Identification of the main environmental challenges in a sustainability perspective for the automobile industry

Master of Science Thesis in the Master Programme, Industrial Ecology

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Abstract

The aim of this master thesis is to identify and describe the type and extent of the environmental concerns attributed to the automobile sector. It is carried out as part of a project that aims to suggest a method for measuring and evaluating the environmental performance of companies by setting relevant and sector specific sustainability criteria. The automobile manufacturing industry has been selected as an example in that project and is the focus of this work as well.

The methodology used consists of a combination of assessment tools and frameworks for identification, classification and evaluation of environmental impacts. The life cycle approach represents the first step of the method together with a framework which suggests four principles for a sustainable society. Then three classification categories are derived (emissions, land and biodiversity disturbances, and use of resources) and all data collected are assigned and classified according to them. The last step consists of the implementation of two ready-made weighting methods in order to prioritise the results and finally suggest the main ones.

The overall results show that the greatest environmental challenge for the automobile sector is the *depletion of non-renewable resources* and in particular crude oil. The vast majority of oil is used during the utilization phase of the car in order for the lifetime energy demands to be covered. In addition, a variety of air pollutants such as carbon monoxide, nitrogen oxides, hydrocarbons but mainly *carbon dioxide* are emitted to the environment through the combustion of gasoline or diesel fuel contributing to significant impacts such as climate change, acidification, eutrophication etc. but also to respiratory and other effects on human health. Among the rest of the studied life cycle stages, raw material acquisition and processing is the second most important contributor to the impacts mentioned above. However, in terms of material efficiency it is shown that the sector has a reduced environmental impact in particular when it comes to the recycling of metals. Greater efforts should be made for plastic and other newly developed materials in order to reduce the waste stream and increase recycling possibilities.

Consequently, there are different improvement options for the automobile industry that can compensate the environmental challenges identified in this study. Alternative fuel options can lead to energy and resource savings as well as emission reductions during the use phase. Substitution of heavier materials with lighter ones can improve fuel and material economy. And finally, increased recycling possibilities can lead to material and energy recovery but also to waste reduction. However, all alternatives should be further evaluated in a sustainability and life cycle perspective to measure the overall savings and also ensure that they are not introducing new problems for the sector.

Preface

This work has been carried out as a thesis for the Degree of Master of Science in Industrial Ecology, at the department of Energy and Environment at Chalmers University of Technology and more specifically at the division of Physical Resource Theory.

The main goal is to identify and describe the environmental effects attributed to the automobile sector as part of a project that aims to suggest a method for measuring and evaluating the environmental performance of companies. This project is carried out by several universities including the Department of Energy and Environment at Chalmers University of Technology and the Department of Psychology at the University of Gothenburg.

Supervisor and examiner of this work is Ulrika Lundqvist, senior lecturer and head of division of Physical Resource Theory.

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1 Introduction

1.1 Background information

This master thesis is part of a project that aims to suggest a method for measuring and evaluating the environmental performance of companies. The project is carried out by several institutions and research organizations including the Department of Energy and Environment at Chalmers University of Technology and the Department of Psychology at the University of Gothenburg. The objective of the project is to introduce a different evaluation method than the ones implemented so far by setting relevant and sector specific sustainability criteria.

Most evaluation processes that are examined for the purposes of the project are characterized by a circular relationship between the interested parties of the society as illustrated in the following figure. The company under evaluation, institutional investors and rating agencies are the three main organizations involved [1].

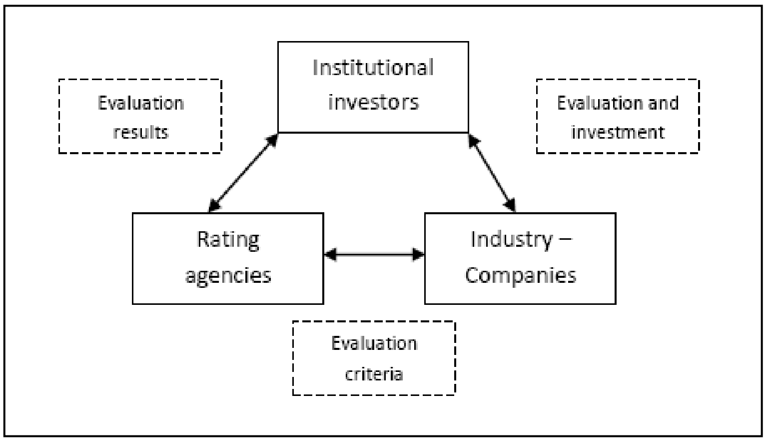

Figure 1.1: The relationship between industry, rating agencies and investors during evaluation and financing processes.

Institutional investors are organizations that have significant monetary capital which is invested in companies or other institutions within an industrial sector. The financial criteria that used to drive funding processes are more and more turning into sustainability evaluation criteria measuring the performance of the company. These criteria include not only economic but environmental and social aspects as well. Therefore, the term *sustainable investment* is used when describing the funding process that aims to provide more efficient and environmentally friendly solutions [2].

In a time when environmental concerns are pressing almost every industrial sector for more radical changes, institutional investors are trying to identify those concerns among the activities connected to the company by collecting information about their environmental performance before any formal decision for investment is established.

This assessment of the environmental performance of a company is made by external organizations, the *sustainability rating agencies* that work exclusively with the evaluation and rating processes and focus on environmental and social issues. They can also have an advisory role to the investors and the companies and in some cases sustainability analysis organizations can provide financial evaluation and consultation as well [3].

Information collection during the evaluation process can be based on meetings with representatives of the company and questionnaires that are sent out to the employees attempting to cover all hierarchic levels. Most of the rating agencies have established internal assessing criteria used as a baseline to estimate a company's behaviour. For this reason, there is a variation between the methods and indicators that different agencies use during their investigation and evaluation process. 'Exclusion' and 'best practice' comparison lists are often met as evaluation methods as well [3].

Although those methods are not easily available to the public, it was shown in an earlier study that environmental relevant and specific to the sector criteria are not always used [1]. Therefore, the performance and rating score of a company may differ between the results of different rating agencies. It is also shown in the same study that the rating agencies examined, (through their assessing criteria) manage to identify and assign with relevant convergence impacts of high importance to a specific sector; however, their conclusions are not the same for those of medium or lower significance [1]. This basically explains the need for improvements and changes to the way those methods have been implemented so far.

As already mentioned this thesis is part of a project that aims to improve the existing assessment methods by suggesting sector specific evaluation criteria. For this reason the focus is mainly on two industrial sectors, the automobile and forestry and paper industry. Both business sectors are responsible for a number of damages caused to the environment although they seem to affect different parts of the natural ecosystem (damage on resources for the automobile's case and land occupation for the paper for example).

Consequently, to suggest relevant evaluation criteria for these two industries, initially there is a need to identify the environmental challenges that the sectors have to face. Then, the derived challenges need to be evaluated in order to propose the main concerns of the sector. These first steps towards a complete evaluation method are the objectives of this study.

1.2 Aim and objectives

In this master thesis the automobile manufacturing industry will be further analysed as an attempt to have an overall picture of the sector before setting any specific evaluation criteria. Using a life cycle approach the objectives of the study are to identify and describe:

- the relevant methods existing for identifying main environmental challenges for an industrial sector
- the type and extent of the environmental impact for the suggested industrial sector using qualitative but also quantitative data whenever this is possible
- the environmental impacts that should be mainly considered in a sustainability perspective

1.3 Thesis outline

Having already given an introduction to the concept and objectives of this study, *Chapter 2* gives a presentation of the methodology used in order to derive the answers to the issues raised above. Information regarding data collection and literature research processes are also included in this chapter together with a section referring to the necessary assumptions and limitations taken into consideration.

Before the presentation of the results there is a general introduction to the automobile sector in *Chapter 3* including both qualitative and quantitative information. Furthermore, there is a brief overview of the environmental concerns attributed to the automobile sector and an introduction to the basic European legislation measures that have been under implementation in order to compensate those environmental effects. This chapter ends by describing briefly the life cycle stages and activities that are included later in the inventory process and are connected to the sector.

Chapter 4 presents the results of this study in different sections divided according to the classification categories defined in the methodology. Furthermore, by applying two ready-made weighting methods to the inventory results, the most significant environmental impacts during the whole life cycle of the studied sector are obtained.

A discussion on the derived results and the methods used is included in *Chapter 5* where some main advantages, disadvantages and limitations are mentioned. Additionally, improvement practices that can compensate those results are briefly discussed throughout the chapter as well.

Finally, *Chapter 6* presents and summarises in brief the main findings in correlation to the objectives of this study.

2 Methodology

2.1 Environmental impacts identification and evaluation

2.1.1 Life cycle analysis

The purpose of the study as stated in the previous chapter is to identify the main environmental impacts of the automobile sector within a life cycle and sustainability perspective. For this reason life cycle thinking is used in order to include all relevant activities of the sector that can have a significant impact on the environment. Life cycle analysis takes into consideration all different stages that can be identified during a product's life cycle starting from material acquisition until the end-of-life processes [4]. Within a broader perspective and having as a functional unit the final product (vehicle) this method is used in order to evaluate the environmental performance of automobile industry as a whole. The different stages identified during the products life cycle include the activities taking place before and during the manufacturing processes as well as during the product's utilization phase and end-of- life treatment processes [4-6].

To be able to incorporate properly the life cycle analysis in this study the automobile sector was divided in four major stages or *"roles of the industry"* [7,8] in an attempt to include all relevant activities mentioned above. These roles are listed below and will be briefly analysed in the following paragraph:

- The sector as a purchaser of resources and services
- The sector as a resource converter
- The sector as a supplier
- The sector as a communicator and exchanger of information

The industrial process of vehicle manufacturing begins with the acquisition of raw materials that will comprise the final product. There is great variety of materials needed (metals, plastics, glass etc.) most of which are not produced within the sector. Energy and other services provided to the sector are also included as part of this stage. Consequently the automobile industry can be described as a *purchaser of resources and services* reflecting to the first stages of the vehicles life cycle. This role refers to the interactions and relationships between the sector and its suppliers and includes material extraction and processing outside the sector as well as every other resource demand. Every industry has the ability to increase or decrease its impact on the environment according to the choice of raw materials and suppliers.

The next role includes the activities taking place inside the manufacturing plant in order to derive the final product. The company converts the incoming resources and materials according to the final purpose (product). As a *resource converter* the sector can also influence its environmental performance by controlling the manufacturing processes in order to become more energy and material efficient, the amount of polluting emissions reaching the environment and the disposed waste.

After the completion of all manufacturing stages the product will be released in the market. The sector as a *supplier* in this step is responsible for the environmental performance and attributes (like fuel economy or recyclability) of the final product. This part of the life cycle includes both the use phase of a vehicle and the end-of-life treatment processes.

Finally, a sector can be described as a *communicator and exchanger of information***.** This role refers mainly to all internal activities for the development and sustainability of the company as for example internal education and training programs, advertisement and more. Although this role can also affect the environmental performance of the sector, it is not included in this study as it does not represent an individual part of the life cycle and does not include direct material or energy flows either.

Figure 2.1 is a simplified illustration of the different steps that can be identified during the life cycle of a vehicle according to the conventional life cycle assessment model [5,6]. The arrows in the figure represent the flow of materials and other resources from one step to the other. Energy inflows exist in every step therefore they are presented once covering all life cycle stages. The presentation of more complex and detailed processes would not be relevant with the purpose of this study and therefore they are not included.

Transportation processes are also excluded in this figure even if they exist. Many data used later in this study include estimation of transportation of materials and products but it was not possible to separate the actual contribution of these activities.

Emissions resulting during the different processes are not shown in the figure below but they will be covered later in the study in quantitative terms together with energy flows since their estimation is essential for the identification of the environmental impacts.

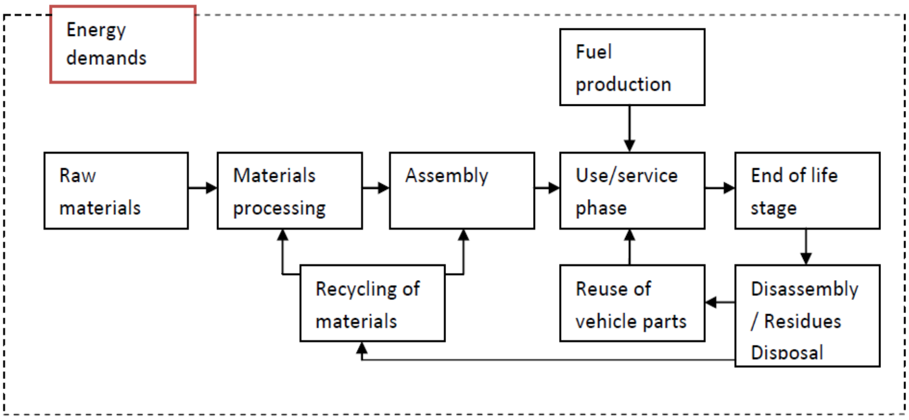

Figure 2.1: A simplified illustration of a passenger car's life cycle [5,6]

2.1.2 Impact classification according to principles for sustainability

In addition to the life cycle approach another method is used in order to classify and indicate the effect of the studied industrial sector on the environment. This method is based on a framework which describes the relationships between the societal activities and the natural environment taking also into consideration sustainability constraints such as availability of resources, assimilation capacity of the ecosystem and availability of land [9,10].

According to this framework there are four general principles for a sustainable society [9,10]

1. *'Substances extracted from lithosphere must not systematically accumulate in the ecosphere.'*
2. *'Society – produced substances must not systematically accumulate in the ecosphere.'*
3. *'The physical conditions for production and diversity within the ecosphere must not systematically be deteriorated.'*
4. *'The use of resources must be efficient and just with respect to meeting human needs.'*

Based on the principles shown above, three classification categories are derived and they will be considered in this study during the inventory process:

- Emissions of polluting substances (principle 1&2)
- Land and biodiversity disturbances (principle 3)
- Efficient use of resources (principle 4)

The first two principles referring to emissions of substances to the environment during extraction of materials as well as during several production processes in the society, are added together in order to represent the first classification category used in this study since they both refer to emitted substances. Land and biodiversity disturbances derived from the third principle, represent the second classification category. Finally efficient use of resources leading to waste minimization and resource prevention refer to the fourth principle and are also included as a separate category during the inventory and analysis process.

By implementing this method for the three different life cycle stages mentioned in the previous section, quantitative data regarding emissions, energy use, consumption of minerals and waste flows are assigned to every activity separately. Consequently, the contribution of the sector to the environmental and societal constraints is identified.

2.1.3 Implementation example

During the inventory process all relevant and mainly quantitative information are collected in a table like the one shown in the example below. The columns of the table represent the life cycle stages of the industrial sector as they are defined in section 2.1.1 while the rows include all factors that could have a significant effect on the environment classified according to the principles and constraints for sustainability mentioned in section 2.1.2.

This structure provides an overall picture of the automobiles industry where all impacts are possible to be classified and assigned to the different life cycle stages. Furthermore, the last column consists of a sum of the different contributors which makes it possible to compare and evaluate the impacts.

Table 2.1: Example of implementation of the methods used in this study

Sustainability indicators	**Measurements**	**Life cycle stages of the company**			**Total**
		Purchaser of resources and services (materials acquisition)	**Resource converter (manufacturing and assembly)**	**Supplier (Utilisation and disposal)**	
Principles 1 and 2	Emissions to air				(kg/car)
	Emissions to water				(kg/car)
Principle 3	Land/Biodiversity				(mostly qualitative data)
Principle 4	Energy needs				(GJ/car)
	Consumption of resources				(kg/car)
	Waste (landfill)				(kg/car)
	Recycling rates				(% rate)

2.1.4 Weighting methods selected for the study

One common way to estimate and analyse the significance of the different environmental impacts is by using a valuation or weighting method [4]. There are several ready-made weighting methods available in the literature and the selection of the most suitable one depends on the purpose of each study [4].

However, the implementation process is often the same. Specific weighting factors are assigned to the environmental loads identified during the inventory analysis and after aggregation of the derived results a total index is obtained. Then, the contribution of the different impacts and measurements to the obtained index can determine the most significant environmental effect. Figure 2.2 illustrates this process by presenting the major steps included. The dashed line indicates that the step of impact characterisation can be excluded and the final damage categories and index can be derived directly [4,11].

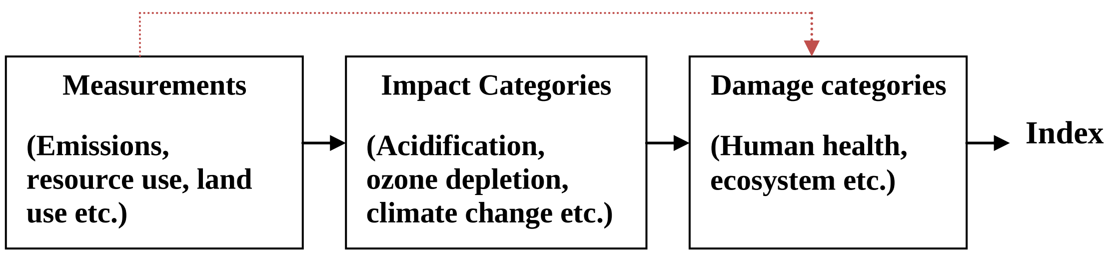

Figure 2.2: The three main steps involved during the weighting process [4,11]

It is important to mention though, that every weighting method prioritise and value the impact on the environment and society in a different way. Consequently, the weighting factors and the final outcome may vary substantially according to the method implemented even for the same study [4,12].

In this thesis two weighting methods are used. The first one is the Eco-Indicator 99 and the second is the EPS 2000. Both methods are based on average European conditions for the establishment of the weighting values but the impact categories included are slightly different. Furthermore, the Eco-Indicator method use the *"distance to target"* principle for determining the weighting values while the EPS method is a monetisation method based on the *"willingness to pay"* [4,12-14]. In brief, distance to target methods relate the weighting factors to a target or problem that has to be solved while monetisation methods rely on the willingness to pay for compensating the damage on the environment, society or any other aspect considered [12-14].

The three major damage categories considered for the Eco-Indicator method are: *human health*, *ecosystem's quality* and *use of resources* which constitute of several impact categories as listed in table 2.2 [13]. Three weighting options are available in this method: the individualist, the egalitarian and the hierarchist which represent three different cultural points of view. The individualist perspective accepts as environmental impact only what is proven to have an effect while according to the egalitarian point of view all potential effects are considered and included in the process. In this study the hierarchist's perspective is used since it represents the average conditions [4,13].

Table 2.2: Introduction of the basic damage and impact categories according to the Eco-Indicator 99 impact assessment and weighting method [13]

Damage categories		
Human health	**Ecosystem quality**	**Resources**
Carcinogenic effects on humans	Damage caused by eco-toxic emissions	Damage caused by extraction of minerals
Respiratory effects on humans caused by inorganic substances	Damage caused by the effect of acidification and eutrophication	Damage caused by extraction of fossil fuels
Respiratory effects on humans caused by organic substances	Damage caused by land occupation and conversion	
Damages to human health caused by climate change		
Human health effects caused by ionising radiation		
Effects caused by ozone layer depletion		

The EPS method divides the impacts in "five safeguard subjects" [4,14]. These safeguards subjects are: human health, biodiversity, abiotic stock resources, ecosystem production capacity and recreational and cultural values each one containing a number of impact categories. Some of those categories are listed in table 2.3.

Table 2.3: Introduction of the main impact categories according to the EPS 2000 method [14]

Safeguard categories			
Human health	**Biodiversity**	**Abiotic Resources**	**Ecosystem production capacity**
Life expectancy	Normalised extinction of species (NEX)	Fossil fuels	Reduced wood production
Morbidity		Elements from earth's crust	Reduced crop production
Nuisance			

2.2 Data collection

The basic sources for the collection of the data presented in this study include scientific databases and journals related to the topic of research as well as reports and publications from automobiles manufacturers and governmental agencies.

General information regarding the automobile sector was collected mainly from the European and American automobile associations, through publications, sustainability and environmental reports, and statistical data.

All quantitative and qualitative data about the environmental situation and the different life cycle stages were mainly collected through previous studies of different research institutions and universities and reports published by different automobile manufacturers in Europe and USA. Additionally, life cycle inventory databases were also used.

2.3 Limitations and assumptions

Throughout the processes of investigation and selection of the most relevant data, a number of assumptions and simplifications are required. The first one refers to the level of details and systems boundaries considered in this study. The automobile is a very broad industry with numerous activities expanded in many countries all around the world [5,6]. It would be rather difficult to consider the local characteristics of the examined processes separately therefore the information collected for European and US conditions are assumed to be representative for the sector in total.

Furthermore, a vehicle itself is a highly complex product consisting of a great number of different parts and materials [5,15]. For this reason, the activities during the life cycle of the studied vehicle are examined more collectively. Exclusion of flows that were either too complicated or of little importance is essential in order to simplify the inventory process and provide more comprehensive results.

Finally, assumptions and self-estimations were also necessary when information could not be collected or showed great variation between the different sources. However, such cases are mentioned and clarified throughout the report.

3 Description of the automobile industry

According to the Global Industry Classification Standard (GICS) the automobile sector (nr 25) consists of the automobile and automobile components manufacturers [16]. This work is focused on the automobile companies (code: 250102010) which include "*companies that produce mainly passenger automobiles and light trucks*" excluding motorcycles, buses and heavy trucks [16].

There are several definitions and classification standards for vehicles. European directive for the approved type of vehicles includes a list that defines the different vehicle categories [17]. According to the directive, general *category M* refers to four wheels motor vehicles designed for passengers carrying and transportation and general *category N* refers to four wheels motor vehicles designed to carry and transport goods [17]. More specific, categories M1 and N1 of this list correspond to passenger car and light truck types of vehicles studied in this report. As stated in the directive [17]:

- ***"*Category M1** includes: *Vehicles designed and constructed for the carriage of passengers and comprising no more than eight seats in addition to the driver's seat***"***
- ***"*Category N1** includes ***:*** *Vehicles designed and constructed for the carriage of goods, having a maximum mass not exceeding 3.5 tonnes***"***

This classification is in accordance with the US definition for light trucks which includes also vehicles weighting below 3.5 tonnes [18]. Some more general classification categories are also available and used by the automobile manufacturers and retailers. For example passenger cars can be divided to mini, small or compact, medium, luxury, sport cars etc. based on existing models and characteristics such as dimensions and weight [19].

The rest of this chapter provides a brief overview of the automobile industry and the production stages of an automobile. The goal is to give the reader a general picture about production statistics, environmental challenges of the sector and legislation concerning passenger cars and light trucks before getting into more detailed information.

3.1 Industry overview

It can be admitted that automobile is among the industries that play major role in the global market, influencing different sectors of the economy worldwide [20]. After the construction sector, it is one of the major end use markets for the steel industry accounting for more than 15% of the total steel needs [21]. Million tonnes of steel are produced every year for the production of the main components of the vehicle like the body, power train, wheels, fuel tanks etc. [22,23]. Indicatively, almost 30 million tonnes of steel are required to produce 15 million light vehicles, which represent the production of vehicles in US [5,24]. Among others aluminium, petrochemical and glass industries are also important suppliers to the automobile sector which represents 7% and 5% of the plastics and aluminium market respectively [25,26]. As it will be discussed later, the share of those materials in an automobile is constantly increasing [5,6,27].

Every year around 70 million newly produced automobiles enter the global market [28], a fact that makes the sector a non-stopping supplier of goods and services. From an economical point of view, the total turnover of the automobile industry distributed between the different companies was around 2 trillion € according to data published for the year 2004, ranking the sector among the six first strongest industries [20,28,29]. A significant amount of these revenues is invested for research and development (R&D) contributing to its rapid progress [20,28,29].

On a social perspective, manufacturing and retailing of vehicles as parts of the automobile industry, are able to support and sustain societies by providing job opportunities for a significant number of people all around the world. It is stated that the automobile industry through direct and indirect employment provide *12 million jobs in EU* [28] and more than *5% of the world's manufacturing employment* [20].

The next figure shows the passenger and light commercial vehicles (LCV) world production during the last decade [20]. In turn, figure 3.2 illustrates how this production is geographically distributed [20]. It would be interesting to mention that during the last years the total demand and consequently the total production of new vehicles showed a short decline mainly due to the international financial difficulties.

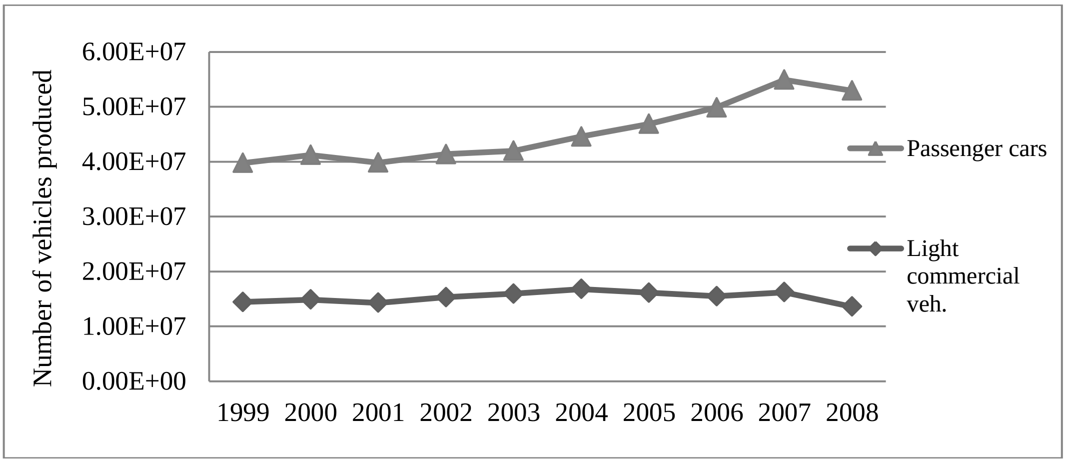

Figure 3.1: World's passenger cars and light commercial vehicles production [20]

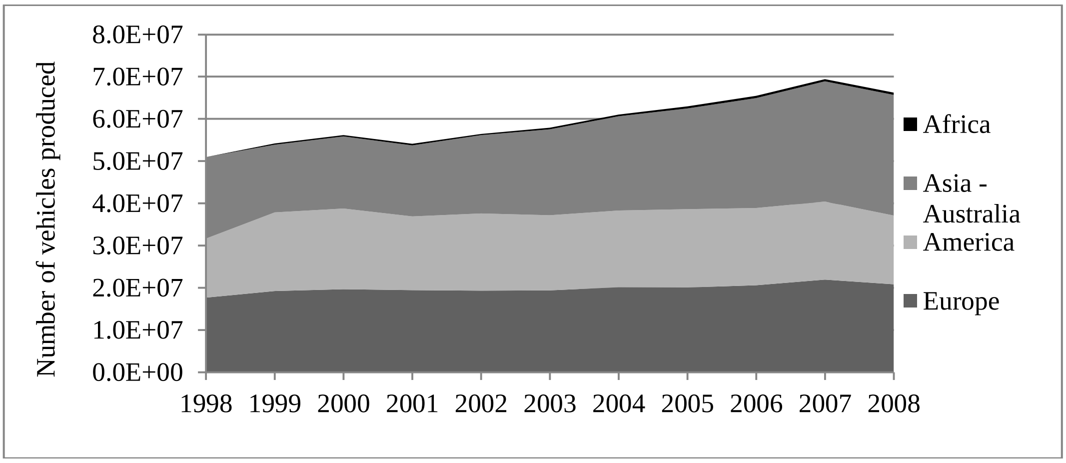

Figure 3.2: Geographical distribution of the world's passenger cars and light commercial vehicles production [20]

One more point that can be derived from the previous figure is a transition among the geographic location of the main manufactures. The share of vehicles produced in Asia the last years is increasing while the situation in Europe and America remains almost constant. Among Asian countries the greatest production takes place in Japan and China whereas in Europe Germany, France and UK continue to be the leading car manufacturing countries with 35, 33 and 28 automobile assembly and components manufacturing plants located there respectively (table 3.1)[20,28].

Table 3.1: Automobile manufacturing plants by country (2009) [20,28]

Country	**Automobile assembly and manufacturing of components plants in EU**
Germany	35
France	33
UK	28
Russia	27
Italy	18
Spain	15
Turkey	10

At a company level Toyota and General Motors are the leading suppliers internationally followed by Volkswagen, Ford, Honda and Nissan according to information published by the Organisation of International Car Manufactures for the year 2008 [20].

The total number of passenger cars being in use worldwide is more than 600 million. Almost 140 million are registered in the United States while in China and India there are 9 and 6 million cars respectively [28]. In Europe there are 230 million vehicles registered in total and more than 90% of these are passenger cars and light commercial vehicles [28]. The annual registrations of selected countries all around the world the last years (1990-2007) is shown in the following graph [30].

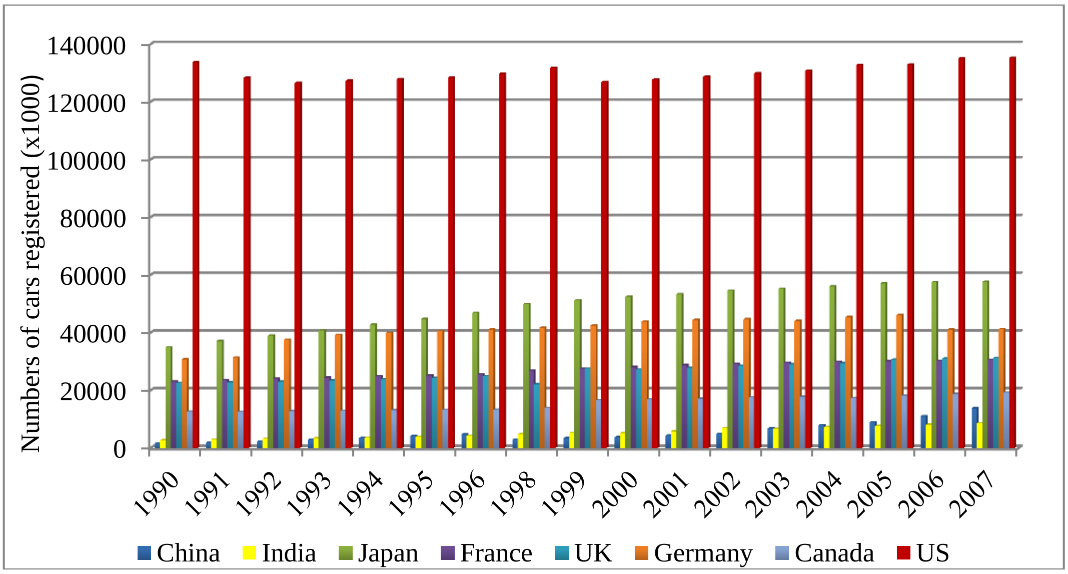

Figure 3.3: Passenger car registrations [30]
**During the year 1997 there were no data available*

According to data published by the automobile associations the average car density in USA reached 776 cars per 1000 inhabitants the year 2006 followed by Canada and Japan with around 550 cars per 1000 inhabitants [28,29]. Graph 3.4 provides some more examples of the global car density the year 2006. However, those numbers at the moment are expected to be slightly higher.

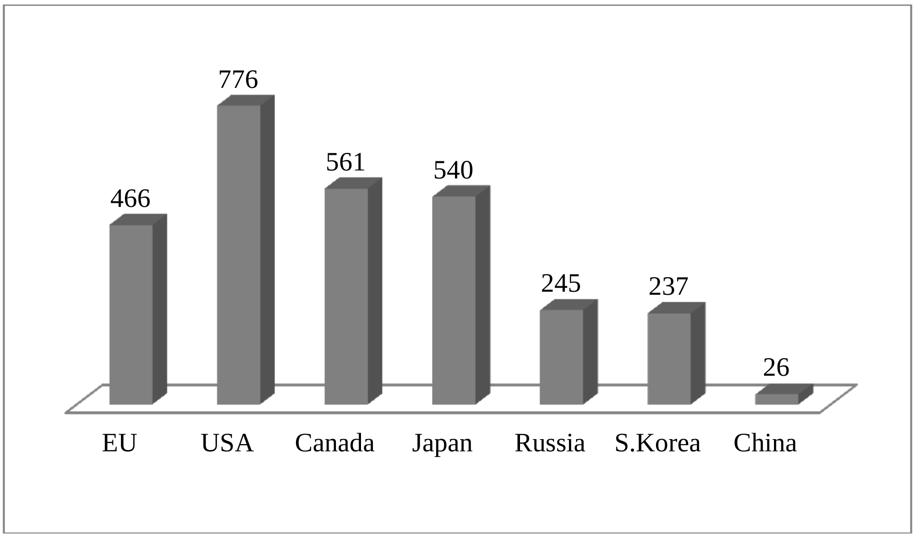

Figure 3.4: Car density (vehicle /1000 inhabitants) the year 2006 [28]

Concluding this section it would be interesting to mention some trends concerning the types of the cars and fuels used mostly today. Taking as example the European fleet and data provided for the year 2006, almost 89% of vehicles used were passenger cars with the majority of them being small and medium size vehicles. Another 9% were light commercial vehicles and the rest 2% were trucks and busses [28,29]. Among passenger cars the tendency regarding fuels are illustrated in figure 3.5. Obviously the two dominant fuels are gasoline (or petrol) and diesel which are oil based while alternative fuels are hardly reaching 1.3% of the share, the year 2008 [31].

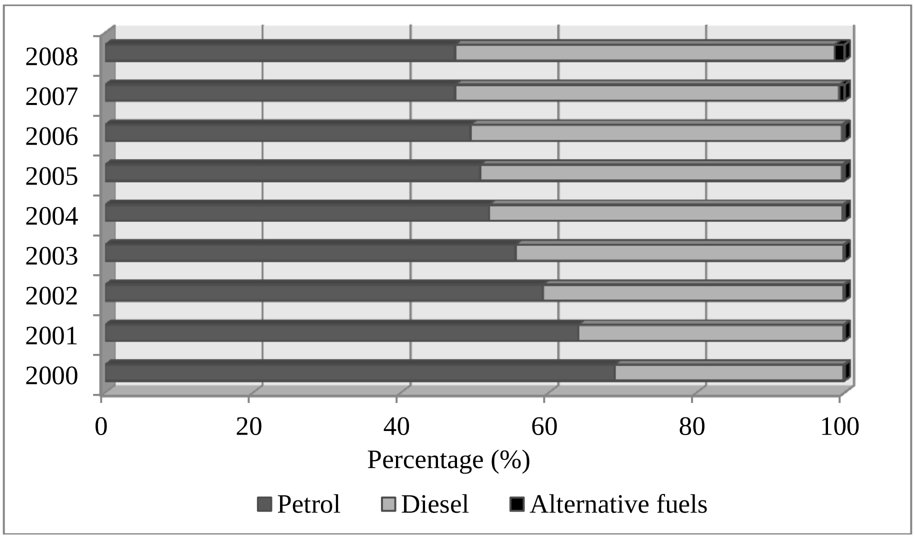

Figure 3.5: Fuel share in new passenger cars in EU [31]

Alternative fuels include: Liquefied Petroleum Gas (LPG), Natural Gas (NG), Electric, Hydrogen, Dual Fuel, Petrol-Bioethanol, Petrol-LPG, Petrol-NG.

3.2 Environmental concerns

Most of the activities related to the automobile industry, directly or indirectly, have significant impact for the environment. Direct activities are connected to the production and use of the vehicle, while indirect are related to all other activities that are not controlled by the sector but influence its overall picture such as the production and distribution of raw materials. Automobile manufacturers are aware of the problem and the steps towards a more sustainable sector are obvious.

When discussing about the environmental impacts of vehicles the focus is primarily on air pollution created during the utilization phase. As previous studies showed, it is the stage of the vehicle's operation where the greatest emissions of various pollutants occur [5,6,15,27]. Direct exhaust emissions of hazardous substances like carbon monoxide, nitrogen oxides and small particles are important contributors to many environmental problems like smog creation and biodiversity disturbances [32]. Those emissions affect the natural ecosystem at a more local level.

At a global level, the transportation sector is pretty much related to greenhouse gas (GHG) emissions and global warming since the utilization of the vehicle and other activities related to the sector are responsible for a significant amount of carbon dioxide emitted to the atmosphere [5,6]. More than 16% of human made CO_2 emissions are caused by road transportation in general whereas another 7% to 10% is assigned to passenger cars only [29].

The amount of certain regulated emissions apart from carbon dioxide has been recorded by the many European countries during the last years [33]. The results concerning the emissions from passenger cars are shown in the following graphs (figure 3.6). For some of the pollutants there is an obvious reduction, like the case of carbon monoxide and sulphur dioxide, mainly due to regulation measures and their requirements for cleaner fuels and 'greener' technologies.

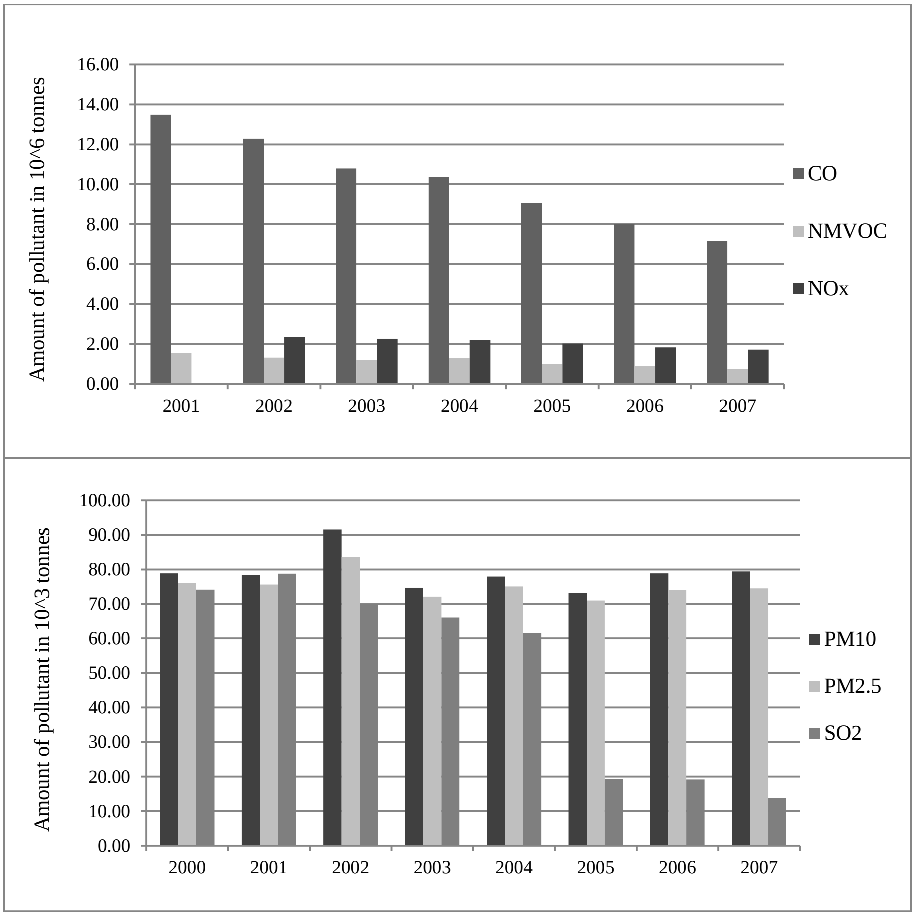

Figure 3.6: Total emissions of regulated substances in the EU [33]

CO= carbon monoxide, NMVOC= non-methane volatile organic compounds, NOx= nitrogen oxides, PM_{10}= particulate matter <=10μm, $PM_{2.5}$ = particulate matter <=2.5 μm, SO_2= sulphur dioxide

Consumption of non-renewable resources like fossil fuels is another important parameter contributing to the environmental depletion caused by the automobiles. As already shown the majority of vehicles use either gasoline or diesel resulting to a great dependence on oil. According to data published by the European Commission, road transportation accounts for 73% of all oil consumption in the EU, a number that is expected to increase the forthcoming years.

In terms of material losses and waste accumulation, 8 to 9 million tonnes of waste are generated from end-of-life vehicles (ELVs) every year [34]. The environmental impact caused by the treatment of old vehicles and vehicle components has been reduced significantly the latest years especially after the implementation of several regulation measures. However, there is still a flow of materials, sometimes scarce or hazardous, that end up in landfills. In addition to that ELV treatment efficiency can be negatively affected by the increasing amounts of newly developed materials that have limited recyclability like the case of plastics and carbon composites [22,27]

3.3 Legislation

The automobile companies individually or through official sector associations are becoming more and more active in taking environmental pollution prevention measures. Compliance with regulation and standards is the main reason for these initiatives followed by efforts for an improved environmental profile, market competition and cost reduction.

Regulation measures established by the European Union like the *Euro 5 and Euro 6 emission standard* and the *ELV directive* are some examples [5,6,34,35]. The most recent *Euro 5* and coming *Euro 6* emission standard ((EC) No 715/2007) refer to the requirements and limitations on the amount of air pollutants emitted from new passenger cars and light vehicles in order to be approved. *Euro 5* is valid since September 2009 for existing vehicles and has to be followed from January 2011 for new registered vehicles while the *Euro 6* standard is to be followed in September 2014 [35].

The threshold values of the selected pollutants for passenger cars are shown in the next table. More information and details can be found in the reference directive published by the European Commission [35].

Table 3.2: EURO 5 and EURO 6 emission standard [35]

EURO 5			**EURO 6**		
Substance	**Limit (mg/km)**		**Substance**	**Limit (mg/km)**	
	Petrol	Diesel		Petrol	Diesel
CO	1000	500	CO	1000	500
Particulates	5	5	Particulates	5	5
NOx	60	180	NOx	60	80
THC + NOx	-	230	THC + NOx	-	170
THC	100	-	THC	100	-
NMHC	68	-	NMHC	68	-

CO= carbon monoxide, NOx= nitrogen oxides, THC= total hydrocarbons, NMHC= non methane hydrocarbons

Additionally, European Commission has set specific thresholds to the amount of carbon dioxide (CO_2) that is allowed to be emitted from vehicles. The current directive suggests a value of less than 120 g CO_2/km by the year 2012 [36] and is expected to become stricter by decreasing the allowed emission levels during the forthcoming years.

The impact of these measures on the carbon dioxide emission rates for passenger cars is illustrated in the next figure. Obviously the share of less polluting vehicles in the European fleet is increasing (around 30% of the cars emit more than 161gr CO_2/km as stated for the year 2008, compared to 80% thirteen years before) but in order for the companies to comply with the forthcoming regulation, more radical measures and cleaner vehicles are needed.

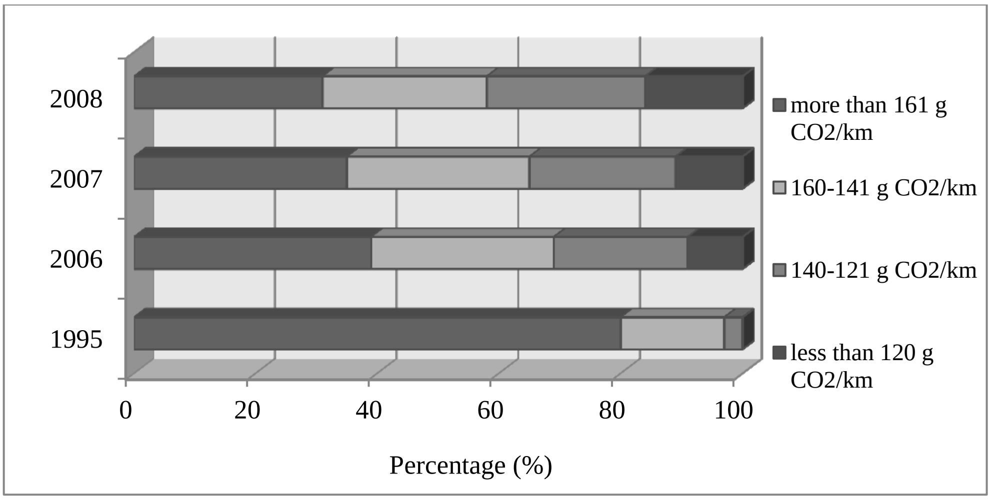

Figure 3.7: Carbon dioxide emissions from passenger cars [28,29]

Both regulation measures mentioned above refer to emissions of air pollutants to the atmosphere. In addition to these, EU has proposed and set into implementation the *2000/53/EC directive* which refers to the treatment and disposal of end of life vehicles. ELV directive aims "*to prevent and reduce the disposal waste from vehicles by reusing, recycling and other recovering methods of end of life vehicles and their components"*. In order for these goals to be achieved the directive promotes and proposes a number of measures [34]:

- Reduction and ban of selected hazardous substances like lead, mercury, cadmium etc.
- Reusing[1] and recycling[2] rates of end of life vehicles should reach 80 % by weight and by vehicle until January 2006 and should increase up to 85% until 2015
- Recovering[3] and recycling rates of end of life vehicles should reach 85% by weight by vehicle until January 2006 and should increase up to 95% until 2015.
- Existing vehicles produced before 1980 should be reused and recycled by 70% by weight and vehicle
- Manufactures should be responsible for their products and ensure recyclability

Common regulation measures are implemented worldwide at a state or international level. In the US the Clean Air Act Amendments (CAAA) set by the Environmental Protection Agency (EPA) regulate also emissions from passenger and light duty vehicles [5,6]. The two stages *Tier 1* and *Tier 2* are already in force since 1994 and 2004 respectively and limit the amount of emissions of certain pollutants as for the case of the Euro standards. Taxes and quality standards for fuels are some additional legislation examples that are under implementation and can lead to improvement of the general environmental performance of the sector [6].

Pollution caused at the manufacturing plants during the activities connected to the production of the vehicle, like releases of substances to air and water or waste disposal, is regulated at a more local level depending on national legislation schemes [6].

[1] *Reuse* means any operation by which components of the end-of-life vehicles are used for the same purpose for which they were conceived [34]

[2] *Recycling* means the reprocessing in a production process of the waste material for the original purpose or for other purposes, excluding energy recovery [34]

[3] *Recovery* in terms of *Energy recovery* means the use of combustible waste as a means to generate energy through direct incineration with or without other waste but with recovery of heat [34]

3.4 The life cycle of an automobile

3.4.1 Material acquisition and processing

The life cycle of an automobile begins with minerals extraction and processing in order to produce the materials and components needed for the final product (figure 2.1). An automobile consists of approximately 15 000 to 20 000 parts [5,15,27], which makes a detailed analysis of all material flows very difficult. Steel, aluminium and polymers are the dominating components with a total share of more than 80% by vehicle [15]. Consequently, natural resources like coal, iron, bauxite, petroleum and natural gas are broadly used as necessary raw materials for the production of those components [15,37].

Table 3.3 lists some of the main materials that constitute a passenger car and their composition according to a study made in US [15]. A detailed table is available in the Appendix of the report (Appendix A).

Table 3.3: Material composition of a family passenger car
Total weight 1500kg.Year 1995 [15]

Material	Mass (%)	Material	Mass (%)
Metals		**Plastics**	
Cast Iron (Fe)	**8.59**	Acrylonitrile Butadiene Styrene (ABS)	0.64
Pig Iron (Fe)	**1.48**	Polyester Resin	0.75
Steel (cold rolled)	**7.46**	Polyethylene (PE)	0.40
Steel (EAF*)	**14**	Polypropylene (PP)	1.6
Steel (galvanized)	**23.3**	Polyurethane (PUR)	2.3
Steel (hot rolled)	**8.23**	Polyvinyl Chloride (PVC)	1.3
Steel (stainless)	**1.23**	**Other**	
Aluminium (cast)	**4.7**	Ethylene Propylene Diene Monomer (EPDM)	0.68
Aluminium (extruded)	**1.4**	Glass	2.8
Copper (Cu)	**1.1**	Rubber (except tire)	1.5
Lead (Pb)	**0.85**	Rubber (extruded)	2.4
Brass	**0.55**	Tire	3
Zinc	**0.021**	Wood	0.15
		Other	8.1
Total			**100 %**

**EAF: Electric arc furnace*

The metallic parts consist of more than 70% of the total amount of components found in the car with steel and aluminium being the dominant materials used for structural applications [15,22]. Steel of various grades is used as a major component for the frame, chassis and body parts of the vehicle. Aluminium is used also for the body, parts of the chassis and engine, interior parts, airbags etc. The rest of the metals and other materials are found in smaller amounts and are used to produce the auxiliary parts of the car. For example cables, radiators, connectors etc. are made from copper [22]. Lead and zinc are also materials used in the car. The main application for lead is the car battery but it is also used as alloying element in steel and aluminium for machining properties [38]. Zinc on the other hand among other purposes, is also used as steel coating for corrosion prevention [38].

Plastic parts represent 9% to 10% of the weight of an average European passenger car [22,39]. Several types of plastics are used depending on their properties and the final application in the vehicle. Indicatively, polypropylene (PP) is used in bumpers, filters, dashboard etc. [22,39]. Polyurethane (PUR) and polyvinyl chloride (PVC) are used as parts of the seats while polyethylene (PE) is mostly used in the dashboard, fuel tank, ventilation components etc. [22,39].

The data shown in table 3.3 refer to 1995 conditions but the situation today has not changed dramatically. However, the need for lighter vehicles in order to achieve better fuel economy has increased the share of plastic and aluminium parts while at the same time replaced heavier materials like iron [5,6,27]. Furthermore, as new technologies evolve like the case of electric and fuel cell vehicles, new compounds have to be considered. Selection of materials that differ in composition between the internal combustion, electric and fuel cell vehicles are shown in table 3.4 [40,41].

Table 3.4: Material composition in different vehicle technologies [40,41]

Material (% by weight)	ICE Baseline	LWICE	HEV	LWHEV	FCV	LWFCV
Steel	58.3	20.3	54.9	19.1	49.2	19.1
Aluminium	7.4	18.4	13.7	19.7	14.5	19.5
Plastic	10.8	1.8	11.5	16.2	11.4	15
Carbon composites	-	18	-	17.8	7.4	23.6
Copper	1.1	3.4	3.5	4.7	4	5.1
Nickel	-	-	-	-	0.06	0.08

ICE= internal combustion engine, LWICE= low weight internal combustion engine, HEV= hybrid electric vehicle, LWHEV= low weight hybrid electric vehicle, FCV= fuel cell vehicle, LWFCV= low weight fuel cell vehicle

3.4.1.1 Production processes of major automobile materials

Almost all of the processes that transform the extracted minerals to be useful for the automobile manufactures materials are done by other external industrial sectors rather than the automobile manufacturing sector itself [5,6].

Steel can be obtained through primary and secondary production. Primary (or virgin) production represents 75% of steel production worldwide and uses iron ore and coal as the basic raw materials [5]. Secondary production on the other hand, is based on iron and steel scrap (recycled materials). Primary production begins with the processing of the raw materials and acquisition of iron which is then transformed to steel usually in a basic oxygen furnace (BOF). The most commonly method used for secondary steel production is the electric arc furnace (EAF) where raw materials are melted and the hot metal is obtained from the bottom of the furnace. Depending on the characteristics of the final component different process routes, such as rolling forming, casting etc. are used today for the production of various steel grades [5,42].

Aluminium is produced from bauxite ore in two stages, the Bayer process (transforming bauxite to alumina) and the Hall-Hroult process (reducing alumina to aluminium). As for the case of steel, aluminium can be produced from scrap (recycled aluminium) too, resulting to a less energy demanding process. Rolling, extrusion and casting aluminium are the main manufacturing routes used for the production of the different automobile components [5,26,42].

For the production of *plastic parts*, oil and natural gas are the major fossil fuels used as feedstock. After refining, distillation and other forming processes the different types of monomers and polymers are extracted and transformed to the plastic components found in the automobile. The most commonly used plastics in cars are: acrylonitrile butadiene styrene (ABS), polyvinyl chloride (PVC), polypropylene (PP) and polyethylene (PE) which constitute parts of the vehicle such as the seats, the interior part, the dashboard etc. [25,39,42].

Float glass is the type of glass used for the automobiles. It is produced using limestone, dolomite, soda ash and sand like regular glass. After the reactions between the raw materials, the glass produced is melted. Tin bath (i.e. float the melted product on molten tin) processes follow in order to become flat [42].

3.4.2 Vehicle manufacturing and assembly

The vehicle manufacturing and assembly is a set of different processes and could constitute a separate industrial sector. It consists of different kinds of activities, complex supply chains and has a great geographical distribution. In summary the major stages that can be recognised during the assembly phase are: the fabrication of the different components, the assembly and painting processes and several finishing activities [43].

Fabrication activities include foundry operations and metal processing as for example forming casting etc. in order for the various components of the vehicle like the engine, the body parts and other accessories to be produced. These activities can take place in the same facilities of a company's assembly plant or finished parts can be provided to the company by different external producers [43].

Next step in the process is the actual *assembly* of the main parts that constitute a vehicle. For example the side parts, the roof, the floor, the main trunk, the engine and other parts are put together mechanically or manually. Different techniques are used in different plants all over the world regarding the joining processes of the vehicle's components and the testing processes that are required [43].

The final steps refer to the *painting and finishing process*. These stages include activities such as anti-corrosion operations, colour coating activities, installing transmissions etc. Moreover, all other smaller parts of the vehicle like for example the gas tank are installed until the vehicle is completed [43].

3.4.3 Use phase and maintenance

The average utilization time of an automobile is around 10 to 15 years. However, this can vary according to the model, driver's behaviour and other unpredictable reasons like car accidents. During that average time frame a passenger car covers a distance of 150 000 to 200 000 km. [15,27,37]

Maintenance and service activities are other parameters that are connected to the utilization stage of a car and have the ability to increase or decrease its life time. Service is required approximately every 15 000 km when no properly functioning or destroyed components should be replaced. A vehicle during its life cycle will change approximately 12 tires, 3 batteries and will need 10 oil changes according to average data [5,15,37]. Some more examples are shown in table 3.5.

Table 3.5: Examples of parts and fluids that are replaced during a passenger car's life time [5,15,37]

Fluids	**Lifetime quantity/car**
Brake fluids	3 litres
Engine oil	121 litres
Windshield cleaner	44 litres
Water	19 litres

Parts to be replaced	**Lifetime quantity/car**
Air filters	6
Oil filters	27
Windshield wiper blades	18-20
Brake pads front	8

Even though new technologies for automobile operation have started to evolve, like for example electric and fuel cell vehicles, the most common process remains the internal engine. The majority of vehicles today use gasoline or diesel as shown in figure 3.5 of a previous section.

The typical fuel combustion process in an automobile can be described by the general equation (1) where a fuel/air mixture reacts is burned towards the production of carbon dioxide and water [44]. However, in the presence of air, nitrogen oxides are also formed. Furthermore, carbon monoxide and sulphur oxides can be produced depending on the level of combustion and composition of the fuel respectively. Hydrocarbons are also possible to be obtained due to incomplete combustion.

$$Fuel + Air \rightarrow CO_2 + H_2O + energy + others(\, CO, NO_x SO_2\,, PM, HC) \quad (1)$$

Fuel consumption rates and consequently the levels of exhaust emission, vary a lot depending on the vehicle model and the type of fuel used. Additionally, the driving behaviour of the user affects also the consumption of the fuel to a great extent. Indicatively, exhaust emissions levels for passenger cars using gasoline and diesel are shown in table 3.6. The data presented in this table refer to measurements obtained according to a specific European driving cycle, NEDC, from different studies and for different car models. The variations show the difficulty to propose an average emission rate since it is highly dependent to many factors like the driving cycle, the location, the model and technology of the vehicle etc.

Table 3.6: Exhaust emissions [37,45]

Fuel consumption	**CO**	**CO_2**	**NOx**	**HC**	**PM**
9 l/100km (gasoline)	0.24g/km	214g/km	0.02g/km	0.01g/km	NA
6.5 l/100 km (gasoline)	0.1 g/km	153g/km	0.013 g/km	NA	0.0024 g/km
5 l/100km (diesel)	0.1 g/km	132 g/km	0.377 g/km	NA	0.03 g/km

CO= carbon monoxide, CO2 carbon dioxide, NOx= nitrogen oxides, HC= hydrocarbon, PM= particulate matter, NA=no data available

An additional step in the life cycle of the vehicle presented so far is the fuel cycle (referred also as well-to-tank stage) and includes the processes connected to the production of the automobile's fuel. Due to the great amounts of gasoline and diesel consumed during a vehicle's operation, tables 3.7 and 3.8 present some information regarding the emissions connected to their production processes. The data included in the following tables are obtained from a study that estimated emission factors for the production of different fuels for a selection of European countries [46].

Table 3.7: Average emission factors for *gasoline* production (Europe) [46]

	CO_2	**CO**	**NO_x**	**NMHC**	**SO_2**	**CH_4**	**PM**
g/GJ	9 220	5.31	44.36	208.57	77.17	17.23	2.27
g/kg fuel	433.57	0.25	2.08	9.80	3.59	0.81	0.11

CO2=carbon dioxide, CO= carbon monoxide, NOx= nitrogen oxides, NMHC= non methane hydrocarbons, SO2= sulphur oxide, CH4= methane, PM= particulate matter

Table 3.8: Average emission factors for *diesel* production (Europe) [46]

	CO_2	**CO**	**NO_x**	**NMHC**	**SO_2**	**CH_4**	**PM**
g/GJ	6 960	4.8	38.37	87.21	58.73	15.63	1.22
g/kg fuel	316.80	0.22	1.75	3.97	2.67	0.71	0.06

CO2=carbon dioxide, CO= carbon monoxide, NOx= nitrogen oxides, NMHC= non methane hydrocarbons, SO2= sulphur oxide, CH4= methane, PM= particulate matter

3.4.4 End-of- life treatment processes and disposal

After the utilization phase the vehicle becomes waste as every other product. More than 90% of end-of-life vehicles are collected and treated, as recent regulation measures impose [22,39]. A series of processes follow in order to extract reusable and recyclable parts and materials and also reduce the volume of the waste. A vehicle today is reused and recycled at an average rate of 80% by weight. Around 65% to70% of this rate corresponds to its metallic components while the rest 10% to 15% corresponds to the parts that are dismantled and reused or recycled [22,39,47]. Some European countries including Sweden and the Netherlands have managed to fulfil the goals set by the ELV directive achieving a rate of 83% by weight reuse and recycling and 90% by weight reuse and recovery the year 2006 [48].

The stages followed in the end of life treatment facilities in consecutive order are: pre-treatment, dismantling, shredding and shredder residues treatment [22,39].

During *pre-treatment* (or de-pollution) vehicle components that contain dangerous and toxic substances are removed. Examples of such components are the operating fluids like different oils and fuels, the battery, the oil filters, components containing mercury and devices like the airbags which contain explosive substances. Most of the parts removed in this stage are recycled or further treated and disposed according to regulation [22,47].

The next step is *dismantling* where the vehicle is disassembled to its major components and the individual parts that can be recycled or reused directly are removed. Parts that have an economic value like the engine or other parts of the body could be directly recovered and reused after some repairing processes. Furthermore, as the vehicle is dismantled the different parts are divided to different material and components fractions and then recycling takes place. Examples of most commonly found components of this fraction include tyres, parts made of glass, catalytic converters etc. [22,47].

Shredding is the following step during the end-of-life treatment process. The goal of shredding is to reduce the volume of the remaining waste and at the same time separate the materials in more homogenous fractions on order to make their recycling easier. The vehicle parts are shredded into smaller pieces and then mechanical and physical processes like magnetic separation, eddy current belt and sink-floating methods are used in order to separate further the different materials according to their type and properties. After these processes the materials are divided to three general categories: *ferrous metals (iron, steel), non-ferrous metals (aluminium, copper) and shredder residues*. Ferrous and non-ferrous materials are directly recycled as scrap metals [22.47].

Shredder residues (SR) (light and heavy fraction) constitute the remaining 25% by weight of the vehicle that is not recycled [22,39,47]. Materials from the SR fraction are more complicated to be extracted since it is a mixture of substances with different properties. Extraction and recycling of those substances is possible but most of the times it is not economically feasible. The majority of the SR fraction ends up in landfills after some last treatment process. Table 3.9 contains information about the composition of selected materials found in the SR.

Table 3.9: Average composition of the shredder residues (light and heavy fraction) [22,39,47]

Material	Content (%by weight)	Material	Content (% by weight)
Polymers	27	Fabric	15
Urethane foam	16	Iron	8
Wood	3	Rubber	7
Glass	7	Non-ferrous metals	4
Wire	5	Minerals	8

Post shredding processes aiming to achieve higher separation and recycling levels by extracting the remaining metals and other parts like plastics and minerals from the SR. Again mechanical and physical separation methods are used. The remaining residues highly consistent of polymers are disposed in landfills in most of the countries worldwide. The total amount of waste end up in landfills from end of life vehicles in Europe is estimated to be around 2 million tonnes per year [22,34]. Taking also into account the fact that concentration of plastics and composites in new vehicles is increasing [6,27], the SR treatment would become much more inefficient. Increasing the possibilities for SR utilization and higher recovery rates is therefore becoming urgent.

4 Results

This section of the study presents the results from the inventory process following the methodology described in the second chapter. The goal here is to classify and present the impact of the automobile industry on the environment as well as to prioritise and suggest the main problems that the sector has to face.

Even though the overall objective of the study is to evaluate the industry as a whole, the data presented and discussed in this section refer to a hypothetical passenger car that is used as an example and serves as a functional unit. For this reason, most of the collected data are converted and calculated according to the studied vehicle. Parameters like material composition and fuel type and consumption need to be defined since their values affect to some extent the overall impact.

4.1 Properties of the studied vehicle

The weight of the chosen vehicle is assumed to be 1300 kg representing a common passenger car [6,31,37,47]. The material composition of the studied vehicle as shown in table 4.1 is estimated after research in previous studies related to vehicles and information collected from vehicle manufacturer reports [5,15,40,42,47,49-51]. As shown in an earlier chapter, a vehicle consists of many different materials. For simplification reasons as well as due to data limitations there is a selection and grouping of the materials studied during the inventory process according to their type and selected properties.

Table 4.1: Material composition of the hypothetical studied vehicle [5,15,22,40,42]

Material	kg/car	% by weight
Ferrous (steel and iron)	845	65%
Aluminium	91	7%
Copper	13	1%
Lead	11	0.85%
Glass	35.4	2.8%
Plastics	117	9%
Rubber	58.5	4.5%
Fluids	78	6%
Others	50	3.85
Total	**1300**	**100%**

Plastics include: acrylonitrile butadiene styrene (ABS) in a rate of 1.7% by weight, polyvinyl chloride (PVC) 1.1% by weight, polypropylene (PP) 3.7% by weight and polyethylene (PE) 0.6% by weight [15,22,39,42,47]. The rest is considered to be miscellaneous polymers and are roughly calculated together [42]. Materials that are not listed separately in the previous table, but can be found in an automobile in smaller proportions include: magnesium, zinc, wood, textiles, paint and more.

The utilization time of the studied vehicle is assumed to be approximately 10 years, travelling a distance of 150 000 km in total [37]. Two different cases are examined concerning the type of fuels used in the vehicle. Although alternatives for power-train systems and fuels exist (like ethanol, biodiesel and hybrid electric vehicles), the internal combustion engine using gasoline or diesel as a fuel is still the representative technology for the vehicles being in use today [36]. Consequently, fuel consumption is set to be 7.5 l/100 km and 6 l/100 km for gasoline and diesel case respectively (average values for urban and high way driving through information from car manufacturers). For both cases the material composition of the vehicle is assumed to be the same since there not significant differences between these two alternatives [37].

4.2 Processes considered during the inventory

According to the methodology described in a previous section, the impacts caused by the activities connected to the automobile life cycle are identified and classified in three categories: emissions to air and water, land and biodiversity deterioration, and resource efficiency (considering fossil fuels and minerals availability). For this reason the rest of the chapter is divided in four parts. The first three represent the classification categories mentioned above including also a short discussion on the findings. In the last part there is an overall evaluation and analysis of the results after the implementation of a weighting method in order to derive some major and most significant impacts.

The identified stages during the life cycle of a vehicle are: the production of the major raw materials (material acquisition), the manufacturing and assembly processes (resource conversion) and finally the utilization and end of life stage (referring to role of the sector as a supplier) [5,6,8,9].

Materials acquisition considers the environmental impact caused during extraction and production of the materials that are used in the automobile. The focus of this work is on the metallic (ferrous and non-ferrous) and plastic compounds which will be covered in more details. As already mentioned steel, aluminium and plastics represent the majority of materials found in a car.

Resource conversion and assembly processes refer to the activities taking place in the automobile manufacturing plant where components are fabricated and joined together in order to derive the final product. These activities include the assembly of the several automobile components, the painting and the finishing processes. For most of the measurements regarding the environmental impacts of this stage, only total average data were collected since allocation to the several activities involved was not possible.

The last stage (*use phase and end of life treatment*) of the vehicles life cycle is divided in four main parts. These are the operation stage, the service and maintenance activities, the fuel production and finally the end-of-life treatment processes. Information and comparisons between those activities will follow.

4.3 Life cycle emissions

The following tables illustrate the life cycle emissions that are identified and accounted to the automobile sector. The two different tables, 4.2 and 4.3, represent the two fuel options considered. The data presented here refer to the hypothetical passenger car that is used as an example in this study. For this reason the numbers shown might differ compared to other studies. However, they can indicate the extent of the impact that is associated to each stage.

Table 4.2: Total life cycle emissions of the automobile sector and the share of the different stages for the case when gasoline is used as a fuel

	Principles 1& 2 – Emissions of substances																			
		Emissions to air										**Emissions to water**								
	Measurements (% of the total)	**CO_2**	**CO**	**NOx**	**SOx**	**VOC**	**HC**	**CH4**	**PM/ dust**	**HF**	**HCl**	**COD**	**BOD**	**PO_4^{3-}**	**SO_4^{2-}**	**NH_3**	**Cl^-**	**DM**	**SM**	**Oils**
Life cycle stages	**Material acquisition**	10.9%	55.7%	22.5%	28.%	15.8%	7.2%	38%	69%	95.7%	87.6%	54%	55%	68%	46%	4.25%	78%	60%	4.1%	2%
	Resource conversion	3.16%	0.7%	16.6%	6.15%	32.2%	7.5%	7%	4.6%	0.1%	1.4%	17.5%	15%	14%	40%	0.75%	20%	15%	3.6%	7.4%
	Use phase and End of life	85.4%	43.6%	61%	65.2%	52%	85.9%	54.6%	26.3%	3.8%	11%	28.5%	30%	18%	14%	95%	2%	25%	92.3%	90.6%
	Total impact (kg/vehicle)	**31610**	**43**	**36**	**53.5**	**12.4**	**98**	**18.5**	**11.7**	**0.1**	**0.27**	**1.37**	**0.2**	**0.044**	**1.8**	**2**	**4.4**	**6.5**	**59**	**6**

Table 4.3: Total life cycle emissions of the automobile sector and the share of the different stages for the case when diesel is used as a fuel

	Principles 1& 2 – Emissions of substances																			
		Emissions to air										**Emissions to water**								
	Measurements (% of the total)	**CO_2**	**CO**	**NOx**	**SOx**	**VOC**	**HC**	**CH4**	**PM/ dust**	**HF**	**HCl**	**COD**	**BOD**	**PO_4^{3-}**	**SO_4^{2-}**	**NH_3**	**Cl^-**	**DM**	**SM**	**Oils**
Life cycle stages	**Material acquisition**	12.6%	56%	9.3%	35%	23.9%	15.2%	46%	53%	95.7%	87.6%	54%	55%	12%	46%	4.25%	78%	60%	4.1%	2%
	Resource conversion	3.7%	0.7%	6.7%	7.5%	48.7%	15.9%	7%	3.2%	0.1%	1.4%	17.5%	15%	2%	40%	0.75%	20%	15%	3.6%	7.4%
	Use phase and End of life	83.7%	43%	83.5%	57.5%	27.4%	69%	47%	43.8%	3.8%	11%	28.5%	30%	86%	14%	95%	2%	25%	92.3%	90.6%
	Total impact (kg/vehicle)	**27245**	**42**	**87**	**43.6**	**8.2**	**46**	**16**	**15.4**	**0.1**	**0.27**	**1.37**	**0.2**	**0.23**	**1.8**	**2**	**4.4**	**6.5**	**59**	**6**

CO_2=carbon dioxide, CO= carbon monoxide, NOx= nitrogen oxides, SOx= sulphur oxide, VOC= volatile organic compounds (non-methane), HC= hydrocarbons (non-methane), CH_4= methane, PM= particulate matter, HF= hydrogen fluoride, HCl= hydrogen chloride, COD= chemical oxygen demand, BOD=biochemical oxygen demand, PO_4^{3-}= phosphates, SO_4^{2-}= sulphates, NH_3= ammonia, Cl^-=chloride, DM= dissolved matter, SM= suspended matter

Furthermore the colours indicate the percentage of the contribution of every substance (S) to the different classification categories: red colour when S>50%, yellow when S ≥ 30%, blue colour when S≥20% and green colour when S≤10% .

Estimations for both cases are according to [15, 32,37,42,46, 49-55]

From the tables shown above and figure 4.1 that follows, it is possible to derive that among the substances examined in this study, the automobile sector is responsible for a great amount of *carbon dioxide* (CO_2) emitted in the air. This amount varies between *27 and 31 tonnes* per vehicle depending on the fuel used. Obviously the level of emissions of carbon dioxide is much larger compared to the rest of the measurements.

The second contributors, in terms of emission level, are *non-methane hydrocarbons* (NMHC) when gasoline is used as a fuel and *nitrogen oxides* (NOx) for diesel. Diesel vehicles tend to release in total less than half of the amount of hydrocarbons compared to gasoline. Additionally, *carbon monoxide* (CO) emissions to air are almost the same for both cases (around 40 kg/vehicle).

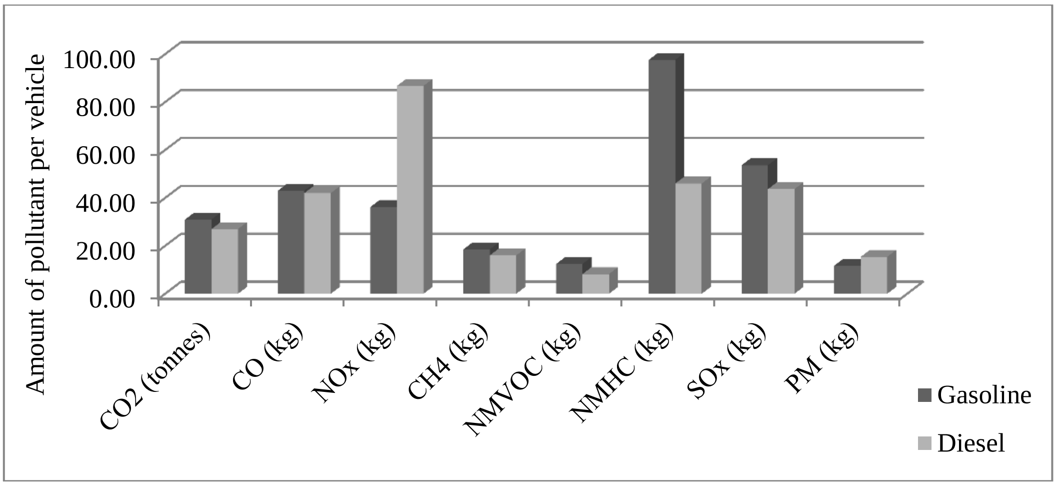

Figure 4.1: Results showing the total level of emissions in air for selected pollutants over a passenger's car life time.
CO_2=carbon dioxide, CO= carbon monoxide, NOx= nitrogen oxides, CH_4= methane, MMVOC= non methane volatile organic compounds, NMHC= non methane hydrocarbons, SOx= sulphur oxides, PM= particulate matter

The rest of the emissions studied including *methane* (CH_4), *volatile organic compounds* (VOC) and *particulate matter* (PM) seem to be released in lower levels compared to the ones discussed so far. However their significance will be evaluated later on the report after the implementation of the weighting method.

Substances such as carbon dioxide, sulphur and nitrogen oxides can also show great variations depending on the sources of primary energy production [37,42,55]. In this study most of the energy produced is based on fossil fuels therefore the amount of pollutants resulting from their combustion tends to be higher compared to the amounts that would be released if renewable and less carbon intensive sources were considered. In addition, nitrogen oxides and carbon monoxide resulting from the operation of the vehicle depend on the technology (type of catalyst) and fuel economy [32]. Whereas the total amount of sulphur oxides emitted depends on the content of sulphur in the fuel [32].

From a life cycle point of view, the distribution of the examined pollutants among the different life cycle stages is shown in the next figure. From this perspective the results are almost the same for the two cases therefore figure 4.2 illustrates the results for the gasoline vehicle.

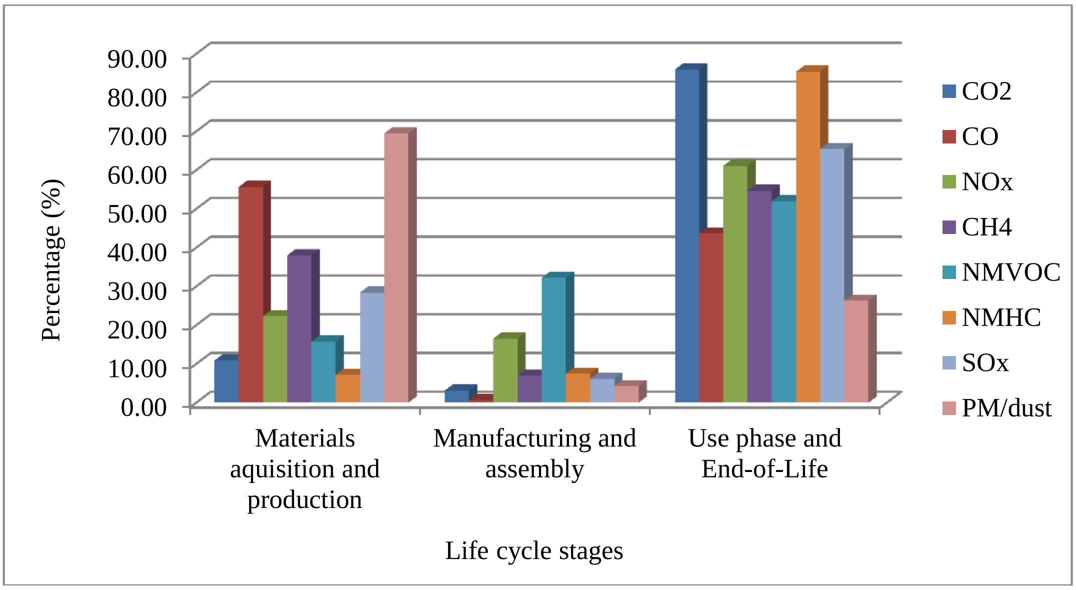

Figure 4.2: Results showing the distribution of emission of substances in the air among the different life cycle stages of an automobile (gasoline scenario)
CO_2=carbon dioxide, CO= carbon monoxide, NOx= nitrogen oxides, CH4= methane, NMVOC=non methane volatile organic compounds, NMHC= non methane hydrocarbons, SOx= sulphur oxides, PM= particulate matter

Obviously the *utilization stage* of the automobiles life cycle is responsible for the greatest amounts of many air pollutants especially greenhouse gases. More than 80% of total carbon dioxide and 55% of methane emissions occur during this stage. Same results are derived for the case of sulphur and nitrogen oxides with a share of 65% and 61% of total emissions respectively, occurring during the operation stage.

Around 86% of the total amount of hydrocarbons is emitted also during the utilisation stage of a gasoline vehicle. However, the majority of them are released during the production of the two fuels compared to the emissions from their combustion.

The following figures focus on the last stage of the vehicle's life cycle (use phase) and illustrate the allocation of emissions of selected substances among the different activities that take place during that stage. More specific, the emission rate accounted to the utilization stage is now distributed between the production of the fuel and operation, repair and end-of-life stage of the vehicle. Figure 4.3 refers to the gasoline case while figure 4.4 illustrates the diesel case.

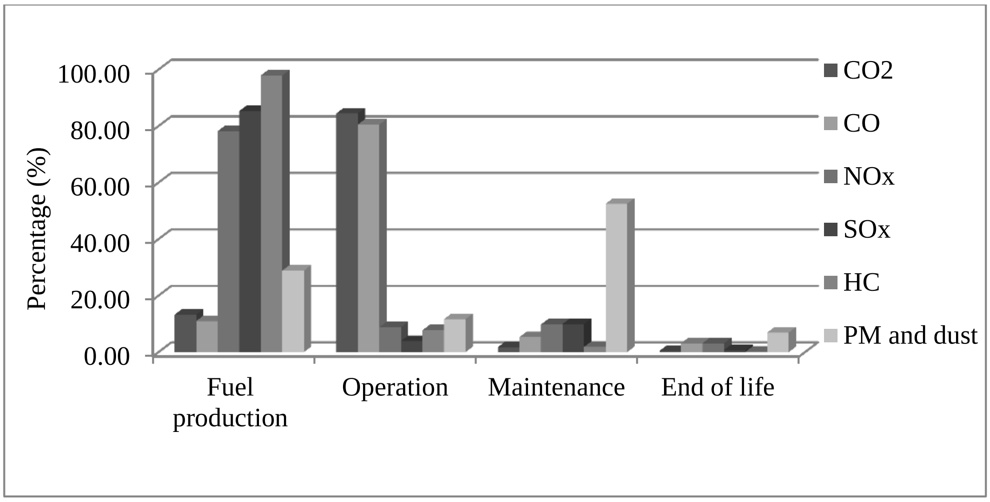

Figure 4.3: Distribution of emissions over the major activities connected to last life cycle stage of the vehicle (gasoline scenario)
CO_2= carbon dioxide, CO= carbon monoxide, NOx= nitrogen oxides, SOx= sulphur oxides, HC= hydrocarbons, PM= particulate matter

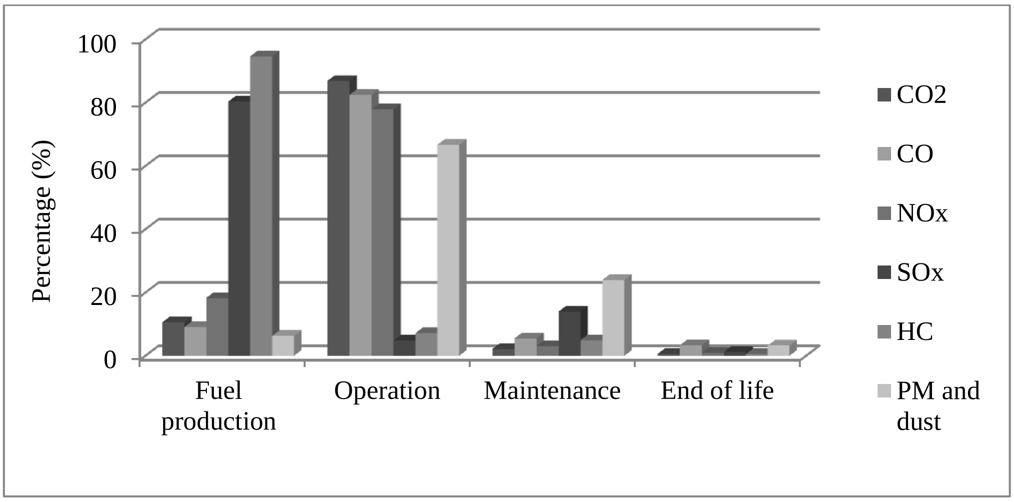

Figure 4.4: Distribution of emissions over the major activities connected to last life cycle stage of the vehicle (diesel scenario)
CO_2= carbon dioxide, CO= carbon monoxide, NOx= nitrogen oxides, SOx= sulphur oxides, HC= hydrocarbons, PM= particulate matter

Looking deeper in the last life cycle stage, we observe that *the production of the fuel* is responsible for an important share of the total emissions resulting during that last stage and need to be studied separately. The emission rate for substances like hydrocarbons and sulphur oxides is much higher during this stage compared to the actual operation of the car. Indicatively, around 80% of sulphur dioxide emissions occur during the production processes for gasoline and diesel while only 4% occurs during the actual utilisation of the car.

On the other hand, carbon dioxide and carbon monoxide are highly connected to the operation phase and the results for both fuel scenarios are almost the same. Around 2 to 3 tonnes of carbon dioxide are emitted during the combustion of the fuel through the utilization of the car. The emission levels for carbon monoxide are much lower in magnitude but again operation phase represents a share of 80% of the total emissions with fuel production being the second contributor.

The main difference between the two fuel scenarios concerns the emissions of nitrogen oxides and particulate matter. Nitrogen oxides for the case of gasoline occur mainly during the production of the fuel while in the case of diesel during the operation stage. On the other hand, emission of particulate matter is highly connected to the operation stage for the diesel vehicle [32,37].

Tables 4.4 and 4.5 contain some more detailed information regarding the emissions for the production of gasoline and diesel. For the calculations, the data presented in tables 3.7 and 3.8 of a previous section and the properties of the studied vehicle are considered. As already mentioned tables 3.7 and 3.8 are based on a study that estimated the emission factors for the production of different fuels in Europe therefore the results shown here correspond to European conditions. More information about the calculation process is presented in the Appendix B of this report.

Table 4.4: Emissions of substances during the production of *gasoline* (Europe) [46]

	CO_2	CO	NO_x	NMHC	SO_2	CH_4	PM
kg/car	3610	2.07	17.34	81.6	29.93	6.75	0.89

CO_2= carbon dioxide, CO= carbon monoxide, NOx= nitrogen oxides, NMHC= non methane hydrocarbons, SO_2= sulphur dioxide, CH_4= methane, PM= particulate matter

Table 4.5: Emissions of substances during the production of *diesel* (Europe) [46]

	CO_2	CO	NO_x	NMHC	SO_2	CH_4	PM
kg/car	2395	1.65	13.24	29.98	20.18	5.37	0.42

CO_2= carbon dioxide, CO= carbon monoxide, NOx= nitrogen oxides, NMHC= non methane hydrocarbons, SO_2= sulphur dioxide, CH_4= methane, PM= particulate matter

Continuing to the stages of *service and end-of-life*, it is derived that both account for less than 2% of the total emissions, the vast majority of which are releases of carbon dioxide. Even for the case that only the last life cycle stage is considered, among operation and fuel production, they still have the smallest share of emissions.

However, when it comes to particulate matter, the repair and maintenance activities result to higher emission rates in particular for the gasoline scenario. The particles connected to this stage refer mainly to dust. Consequently, around 50% of particle releases in the air are caused by the service activities for the gasoline case. The same substances over the whole life cycle represent a rate from 10% to 13%.

Referring again to figure 4.2 shown earlier, the second contributor to the total amount of substances reaching the environment is the stage of *acquisition and production of the raw materials* that comprise the automobile. In general, according to the results of this study, raw materials production accounts for almost 13% of the total emissions that the automobile sector is responsible for. Emission levels for pollutants like carbon monoxide and sulphur oxides may vary a lot since they are highly dependent on the primary energy and electricity sources of every related industry [42]. Only for the case of particulate matter this stage seems to be responsible for the majority of emissions compared to the manufacturing and operation phases.

Information regarding the emissions of substances during this stage is collected from previous studies and life cycle inventory databases [32,42,52-54]. The average emission factors considered in this study are listed in table 4.6.

Table 4.6: Emission factors for the production of the raw materials (Grams per kilogram of material) [32,42,52-54]

g/kg material	CO_2	CO	NOx	SOx	CH_4	PM
Primary Steel	1180	0.0547	1.49	1.52	4.04	1.5
Aluminium	8566	3.08	14	34.2	14.32	9.49
Copper	4200	6.3	38	360	3.6	40
Synthetic Rubber	3178	0.5	5	20	0.12	5
Float glass	130	-	3.6	0.81	-	-
Plastics (general)	3500	0.59	3.7	20	0.13	0.33
ABS	3050	5	5.5	8	30	2.19
PVC	2130	2.6	5	7.6	23	1.2
PP	1670	6.1	3.3	3.8	11.8	0.6
PE	6170	0.99	6.44	36	0.22	0.15
Lead	2990	0.21	7.4	14.8	0.01	0.5

ABS= Acrylonitrile Butadiene Styrene, PVC= Polyvinyl Chloride, PE= Polyethylene, PP= Polypropylene CO_2= carbon dioxide, CO= carbon monoxide, NOx= nitrogen oxides, SOx= sulphur oxides, CH_4= methane, PM= particulate matter

Taking into consideration the material composition of the studied vehicle and the emission factors listed in table 4.6 the contribution of selected materials to the emissions of some major pollutants is calculated and presented in figure 4.5

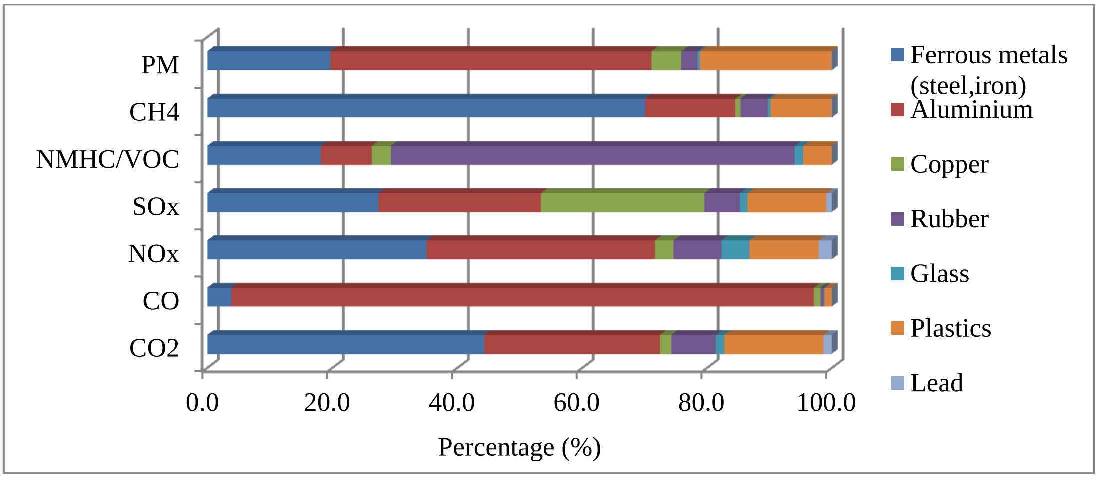

Figure 4.5: Contribution of the production of major materials found in the vehicle to the emission of selected substances in air [32,42,52-54]
PM= particulate matter, CH_4= methane, NMHC= non methane hydrocarbons, SOx= sulphur oxides, NOx= nitrogen oxides, CO= carbon monoxide, CO_2 =carbon dioxide

The production of steel and aluminium parts is responsible for the biggest share of the majority of the substances presented in the previous graph. This can be explained from the fact that added together they represent more than 70% of the materials used by the automobile industry and are essential for the production of the vehicle. Furthermore, production processes for steel and aluminium have high energy demand [5,40,42,54].

However, the percentage of scrap materials entering the production process tends to increase, something that can lead to lower emission rates [5,6,56].

As a *resource converter* the automobile sector is shown to have the lowest impact on the environment. Almost in all cases of the emissions presented, the manufacturing and assembly activities result to lower rates compared to the other two stages (figure 4.2). Energy production in order to meet the operation needs of the plant is the major contributor of those releases. Detailed figures on the distribution of emission levels to the various activities in the assembly plant are not available. However, it is recognised that one of the major concerns of the automobile manufacturers is the release of volatile organic compounds during the painting processes. Solvent based paints are still used by the majority of producers which are the main source of VOCs during that stage. Indicatively per painted vehicle around 1.3 to 2 kg of VOC are emitted to the air [6,49,55]. Among other air pollutants, nitrogen and sulphur oxides represent a share of 16% and 6% respectively but they are highly dependent on the energy supply of the manufacturing plant [55].

Finally, substances released into water as a result of the major activities over a vehicles life cycle are studied as well. Tables 4.2 and 4.3 at the beginning of this section present some examples of the identified substances. A detailed analysis is not possible because of the great number of processes involved, but some representative measurements include biochemical oxygen demand (BOD), chemical oxygen demand (COD), releases of oils, ammonia etc [15,42]. According to the results of this study they are significantly lower than the substances emitted in the air. However, they cannot be neglected. The contribution of the different measured substances to the life cycle stages is shown in the next figure (figure 4.6).

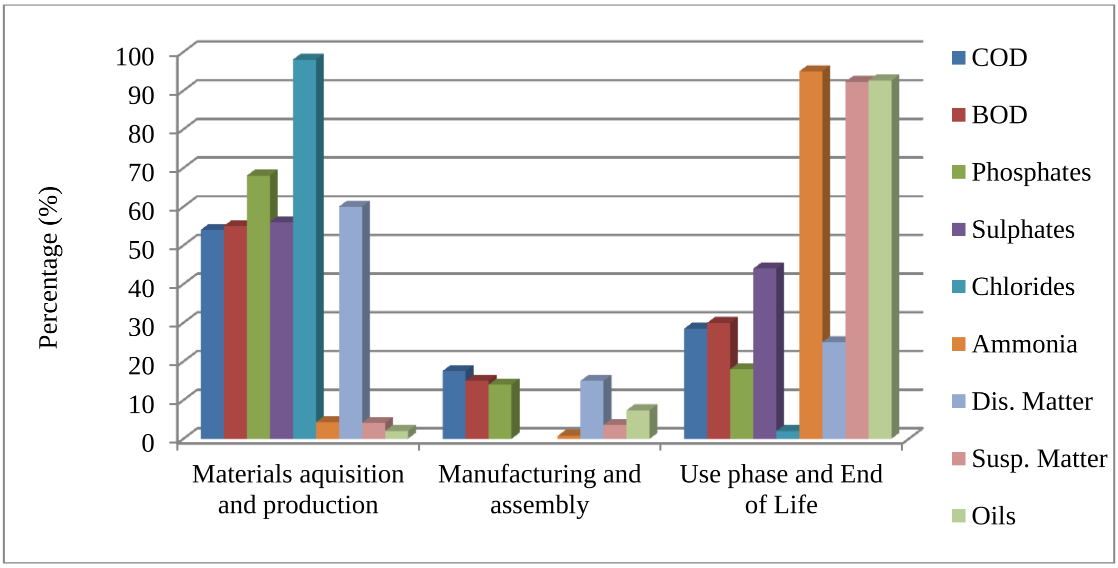

Figure 4.6: Releases of substances into water during the life cycle of the automobile
BOD= Biochemical oxygen demand, (COD) = Chemical oxygen demand

The majority of the releases as shown in the previous figure occur during the production processes of the raw materials as well as during the utilization stage of the vehicle. The manufacturing stage on the other hand, seem to be responsible for the lowest amounts possibly because of the fact that most industries nowadays have on-site wastewater treatment plants that manage to eliminate the amount of pollutants reaching the water resources [6,49-51]. Suspended matter derived the highest amount among the substances that are released to water as a result of the operation stage of the vehicle life cycle. The impact caused by mining processes is more difficult to define and control. Ground and surface water contamination is a common environmental impact connected to mining and drilling processes because of the amounts of hazardous substances released [5,6,57].

4.4 Life cycle impact on land and biodiversity

During the inventory process it was not possible to collect sufficient quantitative data concerning the impact caused by the automobile industry on land and biodiversity. It can be admitted though that the final outcome of the study will not be affected since the automobile sector do not contribute much to the impact included in this classification category. However, there are some effects that are identified and mentioned briefly below.

The acquisition of the required resources for materials and energy productions begins with *mining*. Both surface and underground mining processes are used for the extraction of coal, iron ore, bauxite ore etc. Mining processes can have local but also global effects. Some of the most important local impacts resulting from mining processes are: landscape deterioration, damage of areas used for vegetation, deforestation, occupation of large excavation areas, changes in land use, changes to hydrological and geological characteristics of the local area etc. [5,6,58]. At a more global level, mining processes may lead to extinction of both plant and living species contributing to the irreversible deterioration of the biodiversity. The same impacts are caused from *drilling* processes which are necessary in order to derive the oil that is needed for almost all activities connected to the automobile production [5,6,58].

Land occupation is also connected to *landfill* as a method of waste final disposal. Waste is produced in every stage of the vehicle's life cycle and there is a considerable flow of materials that are disposed to landfills.

Finally, the necessary *infrastructure* such as buildings and road networks can be critical parameters when measuring the impact on this classification category (land occupation and deterioration of landscape are some common effects). However, it is assumed that the present infrastructure is an essential component of the system and that the automobile sector has limited influence on the issues discussed above.

4.5 Energy and resources (efficiency and scarcity)

The last classification category evaluates the use of resources during the different life cycle stages of the vehicle. The focus is on non-renewable and finite ones therefore, efficient use and scarcity need to be considered. For the automobile sector resource efficiency can be evaluated by examining the amount and type of resources used for energy production among the various processes and life cycle stages. Additionally, the same estimations should be made regarding the materials extracted from Earth's crust which are used for the production of the vehicle. Scarcity depends on the availability of the needed resources but is related and affected by the efficient use of those resources by the sector as well.

Table 4.7 illustrates the estimations for the energy demands over life cycle stages as well as the different sources used in order to cover those demands. Again, the actual numbers might differ due to the fact that only general data are obtained and converted in relation to properties of the studied vehicle in an attempt to get an overall picture of the impact.

Characteristics that vary with the location such as the energy supply system for the manufacturing plant and the materials production processes were not examined in detail during the inventory process although most of the data collected refer to average European or US conditions.

Table 4.7: Inventory results for the life cycle use of resources in order to cover the energy demands of the automobile sector [15,37,42]

Principle 4 Resource efficiency	**The life cycle stages**				**Total**	
Measurements	**Material acquisition**	**Resource conversion**	**Use phase and End-of-life**			
			Gasol.	**Diesel**	**Gasol.**	**Diesel**
Energy demands					**(GJ/car)**	
Oil	4%	0.43%	95.5%	95%	**420.7**	**381**
Natural gas	49.4%	14.1%	36.5%	36.5%	**45.5**	**45.5**
Coal	79.4%	10.3%	10.3%	11%	**41.5**	**41.7**
Nuclear	22%	40%	38%	37.5%	**8.22**	**8.17**
Hydro power	59%	26%	15%	16.5%	**2.31**	**2.35**
Total	14.5%	3.1%	82.4%	81%	**518.2**	**479**

The sum of the percentages presented in this table may not come to 100% due to approximations. Furthermore the colours indicate the percentage of the contribution of every measurement (M) to the different classification categories: red colour when M>50%, yellow when M ≥ 30%, blue colour when M≥20% and green colour when M≤10%

Similarly to the case of carbon dioxide and other emissions shown before, *vehicle's operation* is responsible for the greatest share of energy use the majority of which is produced from oil. The total energy demands for the gasoline case can exceed 500 GJ/car while the diesel scenario seems to be more efficient, by achieving around 8% energy saving due to the lower consumption rate presented in the beginning of this section.

The derived energy demands of the operation stage can be distributed between the production of the fuel and the actual operation and end of life stage of the vehicle. Around 39 GJ/vehicle, which corresponds to almost 8% of the total energy requirements, is used for the production of the fuel while only around 0.16% is estimated and accounted to the end-of-life treatment processes. The vast majority of 75% of energy used is connected to the utilisation phase and the demands for fuel. Figure 4.7 illustrates the share of energy that is assigned to the different life cycle stages. The data presented refer to the case when gasoline is used as a fuel. The main difference with the diesel scenario is during the operation phase as already mentioned, where the energy demand is slightly lower since fuel consumption is assumed to be also lower. However, the distribution of the total energy demand among the different stages remains almost the same.

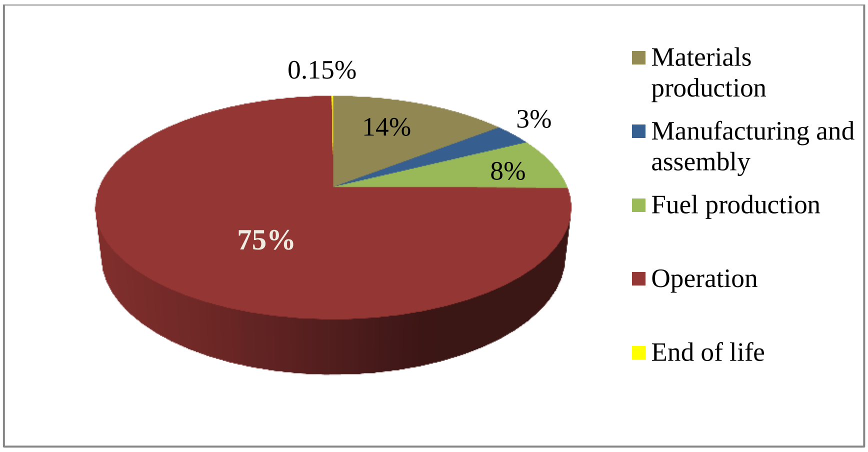

Figure 4.7: Energy demands over the different stages of the vehicles life cycle (gasoline scenario)

The *production of materials and components* that constitute the vehicle need roughly 75GJ or 14.5% of total energy used per vehicle. This amount covers the demands for electricity and process energy. Table 4.8 presents the energy needed for the primary and secondary production of selected materials. The numbers refer to average of data collected from previous studies [5,40,42].

Table 4.8: Energy demands for the production of the needed materials [5,40,42]

Material	Primary production (MJ/kg)	Secondary production (MJ/kg)
Steel and Iron	40	30
Aluminium	217	37.5
Plastics (general)	90	40
ABS	110	51
PE	158	48
PVC	65	30
Glass	24	12
Rubber	78.5	51
Copper	94	23.5
Lead	33	6.6
Motor oil	60	-
Antifreeze liquid	76	-

Aluminium and plastic production processes seem to be the more energy demanding ones compared to steel. However, there are significant savings if recycled materials are possible to be used. Next table shows the amount of energy needed for the production of selected materials of the vehicle considered in this study both from virgin and recycled raw materials. It is derived that a reduction of 16 GJ/vehicle can be achieved if 25% of ferrous and 60% of aluminium parts are produced from recycled materials [5]. In turn, assuming that 50% recycled material is used we reach a 23% reduction. However, the savings can be higher if the calculations consider higher rates and more materials as well [40].

Table 4.9: Scenarios for energy use for the production of selected materials used in this study [5,40,42] (data refer to both fuel cases since material composition is assumed to be the same)

Material	Primary production (no recycling) (GJ/car)	Production including recycling[4] (GJ/car)	Production including recycling[5] (GJ/car)
Steel and Iron	33.8	31.7	30
Aluminium	19.7	9.9	11.5
Plastics	10.53	10.53	7.6
Glass	0.85	0.85	0.8
Rubber	4.59	4.59	3.7
Copper	1.22	1.22	0.8
Lead	0.36	0.36	0.2
Total	**71**	**60**[6]	**55**

Concluding this analysis, it is shown that in terms of resources used for energy production the automobile sector is highly dependent on non-renewable sources like crude oil, natural gas and coal. Those resources are mainly used to cover the energy needs for the operation of the vehicle but also the needs for electricity and process energy during the remaining life cycle stages. The majority of oil as primary energy source is consumed during the actual utilisation stage while coal and natural gas are mainly used during the production of the raw materials.

As stated in the beginning of this section resources need to be evaluated in terms of material flows between the environment and society as well. The focus of this study is on the vehicle, therefore materials needed for construction purposes (e.g. buildings and roads) are not examined. The composition of an average passenger car is presented in table 4.1. The necessary materials enter the system during the first life cycle stages of acquisition and processing. Usually the amount mineral ore extracted for the Earth's crust is higher than the amount of finished material obtained and several types of raw materials might be needed in order to produce one type of finished material e.g. the case of glass. Then the sector as a resource converter after the fabrication and assembly processes discussed in *section 3.4.2* use a part of the produced materials which represents the amount found in the vehicle. During the last stage of end-of-life, parts of the vehicle can be reused and recycled and become input again in several activities and processes in the society. These processes can be connected to the automobile sector or other industrial sectors, although the figures on how those inputs are allocated are not clear.

Table 4.10 presents in quantitative terms the information described so far for a selection of materials in an attempt to derive the savings and losses accounted to the automobile sector. The steps considered in this analysis are: material extraction, production of the vehicle and the end-of-life treatment process.

[4] For the estimations recycling rates for aluminium and steel are assumed: 25% for steel and 60% for aluminium [5]

[5] For the estimations 50% recycling rate is assumed for all materials

[6] This amount is lower than the total energy demands for materials production presented in table 4.7 since there are more components that are not mentioned here e.g. wood, oils etc.

Table 4.10: Material input, use and saving during selected life cycle stages of a passenger car (data refer to both fuel cases since material composition is assumed to be the same) [5,6,15,22,26,37,39,40,42,47,52-54]

Principle 4 Efficient use of materials	**Selected life cycle stages**		
	Material Extraction	**Vehicle production**	**End-of-life processes**
Measurements	**Ore/Element (kg/car)**	**Material composition of the car (kg/car)**	**End-of-life/ Reuse and Recycling (kg/car)**
Aluminium (Bauxite ore)	364	91	-86.5[7]
Ferrous (Steel/Iron)	1248	845	-828[8]
Copper	13	13	-11.5[9]
Lead	11	11	?[10]
Zinc	1.3	1.3	?[11]
Glass[12]	42.5	35.4	- 18[13]

Regarding the end-of-life stage, table 4.10 presented above, includes information about material savings only after the vehicle reaches the end-of-life treatment processes. According to regulation at the end of their life all vehicles should be treated and parts should be reused and recovered. As already mentioned almost 75% of an end-of-life vehicle is recovered and recycled during this last life cycle stage. This percentage does not include parts that are dismantled and recycled or reused separately (engine, tyres, glass etc.) [22]. It corresponds mainly to the metallic components that are recycled up to 98% in total [5,22,39,47]. The rest 25 % that remains as residue consists of plastic, glass and other substances that cannot be further separated. A small percentage can be used for energy recovery but the majority is finally disposed to landfills [22,47]. In turn, table 4.11 focuses on the end-of-life process and shows a part of the materials that are found in the automobile shredder residues and are consequently considered as material losses. The materials shown in table 4.11 are generalised and grouped according to their properties.

Table 4.11: Amount of selected materials that are disposed in landfills after the dismantling and shredding processes [22,39,47]

Material	**Content in the residue**	**Disposal in landfill**	**Rate of material that is lost**
Ferrous	8%	20 kg	2%
Non ferrous[14]	4%	4 kg	3.3%
Polymers	27%	67.5 kg	57.6%
Glass	7%	17.5 kg	49%
Rubber	7%	17.5 kg	30%

[7] Assuming that 95% of the material found in the car is reused and recycled [26]
[8] Assuming that 98% of the material found in the car is reused and recycled [22,47]
[9] Assuming that 85% of the material found in the car is reused and recycled (This rate is an assumption however, the losses of copper cannot exceed 4kg which corresponds to the total losses of non-ferrous materials)
[10] Specific information was not available
[11] Specific information was not available
[12] Glass is produced from a combination of raw materials. The composition assumed here is: 26 kg sand, 8.5kg soda and 8kg limestone for the production of 35.4 kg of glass used in the car [42]
[13] Assuming that 51% of the material found in the car is reused and recycled [22,47]
[14] Non-ferrous materials include aluminium, copper, lead, stainless steel etc. [47]

It can be derived from tables 4.10 and 4.11 that most of the ferrous of and non-ferrous metals that constitute the automobile are recovered and recycled. For the case of polymers the situation is different since the majority of plastic components have either limited recyclability or further recovering processes are not possible or economically viable [22,47]. Regarding glass recycling rates the data may vary among countries and treatment facilities and their recovery can be affected by technical or recycling-market constraints [47].

It should be mentioned here that the tables presented above (tables 4.10 and 4.11) focus on the finished product and end-of-life processes. The data shown can indicate the relationship between the amount of material that is actually used in the car and the amount that is recovered and recycled. In addition, the acquisition stage of the raw materials should also been taken into account however, it is more difficult to define the relationship between the amount of minerals extracted and the amount of material found in the vehicle since different types of resources can be used for the production of one finished material (as for example the case of glass and plastics).

During the production of the vehicle there are additional materials savings through internal recycling processes applied at the manufacturing facilities. More than 80% of metal residues from foundry and metal processing activities are recovered or recycled [49-51].

Additionally, during the inventory process information about the *waste stream* resulting from the different activities connected to the sector were collected. These data are discussed here in order to give a general overview of the situation but they are not included in the following weighting methods and ranking process. This is due to the fact that the chosen weighting methods do not provide a weighting value for estimating the impact from the produced waste.

The first stage of the life cycle, the acquisition and production of the raw materials is responsible for the production of a great amount of waste, the composition of which varies a lot since both mining processes and materials production have to be considered. However, the majority (around 80%) is mineral waste from mining processes, 2.1% is mixed industrial, 12.7% slag and ash and 0.15% hazardous waste [57]. No further indication is possible in terms of recycling or detailed composition of this stream.

Concerning the stages of manufacturing and assembly, the type of waste discussed in this study includes only process waste and not waste produced at the administration facilities by the employees. The total amount of waste produced during this step is lower compared to the other two stages (material acquisition and use phase). The composition of this stream varies since it can include hazardous and toxic waste like paint residues, used oils etc. as well as industrial waste such as packaging, wood, plastics etc. [37]. As already discussed metal residues from various activities are recovered or recycled to a great extent. According to data obtained from automobile companies, waste disposed in *landfills* is almost 12% of the total waste produced in the facilities or about 45 kg/vehicle [49-51].

The type of waste obtained during the operation and maintenance activities include solid waste like batteries, air and oil filters and used tires as well as liquid waste like engine oils, brake fluids etc. [5,6,15,22,37,47]. A significant waste stream is produced also during the end-of-life process as already shown that can reach 200 kg/vehicle [22,39]. General data regarding replacement wastes were discussed in a previous section (3.5.3). In brief, during its life cycle a vehicle will use approximately 12 tires, 3 batteries and will need 120 litters of oil all of which end up as waste [37]. Batteries and engine oils are in their majority recycled. The rate for batteries recycling is reaching 90% [47]. Old car tyres are mainly used for energy recovery before their disposal. However, the reuse of some parts of the tyre and recycling is also possible [47].

In addition to the resources discussed so far, *water* needs to be examined as well. Great amounts of fresh water (around 55 000 litres/car [15]) are used during materials acquisition through the mining processes while the next more important stage for water consumption is the actual operation phase through the cleaning processes. It is estimated that a car will need at least 15 000 litres of water for cleaning over a life time [15,37]. Wastewater in assembly facilities accounts for 65% of the fresh water entering the plant (5600 litres/car [49]) and can be either treated on-site or can be directly disposed to the municipal wastewater treatment plant [6,37,49]. This amount refers only to process water that is used during the cleaning and painting activities [37,49].

4.6 Evaluation and weighting of the inventory results

So far, the results of the study have been discussed in terms of absolute numbers deriving their magnitude according to the different classification categories and life cycle stages. The next step is to characterise and evaluate the results in a more holistic way. For this reason two ready- made weighting methods are used and applied to most of the results. The first method is Eco-Indicator '99 the second is the EPS 2000, both designed to be used in Europe therefore considering the European conditions during the creation of the weighting factors. However, the two methods have different objectives when setting the evaluation parameters as already discussed in the beginning of this report. This a fact can lead to diverse results among the two methods after their implementation [4,12].

Both weighting methods, divide the environmental impact in several categories as already listed in a previous section of this report (section 2.1.4). The procedure of weighting begins with the application of a weighting factor set by the selected method to every inventory result separately. The weighting factors used for the calculations are presented in Appendix C at the end of the report. The same measurement can be included in more than one impact category although the weighting factor will differ. The final result is an index derived after adding the individual indices obtained for every impact category.

It should be mentioned here that not all inventory results are included in the weighting process e.g. releases to water such as chlorides and dissolved and suspended matter as well as the results regarding the produced waste. The reason is that for some measurements no weighting factor is available in those specific methods. An interesting point with the implementation of the Eco-indicator method is that according to the average factors (hierarchist perspective) used in this study there is no value assigned to carbon monoxide emissions and for this reason it is not considered. Additionally, regarding the case of volatile organic compounds average weighting factors are used (indicated by the selected methods) even though the databases of both methods include specific values for compounds such as benzene, toluene, styrene etc. (which considered as volatile organic compounds). The same grouping process is applied to hydrocarbons as well. Finally, characterisation categories may present the impact by considering a fraction of the total parameters available by the two methods. Of course not all of these parameters are accounted to the automobile sector however omissions in the inventory results may exist.

Most of the results presented in the following sections refer to the case when gasoline is used a fuel. The results for the diesel scenario are partially presented when significant differences are observed (complete results for the diesel case can be found in Appendix D at the end of this report). Moreover, during the weighting processes, no recycling rates have been assumed for the minerals and resources used during the vehicle's life cycle.

4.6.1 Weighting inventory results according to the Eco-Indicator '99 method

The results after the implementation of the Eco-Indicator weighting factors to the respective inventory measurements are illustrated in table 4.12 and figure 4.8 that follow. The different colours in the figure represent the three major damage categories considered in the method. More specifically all impact categories illustrated with the blue colour refer to the general *human health* damage category. Moreover, green colour refers to *ecosystem's quality* and red colour to the damage category that evaluates the use of *resources*.

Table 4.12 presents the final index obtained for the two fuel scenarios, as well as the contribution of the different impact categories included, to the overall impact.

Table 4.12: Results after the implementation of the Eco-Indicator '99 weighting method and contribution of the different damage categories (gasoline and diesel case)

	Total index	**Human health**	**Ecosystem's quality**	**Resources**
Gasoline case	**1.72E+03**	27%	1%	72%
Diesel	**1.75E+03**	32.5%	2.5%	65%

Obviously from the derived results (table 4.12 and figure 4.8), fossil fuels extraction represents the major impact for the automobile sector followed by the impact on human health resulting from the emissions of substances that affect the respiratory system as well as effects on humans caused by climate change. Ecosystem's quality with acidification and eutrophication being the dominant effects, seem be the last concern for the sector compared to the impact caused by the use of resources.

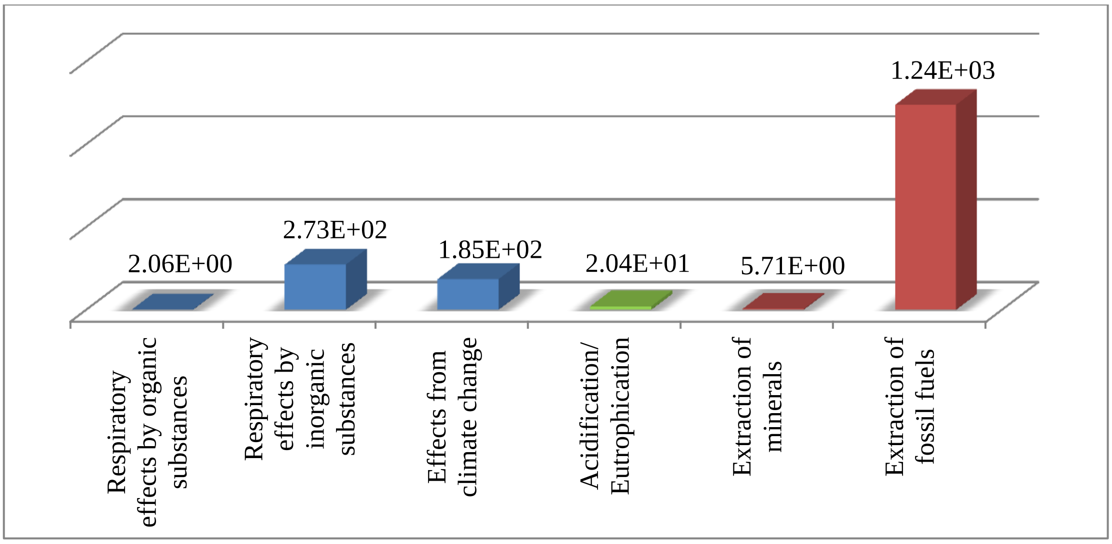

Figure 4.8: Obtained indices according to the Eco-Indicator '99 method (gasoline scenario)

Figure 4.8 showed in more detail the results of the reference case when gasoline is used as fuel in the examined vehicle. Additionally, as it was stated in table 4.12 the overall outcome of the method is the same regardless the fuel used. Resource depletion remains the dominant effect followed by the human health category. However, there are some differences observed between the two options and they are illustrated in figure 4.9 that follows.

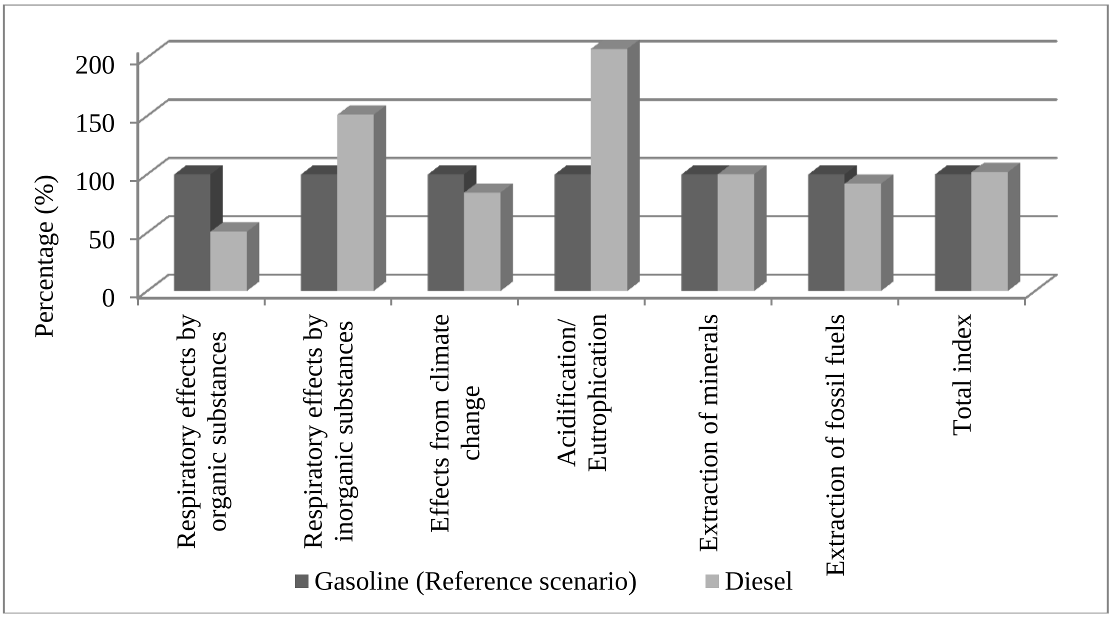

Figure 4.9: Illustration of the results obtained for different impact categories using the Eco-Indicator weighting method. Gasoline is used here as a reference case (100%) and diesel is estimated according to that.

It can be observed that for the most critical impact categories e.g. extraction of resources and effects from climate change the results for the two fuel cases are almost the same with the use of diesel as a fuel to be a slightly better alternative. Important difference is observed for the case of respiratory effects caused by organic substances due to the greatest emissions of methane and volatile organic compounds when gasoline is considered. On the other hand, for the categories of acidification and eutrophication the impact is almost the double for the diesel case compared to gasoline. Emissions of nitrogen and sulphur oxides are the major contributors to this result.

In turn, table 4.13 lists in more detail the contribution of the different measurements on the final index as they are assigned to the impact characterisation categories studied. According to this analysis the major impact of the automobile sector is possible to be derived by comparing the rates of the different measurements and their contribution to the final index.

As already shown, depletion of finite resources is the most important impact assigned to the automobile industry according to the weighted results obtained by using the Eco-Indicator method. The major contributor for this result is the extraction of crude oil, accounting for 62% of the total impact. Apart from natural gas, that is responsible for another 9%, the impact rates for the rest of the resources used by the automobile sector such as minerals and fossil fuels are relatively low.

The second most affected category according to the results shown in tables 4.12 and 4.13 is human health. Carbon dioxide emissions represent 10% of the total impact contributing mainly to the effects on human health through the consequences of climate change. Furthermore, the rates for the emissions of nitrogen and sulphur oxides are relatively high, 4.8% and 4% of the total impact respectively, resulting to respiratory problems as indicated by the characterisation categories of the method. In addition, nitrogen and sulphur oxides are affecting the quality of the ecosystem as well, through acidification and eutrophication processes.

Finally, it is observed that emissions of volatile organic compounds do not seem to be of major importance compared to greenhouse gases and use of resources, as this weighting method indicates.

Table 4.13: Contribution of the weighted inventory results and the different impact categories considered to the final index obtained according to the Eco-Indicator '99 method (gasoline scenario)

Measurements (emissions to air and resources)	Human health				Ecosystem		Resources		Total
	Carcinogenic effects	Resp. Effects (organic)	Resp. Effects (inorganic)	Effect from climate change	Eco-toxic emissions	Acidification/ Eutrophication	Extraction of minerals	Extraction of fossil fuels	
(a) CO_2	-	-	-	10%	-	-	-	-	**10%**
(a) CH_4	-	0.00%	-	0.12%	-	-	-	-	**0.12%**
(a)VOC	-	0.024%	-	-	-	-	-	-	0.024%
(a) NOx	-	-	4.8%	-	-	0.9%	-	-	**5.73%**
(a) N_2O	-	-	-	0.62%	-	-	-	-	**0.62%**
(a) SOx	-	-	4.4%	-	-	0.25%	-	-	**4.65%**
(a) HC	-	0.1%	-	-	-	-	-	-	**0.1%**
(a) Particles	-	-	6.6%	-	-	-	-	-	**6.6%**
(a) PAH	0.00%	-	-	-	0.0%	-	-	-	0.00%
(a) Lead	-	-	-	-	0.0%	-	-	-	0.00%
(r) Aluminium	-	-	-	-	-	-	0.25%	-	**0.25%**
(r) Iron	-	-	-	-	-	-	0.05%	-	0.05%
(r) Copper	-	-	-	-	-	-	0.01%	-	0.01%
(r) Lead ore	-	-	-	-	-	-	0.02%	-	0.02%
(r) Zinc ore	-	-	-	-	-	-	0.01%	-	0.01%
(r) Manganese	-	-	-	-	-	-	0.004%	-	0.004%
(r) Coal	-	-	-	-	-	-	-	0.5%	**0.5%**
(r) Oil	-	-	-	-	-	-	-	62%	**62%**
(r) Natural gas	-	-	-	-	-	-	-	9.4%	**9.4%**

The sum of the percentages presented in this table may not come to 100% due to approximations. The sign "-"means that the respective substance or resource does not affect that impact category.
(a)= emission to air, (r) = resource
CO_2 =carbon dioxide, CH_4= methane, VOC= volatile organic compounds (non-methane), NOx= nitrogen oxides, N_2O= dinitrogen oxide, SOx= sulphur oxides, HC=hydrocarbons, PAH= polycyclic aromatic hydrocarbon

As stated in the previous section not all inventory results are included in the weighting process. More specifically for releases to water such as ammonia, hydrogen chloride, phosphates etc. as well as more aggregated categories such as oils, dissolved matter etc. no weighting values were provided by the method. The situation is the same when it comes to carbon monoxide emissions and waste disposed in landfill or use of water.

4.6.2 Weighting inventory results according to the EPS 2000 method

The second method applied in this study in order to evaluate the inventory results is the EPS 2000 weighting system. This method use different weighting factors to estimate the total impact on the environment compared to the Eco-Indicator presented before and for this reason different results are expected.

The impact categories considered for the EPS methodology and included in the study are: human health, ecosystem's production capacity, abiotic stock resources and biodiversity. Table 4.14 presents the total index that is obtained after adding the different indices obtained for every impact category separately and shows also their contribution to the overall result. Moreover it includes the results for the diesel case as well which are generally the same as for the gasoline case.

Table 4.14: Results after the implementation of the EPS 2000 weighting method and contribution of the different damage categories

	Total index	**Human health**	**Ecosystem's capacity**	**Biodiversity**	**Abiotic stock resources**
Gasoline Case	**1.81E+04**	24%	1.5%	0.25%	74%
Diesel Case	**1.71E+04**	24%	0.7%	0.3%	75%

The outcome after the implementation of the EPS method indicates again that the use of abiotic resources is responsible for the greatest share on the total impact. The inventory measurements included in this category are minerals and other resources for the production of materials and energy respectively. The effect on human health is derived as the second largest category influenced by the automobile sector while the rates for the effect on biodiversity and ecosystem capacity are significantly lower. It should be noted here that the impact categories consisting the damage categories (listed on table 4.14) for the EPS 2000 method are different than the ones presented for the Eco-Indicator. EPS 2000 divides the effect on human health into life expectancy, morbidity and nuisance. Disturbances on ecosystems capacity refer to the use and deterioration of the natural resources like wood, water etc. and finally biodiversity is expressed in terms of species extinction caused by global warming.

The next figure (figure 4.10) illustrates a comparison between the results of the two fuel options according to the EPS 2000 method. Similarly to the previous case, the scenario that gasoline is used as a fuel is considered the reference case and the results for diesel are presented in relation to that. This analysis indicates diesel as a better fuel alternative for all impact categories concerned.

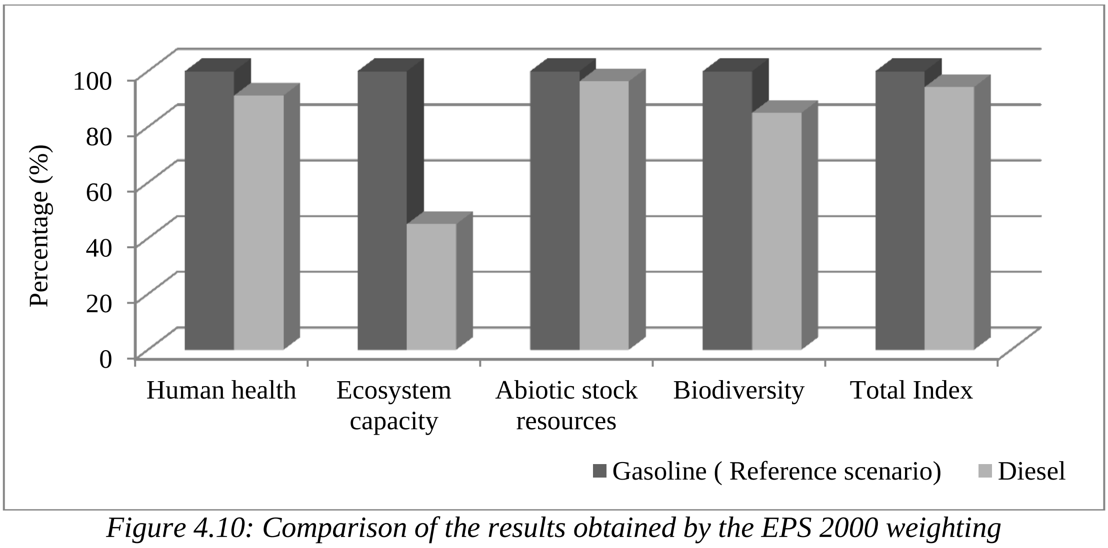

Figure 4.10: Comparison of the results obtained by the EPS 2000 weighting method for two fuel options studied (gasoline and diesel)

Finally, table 4.15 presents in more detail the substances and resources considered during the application of this weighting method and their contribution to the final index. Similarly to the Eco-indicator method shown before, the major impact of the automobile sector is possible to be derived by comparing the impact rates of the different measurements and their contribution to the final index.

Table 4.15: Contribution of the weighted inventory results and different impact categories considered to the final index obtained according to the EPS 2000 method (gasoline scenario)

Measurement	Human health	Ecosystem capacity	A-biotic stock resources	Biodiversity	**Total**
(a) CO	0.07%	0.00%		0.001%	0.08%
(a) CO_2	19%	- 0.12[15]%		0.24%	**19.2%**
(a) CH_4	0.27%	0.001%		0.003%	0.28%
(a) NMVOC	0.00%	0.185%		0.00%	0.185%
(a) NOx	0.43%	-0.005%		0.002%	0.43%
(a) N_2O	1.27%	-0.001%		0.015%	**1.28%**
(a) SOx	0.97%	0.004%		-0.01%	0.96%
(a) HF	0.001%	0.00%		0.00%	0.001%
(a) HC	0.00%	1.45%		0.00%	**1.45%**
(a) HCl	0.003%	0.00%		0.00%	0.003%
(a) Particles	2.3%	0.00%		-0.001%	**2.3%**
(w) BOD				0.00%	0.00%
(w) COD				0.00%	0.00%
(w) P-tot				0.00%	0.00%
(w) N-tot				-0.004%	-0.004%
(r) Aluminium ore			0.88%		0.88%
(r) Iron ore			4.5%		**4.5%**
(r) Copper ore			15%		**15%**
(r) Lead			10%		**10%**
(r) Zinc			0.4%		0.4%
(r) Manganese			0.3%		0.3%
(r) Coal			0.4%		0.4%
(r) Oil			29%		**29%**
(r) Natural Gas			9%		**9%**
(r) Uranium			4.4%		**4.4%**

The sum of the percentages presented in this table may not come to 100% due to approximations. The empty cells indicate that the respective substance or resource does not affect that impact category.
(a)= emission to air, (w) = release to water, (r) = resource
CO= carbon monoxide, CO_2 =carbon dioxide, CH_4= methane, NMVOC= non methane volatile organic compounds, NOx= nitrogen oxides, N_2O= dinitrogen oxide, SOx= sulphur oxides, HF= hydrogen fluoride, HC=hydrocarbons, HCl= hydrogen chloride, COD= chemical oxygen demand, BOD=biochemical oxygen demand

As already mentioned, the deterioration of abiotic resources including fossil fuels and minerals is the most significant environmental impact assigned to sector. Similarly to the results presented in table 4.13, oil consumption remains the most important impact associated to the automobile industry. However, in comparison with the Eco-Indicator, the EPS method assigns higher weighting factors to minerals, especially when they are considered as scarce.

[15] The negative sign at some of the values of the table indicates a positive impact on the environment. To this specific damage category there are substances like carbon dioxide, nitrogen oxides etc. that have a negative weighting factor which affects the overall score and means that those emissions can also contribute positively to the productivity of the ecosystem [14].

For this reason, copper and lead that are used for the production of the automobile materials are included among the most critical effects, accounting together for almost 25% of the total impact. Among the rest of minerals and fossil fuel resources, natural gas has a rate of 9% while iron and uranium account together for another 10% of the total estimated impact.

For the case of carbon dioxide emissions the outcome shows consistency with the method presented before. As a result the human heath category is influenced the most through starvation, desertification, heat stress and other pathways indicated by the EPS method. Finally, the rest of the emissions studied account for a relatively small share (lower than 1%) of the total impact. Indicatively, the impact rates for nitrogen and sulphur oxides are 0.4% and 0.9% respectively.

It should be mentioned here as well that not all inventory measurements are considered and weighted. However, less are the omissions in this case compared to the Eco-Indicator method. Carbon monoxide for example and water quality parameters like biochemical oxygen demand and chemical oxygen demand are now included while waste disposal and water use are not evaluated by the EPS method. Finally, the emissions of volatile organic compounds and hydrocarbons are grouped and average factors indicated by the method are used.

4.6.3 Total results and ranking

At a first level of analysis, the results obtained from the two methods are similar. Both methods indicate as most significant environmental impact, the depletion of non-renewable resources followed by the effects on human health. Additionally, the quality and productivity of the ecosystem does not seem to be so critically affected by the activities of the automobile sector according to the results. However, at more detailed level of evaluation the differences between the two methods are obvious but expected as well. The next table presents an overview of the results obtained from the two methods, as well as a ranking in order to highlight the ten most significant ones. The ranking begins with the most significant impact (1) to the less significant one (10) according to the obtained scores.

Table 4.16: Ranking of the results obtained after the implementation of the two weighting methods for the two fuel options

	Eco- Indicator 99		**EPS 2000**	
Ranking	**Gasoline scenario**	**Diesel scenario**	**Gasoline scenario**	**Diesel scenario**
1	Oil (r)	Oil (r)	Oil (r)	Oil (r)
2	CO_2 (e)	NOx (e)	CO_2 (e)	CO_2 (e)
3	Natural gas (r)	Natural gas (r)	Copper (r)	Copper (r)
4	Particles (e)	CO_2 (e)	Lead (r)	Lead (r)
5	NOx (e)	Particles (e)	Natural gas (r)	Natural gas (r)
6	SOx (e)	SOx (e)	Iron (r)	Iron (r)
7	N_2O (e)	Coal (r)	Uranium (r)	Uranium (r)
8	Coal (r)	Aluminium (r)	Particles (e)	Particles (e)
9	Aluminium (r)	N_2O (e)	HC	NOx (e)
10	CH_4 (e)	CH_4 (e)	N_2O (e)	Aluminium (r)

Blue category: Human Health, Red category: Resources, Green category: Quality of the ecosystem
(a)= emission to air, (r) = resource
CO_2 =carbon dioxide, CH_4= methane, NOx= nitrogen oxides, N_2O= dinitrogen oxide, SOx= sulphur oxides, HC=hydrocarbons

5 Discussion

This section presents a final overview and analysis of the derived results. In addition, it provides a brief discussion on the methodology used, pointing out some advantages and drawbacks.

5.1 Discussion on the results

The main objective of this study is to identify in qualitative and quantitative terms the environmental impacts caused by the automobile manufacturing industry. Furthermore, the obtained results have to be evaluated in a sustainability perspective in order to be able to clearly define and prioritise the environmental effects.

The amount of data collected through the literature research examine all life cycle stages of the vehicle and are divided to three major classification categories. The categories were selected according to the sustainability constraints and principles that consider ecosystems assimilation capacity, availability of land and availability of resources.

The first classification category examines a number of substances and their releases to air and water as a result of the different activities connected to the sector. According to the obtained results the substance with the highest emission rate is *carbon dioxide*. Releases of carbon dioxide occur throughout the whole life cycle of the vehicle but mainly during the actual utilisation stage of the vehicle. The amount of carbon dioxide emissions derived in this study is obviously higher if we consider the total number of cars been in use today that result to more than 7% of all human caused carbon dioxide emissions [29]. Governments through regulation schemes are pressing car manufacturers for lower emission rates, especially during the utilization stage [6,31,35]. Manufacturers on the other hand, in order to comply with those measures, are investing in new technologies and materials that would reduce the emissions and consequently would improve their environmental performance as a sector [49-51]. Among other solutions, they are constantly increasing the share of aluminium, plastics and other light materials in their models in order to become more efficient in terms of fuel consumption and achieve lower emission rates [5,6,27,56,59]. When it comes to technologies that could replace the conventional internal combustion engines, electric vehicles are the ones that have already started to evolve.

The rest of the studied emissions are much lower in absolute numbers varying between some grams to 100 kg per vehicle. Among them, *hydrocarbons* (excluding methane), *sulphur* and *nitrogen oxides* (mainly as SO_2 and NO_2) and *carbon monoxide* are the most significant ones. The major sources behind these emissions are the production process of the automobiles fuels, the exhaust emissions during vehicles utilisation and the production of energy in order to cover the demands for electricity during the production of the vehicle. The actual emission levels for carbon monoxide vary significantly among other studies but as the results show they are highly connected to the production of the different raw materials and to the operation stage of the vehicle [5,15,32,37].

Regarding the operation stage of the vehicle, it has to be mentioned that emissions presented are based on average data. The emission rates for substances during fuel combustion are highly dependent on different parameters such as the model of the car, the speed and generally the driving behaviour, and fuel consumption which are generally difficult to define. However, comparison with previous studies, show consistency with the results presented in this report, in terms of emission rates of selected substances during the utilisation stage [27,37].

The greatest *uncertainties* during the inventory process are connected to the substances released to water over the life cycle stages of vehicle and their actual levels. There are several industrial sectors apart from the automobile's (steel, plastics, aluminium industry) and different processes (mining, assembly, end of life treatment) that are responsible for those emissions therefore, allocation of the impacts to specific activities was difficult and the details required out of the objectives of this thesis. It is shown however, that the majority of such releases occur during the production of raw materials although, the levels in total are rather low compared to emissions in the air.

Among several studies connected to the automobile sector and more specifically to the environmental concerns, there is a great on-going research and discussion regarding the materials that constitute the vehicle [41,59]. However, most of the times they are design oriented, focusing on substitution possibilities of one material option to another in order to compensate the impact connected to the vehicles utilisation phase. Less are the cases when the materials production itself is discussed. According to the results of this study it is the second most important contributor to the environmental impacts caused by the sector in a life cycle perspective and furthermore the activities involved can be related to all three sustainability constraints considered. More specifically, ecosystems assimilation capacity is highly affected by materials production through the generation of great amounts of emissions. Among the materials used in the vehicle aluminium, copper and plastics production present the highest emission rates per kilogram of virgin material produced. Furthermore, mining of the necessary minerals, even though it is only qualitatively covered in this study, plays a vital role to the limitations regarding the availability of land. Surface mining processes occupy large areas of land and entail changes to its initial use [5,6,58]. Finally, resource use and consumption leading to fossil fuels and minerals depletion is considered as the major impact connected to this stage, especially when recycling rates of some materials e.g. plastics, remain low and primary production processes continue to dominate. As a consequence, materials substitution should be discussed also as a solution to reduce the impact from their production.

Land and biodiversity disturbances are referring to the second classification category examined in the study. Both concepts are essential for sustainable development and need to be considered since land use and species extinction are some of the major concerns for the present and future generations [5,6,58]. However it can be shown that the automobile sector do not seem to be responsible for significant effects on this classification category, in comparison to other industrial sectors like forestry and paper or food industry that are highly dependent on land and ecosystems productivity. As already discussed materials acquisition processes may lead to land deterioration and species extinction but is actually the mining sector that has the greatest share of responsibility. The automobile industry can only influence these impacts to a certain extent. The same conclusions are derived for the infrastructure. Roads are essential components of the automobile industry therefore are not referred as impact in this study.

The last classification category examined use of natural resources among the activities of the sector. From the derived results it is shown that the automobile sector is an energy demanding industry with the operation stage of the product using the vast majority of oil consumed in order to cover its needs for fuels.

Overall during the life cycle processes energy demands are covered by non-renewable sources like coal, natural gas and petroleum. Furthermore, electricity production is also based on those resources. Indicatively, the average global electricity mix the year 2004 was 40% coal, 6.7% oil, 19.5% natural gas, 15.7% nuclear and 18% renewable sources (mainly hydro power) [60]. Solutions to reduce this great dependence of the sector on finite resources and especially oil come from the introduction of alternative and more environmental friendly fuels and vehicle technologies that could replace conventional diesel and gasoline combustion. Ethanol as alternative fuel, electric and fuel cell vehicles are some indicative examples. However, all alternatives should be further evaluated in a sustainability and life cycle perspective to measure the overall benefits and also ensure that they are not introducing new problems for the sector.

The responsibility regarding the deterioration of minerals is divided between two interconnected life cycle stages. The first one is obviously the materials acquisition stage. Most of the ferrous and non-ferrous materials used in the car are abundant in Earth’s crust however, they are not infinite and their replacement may require thousands of years. Copper, lead and zinc are among the scarcest materials found in the automobiles [5]. The second one refers to the early designing activities as well as the end of life processes both considered as parts of the utilisation stage of the vehicle or when the sector is the supplier of the product and services.

From the existing practices mainly when it comes to Europe around 15% of the vehicle’s total weight will end up as waste and will be disposed in a landfill [22,47]. The data show that almost 98% of the metallic parts are recovered [22,47]. However, around 200 kg of materials per vehicle will end up as waste. This stream consists mainly from the different types of plastics and other materials that have limited recoverability. The trends of the automobile industry show that the amount of polymers and composites in vehicles is constantly increasing which leads to two controversial results. On one hand there is an improvement in fuel economy thus reduction in energy demands for the operation stage, but on the other hand there is an increase in the waste stream and the energy demands for the materials production stage as well. For this reason there is a need to incorporate recyclability and recoverability possibilities in the early designing processes of the vehicle in order to reduce the impact caused from material losses as well as waste creation.

Other resources apart from minerals can also benefit if recycling rates are increased. It is shown that at least 15% of energy reduction can be achieved if a small share of steel and aluminium is produced from recycled material while the energy savings can reach more than 25% if half of the materials used come from secondary production. It should be mentioned though, that those savings are lower (2% to 4%) when considering the lifetime energy used and in that case focusing on reductions during the use phase can lead to more significant earnings on the overall impact of the sector.

The discussion so far has been focused on the two life cycles stages that tend to cause the largest impact on the environment. The stage of assembly and production of the vehicle seem to be less critical however, the painting process as part of the vehicle production chain is discussed and assessed in several studies. The most important impacts during the traditional (solvent based) painting processes are the emissions of volatile organic compounds as well as the energy requirements of this step [6,55]. According to information collected from automobile manufacturers, environmental management systems have been adopted, thus the impact of several activities at the assembly plant can be more easily controlled and reduced. Increased share of renewable energy sources, on site recycling, capture and treatment of air emissions and on-site treatment and recycling of waste water are some common practices followed by the majority of producers at the manufacturing plants [49-51].

Transportation and distribution of the produced vehicles (and generally of all components and materials) are not included in the figures presented in this report because of their complexity and great geographical expansion although they can affect the impact of that stage when it comes to emissions and resource consumption. It can be assumed though that the overall outcome will not be affected since the results already showed that the use of resources and carbon dioxide emissions as the greatest impacts caused by sector.

Finally, it is worth to mention that the different environmental impacts occurring during the life cycle stages of the vehicle are connected and related to each other. It is shown from the derived results that the sector’s dependence on petroleum, natural gas and coal for the production of the required energy for the various processes (materials production, assembly plants, operation phase), has consequences on both emissions of polluting substances and resource deterioration. Consequently, higher dependence of the sector on these fuels would result to greater effects on the environment and society. Among others, global warming though emissions of greenhouse gases and oil scarcity are referred as most significant ones.

Concluding this part of the discussion there is a short overview of the results obtained after the implementation of the weighting methods. Both methods show consistency on their outcome which suggests the *depletion of resources* as the major impact resulting from the life cycle activities of the automobile industry. According to the Eco-Indicator 99 method the most critical contributor to that damage is the great consumption of crude oil. In addition, impact on human health is also accounted to the sector with the emissions of carbon dioxide, nitrogen oxides, sulphur oxides and particles being considered as the greatest contributors.

Similarly, the EPS 2000 method showed that the damage among resources is the most important impact caused by the automobile sector on the environment. Oil consumption remains the most significant impact among the measurements examined. Additionally, the depletion of minerals and the scarcity of some elements obtain high evaluation factors in this method. For this reason the use of copper, lead etc. is considered among the greatest impacts especially when the estimations refer to primary materials. Even though the amount of copper used in cars is not high compared to iron and aluminium, as already mentioned it is considered scarce since it is more limited in the Earth’s crust. Finally the damage on human health is considered as the second most important impact through the emissions of carbon dioxide and climate change effects.

It is generally observed that the outcome indicated by the Eco-Indicator method shows consistency with the results obtained from previous studies [5,6,27,37]. A further evaluation of the results for both methods could include a sensitivity analysis as well as consideration of recycling rates in the inventory and weighting process focusing on for the resources that obtained the highest scores.

5.2 Discussion on the methodology used

The life cycle approach is used as one of the methods in this study. Dividing the automobile sector in roles which at the same time correspond to the life cycle stages of the product make it possible to examine the majority of the activities and processes, thus reducing the possibilities for significant omissions. Furthermore, based on the sustainability constraints the parameters needed to be measured include: emissions of substances to air and water, materials efficiency in terms of use of scarce metals, resource efficiency focusing more on non-renewable resources and finally land occupation and biodiversity disturbances. These measurements are sufficient to indicate and describe the type and extent of the environmental impacts assigned to the sectors activities.

The vehicle is a high complex product therefore a complete life cycle assessment (following the framework established by the International Organisation for Standardisation) would be very complicated and time consuming. Furthermore, the goal of this study is to examine the automobile sector collectively therefore screening and evaluation of the information gathered is necessary in order to avoid spending time into details without on the other hand omitting important parameters.

The classification categories used in this study give the opportunity to consider all aspects and parameters that the sector could affect from a sustainability but also societal point of view. Even though omissions regarding the number of pollutants covered for every category may exist, we believe that they are indicative and able to lead to the major concerns of the sector. However, it has to be mentioned that there are uncertainties in the presented results since the majority of data are based on average trends and rough estimations.

The results from the two evaluation methods used showed in terms of significance what the results showed in absolute numbers. From this perspective the outcomes can be considered rather reliable. On the other hand, evaluation methods are generally based on estimations and subjective judgments therefore the results should be handled carefully and not used as the only source for conclusions.

One of the drawbacks regarding the use of weighting methods in this study is that the damage on some impact categories such as ozone depletion or land use was not able to be evaluated since the data available were limited. However, it is assumed that the total outcome would not differ significantly because of the fact that both methods value the damage caused to the finite resources higher compared to human health and ecosystem's productivity.

Finally, the two weighting methods (Eco-indicator and EPS2000) classify and evaluate the results according to different impact and damage categories than the ones derived from the methodology used in this study. It would be very interesting to examine up to what extent the outcome would be affected, if a weighting method that is based on the four sustainability principles and constraints is used.

6 Conclusions

As mentioned in the beginning of this report the main objectives of this work are:

- to describe the relevant methods existing for identifying main environmental challenges for an industrial sector
- to identify and describe the type and extent of the environmental impact for the automobile sector using qualitative as well as quantitative data
- to suggest the environmental impacts that should be mainly considered in a sustainability perspective

Starting with the first point, the methodology followed in this study is a combination of existing frameworks and assessment tools like for example the life cycle approach and the four principles for a sustainable society. The aim is to include and evaluate all relevant activities of the sector that could affect the environment in a sustainability perspective considering also constraints such as the assimilation capacity of the ecosystem as well as resource and land availability. The outcome after the completion of this first step provides the answers to the second objective.

According to the inventory results, the automobile sector is responsible for a variety of substances emitted in the air, as well as for the use of a great amount of resources (including fossil fuels and minerals). The higher rates are derived for the emissions of *carbon dioxide* and consumption of *crude oil*. From a life cycle perspective the stage that is responsible for the negative environmental performance of the sector is the *operation stage* where the share for many of the substances examined exceeds 50% and where most of the total primary energy is consumed.

The last objective of this work is fulfilled after the implementation of two weighting methods on the derived inventory results. Both methods indicate that the most important impact caused by the activities of the automobile sector is the depletion of *non-renewable resources*. The dependence of the sector on crude oil in order to cover the energy demands during the use phase of the product contributes mostly to this result. On the other hand the automobile industry is more efficient when it comes to the use of materials since recycling rates especially for the metallic compounds of the car are high.

The second most important impact indicated by the weighting methods is connected to the high emission levels of *carbon dioxide* and *nitrogen oxides* as well. The capacity of the ecosystem to assimilate human made and natural releases is affected, having as a result the accumulation of pollutants that lead to global warming, effects on human health, eutrophication etc.

Land and biodiversity do not seem to be significantly disturbed by the automobile industry compared to the damages caused to resources and the quality of the ecosystem. However, it should be noted that the impact was not quantitatively measured and evaluated and also effects resulting from infrastructure were not considered.

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Appendix

Appendix A: Material composition of a generic passenger car

Table A1 Material composition of a generic passenger car [15]

Plastics		
Material	**Mass (kg)**	**Mass (%)**
ABS-PC (acrylonitrile butadiene styrene-polycarbonate blend)	2.8	0.18
Acetal	4.7	0.31
Acrylic Resin	2.5	0.16
Acrylonitrile Butadiene Styrene (ABS)	9.7	0.64
Acrylonitrile Styrene Acrylate (ASA)	0.18	0.012
Epoxy Resin	0.77	0.050
PA 6-PC (polyamide-polycarbonate blend)	0.45	0.030
Phenolic Resin	1.1	0.072
Polyamide (PA 6)	1.7	0.11
Polyamide (PA 66)	10	0.67
Polybutylene Terephthalate (PBT)	0.37	0.024
Polycarbonate (PC)	3.8	0.25
Polyester Resin	11	0.75
Polyethylene (PE)	6.2	0.40
Polyethylene Terephthalate (PET)	2.2	0.14
Polypropylene (PP)	25	1.6
Polypropylene (PP, foam)	1.7	0.11
Polystyrene (PS)	0.0067	0.00044
Polyurethane (PUR)	35	2.3
Polyvinyl Chloride (PVC)	20	1.3
PP-EPDM (polypropylene-ethylene propylene diene monomer blend)	1.10	0.0067
PPO-PC (polyphenylene oxide-polycarbonate blend)	0.025	0.0017
PPO-PS (polyphenylene oxide-polystyrene blend)	2.2	0.14
Thermoplastic Elastomeric Olefin (TEO)	0.31	0.020
Total Plastics:	**143**	**9.3**

Metals (Non-Ferrous)		
Material	**Mass (kg)**	**Mass (%)**
Aluminum Oxide	0.27	0.018
Aluminum (cast)	71	4.663
Aluminum (extruded)	22	1.438
Aluminum (rolled)	3.3	0.2
Brass	8.5	0.55
Chromium (Cr)	0.91	0.06
Copper (Cu)	18	1.1
Lead (Pb)	13	0.85
Platinum (Pt)	0.0015	0.0001
Rhodium (Rh)	0.00029	0.000019
Silver (Ag)	0.0034	0.00022
Tin (Sn)	0.067	0.0044
Tungsten (W)	0.011	0.00073
Zinc (Zn)	0.32	0.021
Total Metals (Non-Ferrous)	**138**	**9**

Metals (Ferrous)		
Material	**Mass (kg)**	**Mass (%)**
Ferrite (Fe)	1.5	0.10
Cast Iron (Fe)	132	8.59
Pig Iron (Fe)	23	1.48
Steel (cold rolled)	114	7.46
Steel (EAF)	214	13.94
Steel (galvanized)	357	23.29
Steel (hot rolled)	126	8.23
Steel (stainless)	19	1.23
Total Metals (Ferrous)	985	64

Fluids		
Material	**Mass (kg)**	**Mass (%)**
Automatic Transmission Fluid	6.7	0.44
Engine Oil (SAE 10w-30)	3.5	0.23
Ethylene Glycol	4.3	0.28
Glycol-Ether	1.1	0.069
Refrigerant (R 134a)	0.91	0.059
Unleaded Gasoline	48	3.1
Water	9	0.59
Windshield Cleaning Additives	0.48	0.031
Total Fluids:	**74**	**4.8**

Other materials		
Material	**Mass (kg)**	**Mass (%)**
Ethylene Propylene Diene Monomer (EPDM)	10	0.68
Adhesive	0.17	0.011
Asbestos	0.4	0.026
Bromine (Br)	0.23	0.015
Carpeting	11	0.73
Ceramic	0.25	0.016
Charcoal	0.22	0.014
Corderite	1.2	0.081
Desiccant	0.023	0.0015
Fiberglass	3.8	0.025
Glass	42	2.8
Graphite	0.092	0.006
Paper	0.20	0.013
Recycled Textile Fibers	12	0.78
Rubber (except tire)	23	1.5
Rubber (extruded)	37	2.4
Sulfuric Acid (H2SO4)	2.2	0.14
Tire	45	3
Wood	2.3	0.15
Total Other Materials:	**192**	**13**
Total Weight of Generic Vehicle:	**1532**	**100**

Appendix B: Calculations for the estimation of emissions during the production of gasoline and diesel

Tables 4.4 and 4.5 of this report present the emissions during the production of the two fuel scenarios (gasoline and diesel). For the calculations the equations shown below and data from tables 3.7 and 3.8 which were presented in Section 3.4.3, are taken into consideration.

$$T_f\,(l) = fuel\ consumption\left(\frac{l}{100km}\right) \times life\ time\ distance\ travelled\ (km) \quad (2)$$

Where:
T_f: Total volume of fuel needed in liters,
Fuel consumption: 7.5l/100km for gasoline and 6l/100 km for diesel
Life time distance considered: 150 000 km

From the general equation of liquids' density, $\rho = \frac{m}{v}$ we can derive the mass of the needed fuel over the life time of the vehicle in order to estimate the total emissions of selected pollutants, associated with fuel production.

$$m_f(kg) = \rho(\frac{kg}{l}) \times T_f(l) \quad (3)$$

Where,
m_f: the total amount of fuel needed in kg
ρ: fuel's density; 0.74kg/l for gasoline and 0.84 kg/l for diesel [37]

Consequently the total emissions for every substance can be derived by multiplying the mass with the emission factor presented in tables 3.7 and 3.8.

Appendix C: Weighting factors used in the evaluation process according to the Eco- Indicator and EPS 2000 method

Table C1: Eco-Indicator 99 Weighting factors for the substances used in the study - Hierarchist (default) perspective

	Eco-Indicator 99		
Human health	**Impact categories**	**Substance (Emissions to air)**	**Weighting factor**
	Damage on human health caused by climate change	CO_2	5.45E-03
		N_2O	1.79
		CH_4	1.41E-01
	Respiratory effects by organic substances	CH_4	3.32E-04
		NMVOC	3.32E-04
		HC	1.68E-02
	Respiratory effects by inorganic substances	NOx	2.3
		SOx	1.42
		Particles	2.86
	Carcinogenic effects on humans	PAH	4.42
Ecosystem quality	**Combined effect acidification/ eutrophication**	NOx	4.45E-01
		SOx	8.12E-02
	Damage caused by eco-toxic emissions	PAH	6.08E-05
		LEAD	198
Resources	**Resources**	**Resource**	**Weighting factor**
	Extraction of minerals	Bauxite ore	1.19E-02
	Extraction of minerals	Iron ore	6.90E-04
	Extraction of minerals	Copper ore	9.87E-03
	Extraction of minerals	Zinc	9.73E-02
	Extraction of minerals	Lead	2.63E-02
	Extraction of minerals	Manganese ore	3.35E-03
	Extraction of fossil fuels	Coal	5.99E-03
	Extraction of fossil fuels	Natural Gas	1.08E-01
	Extraction of fossil fuels	Crude oil	1.40E-01

Table C2: EPS 2000. Weighting factors for the substances used in the study

EPS 2000		
Impact categories	**Substance**	**Weighting factor**
Human health	(a) CO	3.28E-01
	(a) CO_2	1.09E-01
	(a) N_2O	3.78E+01
	(a) CH4	2.69E+00
	(a) NMVOC	2.14E+00
	(a) HC	2.14E+00
	(a) HF	2.07E+00
	(a) NOx	2.15E+00
	(a) SOx	3.28E+00
	(a) Particles	3.60E+01
	(a) HCl	2.12E+00
Ecosystem capacity	(a) NOx	2.70E-02
	(a) SOx	1.51E-02
	(a) CO	-1.99E-03
	(a) CO_2	-6.96E-04
	(a) CH_4	5.62E-03
	(a) N_2O	-1.51E-02
	(a) HF	2.59E-02
	(a) HCl	2.59E-02
Biodiversity	(a) CO	4.16E-03
	(a) CO_2	1.39E-03
	(a) CH_4	3.40E-02
	(a) NOx	8.25E-03
	(a) N_2O	4.55E-01
	(a) SOx	-3.24E-02
	(a) HF	-1.90E-02
	(a) HCl	-2.07E-02
	(a) Particles	-5.73E-04
	(w) BOD	2.01E-03
	(w) COD	1.01E-03
	(w) N-tot	-3.81E-01
	(w) P-tot	5.50E-02

EPS 2000		
Impact categories	**Resource**	**Weighting factor**
Abiotic stock resources	(r) Aluminium ore	4.39E-01
	(r) Iron ore	9.61E-01
	(r) Copper ore	2.08E+02
	(r) Zinc ore	5.71E+01
	(r) Lead ore	1.75E+02
	(r) Manganese ore	5.64E+00
	(r) Coal	4.98E-02
	(r) Natural Gas	1.10E+00
	(r) Crude oil	5.07E-01
	(r) Uranium	1.19E+03

(a)= emission to air, (w) = release to water, (r) = resource

Table C3: Energy content of selected fuels used for the necessary conversions

Fossil Fuel	Energy content
Natural gas	30.3 MJ/kg
Coal	29.3 MJ/kg
Crude oil	41 MJ/kg

Appendix D: Presentation of the weighting results for the diesel scenario

Table D1: Contribution of the weighted inventory results and different impact categories considered to the final index obtained according to the Eco-Indicator method (diesel scenario)

Measurements (emissions and resources)	Human health				Ecosystem		Resources		**Total**
	Carcinogenic effects	Resp. Effects (organic)	Resp. Effects (inorganic)	Effect from climate change	Ecotoxic emissions	Acidification/ Europhication	Minerals extraction	Fossil fuels	
(a) CO_2	-	-	-	8.63%	-	-	-	-	**8.63%**
(a) CH_4	-	0.00%	-	0.11%	-	-	-	-	**0.11%**
(a) NMVOC	-	0.02%	-	-	-	-	-	-	0.02%
(a) NOx	-	-	11.4%	-	-	2.2%	-	-	**13.6%**
(a) N_2O	-	-	-	0.16%	-	-	-	-	**0.16%**
(a) SOx	-	-	3.5%	-	-	0.2%	-	-	**3.7%**
(a) HC	-	0.04%	-	-	-	-	-	-	0.04%
(a) Particles	-	-	8.5%	-	-	-	-	-	**8.5%**
(a) PAH	0.003%	-	-	-	0.0%	-	-	-	0.003%
(a) Lead	-	-	-	-	0.0%	-	-	-	0.00%
(r) Aluminium	-	-	-	-	-	-	0.25%	-	**0.25%**
(r) Iron	-	-	-	-	-	-	0.05%	-	0.05%
(r) Copper	-	-	-	-	-	-	0.01%	-	0.01%
(r) Lead	-	-	-	-	-	-	0.02%	-	0.02%
(r) Zinc	-	-	-	-	-	-	0.01%	-	0.01%
(r) Manganese	-	-	-	-	-	-	0.004%	-	0.004%
(r) Coal	-	-	-	-	-	-	-	0.5%	**0.5%**
(r) Oil	-	-	-	-	-		-	55.1%	**55.1%**
(r) Natural gas	-	-	-	-	-	-	-	9.2%	**9.2%**

The sum of the percentages presented in this table may not come to 100% due to approximations. The sign "-" indicates that the respective substance or resource does not affect that impact category.
(a)= emission to air, (r) = resource
CO= carbon monoxide, CO_2 =carbon dioxide, CH_4= methane, NMVOC= non methane volatile organic compounds, NOx= nitrogen oxides, N_2O= dinitrogen oxide, SOx= sulphur oxides, HF= hydrogen fluoride, HC=hydrocarbons, HCl= hydrogen chloride, COD= chemical oxygen demand, BOD=biochemical oxygen demand

Table D2: Contribution of the weighted inventory results and different impact categories considered to the final index obtained according to the EPS 2000 method (diesel scenario)

Measurement	Human health	Ecosystem capacity	A-biotic stock resources	Biodiversity	**Total**
(a) CO	0.08%	0.00%		0.001%	0.08%
(a) CO_2	17.7%	-0.1%		0.22%	**17.9%**
(a) CH_4	0.25%	0.001%		0.003%	0.26%
(a) NMVOC	0.00%	0.13%		0.00%	0.13%
(a) NOx	1.09%	-0.014%		0.004%	**1.08%**
(a) N_2O	0.35%	-0.00%		0.004%	0.36%
(a) SOx	0.8%	0.004%		-0.003%	0.8%
(a) HF	0.001%	0.00%		0.00%	0.001%
(a) HC	0.00%	0.7%		0.00%	0.7%
(a) HCl	0.003%	0.00%		0.00%	0.003%
(a) Particles	3.2%	0.00%		-0.001%	**3.2%**
(w) BOD				0.00%	0.00%
(w) COD				0.00%	0.00%
(w) N-tot				-0.004%	-0.004%
(w) P-tot				0.00%	0.00%
(r) Aluminium			0.93%		**0.93%**
(r) Iron			4.75%		**4.75%**
(r) Copper			15.8%		**15.8%**
(r) Lead			11.25%		**11.25%**
(r) Zinc			0.4%		0.4%
(r) Manganese			0.3%		0.3%
(r) Coal			0.4%		0.4%
(r) Oil			27.5%		**27.5%**
(r) Natural Gas			9.7%		**9.7%**
(r) Uranium			4.6%		**4.6%**

The sum of the percentages presented in this table may not come to 100% due to approximations. The empty cells indicate that the respective substance or resource does not affect that impact category.
(a)= emission to air, (w) = release to water, (r) = resource
CO= carbon monoxide, CO_2 =carbon dioxide, CH_4= methane, NMVOC= non methane volatile organic compounds, NOx= nitrogen oxides, N_2O= dinitrogen oxide, SOx= sulphur oxides, HF= hydrogen fluoride, HC=hydrocarbons, HCl= hydrogen chloride, COD= chemical oxygen demand, BOD=biochemical oxygen demand