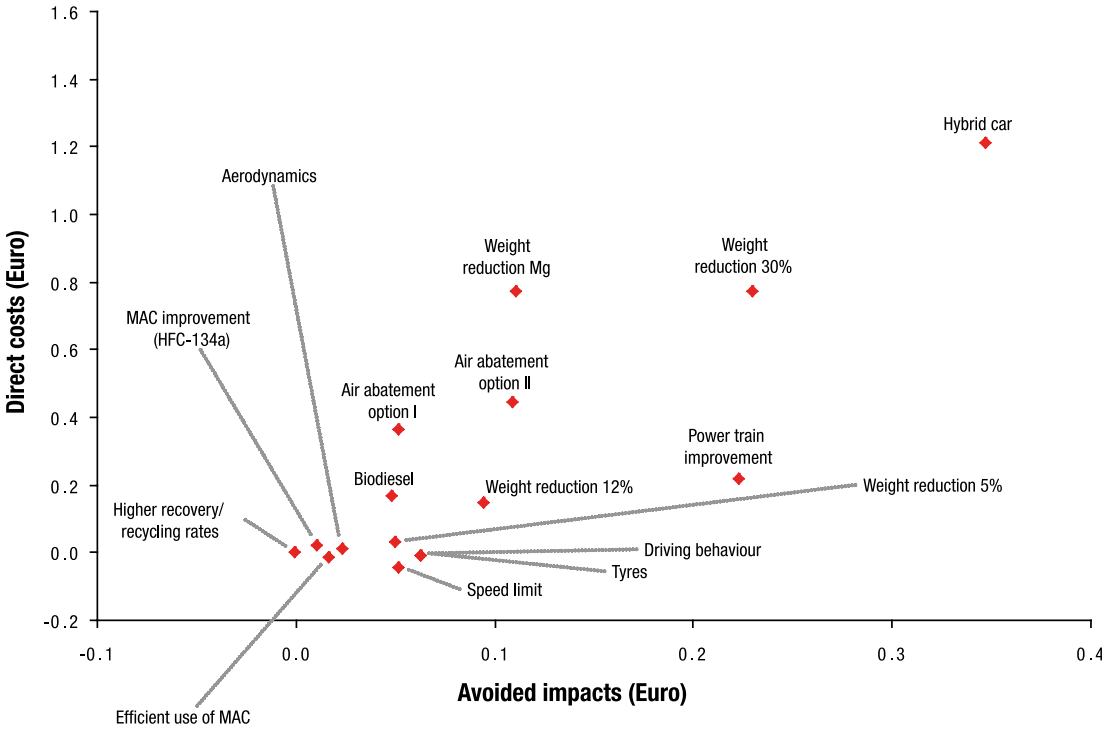


Figure 51: Avoided impacts and direct costs of the different improvement options per 100 km (diesel car)



The estimates made in this project illustrate substantial technical potential for the improvement of cars. In order to conclude in terms of untapped potential, the existing and the expected new environmental legislation on passenger cars has to be fully considered.

The European policy (and also the national policy) considers the environmental impacts from cars over the years and already addresses some of the important issues at different stages of a car's life cycle (e.g. air pollution, CO_2 emissions, end-of-life waste, batteries, etc.). This has already fostered substantial improvements (see for instance NO_x emission levels).

The new air pollution standards (EURO5 and EURO6) were adopted recently by the European Council and the European Parliament.

Further improvement potentials have recently been considered in the policy framework, giving rise to new proposed actions which, if adopted and implemented, will further exploit the identified technical potentials of cars. This concerns:

- the review of the Community strategy to reduce CO_2 emissions and improve fuel efficiency from passenger cars and light commercial vehicles and the impact assessment
- the proposal for a new Directive regarding the fuel quality and its impact assessment
- the report on the targets contained in the Directive on end-of-life vehicles and the impact assessment.

Table 90 provides an overview of the improvement options for cars with:

- an indication of the environmental benefit (as expressed in terms of the two reference cases)
- an indication regarding policies already in existence or expected new policies. Is this development likely to happen, either due to the autonomous development or due to legislation (or both), or can it be considered as one additional technical potential to be pushed by any policy action?

Overall, as can be seen from this table, a majority of the options considered in this project (either qualitatively or quantitatively) are considered in the policy framework. This policy framework is also evolving towards more ambitious targets, especially when considering two particularly important environmental challenges, namely greenhouse gas emissions and air pollution.

A regular assessment of the actual effect of these policies will, of course, answer the question of their success in fostering the technological progresses targeted.

In addition, the project did not analyse the potential impact of these different environmental improvement options when applied to the European car fleet. Some of them would have their effect only on the new car fleet and this effect would gradually increase over time due to the turn-over of the car fleet. Other options, if implemented, could help reducing the impacts of the overall car fleet immediately. For some of them, the actual effect is however highly depending on the consumer choice and the possible policies to support their implementation.

This factor indeed very much influences the evolution of the environmental effects of road transport and it is worth remembering that mobility is continuously growing simultaneously with a growing demand for more comfort and space in driven cars.

Table 90: Overview of the different improvement options in relation with the policy framework

Life cycle phase	Process	Option		Quantified	Level of coverage in EU legislation		Possible new challenge	Main analytical gap
					Existing	Possible further developments		
Production phase	Raw material mining	Improving process		No	IPPC, ETS, LCP, etc.	IPPC under review, ETS - second period		
	Material processing	Improving process		No	IPPC, ETS, LCP, etc.	IPPC under review, ETS - second period		
	Car design and assembling	Improving energy efficiency		No	IPPC, ETS, LCP, etc.	IPPC under review, ETS - second period		
		Improving the application of solvents, paints and adhesives		No	IPPC	IPPC under review, new BREF finalised		
		Design for better dismantling		No	EOL Directive (target 2006)	EOL Directive: assessment of target for 2015		
		Material substitution	Choosing recycled/renewable/recyclable/low environmental profile materials	No	EOL Directive (target 2006)	EOL Directive (target 2015?)	Growing contribution of plastics and new materials (composites) in new cars with a lower recycling potential	
			Optimising the design and choosing light materials	Yes	Directive EURO4; 2000/53/EC; EuroNCAP safety test	See new proposed measures for the CO_2 emission reduction strategy	Reduced recyclability: composites and alloys	Environemntal profiles for new materials (composites, etc.); dynamic effects (autonomous improvements) not captured in LCA
		Improving the car body aerodynamics		Yes		See new proposed measures for the CO_2 emission reduction strategy		
		Higher MAC efficiency	Improving the efficiency of climate control systems	Yes		See new proposed measures for the CO_2 emission reduction strategy		
			Substitute refrigerant	Yes		Directive 2006/40/EC on AC systems in motor vehicles		Little information on new fluids
Well-to-tank	Primary energy extraction	Improve the efficiency of the process		No	IPPC, ETS, LCP, etc.	IPPC under review; second period ETS		
	Fuel production	Improve the efficiency of the process	Improving the refinery process	No	IPPC, ETS, LCP, etc.	IPPC under review; second period ETS		Allocation problems in LCA
			Design the process for cleaner fuel production	No	Directive 2003/17/EC	?		
	Fuel distribution	Improving technical equipment for fuel distribution		No	Directive 2004/42/EC	EU regulation covering stage II vapour recovery of petrol?		
Use phase	Car driving	Reducing fuel consumption and air pollution from car driving	Emission control systems for current engines	Yes	EURO4, EURO5, EURO6		CO_2 penalty associated with some technologies; PGM related environmental impacts	
			More efficient power trains	Yes	Voluntary agreement with automitive industry (140 CO_2 g/km target)	See new proposed measures for the CO_2 emission reduction strategy (including a compulsory target to be achieved by motor vehicle technologies)		Environmental impacts from batteries (hybrids)
		Alternative fuels		Yes	Directive 2003/30/EC	EU Strategy on biofuels (COM(2006)34final; renewable energy road map (COM(2006)848: 10% target by 2020	Higher emission levels for some pollutants => selecting the most optimal routes?	High uncertainty on non CO_2 emissons (WTT and TTW, second generation); competition with other land uses; competition with other biomass energy uses; impossibility to capture the huge diversity in production pathways in one LCA estimate
				No				
		Properly inflate tyres		Yes		See new proposed measures for the CO_2 emission reduction strategy		
		Adapt speed vehicle		Yes	In some Member States	?		
		Driving behaviour		Yes		See new proposed measures for the CO_2 emission reduction strategy		
		Optimise use of air conditioning		Yes			?	Potential hard to assess (highly dependent on consumer behaviour)
	Worn spare parts disposal	Increase recovery and recycling of tyres		No	Directives 1999/31/EC; 2000/53/EC; 2000/76/EC			Limited data on tyres waste treatments; assumptions to be made on avoided impacts
		Increase recovery and recycling of batteries		No	EOL Directive; battery Directives		Batteries in hybrids?	Toxicity impacts would need to be included in a detailed assessment
		Increase recovery and recycling of lubricants		No	Directive 2000/76/EC about waste oils	?		Toxicity impacts would need to be included in a detailed assessment
End-of-life	Waste treatement	Increase recycling and recovery		Yes	EOL Directive (target 2006)	EOL Directive: assessment of target for 2015	Development of technological solutions needed	Limited data on plastic waste treatments; assumptions to be made on avoided impacts; large range of impacts making it difficult to derive any general conclusions; impossibility to capture the huge diversity of technical options and different plastics

8. Conclusions

The IMPRO-car project has primarily analysed the different technical options that could help in reducing the life cycle impacts from passenger cars used in the EU-25.

The analysis started with a life cycle assessment of two generic car models (petrol and diesel) from which characteristics were defined in such a way as to represent, as much as possible, the "average" car purchased in the EU-25. The two cars correspond to the "medium/large" segment of the car market.

Despite the sensitivity of estimates to some factors like the car weight, the mileage, etc., the following general conclusions can be unambiguously made:

Primary energy use and **GHG emissions** are dominated by the TTW part, followed by the WTT and production phases.

The size and breakdown of the other energy-related impacts, namely **photochemical oxidation, eutrophication and particles** differ from one case to the other. For the petrol car , the WTT part dominates, followed by the production phase, whereas, for the diesel car, the TTW part dominates, followed by the WTT part and the production phase.

The generation of **solid waste** is shared between the production, WTT and EOL phases. **Abiotic depletion** is dominated by production and spare parts (lead). Emissions of **ozone depleting substances** are suggested to be entirely dominated by WTT.

The analysis, also supported by other studies and data sets, indicates that, per 100 km driven, the petrol system is less environmentally friendly in respect to greenhouse gas emissions and primary energy. The diesel car was shown to be less environmental friendly regarding photochemical pollution, eutrophication and particulate matters. However, when considering the aggregated impacts as roughly estimated by assigning a monetary value, the two cars are suggested to perform similarly. What differs is the relative contribution of the different impact categories.

A comprehensive literature review led to the identification of the various improvement options that are currently or are expected to be technically available from between 2020 to 2030. The two car models subjected to life cycle assessments were used as benchmarks against which various improvement options were analysed. This led to the conclusions that most of the options technically feasible would result in increasing the car's performance regarding the majority of the environmental impact categories.

Some of them are expected to generate disbenefits for at least one of the impact categories and the main potential trade-offs suggested with these results concern the energy-related impacts (especially GHG) and waste (in the case of recycling/recovery, hybrid cars, the weight reduction option and biofuels).

Most of the options have similar impacts (when compared with the reference) when comparing the diesel car and the petrol car. The two main exceptions concern power trains of which the untapped potential is bigger for petrol cars and the air abatement systems which show a bigger potential for diesel cars.

Besides the car efficiency options, those that would rely more on changes in the driver behaviour are also shown to have environmental improvement potential. This is the case regarding eco-driving and speed limitation.

As noted earlier, parameters like the weight, the power or the car's volume all affect the life cycle's environmental impacts. These parameters are all subject to consumer decisions when a new car is purchased.

In terms of the overall environmental gain, the options with a very significant potential can be broadly distinguished from others where the benefits are of a lower magnitude. The first class is composed of the options where the energy use (and thus CO_2 emissions) from TTW (and indirectly from WTT) is substantially reduced.

Generally, the higher the avoided environmental cost is, the higher the direct cost is. Some options are, however, suggested to be more cost-effective than others. The hybrid car is shown to be more costly than the other improvement options, per unit of avoided environmental cost. Options that are less reliant on technological changes such as driving behaviour are shown to be win-win options (see also speed limits and efficient use of MAC). The option reducing the rolling resistance of tyres is also shown to be a win-win option.

Overall, a majority of the options considered in this project (either qualitatively or quantitatively) are considered in the policy framework which is also evolving towards more ambitious targets, especially when considering two particularly important environmental challenges, namely greenhouse gas emissions and air pollution. A regular assessment of the actual effect of these policies will of course answer the question of their success in fostering the technological progress targeted.

On the other hand, the project did not analyse the potential impact of these different environmental improvement options when applied to the European car fleet. Some of them show their effects only on the new car fleet and these effects would gradually increase over time due to the turn-over of the car fleet. Other options, if implemented, could help reduce the impacts of the overall car fleet immediately. For some of them, the actual effect is, however, highly dependent on consumer choice and the possible policies to support their implementation. This factor does indeed highly influence the evolution of the environmental effects of road transport and it is worth remembering that mobility is continuously increasing.

9. Appendix I – Methodological aspects

9.1. Characterisation factors for photochemical pollution

9.1.1. Introduction

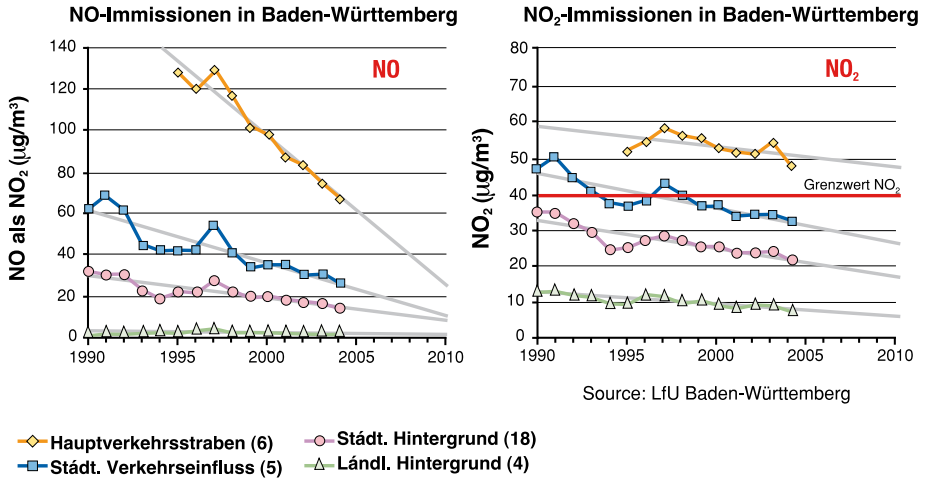
Photochemical pollution refers to ozone formation that takes place when volatile organic compounds (VOCs) and carbon monoxide (CO), released into the atmosphere, are degraded, and during their reaction with nitrogen oxides (NO_X), initiated by sunlight, form ozone.

Nitrogen oxides are not consumed during ozone formation, but have a catalyst-like function. The reactions take place in the troposphere, the lower 8 - 12 km of the atmosphere, where they are the primary source of ozone. Due to its high reactivity, ozone attacks organic substances present in plants and animals or materials exposed to air. This leads to an increased frequency of humans with problems in the respiratory tract during periods of photochemical smog in cities, and where the troposphere concentration of ozone is increasing, it may cause stress to vegetation leading to substantial losses in agricultural yields.

So far, LCA characterisation methods have considered characterisation factors for NMVOC and CO but no factor was considered for NO_X. The role of NO_X was considered with a simple approach distinguishing two types of factors, respectively applicable for low and for high background levels of NO_X.

In 2004, road transportation in the EU-15 was responsible for 3 859 kt NO_X, namely 42% of the EU-15's total emissions. This means that the transport sector itself determines, to a large extent, the background level of NO_X. It should also be noted, that while the concentrations of ambient NO_X are on a downward trend (see Figure 52), concentrations of NO_2 have often been static or even rising. The development of ambient NO_2 concentrations as observed near roadsides can be explained by an increasing contribution of direct emissions of NO_2 specifically from diesel-powered vehicles. Instead of a 5% share of NO_2 in the emitted NO_X typically assumed in standard atmospheric pollution models, modern diesel cars can be as high as 30% to 80%[df]. Considering the approach commonly applied in an LCA, this would thus represent a serious flaw in a life cycle analysis for transport.

Figure 52: Evolution of the concentrations of NO and NO2 measured in Germany



Source: Schindler[dg]

df EU level workshop on the impact of direct emissions of NO_2 from road vehicles on NO_2 concentrations, Brussels, 19 September 2006, Summary meeting notes.

dg Schindler K.P. (VW), 2006, LDV technology: state of the art and anticipated developments, presentation during the EU level workshop on the impact of direct emissions of NO_2 from road vehicles on NO_2 concentrations, Brussels, 19 Sept 2006.

The air quality measurements made over the last few years in different European countries also show that the concentrations of NO (which acts as a destructor of O_3) are declining, whereas concentrations of NO_2 (which is a precursor of ozone) are kept almost constant.

The chemical reactions involved in the formation of ozone are extremely complex and actually involve many different substances and the overall balance of production and destruction of ozone is highly non-linear.

Some recent studies are however relevant when attempting to adapt the current approach to make it more relevant for such a transport study:

- the approach proposed by Hauschild et al. (2006)[dh] to better reflect the spatial differentiation in the characterisation of photochemical ozone formation
- the proposal made by Labouze et al. (2004)[di] for a new set of characterisation factors for different gas species on the scale of western Europe
- the TOFP indicator proposed by de Leeuw (2001)[dj] and used in the TREMOVE model.

The different values proposed in these three studies will now be described along with the derivation of a set of characterisation factors which were used in this project.

9.1.2. Relevant indicators

Ozone is a very reactive molecule and when it is present at certain concentration levels in the lower layer of the troposphere it induces damage to human health, to animals and to vegetation.[dk]

Each of these effects are characterised by different thresholds above which the risk becomes significant. These are defined in Directive 92/72/EEC: AOTx is an accumulated value given in ppb.hours and is calculated over a certain period of time as the sum of the exceedance of the ozone concentration above x ppb for daylight hours (from 8h00 to 20h00).

These thresholds are as follows :

- **vegetation** exposure to photochemical ozone is generally characterised by the accumulated exposure to ozone above threshold (AOT40), which is the accumulated dose over a threshold of 40 ppb
- **human** exposure to photochemical ozone is generally characterised by the accumulated exposure to ozone above threshold (AOT60), which is the accumulated dose over a threshold of 60 ppb. This threshold is considered in relation to chronic effects. AOT90 is used to characterise shorter term effects.

Effects induced during peak episodes are not considered here as they depend even more on the site location and weather conditions.

dh Hauschild M. Z., Potting J., Hertel O., Scöpp W., Bastrup-Birk A., 2006, Spatial Differentiation in the Characterisation of Photochemical Ozone Formation, International Journal on LCA, **11**, Special issue 1, pp 72 - 80.

di Labouze E., Honoré C., Moulay L., Couffignal B., Beekmann M., 2004, Photochemical Ozone Creation Potentials – A new set of characterization factors for different gas species on the scale of Western Europe.

dj De Leeuw F.A.A.M.,, 2001, A set of emission indicators for the long-range transboundary air pollution, Environmental Science and Policy 5 (135 – 145).

dk It is also worth noting that higher average ozone concentrations in the troposphere contribute to climate change. It is, however, not possible to take account of this effect in this study.

9.1.3. Comparison of different values

The CML method proposes two sets of coefficients for low and high background NO_X levels.

Labouze et al.[114] have implemented a chemistry-transport numerical model (CHIMERE-continental) to calculate POCP. They derive spatially and temporally averaged values for POCPs on western Europe. Table 91 displays the factors derived for impacts on vegetation and long term impacts. An average of these two sets of values is also given.

For $NO_{X,}$ they conclude an a significant spatial variability over western Europe: for some areas, the POCP values are negative, especially in the high emission regions in northwest Europe. "There, additional $NO_{X,}$ emissions lead to smaller ozone peak values indeed, mainly because NO_2 inhibits ozone production by trapping the OH radical (Sillman 1999, Honoré 2000). This effect is comparatively less pronounced over the Po valley, where radiation and thus radical production is larger than over North-western Europe. In the emission poor regions in the southern part of the model domain, POCP values above 100 are frequently calculated"[114]. The average values, even for $NO_{X,}$ are however positive.

Table 91: Average POCP derived by Labouze et al.[114]

Pollutant	Cumulated over period considered		Average of threshold based values	
	Impact on vegetation	Long term impact on health	Central value	Range variation (%)
	POCP AOT 40	POCP AOT 60		
CO	0,019	0,023	0,02	10
CH_4				
TOTVOC	0,27	0,32	0,30	8
NOx	0,59	0,66	0,63	6
C_2H_4	1	1	1,00	0
C_2H_6	0,033	0,048	0,04	19
NC_4H_{10}	0,15	0,19	0,17	12
C_3H_6	0,75	0,82	0,79	4
C_5H_8	0,33	0,39	0,36	8
APINEN	0,11	0,15	0,13	15
Oxyl	0,53	0,59	0,56	5
HCHO	0,43	0,4	0,42	4
CH_3CHO	0,11	0,2	0,16	29
CH_3OE	0,14	0,17	0,16	10

Hauschild et al.[113] have used the European RAINS model to calculate site-dependent characterisation factors for NMVOC and NO_X for 41 countries or regions within Europe. Compared to the midpoint characterisation modelling, the approach is spatially resolved and comprises a larger part of the cause-effect chain, including exposure assessment and exceeding of threshold values. They derive site-dependent and site-generic characterisation factors for the exposure of vegetation and human beings.

The analysis concludes that few countries have negative characterisation factors for ozone exposure of human beings for 2010.

The average values are given in Table 92, for CO, methane, total VOC and NO_X, for 1995 and for 2010.

Table 92: Averaged POCP derived by Hauschild et al.[113]

Pollutant	Vegetation (cumulative exposure above 40 ppb) m^2*ppm*hours/g subst emitted				Health (based on cumulative exposure above 60 ppb) pers*ppm*hours/g subst emitted			
	1995		2010		1995		2010	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
CO	0.73	1.21	0.61	1.02	0.00006	0.00013	0.00008	0.00014
CH_4								
TOTVOC	0.73	1.21	0.61	1.02	0.00006	0.00013	0.00008	0.00014
NOx	1.76	2.87	1.63	2.26	0.00012	0.00027	0.00011	0.00023

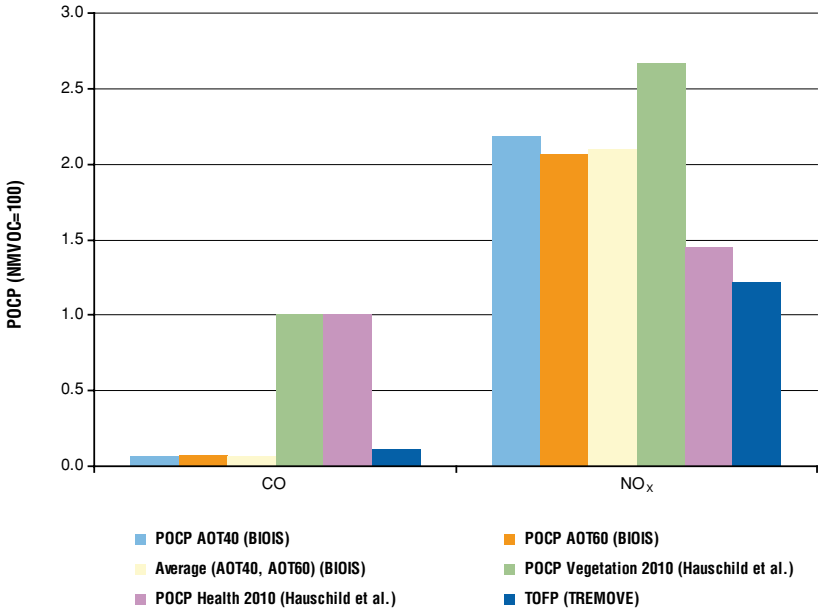
De Leeuw[115] proposed a set of indicators to measure the long range transboundary pollution. Regarding tropospheric ozone, the indicator proposed is the tropospheric ozone formation potentials (TOFP). By definition, the TOFP is set to 1 for NMVOC. The values assigned for the other substances involved are given in Table 93.

Table 93: TOFP values according to de Leeuw[115]

Pollutant	TOFP (NMVOC-eq)
CO	0.11
CH_4	0.014
TOTVOC	1
NO_x	1.22

The three sets of coefficients are compared in Figure 53. The comparison is, however, only possible for CO and NO_x and they are presented through the POCP expressed as NMVOC equivalent.

Figure 53: Comparison of POCP in Labouze et al., Hauschild et al. and de Leeuw



This comparison shows that, when expressed in terms of NMVOC POCP value, Hauschild et al. provides values for CO that are much higher than by using the TOFP and than those suggested by Labouze et al.

The values for NO_x values are less divergent in the same range, although still show a large range. Labouze et al. values (40, 60 and average) somehow in the middle of what Hauschild et al. suggest for vegetation and human health. The TOFP values are lower.

9.1.4. Conclusions for the project

Using Labouze et al. values (the mean between vegetation and human health) would not lead to important differences compared with what Hauschild et al. suggest. Using Hauschild et al. values in this project would add complexity because they are not straightforwardly applicable for producing midpoint indicators. The values provided by Labouze et al. were considered and POCP factors corresponding to the average of the values suggested for vegetation and health were apllied (respectively based on AOT60 and AOT40 thresholds) (see Table 94).

Table 94: POCP values for the project

pollutant	Central value (C_2H_4-eq)
CO	0.0210
CH_4	0.0041
TOTVOC	0.2950
NO_x	0.6250

9.2. Direct costs of the improvement options

The way the net present value of the life cycle costs incurred by the new option as compared with the base case is discussed here.

For this purpose the following terminology is used:

- subscript * denotes new costs associated with the new option
- *j* denotes one year j between the initial investment and the last year (LIFE)
- *I, I** stand for the initial investments
- *W, W** stand for the waste treatment costs at the end of life
- *E, E** = annual energy use
- p_j= energy price in year j
- *b, t* and *l* stand for battery, tyres, and lubricants respectively
- CY_i, CY_i* stand for annual costs for spare part *i (b. t, l)*: if the cost of one battery is *C*, then an annual cost should be computed on the basis of the annual mileage of the car *(MY)* and average mileage driven with one battery (M_b), i.e. CY = C/M*MY
- discount rate *d* (4%).

The net present value of the life cycle cost changes is composed of four main components:

1. Investment change ΔI:

$$\Delta I = I^* - I$$

2. Net present value of fuel cost change (*NPV(fcs)*):

$$NPV(fcs) = \sum_{j=1}^{LIFE} \frac{p_j (E^* - E)}{(1+d)^j}$$

3. Net present value of cost changes in spare parts *i*

$$NPV(sp) = \sum_i \sum_j^{LIFE} \left(\frac{CY_i^* - CY_i}{(1+d)^j} \right)$$

4. Net present value of cost changes for waste treatment:

$$NPV(EoL) = \frac{(W^* - W)}{(1+d)^{LIFE}}$$

The net present value (NPV) is then the sum of these four components considering a 4% discount rate.

In this study, the retail and transportation margins are added to the manufacturing costs to evaluate the final retail price (excluding taxes). In particular, a factor of 1.16 is assumed for the ratio between retail prices and manufacturing costs.

9.3. External costs

External costs are defined as those costs, arising from an economic or more in general human activity, which are borned by individuals and society without being paid or compensated for. The following information details external costs associated with environmental damage, which are known as negative externalities and which correspond to the economic value assigned to an environmental damage deriving from an economic activity which is not included in the market price of its output as a private cost. Considering the full life cycle of a product, such damage covers damage to human health, flora and fauna, ecosystems and materials.

A lot of research effort has been dedicated to the development of methodologies and to the quantification of environmental externalities, through a series of projects financed by the European Commission, and especially the ExternE project (DG Research). This particular project focused on the externalities of energy production and consumption.

ExternE introduced the impact pathway approach, modelling the long chain from polluting substance releases to the different physical damage impacts (covering as much as possible mortality, morbidity, loss of crop production, natural species, material damage). These physical impacts are then valued in monetary terms by using the results from contingent valuation studies, complemented, in some cases with other approaches.

The ExternE method produces "marginal" costs, meaning that the euros assigned to a unit of pollutant correspond to the additional impacts generated by such an additional emission unit. The ExternE methodology and results have been and are still being further developed in the framework of different projects (NewExt, ExternE-Pol, NEEDS, and EXIOPOL).

Due to the focus of the project (energy) and also due to missing information and the difficulty in quantifying some impacts (biodiversity for instance), the ExternE project may present some limitations when seeking to apply its results to the IMPRO project framework.

Other proposed values found in literature have been considered by this project with a view to complementing or updating some of the values proposed by ExternE. In the study done by O2 France and BIOIS in 2003[193] different existing studies (including ExternE) were reviewed in order to derive coefficients covering more types of impact categories. An additional advantage is that the concluding table of coefficients – and uncertainty ranges – fits very well with the impact categories considered here.

The ExternE method[dl] and subsequent developments have produced site-dependent estimates for external costs related to energy use (e.g. in electricity production, in transport), following the pathway impact approach and using studies that haved investigate the willingness-to-pay (WTP) method to monetary value damages such as life loss, increased morbidity, crop damage, ecosystems. The physical damage is estimated on the basis of dose-response functions relating the quantity of a pollutant released to the environment with its damage to the final receptors.

The ExternE results have been used in the CAFÉ programme in order to analyse the costs and benefits of air pollution reduction in EU-25[dm]. The method followed in the CAFÉ programme when calculating external costs[dn],[do] are referred to below. In the methodological note prepared by AEA Technology (2005), damage per ton of emissions is provided per country, and also for the EU-25.

Health impacts, and more specifically mortality, can be measured by different methods. One main aspect is the use of either the value of life year (VOLY) or the value of statistical life (VSL). In addition, the median or the mean for those key values can be used, giving different results. Another parameter considered for the sensitivity analysis is also the assumption regarding the threshold of pollutant concentration: for ozone it is generally admitted that health impacts below 35 ppb are negligible although it seems that such a threshold does not exist for PM2.5.

Impacts considered in the values used in CAFÉ were:

- health impacts related to ground-level ozone (excluding high pollution peaks), aerosols (secondary, associated with SO_2, NO_X) and particulates (PM2.5). These two impacts have been proven to be the dominant ones for air pollution
- impacts on crops as a result of ozone (ozone is recognised as the most serious regional air pollution problem for agriculture in Europe
- impacts on forest biodiversity.

dl EC Commission (DG Research), 2005, ExternE – Externalities of Energy, Methodology 2005 update (EUR21951).

dm EC Commission, 2005, Commission Staff working paper – Annex to The Communication on Thematic Strategy Air Pollution and the Directive on "Ambient Air Quality and Cleaner Air for Europe, Impact assessment (SEC(2005)1133).

dn AEA Technology Environment, 2005, Methodology for Cost-benefit analysis for CAFÉ – Volume 1, Overview of methodology (service contract for carrying out Cost-Benefit analysis of air quality related issues, in particular in the Clean Air for Europe (CAFÉ) Programme.

do AEA Technology Environment, 2005, Damages per ton of PM2.5, NH_3, SO_2, NO_X and VOCs from each EU25 Member State (excluding Cyprus) and surrounding seas (service contract for carrying out Cost-Benefit analysis of air quality related issues, in particular in the Clean Air for Europe (CAFÉ) Programme.

The estimates regarding these two last impacts are however much more incomplete.

The substances considered were :

- greenhouse gases
- particles (PM10, PM2.5)
- SO_2
- NO_x
- VOC
- CO
- PAH
- As, Cd, Cr-VI, Ni
- Hg, Pb.

Table 95 provides the average damage as used in the CAFÉ programme, considering a cut-point of 35 ppb for ozone impacts. In the three last columns ranges for the different values were derived based on the extreme values from CAFÉ. The central value is the average of these two extremes.

Table 95: Average damage as used in the CAFÉ programme and in this report

EU-25 average	Estimates reported in AEA Technology				Values for this report*		
	Median VSL and VOLY		Mean VSL and VOLY		Min	Central value	Max
	35 ppb threshold		no threshold				
NH3	11	16	21	31	11	13.5	16
NOX	4.4	6.6	8.2	12	4.4	5.5	6.6
PM2.5	26	40	51	75	51	63	75
SO2	5.6	8.7	11	16	5.6	7.15	8.7
VOC	0.95	1.4	2.1	2.8	0.95	1.175	1.4

** For PM2.5, 35 ppb threshold excluded. Others: 35 ppb ozone threshold assumed*

** For PM2.5, 35 ppb threshold excluded. Others: 35 ppb ozone threshold assumed*

The ExternE project also suggested monetary values for CO_2 emissions. A lower value of 9 Euro/t CO_2 was proposed along with a 50 Euro/t CO_2 upper value. A 19 Euro/t CO_2 central value was suggested, which was based on the current estimates of avoidance costs for reaching the broadly accepted Kyoto aim. For this project, values derived from ExternE were primariliy used.

Regarding the effects of POCP and PM, the average values derived in Table 95 were used for the individual substances covered and these values were extended to the other substances involved in the same impact category, by multiplying the nominal monetary factor with the characterisation factor.

Regarding acidification and eutrophication, the values selected by the O2 France/BIOIS study were included based on existing studies about external costs. The selected values were 5.25 Euro/kg PO_4-eq for eutrophication and 2.68 Euro/kg SO_2-eq for acidification.

For climate change, more recent indications were considered both regarding mitigation and regarding the likely impacts from climate change. Although proposing a 19 Euro/t CO_2 value (based on the avoidance costs for reaching the broadly accepted Kyoto aim) the ExternE report also recognises that "there is a

tendency to strive for higher goals than the Kyoto ones". The current discussions about post 2012 targets clearly admit the need to implement much more stringent emission values in the future. This is guided by the fact that avoiding major climate change impacts may require stabilising the CO_2-eq concentration at levels lower than 550 ppmv. This will make the avoidance costs of CO_2 much higher than 20 Euro/ton CO_2. The impact assessment made by the Commissions concerning its Commission's communication about "Limiting Global Climate Change to 2 degrees Celsius" (COM(2007)2), estimates that, in 2020, the world average carbon price of carbon will be 31 Euro/t CO_2 and 65 Euro/t CO_2 in 2030 (and this will be for all sectors and all regions of the world) under a scenario where global emissions go back to a level 8% higher than 1990 levels[dp].

There are more and more scientific indications that the scale of impacts from climate change and also the likelihood of abrupt changes have been underestimated in previous studies. This is supporting the use of higher values than those applied so far. In a recent review about the question of social costs of climate change, Downing et al.[dq] concluded that 50 Euro/t C (14 Euro/t CO_2) is the likely lower value for the social cost of carbon (SCC). It is much more difficult to assign a value to the upper level, however, 350 Euro/t C (95 Euro/t CO_2) could be reasonable. A survey made from different studies suggests that there is a 5% probability of exceeding this threshold, if abrupt changes like the breakdown of thermohaline circulation, high climate sensitivities are considered[dr].

A "central" value is difficult to assign. Based on the above considerations, it is suggested that 50 Euro/t CO_2 is considered. This value remains lower than what was suggested in the Stern report[194], namely that, in the hypothesis of a business as usual emissions trajectory, the current social cost of carbon might be around 85 USD/t CO_2 (year 2000 prices). The values used in this project are summarised in Table 96:

Table 96: Monetary values used for the different classes of substances

Impact category	Reference	Minimum	Central value	Maximum	Source
		Euro/kg	Euro/kg	Euro/kg	
Climate change	CO_2-eq	0.01	0.05	0.10	IPTS proposal based on the Downing report and longer term avoidance costs
Acidfication	SO_2-eq	0.11	2.68	5.25	O2 France/BIOS
Eutrophication	PO_4-eq		4.70		O2 France/BIOS
POCP*	C_2H_4-eq	4.63	5.79	6.95	Impact assessment CAFÉ programme (based on ExternE)
PM2.5	PM2.5	26.00	33.00	40.00	Impact assessment CAFÉ programme (based on WHO studies)

** The values are derived from the values estimated for NO_x and using a characterization factor of 0.95 for NO_x*

Some impact categories were excluded from the above comparison because they were not considered in each of the options considered. One of these categories is waste: the BIOIS study about ELVs uses a value for waste (bulk waste) which estimates the per kg waste disamenity impacts. The value proposed is in a range of 0.004 Euro/kg waste to 0.019 Euro/kg waste. These values were proposed in the IMPRO projects.

dp Under such a scenario, there is a 50% probability that global temperatures would be stabilised to 2 °C above the pre-industrial temperature.
dq Downing T.E et al, 2005, Social cost of carbon: a closer look at Uncertainty (for Defra, UK)
dr In addition, most of the studies do not consider effects such as low probability events, social contingent effects.

9.4. Selection of relevant socio-economic criteria

Table 97: Social impacts and relevance for this project

Social impacts	Relevance of the critera groups (Is the group of criteria of any relevance with regards the topic dealt with?)	Relevance for the technical option (The question is whether we can anticipate any impacts associated with the implementation of the technical option, whatever the policy supporting the achievement of the technical potential.)	Likely relevance of importance (When the criteria is beforehand relevant for technical option assessment, which degree of relevance can we expect in this specific case)	Comment
Employment and labour markets	Y			
Does the option facilitate new job creation?		N		
Does it lead directly to a loss of jobs?		N		
Does it have specific negative consequences for particular professions, groups of workers, or self-employed persons?		N		
Does it affect the demand for labour?		N		
Does it have an impact on the functioning of the labour market?		N		
Standards and rights related to job quality	N			
Social inclusion and protection of particular groups	N			
Equality of treatment and opportunities, non-discrimination	N			
Private and family life, personal data	N			
Governance, participation, good administration, access to justice, media and ethics	N			
Public health and safety	Y			
Does the option affect the health and safety of individuals/ populations, including life expectancy, mortality and morbidity, through impacts on the socio-economic environment (e.g. working environment, income, education, occupation, nutrition)?		Y	High	see environmental impacts
Does the option increase or decrease the likelihood of bioterrorism?		N		
Does the option increase or decrease the likelihood of health risks due to substances harmful to the natural environment?		Y	High	see environmental impacts
Does it affect health due to changes in the amount of noise or air, water or soil quality in populated areas?		Y	Medium	see environmental impacts
Will it affect health due to changes energy use and/or waste disposal?		Y	High	see environmental impacts
Does the option affect lifestyle-related determinants of health such as use of tobacco, alcohol, or physical activity?		N		
Are there specific effects on particular risk groups (determined by age, gender, disability, social group, mobility, region, etc.)?		N		
Crime, terrorism and security	N			
Access to and effects on social protection, health and educational systems	N			

10. Appendix II – Life Cycle assessment results

10.1. Primary energy resources

Almost the entire LC primary energy resources uptake is related to the TTW phase. The remaining part is consumed within the petrol system in the following processes:

- primary energy resources in the WTT phase are consumed in the form of electricity and other types of energy for the refinery process and the distribution of the fuel
- the production phase consumes primary energy indirectly through the use of steel, aluminium and plastics, and directly for assembling purposes
- spare parts production consume energy mostly for the production of synthetic rubber and carbon black used for the manufacturing of tyres
- primary energy consumed in the EOL is barely visible.

The credit associated with the metals recovery and recycling when compared with the total primary energy consumption is not significant and it is mainly related to aluminium recycling.

The primary energy uptake per 100 km for the diesel system is lower than for the petrol one because of the TTW lower energy use.

10.1.2. Global warming

The emissions of different greenhouse gases by the life cycle phases for the **petrol car system** are shown in Table 98. The largest fraction consists of CO_2 and is mainly emitted during the TTW phase, followed by the WTT.

Table 98: Percentage contribution by substances emitted in the different phases on the total GWP impact (petrol car)

Substances	Production	Spare parts	WTT	TTW
Carbon dioxide	4.5	0.4	12.3	76.2
Methane	0.1	--	0.9	--
HFC-134a	--	--	--	2
Remaining substances	3	0.3	--	--
Total	**8**	**1**	**13**	**78**

As CO_2 emissions result from fuel use, the pattern for GHG emissions is, to a large extent, similar to what we observed for primary energy. The relatively low contribution from the production phase mainly stems from the energy consumption during the assembling phase and from the production of basic materials such as polypropylene and steel (see Table 99). When compared with a pure virgin metal scenario, the CO_2-eq avoided emissions are mainly achieved with the recycling of aluminium and steel.

Table 99: Percentage contribution to the GWP impact deriving from the processes involved in the different phases (petrol car)

Processes	%	Phases
TTW	78	TTW
Energy in refinery	6	WTT
Electricity	1	Production
Energy in manufacturing	1	Production
Polypropylene	1	Production
Steel	0.4	Production
Remaining processes	13	

The impact on global warming deriving from the diesel system follows the same pattern as in the petrol one. The GHG emissions per 100 km are slightly lower, again as a result of lower per 100 TTW emissions.

10.1.3. Acidification

Impacts on acidification mostly depend on substances emitted during the extraction and transportation of crude oil as well as production of unleaded petrol (WTT).

The emissions of SO_2-eq during the production of materials used in cars and its components depend, to a large extent, on the zinc coating process for the body in white. Spare parts production has a negligible contribution on this category. Table 100 displays the processes that mostly contribute to the overall impact on acidification.

Table 100: Percentage contribution to the acidification impact resulting from the processes involved in the different phases

Processes	%	Phases
Energy in crude extr.	23	WTT
Energy in refinery	12	WTT
Zinc	8	Production
Palladium	7	WTT
Transportation	7	WTT
Platinum	3	Production
TTW	2	TTW
Rhodium	2	Production
Polypropylene	1	Production
Palladium	1	Production
Remaining processes	32	

Amongst the different acidifying substances emitted, SO_2 is the one emitted in the largest amount (see Table 101) and mainly from the WTT phase. Emissions of SO_2 occurring during the production phase are also significant. Significant amounts of NO_x and ammonia are emitted in the WTT and in the production phase respectively.

Table 101: Percentage contribution by substances emitted in the different phases on the total AP impact

Substances	Production	Spare parts	WTT	TTW
Sulphur dioxide	15	1.1	60.5	--
Ammonia	9	--	--	--
Nitrogen oxides	2.8	0.4	9	2.2
Remaining substances	--	--	0.1	--
Total	**27**	**1**	**70**	**2**

The impact on acidification in the case of the diesel car presents some substantial differences. In particular, the WTT phase is suggested to emit less per 100 km than the petrol car. This is however largely influenced by the allocation principle adopted for assigning WTT emissions the different co-products.

On the other hand, due to the higher NO_x emissions per driven km characterizing the Diesel system, the TTW phase is much higher than that in the petrol system. The contribution of the TTW phase on the overall acidification impact for the diesel system is 16%.

10.1.4. Particles

For the **petrol car system**, most of the estimated emissions of PM2.5 are attributed to the WTT phase and depend on the energy use in crude oil extraction and refinery process and, to a lower extent, on the transportation of crude oil, as indicated in Table 102. The impacts related to the production phase mainly depend on iron ore extraction and zinc production.

Table 102: Percentage contribution to the PM2.5 impact deriving from the processes involved in the different phases

Processes	%	Phases
Energy in refinery	26	WTT
Energy in crude extr.	23	WTT
Transportation	5	WTT
Iron ore	3	Production
Zinc	3	Production
Remaining processes	44	

The impact on this category estimated for the **diesel system** is substantially higher than for petrol and this difference depends on the emissions occurring during the TTW phase. The overall PM2.5 emissions in the diesel system amount to 7 kg and the TTW contributes with 50%.

10.1.5. Eutrophication

The largest contribution to eutrophication stems from ammonia, NO_x and COD (see Table 103).

Table 103: Percentage contribution by substances emitted in the different phases on the total EP impact

Substances	Production	Spare parts	WTT	TTW
Ammonia	21.6	--	--	--
Nitrogen oxides	8.1	0.7	25.6	6.1
Phosphate	0.7	--	--	--
COD	0.7	0.7	32	--
Nitrate	0.7	--	--	--
Remaining substances	1.3	--	2	0.1
Total	**33**	**1**	**60**	**6**

The WTT phase, especially for the extraction of crude oil and its transportation, together with the production phase are responsible for significant contributions. The production phase contribution largely stems from the zinc coating process (see Table 104).

Table 104: Percentage contribution to the eutrophication impact deriving from the processes involved in the different phases

Processes	%	Phases
Crude extraction	26	WTT
Zinc	19	Production
Transportation	7	WTT
Energy in crude extr.	7	WTT
TTW	6	TTW
Remaining processes	36	

The diesel car system differs from the petrol system regarding the WTT and TTW phases. Regarding the TTW part, this is due to higher NO_x emissions. In that case, the contribution of the TTW phase to the overall eutrophication is about 33%.

10.1.6. Ozone depletion

The impact on ozone depletion estimated for the petrol car is mostly due to the emissions occurring during the extraction of the crude oil, as shown in Table 105 and Table 106.

Table 105: Percentage contribution to ozone depletion deriving from the processes involved in the different phases

Processes	%	Phases
Crude extraction	94	WTT
Transportation	1.5	Production
Chlorine mercury cell	0.3	Production
Remaining processes	4.6	

Table 106: Percentage contribution by substances emitted in the different phases on the total ODP impact

Substances	Production	Spare parts	WTT	TTW
Methane bromo chloro difluoro-Halon1211	1.5	--	--	--
Methane bromo trifluoro-Halon1301	1.5	1.5	88.1	--
Remaining substances	--	--	7.4	--
Total	**3**	**1.5**	**95.5**	**--**

The diesel system does not present relevant differences in this category.

10.1.7. Photo-oxidant formation

As shown in Table 107, the largest contributions for the petrol car result from WTT and mainly depend on energy used for crude oil extraction, transportation and the refinery process. The emissions occurring during palladium production represent a substantial part of the WTT overall impact. A substantial contribution results from the TTW phase. The production phase mainly contributes emissions directly related to the production of polypropylene and steel.

Table 107: Percentage contribution to the 'Photochemical oxidation' impact deriving from the processes involved in the different phases

Processes	%	Phases
Energy in crude extr.	25	WTT
TTW	19	TTW
Energy in refinery	10	WTT
Transportation	6	WTT
Refinery	3	WTT
Transportation	3	Production
Steel	2	Production
Polypropylene	2	Production
Remaining processes	31	

Table 108 displays the compounds emitted in largest amounts in the different phases of the system. The compounds that contribute the most are NO_x emitted during the WTT, the TTW and the production phases.

Table 108: Percentage contribution by substances emitted in the different phases on the total POCP impact

Substances	Production	Spare parts	WTT	TTW
Nitrogen oxides	11.7	1.6	58	16.3
Carbon monoxide	1	2.4	--	0.4
Pentane	0.1	--	--	--
Remaining substances	1.2	--	5	2.3
Total	**14**	**4**	**63**	**19**

The diesel system has an overall POCP impact much higher than the petrol one depending on the TTW phase and the related emissions of NO_x that contribute 50% of the overall impact.

10.1.8. Bulk waste

This category includes the amount of solid non-hazardous wastes produced during the different life cycle stages. The highest amounts are produced during the production phase and they derive mainly from the steel production and the refinery process (see Table 109).

Table 109: Percentage contribution to bulk waste deriving from the processes involved in the different phases

Processes	%	Phases
Steel	27	Production
Fuel distribution	14	WTT
Refinery	12	WTT
Remaining processes	46	

Solid non-hazardous wastes produced in the diesel system have almost the same pattern as the petrol one. The differences stem from the production phase, as the diesel car has a slightly different material composition, and to some extent from the WTT phase (higher in the petrol system) because of the allocation criteria adopted in the Ecoinvent database, which are value-based and attribute a larger share of the total environmental impact deriving from the refinery process to the petrol's supply chain.

10.1.9. Abiotic depletion

Table 110 shows the consumption of resources other than primary energy. This environmental impact category is almost entirely dominated by the production phase and the spare part production. Lead used in batteries determines the largest part of the impact on this category. The rest is due to zinc consumption for coating the body in white, copper for electronic components and precious metals from the catalyst.

Table 110: Percentage contribution to the abiotic depletion impact deriving from the processes involved in the different phases

Processes	%	Phases
Lead	56	Spare parts
Zinc	28	Production
Copper	6	Production
Lead	6	Production
Rhodium	2	Production
Remaining processes	3	

Table 111 shows the type and amounts of resources used by the different life cycle phases.

Table 111: Percentage contribution by substances emitted in the different phases on the total AD impact

Substances	Production	Spare parts	WTT	TTW
Lead ore	2.8	55.4	0.1	--
Zinc ore	24.9	--	--	--
Copper ore	5.5	--	--	--
Rhodium ore	2.8	--	--	--
Remaining substances	8.3	--	0.2	--
Total	**44.3**	**55.4**	**0.3**	**--**

The diesel system has a larger impact on this category because of the slightly different material composition and use assumed for the two car types.

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11. Appendix III – Glossary

ABS	Acrylonitrile Butadiene Styrene
AC	Air Conditioning
ACEA	European Automobile Manufacturers' Association
AD	Abiotic Depletion
AMT	Automated Manual Transmission
AP	Acidification Potential
ASR	Automotive Shredder Residue
ASF	Automotive Shredder Fuel
ATF	Authorised Treatment Facility
BAT	Best Available Techniques
BOF	Blast Oxygen Furnace
BREF	Best Available Techniques Reference Document
BTL	Biomass-to-Liquid
BTX	Benzene, Toluene, Xylene
BW	Bulk waste (solid waste)
CAI	Controlled Auto Ignition
COD	Chemical Oxygen Demand
CVT	Continuous Variable Transmission
CVVT	Continuous Variable Valve Timing
DDGS	Dried Distillers Grains with Solubles
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
DVR	Deutscher Verkehrssicherheitsrat e.V. (German Road Safety Council)
EAF	Electric Arc Furnace
ECE	European Test Cycle (UN Economic Commission for Europe)
EF	Emission Factor
EGR	Exhaust Gas Recirculation
ELV	End-of-life Vehicles
EOL	End-of-life
EP	Eutrophication Potential
ETS	Emissions Trading Scheme
EUDC	Extra Urban Driving Cycle

EU19+2	When referring to TREMOVE results, means all EU-25 Member States except Malta, Cyprus, Slovakia, Estonia, Lithuania and Latvia plus two non-EU countries (Norway and Switzerland)
FC	Fuel Consumption
FDC	Fixed Displacement Compressor
FFV	Flexi-Fuel-Vehicle
GDI	Gasoline Direct Injection
GHG	Greenhouse Gas
GSI	Gear Shift Indicator System
GWP	Global Warming Potential
HC	Hydrocarbons
HCCI	Homogeneous Charge Compression Injection
HDPE	High Density Polyethylene
HEV	Hybrid Electric Vehicle
HFC	Hydrofluorocarbon
HPDC	High Pressure Die Casting
HSS	High Strength Steel
HVAC	Heating, Ventilation and Air Conditioning
ICE	Internal Combustion Engine
IPP	Integrated Product Policy
IPPC	Integrated Pollution Prevention and Control
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCP	Large Combustion Plant
LNC	Lean NO_x Catalyst
LNT	Lean NO_x Trap
LPG	Liquefied Petroleum Gas
LRRT	Low Rolling Resistance Tyres
MAC	Mobile Air Conditioning
NEDC	New European Driving Cycle
NiMH	Nickel Metal Hydride
NMVOC	Non-Methane Volatile Organic Compound
ODP	Ozone Depletion Potential
PA	Polyamide
PAH	Polycyclic Aromatic Hydrocarbon
PCB	Polychlorinated Byphenyl
PDF	Probability Density Function
PE	Polyethylene

PE	Primary Energy
PET	Polyethylene Terephtalate
PFC	Perfluorocarbon
PGM	Platinum Group Metals
pkm	Passenger kilometre
PM	Particulate Matter
PM2.5	Particulate Matter below 2.5 µm diameter
PM10	Particulate Matter below 10 µm diameter
POCP	Photochemical Oxidation Potential
PP	Polypropylene
ppm	Parts per million
PST	Post-shredder Treatment
PU	Polyurethane
PVC	Polyvinyl Chloride
SCR	Selective Catalytic Reduction
STT	Stop and Start System
SUV	Sport Utility Vehicle
SWG	Stakeholder Working Group
TEWI	Total Equivalent Warming Impact
TOFP	Tropospheric Ozone Formation Potential
TPMS	Tyre Pressure Monitoring System
TTW	Tank-to-wheel
TWC	Three-way Catalyst
VDC	Variable Displacement Compressor
vkm	Vehicle kilometre
VOC	Volatile Organic Compounds
VOLY	Value Of Life Year
VSL	Value of Statistical Life
VTEC	Variable Valve Timing and Lift Electronic Control
VVC	Variable Valve Control
VVEL	Variable Valve Event and Lift
VVT	Variable Valve Timing
VVTi	Variable Valve Timing with Intelligence
WTP	Willingness-to-pay
WTT	Well-to-tank

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European Commission

EUR 23038 EN – Joint Research Centre – Institute for Prospective Technological Studies

Title: Environmental Improvement of Passenger Cars (IMPRO-car)

Authors: Françoise NEMRY, Guillaume LEDUC, Ignazio MONGELLI, Andreas UIHLEIN

Luxembourg: Office for Official Publications of the European Communities
2008

EUR – Scientific and Technical Research series ; ISSN 1018-5593

ISBN 978-92-79-07694-7

DOI 10.2791/63451

Abstract

This report on "Environmental improvement potential of passenger cars" is the second scientific JRC's contribution to the European Commission's Integrated Product Policy framework which seeks to minimise the environmental degradation caused the life cycle of products. A previous study coordinated by the JRC (EIPRO study) had shown that private transport is responsible for 20% to 30% of the environmental impact of private consumption in the EU.

This report presents a systematic overview of the life cycle of cars, from cradle to crave. It also provides a comprehensive analysis of the technical improvement options that could be achieved in each stage of a car's life cycle and which could be marketed within the next two decades. The report assesses the different options, their environmental benefits, their cost-effectiveness, their trade-offs, and the socio-economic barriers that these options would have to face.

The report has focused on the technical improvements related to the design of cars, such as the reduction of weight, improvement of the power train, reduction of rolling resistance of tyres. It also analyses improvements that rely on the driver's behaviour as speed control and eco-driving. The report examines each of the options taking into account the technical potential, the existing legislation and policy developments, and the barriers and drivers for the implementation of the different options.

The study presents the consequences that the adoption of these options might have on the environment such as global warming, generation of solid waste, acidification, energy consumption, etc. The study has also quantified the costs associated with the different options were implemented.

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Environmental Improvement of Passenger Cars (IMPRO-car)

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LF-NA-23038-EN-C

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ISBN 978-92-79-07694-7