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Methodologies for Life Cycle Assessment of Passenger Vehicles

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METHODOLOGIES FOR LIFE CYCLE ASSESSMENT OF PASSENGER VEHICLES

By

Kyle Capitano

A Thesis
Submitted to the Faculty of Graduate Studies
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the Degree of Master of Applied Science at the
University of Windsor

Windsor, Ontario, Canada

METHODOLOGIES FOR LIFE CYCLE ASSESSMENT OF PASSENGER VEHICLES

By

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15 September 2015

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ABSTRACT

This thesis examines various guidelines for conducting LCA studies on passenger vehicles, and ultimately develops a new LCA guideline. The new guideline balances workload and capturing the major factors of the vehicle’s life cycle.

For the analysis, three guidelines were applied to multiple FCA vehicles, representing conventional and alternative fuel drivetrains. The results of each guideline were assessed for their sources of variation, and the weight of each variable on the vehicle lifecycle. From the results, the vehicle’s material breakdown, basic driving emissions, use of climate control systems, and maintenance of parts, were found to have the highest environmental impact.

The new guideline was developed and applied to the same case studies, maintaining close agreement with the previous results. The results were also compared to LCA studies from other manufacturers. Impact categories that depend on the use phase showed little variation, but production dominated categories showed large discrepancies between manufacturers.

DEDICATION

This work is dedicated to my friends and family that have supported me throughout this project. I would like to especially thank the students from the Politecnico di Torino, whose support and generosity greatly enriched the experience abroad.

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LIST OF ABBREVIATIONS

ADP	Abiotic Depletion Potential
AFV	Alternative Fuel Vehicle
AP	Acidification Potential
BEV	Battery Electric Vehicle
BMEP	Brake Mean Effective Pressure
CBG	Compressed Bio Gas
CML	Center of Environmental Science of Leiden University
CNG	Compressed Natural Gas
DE*	Germany
ELV	End of Life Vehicle
EP	Eutrophication Potential
EPD	Environmental Product Declaration
EU	European Union
EUCAR	European Commission for Automotive Research
EV	Electric Vehicle
FCA	Fiat Chrysler Automobiles
FFV	Flex Fuel Vehicle
GHG	Greenhouse Gas
GLO*	Global
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
ILCD	International Reference Life Cycle Data System
IMDS	International Materials Data System
ISO	International Organization for Standardization
JRC	Joint Research Center
KRMS	Knowledge-based Recyclable Materials System
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
LPG	Liquefied Petroleum Gas (Propane)
NEDC	New European Driving Cycle
NG	Natural Gas
NREL	National Renewable Energy Laboratory
OEM	Original Equipment Manufacturer
ODP	Ozone Depletion Potential
PCR	Product Category Rules
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
PHEV	Plug-in Hybrid Electric Vehicle
PL*	Poland
PM	Particulate Matter

POCP	Photochemical Ozone Creation Potential
REPA	Resource and Environmental Profile Analysis
RER*	Europe
SETAC	Society of Environmental Toxicology and Chemistry
THC	Total Hydrocarbon Emissions
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
TTW	Tank-to-Wheel
US	United States
US EPA	United States Environmental Protection Agency
VOC	Volatile Organic Compounds
WTT	Well-to-Tank
WTW	Well-to-Wheel

**denotes abbreviations used as geographical codes in GaBi*

CHAPTER 1

INTRODUCTION

Problem Definition

The concept of Life Cycle Assessment (LCA) originated in the late 1960's, but was not formalized until the 1990's when the United States Environmental Protection Agency (US EPA) and the International Organization for Standardization (ISO) began publishing guidelines for LCA type studies (Jensen, et al. 1997). Despite its long history however, use of LCA varies from one major industry sector to another. The automotive industry has been applying LCA tools since before the ISO standards were published, but there is still no single, agreed upon standard, besides the ISO framework, for applying LCA to entire vehicles (ACEA 2012). This lack of an agreed upon standard or guideline has led to numerous studies by multiple manufacturers, each with unique methodology, assumptions, and conclusions. Although the usefulness of LCA is generally agreed upon amongst automakers, the resulting confusion from the differing studies has left some automakers questioning the validity, and their own understanding, of LCA (ACEA 2012). It can also be difficult to compare the LCA outcomes from one manufacturer to another, or from vehicle to vehicle, which to some degree, defeats the core purpose of conducting comparative LCAs.

One such automaker coping with the growing adoption of LCA is Fiat Chrysler Automobiles (FCA). Having recently completed their first full vehicle life cycle assessment (Fiat S.p.A. 2014), FCA must now assess their newly developed LCA methodology. The specific issues include:

- Which are the most critical criteria when conducting an LCA on whole vehicles?
- How can the methodology be improved for comparability to other studies? and;
- How does their analysis method compare to those used by other manufacturers?

Thesis Objective

This thesis examines a selection of the currently published guidelines for conducting LCA. As part of the examination, each of the LCA methodologies will be applied to multiple FCA vehicles sharing a similar chassis, but with differing fuel types. Not only will this application serve to answer the questions posed above, but it will also help to increase FCA's knowledge base on the environmental impacts of their alternative fuel vehicles (AFVs). Moreover, the questions above are applicable to any automotive manufacturer applying LCA to its vehicles, and the results of this thesis will be applicable for both automakers, researchers and any original equipment manufacturer (OEM) in the auto industry.

Following the LCA studies, the current guidelines will be compared against their ability to identify the most critical criteria of the life cycle, produce reliable results for a range of scenarios, and the workload required. The thesis will then attempt to identify an ideal guideline: either by nominating one of the current guidelines, suggesting modifications, or by creating a new, unique guideline. The thesis will also comment on the applicability of the guidelines as possible bases for future regulations, or as standards for making environmental product declarations (EPDs).

Motivation

Just as automakers have had a growing interest in LCA over recent years, so too have regulators, particularly those within the European Union (EU). Global concern for climate change is growing, a trend that can be seen by the increasingly strict emissions limits being set by government units worldwide (Figure 1). At the same time, regulators are becoming increasingly aware of not just global warming, but of all environmental impacts from industrial activities. This increased awareness has led to speculating whether LCA based regulations for industries may be forthcoming in the near future (ACEA 2012).

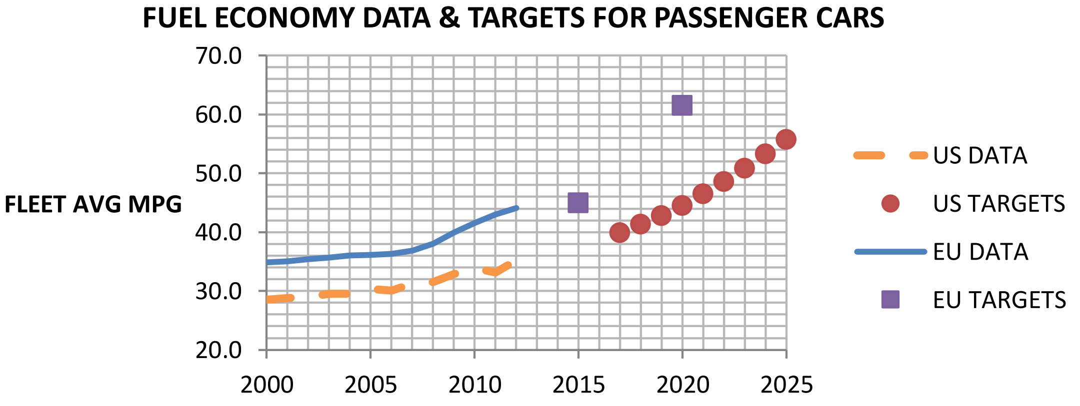


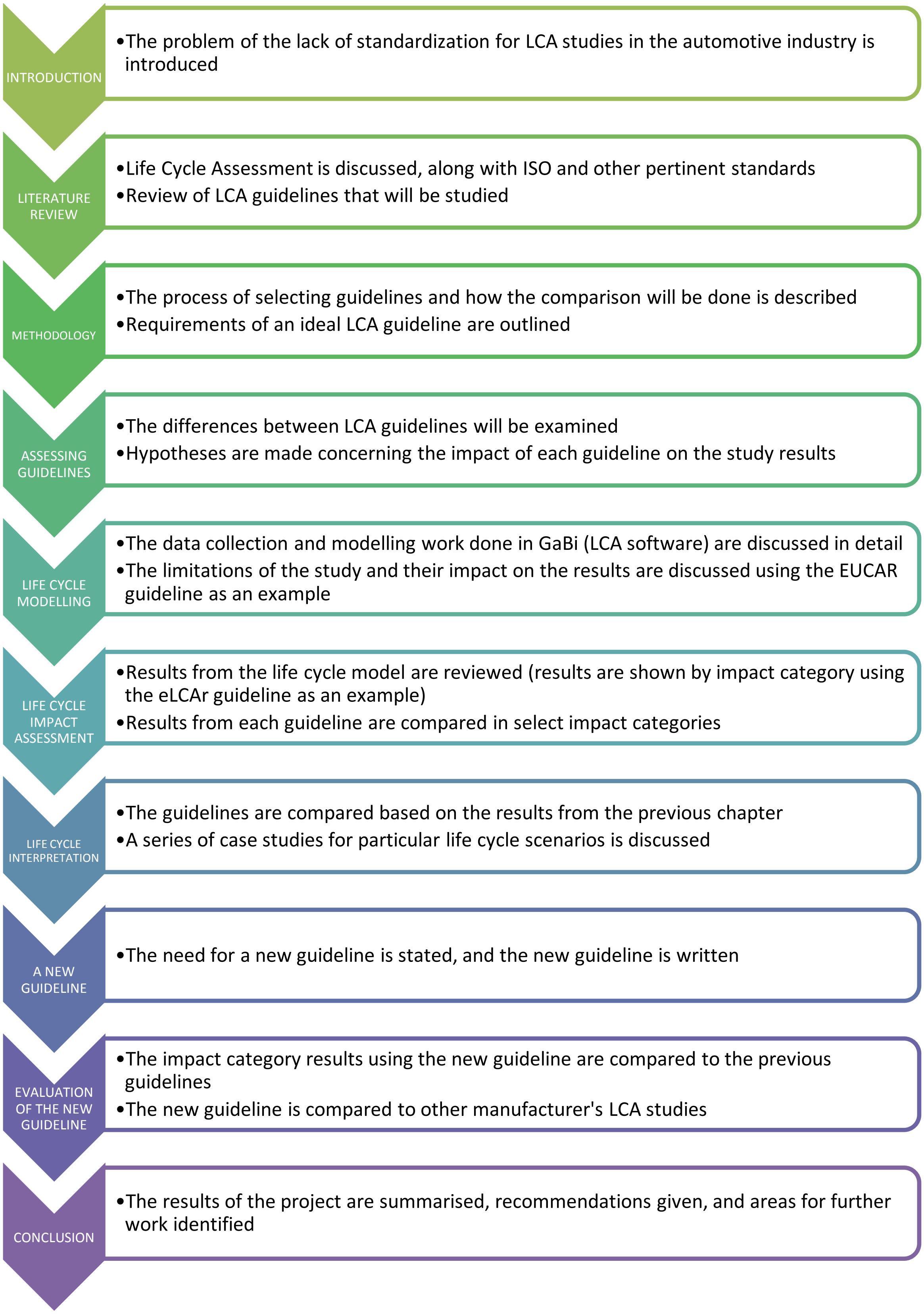
Figure 1: Trend of fuel economy vs. time in the US and EU with projection of future regulations. Data taken from multiple sources: (Alson, Hula and Bunker 2013), (European Environment Agency 2013), (Department of Transportation 2012)

In addition to environmental protection, regulators are concerned with environmental product declarations (EPDs). Companies regularly use EPDs to describe or advertise the environmental benefits of their products over competitors, so it is necessary that the EPD process generates results that are both accurate and consistent. A good understanding of LCA methodology can assist regulators to ensure the EPD process meets these requirements, as well as giving automakers a competitive advantage should standards become a reality. The first set of product category rules (PCRs) for passenger vehicles was released in 2005, but has now expired and may be replaced (EPD International AB 2015). In 2015, the European Commission is currently in the pilot phase of a program to develop standards for writing EPDs, known as the Product Environmental Footprint (PEF) program (European Commission 2014).

The automotive market place is also changing. Automakers are diversifying their brand images, and marketing their company's sustainable initiatives. LCA studies generate reputable data that companies can use for reporting initiatives and progress on a company-wide level. Publications such as Fiat's yearly "Sustainability Report", and the company's inclusion in third party analyses such as the Dow Jones Sustainability Index, are becoming increasingly important to their growth strategy.

Methodology in Brief

To conduct the analysis proposed in this thesis it was first necessary to review the current literature on LCA methodologies and, in particular, any guidelines that are specific to automotive applications. They were compared to identify the differences between their suggested criteria, and their scope of analysis. These methodologies were then applied to a set of FCA vehicles, through which the effect of the criteria and scope of each methodology was determined for a wide range of analysis scenarios. Deeper investigation into the results of the LCA revealed exactly which criteria, for which scenarios, have the greatest, or least, impact on the outcome of the study. The need for a new guideline was then evaluated. Finally, the new guideline was developed and applied to the original vehicles, to assess the difference between the original guidelines and the new one. The new guideline was also compared against LCA study results published by other automakers. The flowchart on the following page illustrates the workflow through each chapter, detailing the contribution of each chapter to the whole.



INTRODUCTION	•The problem of the lack of standardization for LCA studies in the automotive industry is introduced
LITERATURE REVIEW	•Life Cycle Assessment is discussed, along with ISO and other pertinent standards •Review of LCA guidelines that will be studied
METHODOLOGY	•The process of selecting guidelines and how the comparison will be done is described •Requirements of an ideal LCA guideline are outlined
ASSESSING GUIDELINES	•The differences between LCA guidelines will be examined •Hypotheses are made concerning the impact of each guideline on the study results
LIFE CYCLE MODELLING	•The data collection and modelling work done in GaBi (LCA software) are discussed in detail •The limitations of the study and their impact on the results are discussed using the EUCAR guideline as an example
LIFE CYCLE IMPACT ASSESSMENT	•Results from the life cycle model are reviewed (results are shown by impact category using the eLCAr guideline as an example) •Results from each guideline are compared in select impact categories
LIFE CYCLE INTERPRETATION	•The guidelines are compared based on the results from the previous chapter •A series of case studies for particular life cycle scenarios is discussed
A NEW GUIDELINE	•The need for a new guideline is stated, and the new guideline is written
EVALUATION OF THE NEW GUIDELINE	•The impact category results using the new guideline are compared to the previous guidelines •The new guideline is compared to other manufacturer's LCA studies
CONCLUSION	•The results of the project are summarised, recommendations given, and areas for further work identified

Figure 2: Workflow diagram for thesis chapters

CHAPTER 2

LITERATURE REVIEW

2.1 LCA Frameworks and Methodology

Evolution of LCA

The name "Life Cycle Assessment" was first adopted in 1990 during a workshop of the Society of Environmental Toxicology and Chemistry (SETAC). However, the idea was not new at the time (PE International 2015). LCA type studies first appeared in the late 1960s, in response to growing concerns over energy consumption. These early studies only considered a limited number of inputs and outputs, focusing primarily on total energy use and emissions, but also varied greatly in the assumptions and input data used (Scientific Applications International Corporation (SAIC) 2006). Interest in life cycle studies grew rapidly throughout the 70's however, and some standardized methodologies began to emerge. The first method to be published, known as Resource and Environmental Profile Analysis (REPA), consisted of a Life Cycle Inventory (LCI) of materials, energy use, and associated emissions throughout the product's life cycle (Scientific Applications International Corporation (SAIC) 2006). Through the end of the 70s and most of the 80s growth of LCA slowed, but interest remained and LCA studies slowly expanded to include impacts assessment and interpretation phases. In 1993 the US EPA published "Life-Cycle Assessment: Inventory Guidelines and Principles" and a few years later in 1997, ISO released their first standard on Life Cycle Assessment, ISO 14040. The new ISO standard incorporated requirements for defining the goal and scope of the study, inventory analysis, impact assessment, and interpretation of the results (Vigon, et al. 1993) & (ISO 2006).

Common Frameworks

The two frameworks introduced in the preceding paragraph, ISO14044 and the US EPA's "Life Cycle Assessment: Principles and Practice", have formed the basis for most LCA studies carried out since their introduction. These frameworks provide a basic format for conducting LCA on any product, process, or industry, and are both very similar in nature. The ISO framework is shown in Figure 3.

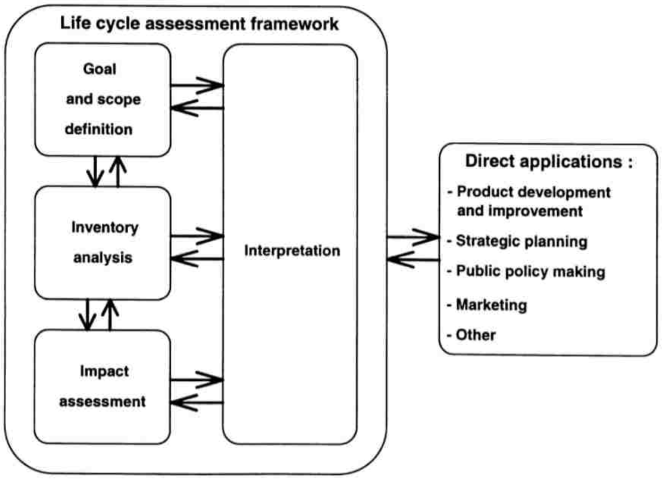


Figure 3: Phases of an LCA study, as depicted in ISO 14040 and cited by the US EPA (ISO 1997)

The US EPA framework is written mostly as a guide to suggested best practices, whereas the ISO methodology provides a slightly stricter set of analysis steps that must be carried out. Even though the creation of these frameworks has helped to standardize LCA practice, and increased the quality of LCA studies, they are too general to provide specific answers for applying LCA to a particular product (European Commission 2014). Ensuring consistently comparable LCA studies within an industry requires guidelines that are more detailed.

LCA in Detail

The basic LCA framework is comprised of four assessment phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and life cycle interpretation (ISO 2006). In the goal and scope definition phase, the goals of the study are defined as well as the functional unit, system boundaries, and data quality criteria. The ISO framework states that the goals of the study should be developed taking into consideration the intended use of the study, anticipated audience, and motivation for making the study (ISO 2006). The functional unit defines the performance specifications and the number of products associated with the material and energy inventory. Performance specifications are particularly important in comparative studies; however, this case will be discussed later. The system boundaries separate the product being studied from the surrounding environment and through them pass only elementary flows of materials or energy. Materials include both raw materials for manufacture as well as waste emissions such as CO_2 or VOCs, and the inventory does not discriminate with respect to the material state (ie. solids, liquids, and gases). During the inventory phase, data are collected to quantify the input and output flows for all life cycle stages, as shown in Figure 4. Both the ISO and EPA frameworks give the same suggested methods for allocating inputs and outputs in cases where manufacturing processes result in multiple products and/or co-products (Scientific Applications International Corporation (SAIC) 2006). The preferred allocation processes are unit-process division or expansion, whereby distribution of flows is determined analytically, but partitioning can also be done to approximate the distribution based off any physical principle that makes sense given the circumstance. How recycled materials are considered is somewhat unclear, particularly for open-loop recycling programs, but for closed-loop programs, both frameworks suggest crediting the recycled materials to the virgin supply.

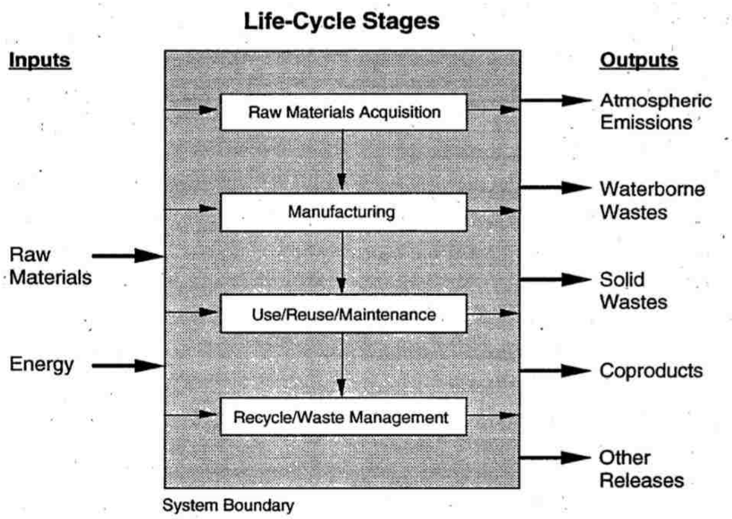


Figure 4: Life cycle stages as depicted for the inventory phase (Vigon, et al. 1993)

In regards to the impact assessment phase, both frameworks cover the same steps shown in Figure 5; however, categorization, classification, and characterization are mandatory in the ISO 14000 framework. Weighting and combining the results must always be done with caution as this involves value-choices, and are not recommended for comparative assessments by either framework (ISO 2006). The classification, characterizations, and weighting steps are necessarily complex, since similar environmental effects of different pollutants must be evaluated and balanced, and therefore many methodologies exist specifically for the LCIA phase. Depending on the impact category and specific emission, classification and characterization may also require geographic factors to account for the location of the emission or a specific ecosystem's sensitivity. A detailed evaluation of LCIA methodologies is beyond the scope of this thesis; however, a concise review of current methodologies has already been published by the European Commission's Joint Research Center (European Commission - Joint Research Center - Institute for Environment and

Sustainability 2011). For the studies conducted in this thesis, the method developed by the Leiden University Institute of Environmental Sciences (CML 2001) has been followed, as well as the methods suggested by the International Reference Life Cycle Data System (ILCD) for impact categories not used in the CML method. The CML 2001 method has been developed for a European context and is one of the most used LCIA methods available (Martinez, et al. 2015).

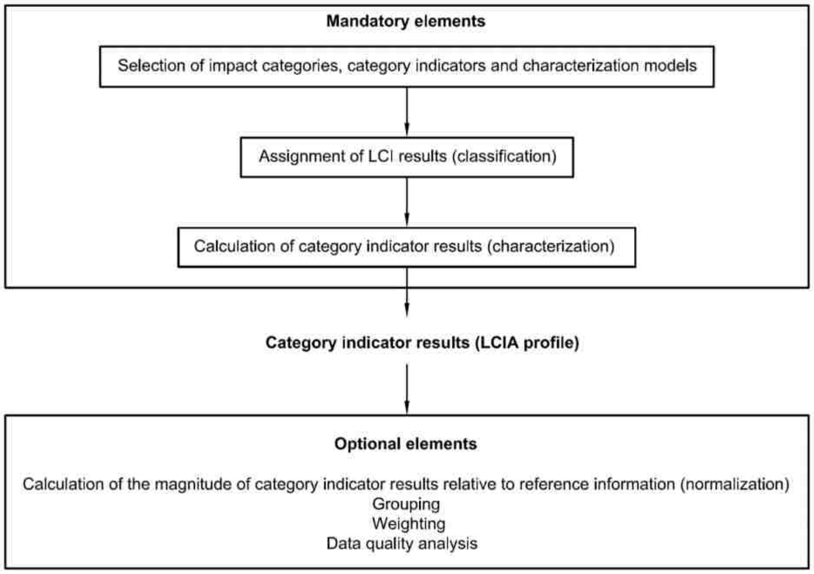


Figure 5: Mandatory and optional elements for Life Cycle Impact Assessment (ISO 2000)

The final phase of the LCA framework is the interpretation phase, which is mainly used for reviewing the completeness of the study and identifying any flaws or critical issues that may have been overlooked. During this phase, conclusions can be drawn from the results of the study and a course of action can be decided on or recommended.

2.2 LCA and the Automotive Industry

Applying LCA to Passenger Vehicles

One year after the publication of ISO 14040 in 1997, the European Commission for Automotive Research (EUCAR), printed its own guideline for the application of LCA in the automotive sector (Rover Group Ltd 1998). The **EUCAR guideline** was one of the first published documents to suggest specific methods for considering details such as; data quality, use phase conditions, and impact assessment, and it still represents a viable standard for the needs of today's automakers. At the time of its publication however, the majority of automotive LCA studies focused only on individual materials, components, or fuel cycles, (ECOBILAN S.A. 1996) and so the EUCAR guideline does not describe a full vehicle LCA in significant detail. In Chapter 4, the EUCAR guideline will be discussed in greater depth and compared to the other guidelines.

Some of the first applications of LCA to an entire vehicle are the studies by Kobayashi and Lave, published in 1998 and 2000 respectively (Kobayashi, et al. 1998) & (Lave, et al. 2000). Both of these studies are academic in nature and use generic or hypothetical data for the vehicles being considered. Kobayashi uses a detailed breakdown of typical materials found in passenger vehicles to calculate the production phase emissions, similar to the technique used by FIAT shown in Figure 6. Although simple in approach, this method represents a robust strategy for full vehicle LCA.

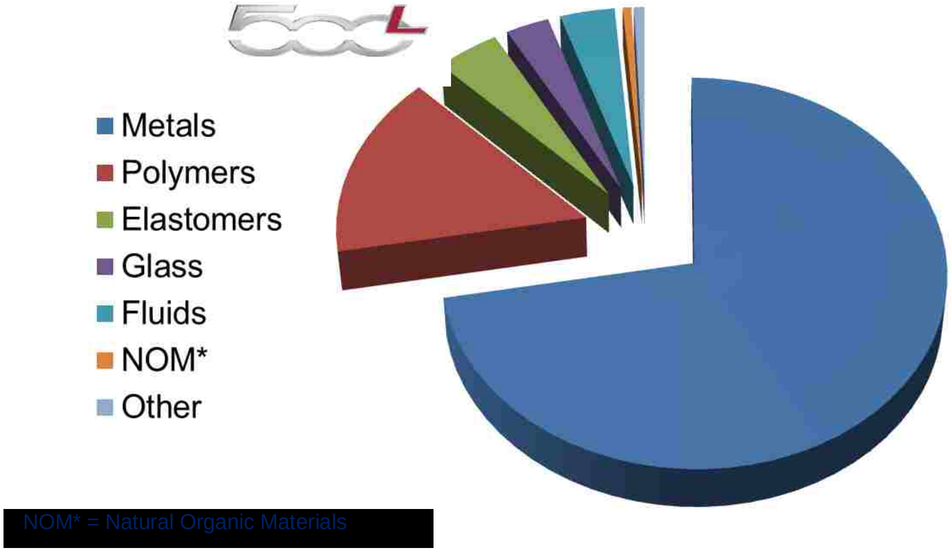


Figure 6: Material breakdown as used by FIAT in their LCA study of the FIAT 500L (Bonino, Life cycle assessment (LCA): Fiat 500L bi-fuel 2013)

The study by Kobayashi only applies LCA to a single vehicle however, while the study by Lave introduces the complexity of comparing different vehicles running on different fuel types. Of particular difficulty when comparing multiple vehicles, on different fuels, is defining a realistic functional unit while maintaining equal functionality. Indeed, the study by Lave is unable to achieve this aspect and as such considers electric and internal combustion engine (ICE) vehicles separately (Lave, et al. 2000). Many recent LCA studies by vehicle manufacturers refer to the New European Driving Cycle (NEDC), or other regulated drive cycles, for their comparisons, but they are overshadowed by the fact that electric vehicles (EVs) are not able to achieve equivalent range or top speed as their ICE counterparts; so equivalent functionality has not been achieved (Del Duce, et al. 2013). As LCA is used more frequently by OEMs, and alternative fuels gain in popularity, the problem of achieving equivalent functionality will continue to grow in importance.

Environmental Product Declarations

Environmental product declarations (EPDs) are claims made by companies regarding the environmental impact of their products. They interest both automakers and regulators because of their use as an advertising medium. Regulations for making an EPD are created by writing a set of product category rules (PCRs) that describe the method of analysis that must be done to generate the EPD. These PCRs are often based on LCA methods and could both contribute to, and benefit from, the development of LCA methodology.

In 2005, a first set of PCRs for passenger vehicles was developed under the INTEND project (Macroscopio spa 2005). Only the manufacturing and use phases are included, while end of life vehicle (ELV) treatment is neglected due to the uncertainty from open loop systems. Only the main parts of the vehicle (e.g. body, engine, gearbox) are considered, while parts that vary between vehicle's trim levels (e.g. seats, interior panels, electronics, etc…) are excluded (Macroscopio spa 2005). These exclusions simplify the PCR, but reduce the overall accuracy of the analysis. Other parameters and assumptions, such as the drive cycle, are specifically stated in the PCR, meaning results from different manufacturers should be highly comparable, but the accuracy and relevance of the analysis depend on these same assumptions. This PCR has since expired, but now it may be replaced with the outcome from the European Commission's Product Environmental Footprint (PEF) project.

The PEF project is an ongoing project by the European Commission to address the need for standardizing how product manufacturers make environmental declarations (European Commission 2014). Its three-year pilot phase was launched in 2013. The *Environmental Footprint Guidance document* states the problem with current standards:

> *"Existing life cycle-based standards do not provide sufficient specificity to ensure that the same assumptions, measurements, and calculations are made to support comparable environmental claims across products delivering the same function"* – (European Commission 2014)

The problem statement above closely resembles that of this thesis. However, the PEF project is more concerned with generating a framework for creating PCRs: what would become known as Product Environmental Footprint Category Rules (PEFCRs). Interestingly, the results of this thesis could augment or further inform the development of the PEF guide, particularly concerning the automotive sector. However, there has been resistance to the PEF program because of areas where the PEF guide has deviated from the ISO 14040 standard (Finkbeiner 2013). The PEF guide has also been criticized for not being sufficiently capable of achieving its stated objectives, namely increasing harmonization and comparability across LCA studies on similar products (Chair of Sustainable Engineering 2014).

Environmental Impacts and Understanding of Results

A key aspect of all LCA frameworks is that they not only account for the entire life cycle of the vehicle, but also that they capture a well-rounded view of the many, diverse environmental impacts associated with a product. Unfortunately, this benefit is lost when an industry becomes fixated on a single environmental impact, a problem that is apparent in the automotive industry. A typical example can be seen in Figure 7, where a presenter has illustrated the breakdown of the "environmental impact" of a typical car (Jonnaert 2015). The illustration does not describe the impact category used, but closely resembles the breakdown of the global warming potential (GWP) impact or fossil energy consumption of a typical vehicle. Given the presented information, one might assume that production and end-of-life phases are negligible, so Well-to-Wheel (WTW) methods that focus on fuel energy related impacts should be sufficient in gauging the environmental impacts of a vehicle. This conclusion would be invalid however, as it neglects other environmental impact categories, such as Acidification Potential (AP) or Abiotic Depletion Potential (ADP), which are strongly influenced by the production phase (Bonino 2015). The focus on a single indicator then increases the risk of making decisions that could result in increasing the environmental impacts in other categories.

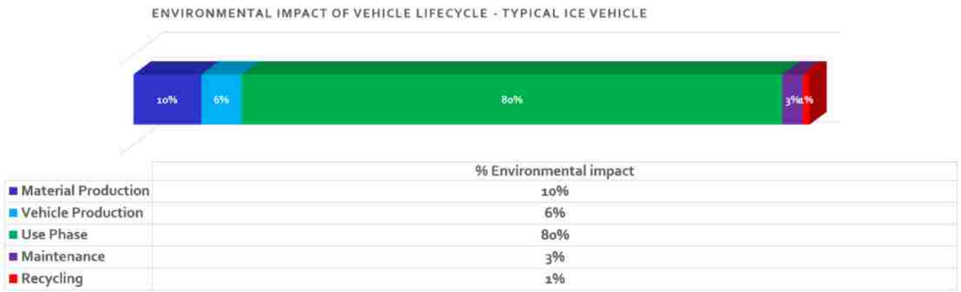


Figure 7: Considering only a single impact category can reduce the value of an LCA (Jonnaert 2015)

The problem of fixating on a single impact category is further aggravated when a lack of understanding exists within an industry. The effect of vehicle pollution on global warming has been a key topic within the auto industry for many years, so the GWP impact category is well understood by most key stakeholders. On the contrary, ozone depletion potential (ODP) is a new topic for the auto industry, as it is associated primarily with the consumption of lithium and solvents in the production of electric vehicles. The impact of the auto industry on ozone depletion is less understood than GWP, and this lack of understanding could lead decision makers within the industry to neglect the impact, or feel that it is of less importance than more commonly known impacts. Within the context of this thesis then, it will be necessary to recognize the relevance of each of the impact categories chosen, so that the intended audience can interpret and benefit fully from the life cycle analysis.

2.3 Alternative Fuel Vehicles

From a life cycle perspective, there are unique advantages and disadvantages for different types of alternative fuel vehicles (AFVs). According to a 2001 study on toxic emissions from mobile sources, vehicles running on ethanol (E85) emit substantially more acetaldehyde emissions than conventional gasoline, while formaldehyde emissions are increased by about 200% by both E85 and CNG fuels (Winebrake, Wang and He 2001). The study in question examined 14 different types of light duty vehicles; including HEVs, PHEVs, EVs, FFVs, LPG, CNG and CNG bi-fuel, and compared them across emissions of five air toxics: the three already mentioned, plus butadiene and benzene. Looking at all of the air toxic results, the battery electric vehicles (BEVs) outperformed the rest in both urban (usage phase) and total (fuel cycle) categories, while the gaseous fuels (LPG, CNG, and Bi-fuel) outperformed even the HEVs in most categories. As will be discussed later however, because EV emissions depend on the method of electricity production they are subject to variations in regional electricity supply.

The study by Winebrake, *et al.* excluded the more common air pollutants from mobile sources, such as CO_2, NO and NO_2 and chose to focus on select air toxics. A more typical study was conducted by a group at Carnegie Mellon University, which did account for life cycle CO_2 emissions by evaluating the AFVs based on global warming potential (an index created by weighting the emissions of known GHGs based on the strength of their effect and measured in kg CO_2 equivalent/vehicle lifetime) (Lave, et al. 2000). This study examined nine different fuel/engine combinations as well as conventional gasoline using the input-output LCA method, which will be discussed later in the methodology section. In order to represent accurately the fuel classes, each vehicle was compared on an equal basis, meaning each vehicle was of approximately the same size, with similar power and range. EVs are excepted because they currently lack the energy density to compete with the range of ICE vehicles. Using US data for energy generation, the EVs and HEVs showed much lower global warming potential than all other vehicles studied. The only alternative vehicles studied were dedicated CNG vehicles, but they had the least global warming potential of the ICE group. In their conclusion, the authors stated that while CNG appeared to be an attractive alternative, it is hampered by the limited energy density of the fuel. In order to achieve equivalent range to a gasoline vehicle (approx. 600km) they estimated a CNG vehicle would need to gain about 200kg in fuel, storage tanks, and supporting structure.

Battery Electric Vehicles

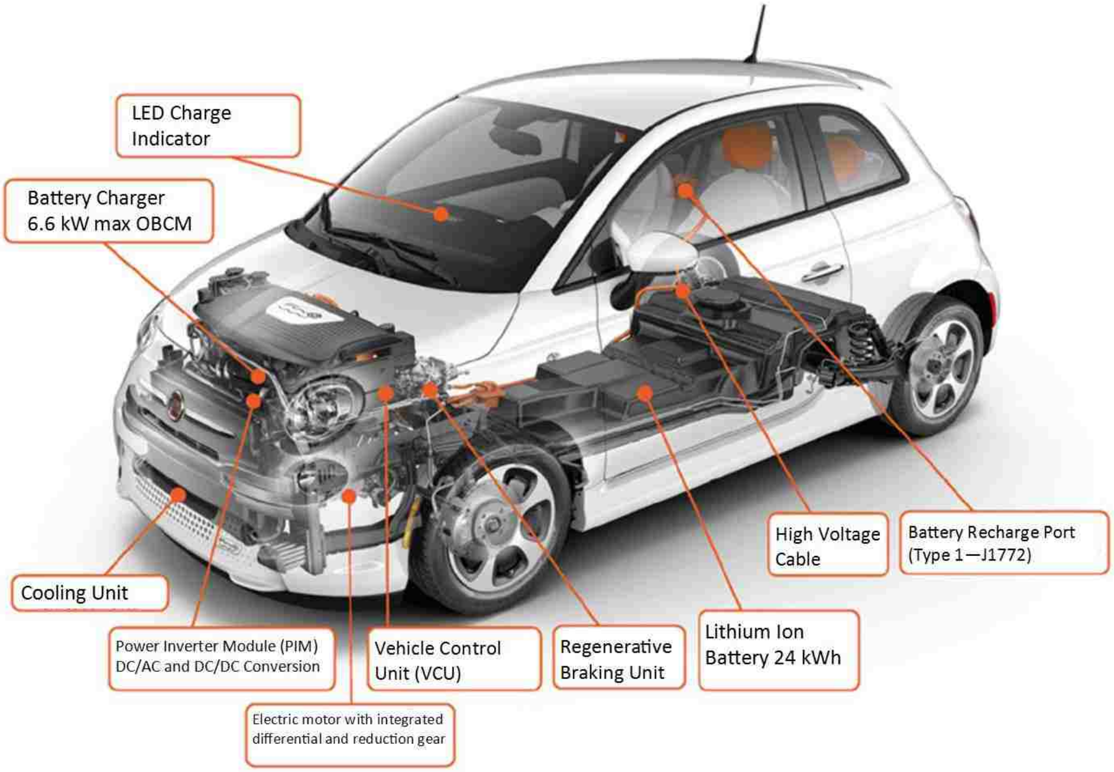


Figure 8: Illustration of the Fiat 500 electric
**The figure above has been modified, from its original design in a Fiat technical report (courtesy FCA Italy S.p.A.)*

Battery electric vehicles use one or more electric motors for propulsion and draw all of their energy from batteries carried on board, as distinguished from any form of hybrid electrical vehicle that uses an IC engine. The illustration in Figure 8 shows the layout of the Fiat 500e. The batteries are typically placed under the floor to avoid negatively affecting the vehicle's handling from the large mass, and to minimize the loss of storage space. The vehicle shown uses a single electric motor; however, two and four motor configurations are also common. Gearboxes are typically not required due to the flat power curves associated with electric motors; however, a reduction gear set is often needed to provide adequate torque to the driving wheels. From a life cycle perspective, one topic that has received little attention is the effect of battery disposal in the end of life phase. Zackrisson, *et al.* studied the impact of battery production and use and found that a 10 kWh battery will account for about 4400 kg CO_2 of energy use during production; however, no attempt was made to examine the effects of toxic materials and rare metals on the environment (Zackrisson, Avellan and Orlenius 2010).

Electricity Production

Unlike combustion engine vehicles, where the vehicle's emissions depend on the fuel being used, emissions associated with electric vehicles depend on the method of electricity generation. Typically, GWP emissions per kilometer from BEVs due to electricity production are less than from IC engines. While this is not always true, examples proving the contrary are rare (Huo, et al. 2013). Figure 9 compares the average, electricity grid mix for all EU-27 countries with the grid mix from Sweden (thinkstep AG 2015). Both of these mixes have been used in this thesis and are discussed in Chapter 7. The average mix uses a much larger percentage of Lignite, Hard Coal, and Natural gas, which will create much higher emissions than from Nuclear or Hydroelectricity. As with ICE vehicles, the life cycle GWP emissions of EVs are still dominated by the use phase, despite the increased efficiency of electricity production and electric motors.

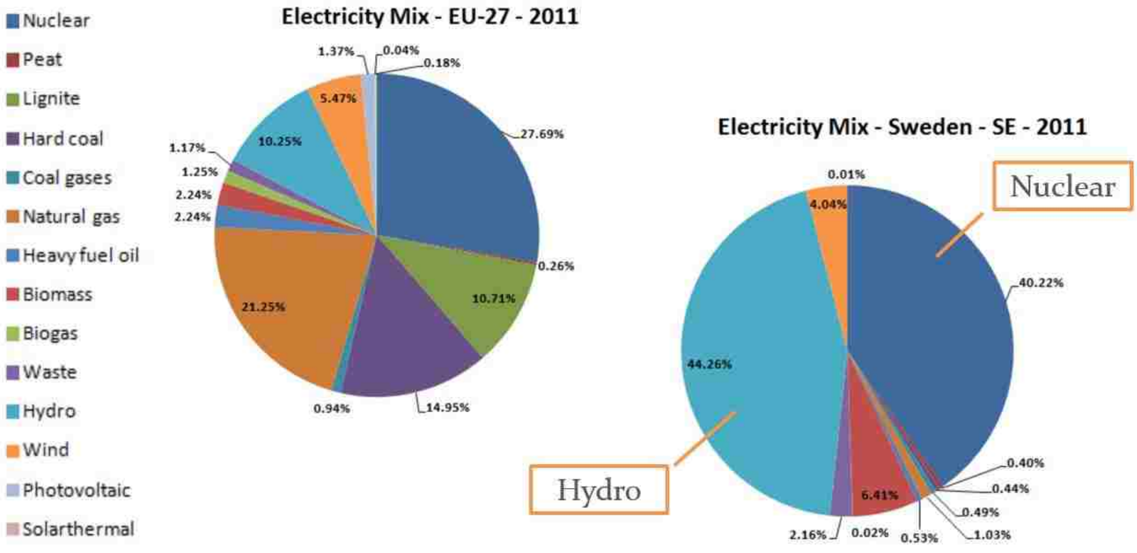
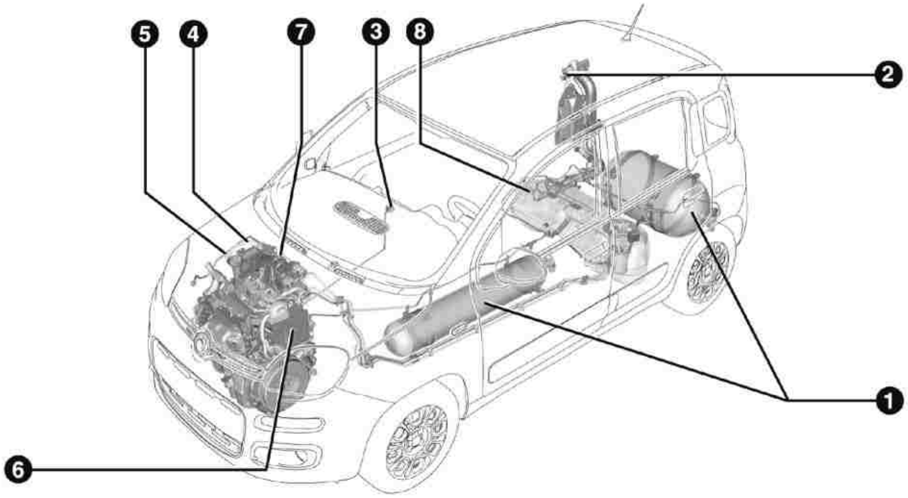


Figure 9: Comparison of electricity grid mix between the EU-27 average mix and Sweden Note that the data for the Swedish mix is included in the average mix data for the EU-27

Bi-Fuel Technology

Although there are many varying definitions of a bi-fuel vehicle, most definitions specify that the vehicle should have two separate fuel systems and be capable of operating independently on either fuel (NGV Global 2011). Aside from the addition of the secondary fuel system there are relatively few differences between bi-fuel and conventional vehicles. A typical layout using CNG and gasoline is shown in Figure 10 (Fiat Group Automobiles S.p.A. - Parts & Services - Technical Services - Service Engineering 2014). CNG storage tanks are placed in the trunk and under the floor: maximizing the volume of CNG storage without diminishing the vehicle's luggage capacity is critical for consumer appeal. A tank regulator (not shown) drops the pressure from a maximum of 25,000 kPa to a safe pressure for the fuel supply lines. In the engine bay, the gas is passed through a second pressure regulator and distributed to the injection ports where it is injected by dedicated fuel injectors. In the vehicle in Figure 10 there is only one engine control module (ECM), however some bi-fuel vehicles have separate ECMs for each fuel system. The vehicle is typically started under gasoline, at which point the driver can manually turn on the CNG system. The vehicle will then operate under only CNG and switch back to gasoline when the CNG supply has expired. Most bi-fuel vehicles available have longer combined ranges than their gasoline equivalents, which is because the gasoline tank is not usually downsized. The range of a typical bi-fuel vehicle on only CNG is usually around 350 km, or less than half of the vehicle's range on gasoline (Federmetano 2013).



1. CNG Storage Tanks 2. CNG Filler Cap 3. Gasoline/CNG Switch 4. Pressure Regulator
5. Gas Distributor 6. ECM (Engine Control Module) 7. Gas Injectors

Figure 10: Illustration of the bi-fuel system on a Fiat Panda Natural Power

Assuming that a bi-fuel vehicle is used predominantly with CNG, they typically show an overall reduction in life cycle GHGs due to the reduction of CO_2 emissions during the use phase, despite requiring more energy for the additional components and compression of the NG during refueling (Bonino 2013).

Compressed Natural Gas Fuel Properties

Natural gas found in pipelines across North America is composed of approximately 87-97% methane (CH_4), 1.5-7% ethane (C_2H_4), various other hydrocarbons in trace amounts, and about 5.5 mg/m^3 of sulfur for odor (Chemical Composition of Natural Gas n.d.). Because NG is almost entirely composed of methane, for most analyses only the chemical and physical properties of methane are considered. Methane has the highest ratio of hydrogen to carbon of all hydrocarbons, giving it the highest ratio of heat of combustion to molar mass in that group (Pourkhesalian, Shamekhi and Salimi 2010). Unfortunately, methane is a gas at room temperature, meaning the energy per unit volume is naturally very low. Even when compressed to over 20,000 kPa (U.S. Department of Energy 2013) the low energy per unit volume means that CNG vehicles struggle to achieve comparable range to gasoline vehicles.

Using methane in an internal combustion engine poses its own challenges and has both advantages and disadvantages. In a typical liquid fuel injection system, the fuel is vaporized on injection into the air box; which has the effect of cooling the intake charge and leads to increased volumetric efficiency. When injecting a gas however there is no vaporization of the fuel, so the intake charge remains at ambient temperature. In addition, because of the lower fuel density a greater volume of fuel is required. Combined, these two properties reduce the IC engine’s volumetric efficiency. Another problem is that methane has a slower flame propagation speed than gasoline, meaning that to achieve peak combustion pressure the spark must be advanced further. The greater spark advance increases the expansion of the combustion chamber gases prior to top-dead-center, increasing the negative work done by the piston and peak cylinder pressure. The combined effect is a drop in brake mean effective pressure (BMEP) and higher brake specific NOx creation. Furthermore, although methane has much lower volatile organic compound (VOC) emissions (Winebrake, Wang and He 2001), it has much higher CH_4 emissions (Martins, Rocha and Sodré 2014). Despite these disadvantages, methane’s high ratio of heat capacity to molar mass results in the lowest brake specific fuel consumption and CO concentrations of all hydrocarbon based fuels (Pourkhesalian, Shamekhi and Salimi 2010). Table

1 illustrates how some of the key performance indicators for IC engines are affected when an engine is run on methane, as opposed to gasoline, and tuned for similar power output.

Vol. Eff.	BMEP	BSFC	BSNOx	CO	CO2	CH_4	VOCs
reduction	reduction	**reduction**	increase	**reduction**	**reduction**	increase	**reduction**

Table 1: Typical effects of methane on key performance indicators for an IC engine
Items in bold are considered as improvements over gasoline

Natural Gas Production & Distribution

Further promoting interest in CNG is the recent growth in the American natural gas industry, particularly due to the rapid development of shale gas and hydraulic fracturing techniques. According to a recent report by the Economist Intelligence Unit, shale gas production has grown so fast that the US is now poised to become the largest producer of oil and natural gas based liquids in the world by 2015 (The Economist Intelligence Unit 2014). Natural gas is also more affordable than gasoline; since 2005 the US DOE has tracked prices of alternative fuels and during this time period NG has never been more expensive than gasoline on a $/gasoline gallon equivalent basis (Clean Cities Alternative Fuel Price Report 2014). Because NG is produced domestically, its price is also much more stable than imported oil. Moreover, since the majority of homes in the US already have NG coming to them, there is the possibility to refill bi-fuel cars at home, although home refueling has not had the impact some experts would have hoped for (Mcallister 2013).

US natural gas production comes from primarily four sources: coalbed wells, shale reserves, oil wells, and gas wells. Figure 11 shows gross withdrawals from US NG wells for each of these four sources (Natural Gas Gross Withdrawals and Production 2014). Historically, NG production was dominated by gas wells, as the natural gas trapped in these wells is easy to reach and requires very little processing to prepare for distribution. In recent years however, the combination of horizontal drilling and hydraulic fracturing (or fracking) technology have dramatically increased the production from shale gas (Arthur, et al. 2008). This type of gas extraction does however, have some unique environmental impacts due to the high volumes of water consumed (Arthur, et al. 2008), and increased leakage of methane during the fracturing process (Howarth, Santoro and Ingraffea 2011). According to Howarth, *et al.*, GHG emissions from shale gas production could be between 20 and 200% greater than conventional gas production due to methane leakage.

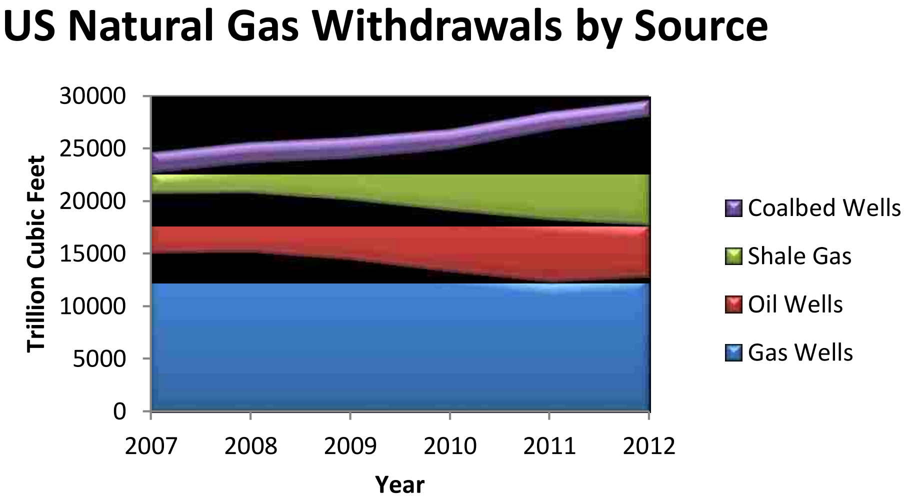


Figure 11: Total US production of natural gas vs. time, by source

Bio-Methane

Another promising technology that has created interest in bi-fuel vehicles, more so in the EU than in the US, is bio-methane. Bio-methane, or *biogas* as its more commonly called, can be produced through fermentation using a number of different feed stocks, the most common being farmed crops, or waste/manure (Edwards, et al. 2014). In a 2014 report by the European Commission's Joint Research Center (JRC), it was found that by preventing the spreading of manure on farmer's fields and instead converting the waste into biogas, the net effect would be to remove GHGs from the atmosphere (Edwards, et al. 2014). Figure 12 shows the net GHG emissions for biogas as described in the JRC report; and although these numbers only represent a limited use, best-case scenario, they give some indication of the potential for biogas to reduce GHG emissions from automobile use. Another scenario for the production of biogas is discussed by Hatton (2015), in their article for Racecar Engineering. Hatton describes the use of engineered, bio-organisms that can be fed with solar energy and waste CO_2 in order to create bio-methane. Using this method, biogas ICE vehicles could realistically produce fewer GHG emissions than even electric cars running on renewable electricity, while also having the capability to be up-scaled to the point of providing a sufficient replacement for conventional fossil fuels (Hatton 2015).

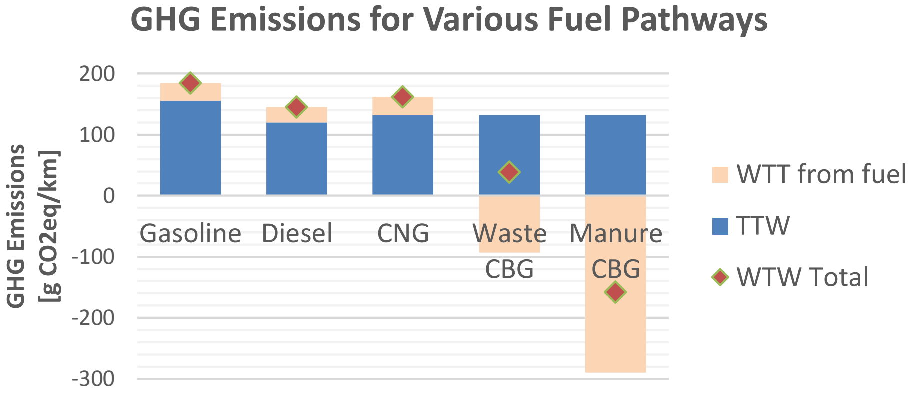


Figure 12: WTW GHG emissions from use of select biogas pathways.
**Compressed Biogas (CBG)*
Further analysis of this data and its applicability to automotive LCA is provided in the appended presentation (Appendix A).
Data extracted from (Edwards, et al. 2014)

2.4 Automotive LCA Literature Reviews

Previous reviews of LCA studies in the automotive sector, conducted by the JRC in 1996 and by Messagie, *et al*. (2013), have found that automotive LCAs tend to have a heavy focus on GHG emissions (ECOBILAN S.A. 1996). The literature reviews also mention the need for methodological improvements, and the need to balance the workload with the validity of the results. The EUCAR methodology attempted to solve many of the issues found in the JRC's 1996 review. From Messagie, *et al.*'s review in 2013 however, it is evident that the same methodological issues are still prevalent. Table 2 summarizes the two literature reviews, highlighting the issues that will be explored further in this thesis.

	Methodological Issues	High Impact Assessment Areas	Suggested Areas for Improvement
Overview of Life-Cycle Assessment Studies in the Automotive Sector – (ECOBILAN S.A. 1996)	**- Methodology harmonization** - Lack of studies on whole vehicles - Mostly European centered	*- NA*	**- Focus on yielding quick, but valid results** - Creation of reliable LCA databases **- Creation of common guidelines**
Key outcomes from Life Cycle Assessment of vehicles, a state of the art literature review – (Messagie, Macharis and Van Mierlo 2013)	**- Lack of consistency in results from similar studies** - Data unavailability, especially for non OEM commissioned groups - Use of NEDC for use phase emissions	- selection of vehicle and lifetime - electricity and fuel sources **- Assumptions in LCI phase** - LCIA impact categories used	**- Consideration of impact categories beyond GWP** - Increase detail in LCI phase - Assessment of real recycling scenarios - Using a more realistic driving cycle - Including uncertainty and variability in results

Table 2: Results from previous literature reviews on automotive LCA studies

CHAPTER 3
METHODOLOGY

Selecting Suitable Life Cycle Assessment Guidelines

The guidelines selected for analysis should be both specific to passenger vehicles and unique in their approach. For instance, the two frameworks discussed in the previous chapter (US EPA and ISO) would not be suitable for use in this comparison since they are too ambiguous. Because the frameworks are designed for use in many industries, they are written in broad terms, such that it would be relatively easy to complete an LCA study that conformed to both frameworks simultaneously. This overlap diminishes the ability to compare the methodologies since LCA studies adhering to either one could conceivably be the same: therefore, the more specific and different the demands of the guideline, the more likely that a unique solution will be found. Each guideline used should also have a roughly similar scope of analysis, so that comparisons can be drawn across many phases of the analysis. If a certain guideline omits a phase of the analysis, but provides reasoning or evidence of that phase being negligible, then this guideline would still be allowable since the guideline has still considered all phases of the analysis. Lastly, all the guidelines chosen should still be technically relevant and reasonably state-of-the-art. For example, it would be inappropriate to compare one guideline against an older version of itself, because the older revision would presumably be outdated and the newer revision considered more complete.

Analysis of Guidelines

Once a suitable set of guidelines has been determined, they will be tested by being applied to a series of similar vehicles produced by FCA. Table 3 summarizes the vehicles proposed for this analysis. The Fiat 500 model line has been selected since it is one of Fiat’s most popular models (carsitaly.net 2015) and is the only Fiat model also offered with an electric powertrain (although only in California and Oregon, as well as limited use for urban car sharing programs in Italy). A CNG powered version of the 500 does not exist currently; however, data can be taken for the CNG fuel system from the Fiat Panda. The Panda and 500 share the same chassis, and come with a similar range of engines, making the Panda a suitable surrogate (topgear.com n.d.). By using gasoline, electric, and natural gas models, the vehicles studied cover a wide range of fuel options representing the current state-of-the-art of the automotive industry (conventional fuels, electrified powertrains, and alternative fuels).

	Fiat 500	Fiat 500e	Fiat 500 Natural Power	Fiat 500 GPL
Fuel	Gasoline	Battery electric	Gasoline + Compressed Natural Gas	Gasoline + Liquefied Petroleum Gas
Modifications from gasoline		Battery + electric motor + gearbox	CNG storage tank + fuel system	LPG storage tank + fuel system

Table 3: Vehicles proposed for study and their characteristics.
**Note that the 500 Natural Power and GPL models have the same gasoline fuel system as the standard model, in addition to the secondary fuel system, while the 500e has only an electric powertrain.*

By applying each guideline to multiple AFVs, the flexibility of the methodology to account for many different input parameters can be assessed. It will also be possible to see the effects of each assumption or parameter used by further analyzing the LCA results. This analysis of the results will be done by examining the breakdown of each impact category, to identify the material flows that have a strong effect in each. The assumptions and parameters associated with each material flow will then be determined and the most critical parameters missing from each guideline can be identified. As well, variables that require more data but that do not significantly affect the study can also be identified.

Finding an Ideal Guideline

The ideal guideline should balance the work required to complete the study, while still capturing the most important variables in the vehicle's life cycle. If the current guidelines are insufficient at meeting the ideal requirements, a new guideline will be created. The intended application will be use by automakers in basic, comparative LCA studies of small passenger cars. For automakers operating in multiple markets, the guideline should give advice for LCA studies with a North American or European focus. PCRs require very strict and exacting criteria, but the new guideline will need to be more flexible so that automakers can choose the most appropriate scenario for their studies. The guideline will, therefore, not be developed with the intention of use as a PCR.

Developing requirements for an LCA guideline is a formidable challenge. There is a very broad scope of variables to consider, and an inherent lack of knowledge on true environmental impacts. For instance, attempting to determine the accuracy of an LCA study is a rather futile endeavor, since it is impossible to know the exact environmental impact of a particular product without knowing the exact details of the product's life cycle scenario. Because LCAs are often developed for a particular set of circumstances, the results of the LCA would only be applicable in that scenario and difficult to extrapolate to others.

Instead, to reduce the complexity, a condensed set of requirements have been chosen for the new guideline proposed herein.

1. The most basic and starting requirement is that the new guideline should be *robust,* or valid in many situations, by various OEM's. Robustness requires that the guideline consider a broad enough range of variables that might change or otherwise have a significant impact on the results, based on the chosen scenario.
2. The variables that have the most significant effects on the study results or outcomes should be identified, and recommendations will be given for making assumptions on the key parameters of the study (use phase length, drive cycle and use pattern).
3. The guideline should also identify variables that do not have a significant impact on the study's outcome, such that these variables can be ignored in future studies. By limiting the number of variables that the LCA practitioner's must address, it will be possible to reduce the workload associated with LCA studies. More time could then be placed on improving knowledge of the higher impact life cycle variables.

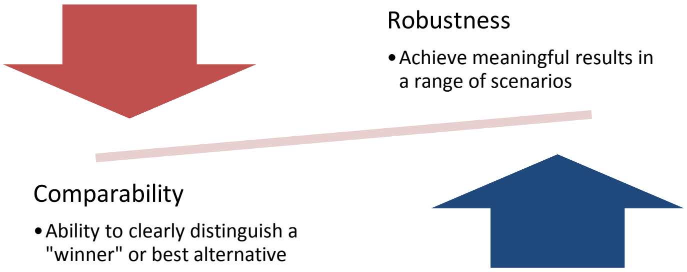


Figure 13: Relationships between robustness and comparability

The trade-off between robustness and the comparability of separately conducted studies is presented in Figure 13. Robustness requires considering a broad spectrum of variables, but this means that the results of the study could change significantly based on the assumptions made. Variations in results from different OEM's will make product comparisons more difficult. However, this outcome may be a necessary trade off to include a variable that may change the outcome of a study, or avoid making an incorrect conclusion. By limiting the variables considered to only those with the greatest impact, and providing clear recommendations on how to develop the study, the new guideline should still be able to enhance the comparability between studies.

Applying the Guideline

If a new guideline is developed, then the LCA study for each of the chosen vehicles will be re-evaluated and the results compared against those from the original studies. The overall benefits and improvements of the new guideline can then be evaluated referring to the original starting points. For a further evaluation of the guideline, the results of the final study will be compared to LCA results published by other OEM's. This comparison will highlight any potential areas for improvement that were not considered in the original scope of the guideline, and give the ability to comment on the comparability of the new guideline to other methods.

GaBi Life Cycle Software

To complete the life cycle assessment, Thinkstep's GaBi software will be used. GaBi is a process model life cycle assessment tool: each step in the product life cycle is defined as a separate object (Hendrickson, et al. 1997). The process model contrasts the economic input-output (EIO LCA) method, which uses a correlation matrix to relate activities and emissions between all sectors of the economy. In his study, Hendrickson compares the results of both GaBi and EIO LCA and found that while the EIO LCA did account for a larger range of emissions, the emissions that were accounted for in both models were not significantly different. The EIO LCA model tended to predict higher emissions because it counts emissions in other industry sectors (Hendrickson, et al. 1997). For this thesis, the differences between GaBi and EIO LCA are relatively inconsequential because the focus is on comparing the assumptions used for each analysis. For this purpose, the GaBi model allows for better control of the processes occurring within the system, making it easier to compare and contrast the effects of small changes to the analysis.

Methodology Summary

A summary of the methodology is shown in Table 4. During the analysis phase, the most important life cycle factors are determined as well as potential areas for improving the comparability of similar studies. This knowledge is then used to evaluate the current guidelines, and, if necessary, a new guideline will be created.

Preparation	Modelling	Analysis	Synthesis	Evaluation
- Selection of suitable guidelines	- Create GaBi model for each vehicle and guideline	- Evaluate pros and cons of each guideline - Determine highest weight aspects of the life cycle	- Modify current guideline or create new guideline	- Compare new guideline to previous guidelines - Compare new guideline to LCA studies by other OEMs

Table 4: Methodology summary

CHAPTER 4

ASSESSING GUIDELINES

Selection of Guidelines

In Chapter 2, several of the LCA guidelines considered for testing were already introduced: EUCAR's *Automotive LCA Guidelines* and the *Product-Category Rules for preparing an environmental product declaration for "Passenger vehicles" (PCR 2005:3)*. The study by Kobayashi was also intended to be a model for future LCA studies on vehicles, so the application of his method was considered as a guideline as well. The only guideline considered here that was not introduced in the literature review is the recently published eLCAr *Guideline for the LCA of electric vehicles*. Although the eLCAr guide was specifically developed for application to electric vehicles, the suggested practices and assumptions can be easily carried over for use on ICE vehicles. Table 5 below gives a brief summary of the scope for each of the guidelines considered.

	eLCAr	**EUCAR**	**PCR**	**Kobayashi**
Pages (~)	140	20	10	8
Year of Publication	2013	1998	2005	1998
Goal and Scope Definition	X	X	X	X
Production	X	X	X	X
Use Phase	X	X	X	X
End of Life Vehicle	X	X		X
Life Cycle Impact Assessment	X	X	X	
Life Cycle Interpretation	X		X	

Table 5: Comparison of scope for the considered guidelines

The eLCAr guide covers all formalized aspects of LCA and is fully compliant with both ISO 14044 and the ILCD Handbook (Del Duce, et al. 2013), making it one of the most complete and exhaustive guidelines available today. The system boundaries described in the eLCAr guide are illustrated in Figure 14. Although these boundaries include many aspects that other methods do not, such as road infrastructure, the other methods have similar construction.

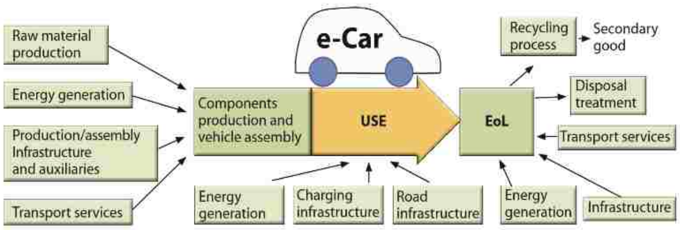


Figure 14: System boundaries, as illustrated in the eLCAr guideline (Del Duce, et al. 2013)

The EUCAR guideline and Kobayashi's method also attempt to comply with ISO 14040, but they exclude certain aspects of the analysis. The EUCAR guideline does not contain any recommendations for interpretation of the analysis beyond the assessment phase, while Kobayashi ignores both LCIA and interpretation phases. Although Kobayashi's method seems to use a thorough technique for the LCI phase, similar to that of the EUCAR guideline, he has neglected the LCIA and Life Cycle Interpretation phases; therefore, his method was not selected for further evaluation. In contrast to the other guidelines, the PCR represents a minimal LCI phase. It excludes ELV treatment and only requires the consideration of main chassis and powertrain components during part production and logistics. However, these simplifications are not expected to result in a significant reduction of the study's accuracy because the end-of-life and production phases typically have a small impact on the total life cycle emissions. The PCR provides a good starting point to contrast other methods because of its simplicity. Moving forward, the eLCAr, EUCAR, and PCR guidelines were considered.

Guideline Specifications

Each guideline considered provides a mix of specific criteria, as well as suggestions that are more open for the LCA practitioner to interpret. For this thesis, where there is ambiguity surrounding a certain variable within the guideline, the value or method most different from those suggested by the other guidelines will be used to demonstrate the maximum possible variation in results. Table 6 summarizes select analysis aspects that are described in each guideline.

	eLCAr	EUCAR	PCR
Functional Unit			X
Foreground vs. Background Data	X		X
Data Quality	X	X	X
Allocation	X	X	X
In Process (Closed-Loop) Recycling	X	X	
Co-Product Evaluation	X		
Allocation to Individual Components		X	

Table 6: General issues or processes covered by the available guidelines

The PCR necessitates a strict definition of the functional unit such that all studies completed will be comparable, while both the eLCAr and EUCAR guides leave the functional unit up to the discretion of the practitioner. The eLCAr guideline does however, stress the need for functional equivalence when undertaking comparative studies, such as in the case of a BEV compared to an ICEV (Del Duce, et al. 2013). In the BEV case, it may be necessary to add the use of a rental car for long distance trips to achieve functional equivalence, so the effect of these additional considerations could also be evaluated.

Allocation of production data refers to assigning generic data from an assembly plant producing many products, to one product. Each guideline recommends a similar mix of alternatives, although preference seems to vary amongst them. Depending on the production scenario, allocation can have a significant impact on production emissions, so it is important that the method chosen accurately reflects the real scenario. Consider the case of a paint shop that is painting both small cars and large vans. If allocation by the number of vehicles was used for all production data from that plant, VOC emissions for the small car may be overestimated. If instead, allocation of VOC emissions were done by surface area or weight of all products painted, then VOC emissions would be significantly reduced for the smaller vehicle. The PCR recommends mass and strictly forbids economic allocation due to variations created by changes in the economy, while the EUCAR and eLCAr methods suggest allocation by number of products produced, mass, or surface area. In-process recycling is typically allowed for credit against the virgin material coming in, but the PCR does not permit the use of any credits. Depending on the material and recycling program considered, recycling credits can have a significant or negligible impact on production emissions, so it will be important to consider these effects (Broadbent 2011).

The use phase of the automobile is often considered the most important phase of the life cycle since it accounts for the largest percentage of GHG emissions. It would make sense then, that any factors considered in the use phase should have a large impact on the overall results of the study. Table 7 shows the factors related to this phase included in each guideline in which the eLCAr guideline is the most exhaustive. This arises because the usage of accessories, such as heating, air conditioning, and lights, has a much higher impact on the range and power draw of electric vehicles than ICE vehicles (Del Duce, et al. 2013). Another factor for planning the use phase is that with an EV the power required for each drive cycle can be quite easily calculated because an electric motor has an almost constant efficiency curve versus speed. With an ICE vehicle however, the engine efficiency is non-trivial, so it is much more difficult to calculate the required power for a drive cycle without full scale testing (Del Duce, et al. 2013).

	eLCAr	**EUCAR**	**PCR**
Lifetime (mileage)	150,000 to 250,000 km	150,000 km (<1500 kg) 200,000 km (>1500 kg)	150,000 km (M1 Type)
Lifetime (years)	10 to 13	12	10
Basic drive cycle	NEDC, CADC, or WLTC	NEDC	NEDC
Climate control systems use	X	-	-
Auxiliaries use	X	-	-
Non-exhaust emissions	X	-	-
Noise	-	-	X
Vehicle maintenance	X	X	-
Road construction	X	-	-

Table 7: A selection of specifications for the use phase that differ across each guideline

Some recently published OEM LCA studies have cited that vehicle maintenance does not have a large impact on the overall life cycle of the vehicle (Volkswagen AG 2008). One exception for BEVs is the consideration of including a second battery to replace the first one. The battery has a large impact on the production phase emissions, and there is little data available for the lifetime of traction batteries in EVs (Gerssen-Gondelach and Faaij 2012). In the case of the Fiat 500e, the battery is covered under an 8 year warranty, however all guides recommend a vehicle lifetime exceeding 8 years, so the use of a second battery should be considered (FCA US LLC 2015).

The impact categories used and their method of evaluation can have significant results on the interpretation of the LCIA. All the guidelines selected suggest a specific list of impact categories, shown in Table 8. However, the methodology followed for calculating the midpoints and endpoints can alter the results even if the same impact categories are used. Midpoints are more typically used in automotive LCA studies and they represent the category indicator results (example Figure 4, on page 7). Endpoints meanwhile represent the outcomes after weighting all impact categories and summing the effects. However, because endpoints involve aggregation, they may not be easily understood. The PCR gives its own set of instructions for calculating midpoints and neglects endpoint analysis, but the EUCAR and eLCAr both suggest multiple methodologies (Macroscopio spa 2005, Del Duce, et al. 2013, Rover Group Ltd 1998). It is not within the scope of this thesis to provide a detailed analysis of multiple LCIA methodologies, as this is a complex topic and has already been covered in detail by the ILCD (European Commission - Joint Research Center - Institute for Environment and Sustainability 2011). The ILCD has reviewed numerous methodologies for calculating each impact category and assigned recommendation levels for specific methodologies. The recommendation levels are based on relevance, robustness, and transparency of the evaluated methodology (European Commission - Joint Research Center -

Institute for Environment and Sustainability 2011). For an automotive guideline, sensitivity to individual flows used in the life cycle model, and their ability to portray different advantages and disadvantages of each alternative fuel, should also be considered when recommending impact categories. Further work beyond this thesis could include estimating the contribution of the automotive industry as a whole on each impact category, and comparing to global or regional emissions.

Impact Category (*midpoints*)	**eLCAr**	**EUCAR**	**PCR**	ILCD Class	Contributors
Global Warming	X	X	X	I	Combustion of fossil fuels
Ozone Depletion	X	X	X	I	Use of refrigerants
Acidification	X	X	X	II	Electricity production
Eutrophication	X	X	X	II	
Photochemical Oxidant Formation	X	X	X	II	Non CO_2 tailpipe emissions
Resource Depletion	X	X	X	II/III	
Human Toxicity	X	X		II/III	
Environmental Toxicity	X	X		II/III	
Chemical Oxygen Demand		X			
Land Use	X	X		III	
Nuisance		X			
Occupational Health and Safety		X			
Solid Waste (Hazardous)		X			
Solid Waste (Non-Hazardous)		X			
Waste Heat Production		X			
Carcinogens	X				
Respiratory Inorganics	X			I	PM and dust emissions
Ionizing Radiation	X		X	II	Nuclear energy

Table 8: Suggested impact categories for each guideline and their ILCD recommendation level
**Categories without an ILCD Class specified are not listed in the ILCD Handbook*

Hypotheses

Predictions of the effect of each guideline on the results of the LCA study are shown in Table 9. However, there is little evidence to suggest how much the results will change given the variations in each guideline. Some studies have cited that maintenance has a small impact (Volkswagen AG 2008), although this may only be considering GWP. Other factors, such as climate control systems or charging infrastructure, are suspected to have a high impact (Messagie, Macharis and Van Mierlo 2013)

	Guideline Features	Suspected Impact
PCR	- Limited scope (no end-of-life phase)	- reduced or missed environmental impacts
EUCAR	- Includes vehicle maintenance	- increased use phase emissions - use phase will become more important in impact categories typically dominated by production phase
eLCAr	- Includes use of climate control systems	- Increased use phase emissions, which will be more prevalent for BEVs
	- Includes use phase factors not directly part of vehicle (ie. road maintenance, charging infrastructure)	- Increase in use phase importance in impact categories besides GWP

Table 9: Hypothesis of the major effects each guideline will have on the LCA study

CHAPTER 5

LIFE CYCLE MODELLING & INVENTORY

5.1 Inventory Data Scope & Details

Primary Data Collection

The data required for conducting the LCA studies were collected with the aid of FCA's Logistic and Supply Chain Masterplan, Network Design, and Environmental Health and Safety departments, as well as Robert Bosch Battery Systems. Table 10 lists the facilities included for primary data collection, along with the scope of primary and logistical data collected.

Facilities Included		
FCA US LLC Toluca Car Assembly Toluca, Mexico	FCA Italy S.p.A. Termoli Plant *(Engine)* Termoli, Italy	Robert Bosch Battery Systems, LLC Manufacturing Facility *(EV Battery)* Springboro, Ohio, USA
FCA Italy S.p.A. Tychy Assembly Plant Tychy, Poland	FCA Italy S.p.A. Stabilimento Mirafiori *(Gearbox)* Turin, Italy	
Plant Operations Data		
Plant electricity usage Plant water consumption Categorized wastes (non-hazardous, hazardous, and VOC's), including waste destination (landfill, incineration facility or energy recovery plant) Additional materials associated with part delivery and handling Quantity of in process, raw material recycled		
Logistics Data		
Shipment of assembled engines from Termoli plant to Tychy assembly plant Shipment of assembled gearboxes from Mirafiori plant to Tychy assembly plant Shipment of EV batteries from Bosch, Springboro facility to Toluca Car Assembly Shipment of electric motors from Reutlingen, Germany to Toluca Car Assembly		
Vehicle Data		
Materials breakdown		

Table 10: List of facilities included for primary data collection, as well as scope of data.

The facilities included above only represent a fraction of the actual work to manufacture the vehicle, since the vast majority of components arrive pre-fabricated from suppliers. Manufacturing operations carried out within the assembly facilities are only those for the forming and welding of the body-in-white, although this accounts for roughly ¼ of the vehicle's mass. Primary data was also supplied for the assembly of the traction battery for the Fiat 500e, however, it was unclear which operations are carried out within the Springboro facility and which parts arrive pre-fabricated.

In regards to the use phase, primary data included fuel consumption based on drive cycle testing, and maintenance parts and materials. Where possible, the vehicle's owner's manual was used to judge oil, coolant, and other service intervals, as well as data collected and presented in the EUCAR guideline (Rover Group Ltd 1998) on average component service life (refer to appendix D). Although the data collected is quite old, circa 1994, and newer model vehicles should have longer component lifespans, the data nonetheless represents a worst case scenario for vehicle maintenance. The end of life phase is difficult to model due to limited involvement with vehicle recyclers and the unknown path of post recycling material. The end of life phase has therefore, been modelled based on the main recovery scenarios outlined in the EUCAR guideline (Rover Group Ltd 1998).

Allocation of Primary Data

Each of the guidelines used for preparing the LCA studies suggest a number of methods for allocating primary data, such as plant electricity consumption, that cannot be otherwise attributed directly to a single product. The simplest and most often used method is allocation by the number of products produced, and this method is recommended by both the EUCAR and eLCAr guidelines (Del Duce, et al. 2013) (Rover Group Ltd 1998). Allocation by number of products can, however, be misleading if the range of products manufactured in a single plant varies widely, such as the case of Toluca Car Assembly plant, where the small Fiat 500 is manufactured alongside much larger vehicles such as the Dodge Journey and Fiat Freemont. For this reason, the PCR guideline suggests allocation by mass in all cases where allocation is necessary (Macroscopio spa 2005). Unfortunately, the data required for allocation by mass was unavailable from FCA, so allocation of materials and energy by the number of products has been done for all guidelines. A previous LCA study by Fiat showed that the assembly plant operating data had a small impact on the outcome of the study, so the allocation method should not greatly influence the results (Bonino, Life cycle assessment (LCA): Fiat 500L bi-fuel 2013). As well, plant VOC emissions are already monitored closely and reported from the plant by surface area painted, so no further allocation was necessary.

Logistics

Logistics data for the shipment of finished vehicles was estimated using the online EcoTransIT World tool. For the Fiat 500e, manufactured in Toluca, Mexico, the impacts of shipping to San Francisco, USA, and Turin, Italy, were evaluated. These cities were chosen for their location because both represent an approximate mid-range to the vehicle's potential market, California and Oregon, and the European Union respectively. For the other vehicle models, all manufactured in Tychy, Poland, for the EU market, shipment to Turin was once again assumed. In the case of the use phase for the 500e, transportation of a replacement battery was also considered, this time from the Robert Bosch Battery Systems Manufacturing Facility in Springboro, Ohio, to the same two cities.

Figure 15: Maps indicating the route of the finished Fiat 500e from Toluca to North American and EU markets

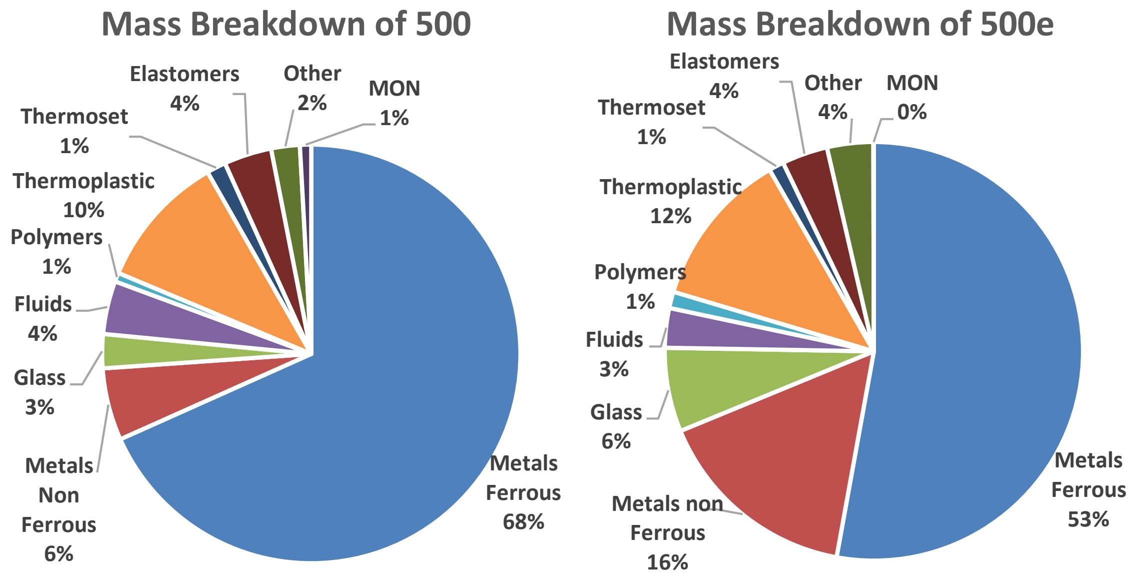
Vehicle Materials Data

Materials data for the Fiat 500 and Fiat 500e were collected using different procedures because of the different data management systems in North America and Europe. In Europe, all vehicle manufacturers and Tier 1 parts suppliers are required to use the International Materials Data System (IMDS), which catalogues the materials of the vehicle based on specific material codes (refer to Appendix E). In North America however, the 500e vehicle materials data were collected using the Knowledge-based Recyclable Materials System (KRMS), which uses a more simplified set of material classifications. In order to improve the consistency between the 500 and 500e data sets, the material breakdown data for the 500 was converted to match the categories used for the 500e. The loss of data associated with the conversion has been discussed in the following section on the limitations of the study. The finalized data for both the 500 and 500e models is shown in Table 11 and Figure 16.

Material Categories	**Fiat 500** (1.2L Gasoline)	**Fiat 500e**
Metals Ferrous	643.56	744.35
Metals Non Ferrous	52.60	224.31
Glass	24.76	91.32
Fluids	38.67	43.01
Polymers	6.51	17.86
Thermoplastic	98.16	170.39
Thermoset	14.02	16.33
Elastomers	34.74	49.91
Other	20.84	50.23
Monomers	8.21	0.53
	942 (kg)	**1386 (kg)**

Table 11: Materials categories and vehicle masses used for the LCA studies

From the data in Table 11 one can see that the Fiat 500e uses much more ferrous metal, non-ferrous metal, and thermoplastics than the Fiat 500. A significant portion of this weight is due to the battery pack; however, the chassis and body also have an impact. Specifically, the body of the 500e has been reinforced to meet stricter side impact regulations in North America. It is also worth noting that the Fiat 500e is not an optimized design for an EV, rather a conversion of the standard Fiat 500. If the chassis and body were optimized around the battery pack and electric drivetrain, the vehicle could potentially be lighter. The impact of these modifications is further discussed in Chapter 7, in the case study on cross-market vehicle comparisons.


Mass Breakdown of 500

Mass Breakdown of 500e

Figure 16: Overall material breakdown for Fiat 500 and Fiat 500e

In addition to the basic material breakdown, some specialty materials, such as the coolant fluid, engine oil, and brake linings/pads, were modelled separately for their unique environmental impacts, and because they are replaced at regular service intervals. As well, for the 500e's electric battery and 500 Natural Power's CNG storage tanks, separate and unique material breakdowns were generated. Table 12 provides a summary of the additional materials considered. With the exception of the exhaust catalyst and engine oil, which are not present in the 500e, the use of these materials was modelled for all vehicles.

Vehicle Component	**Mass (kg)**	**Replacement Interval**	**Material Classification**
Coolant fluid	5.05	30,000 km	Ethylene Glycol
Battery (Electrolyte mass only)	2.78	4.3 yrs	Electrolyte
Windscreen washer fluid	2.50	30,000 km	Methanol (diluted 1:1)
Brake fluid	0.50	30,000 km	Polyethylene glycol
Break pads / linings	6.44	60,000 km	Ceramic (copper + ceramic fiber)
Engine oil	5.39	30,000 km	Oil based
Exhaust catalyst	0.003	120,000 km	Platinum

Table 12: Detailed breakdown of specialty materials
*(*these weights are included in those listed in Table 8)*

The materials data for the traction battery in the Fiat 500e was provided via the IMDS system, with some additional material classifications as well. Of particular interest for the LCA are the Electrolyte and Lithium compounds used inside the battery's cells because these materials are energy intensive in their production and come from diminishing reserves (Gaines, et al. 2010).

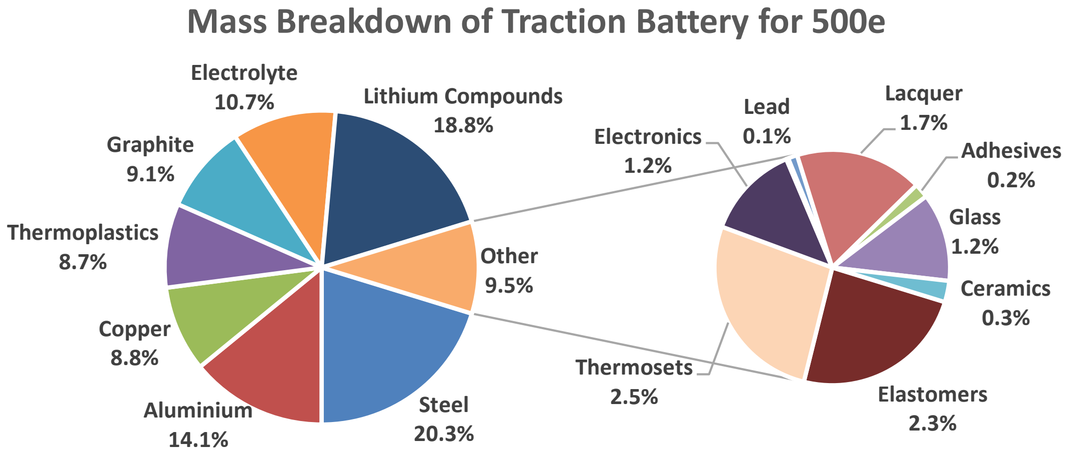


Figure 17: Material breakdown of the traction battery for the Fiat 500e. Total battery mass is 272 kg.

Use Phase Data

As suggested by all three guidelines, the basic use phase fuel consumption has been calculated using the vehicle's homologation data based off the NEDC, or US EPA driving cycles. Although these driving cycles are often criticized for not reflecting true driving patterns or habits (Del Duce, et al. 2013), they do serve as an equal basis for comparison. This method does, however, introduce the problem of comparing vehicles sold in different markets, because their actual consumption data will be no longer comparable. Additionally, homologation data fails to capture some of the discrepancies between alternative and conventional fueled vehicles, such as increased methane emissions from using CNG. For this analysis the method used in the JRC's Tank-to-Wheels Report has been adopted (Huss, Maas and Hass 2013). The approach assumes that for a gasoline or LPG vehicle, 10% of the total hydrocarbon emissions (THC) limit is methane, while for a CNG vehicle 60% of the THC limit is methane. All other non CO_2 tailpipe emissions have been assumed to be those of the regulatory limits.

Previous FCA life cycle assessments have not included the use of a second traction battery during the life of the Fiat 500e, based on the 160,000 km warranty provided. However, the warranty is only valid for 8 years and the minimum lifetime suggested by the guidelines is 10 years. Both the eLCAr and PCR guidelines suggest evaluating the necessity of using a second battery during the lifetime of an electric vehicle. Although it is not explicitly stated in the EUCAR guideline, replacing the traction battery should be included with the vehicle maintenance parts, and so it has been added to all use phases.

In addition to the basic driving cycle, the eLCAr guideline suggests calculating the power draw to operate the climate control and other auxiliary systems on board the vehicle (Del Duce, et al. 2013). Power draw calculations are a relatively simple procedure for electric vehicles, although a large number of assumptions are required for determining the usage pattern. Table 13 outlines the parameters used in this study. Climate data for Milan was used, as it was the nearest city to Turin with available climate data, and was taken from the European Climate Assessment and Dataset project (A.M.G. and Coauthors 2015). The climate control systems are modelled using the maximum electrical power consumed as listed in the Fiat 500e technical specifications for the cabin heater and A/C units, and the same method as the eLCAr guideline was applied to determine the usage pattern and annual energy consumption (Del Duce, et al. 2013). The main assumptions for determining the climate control systems use pattern are:

- 3 trips per day: 2 at daily maximum temperature and 1 at daily minimum temperature
- Maximum A/C when temperature is greater than 25°C
- Medium A/C (1/2 power) when temperature is between 20 and 25°C
- No A/C or heating when temperature is between 15 and 20°C
- Medium heating when temperature is between 10 and 15°C
- Maximum heating when temperature is less than 10°C

A full explanation of the assumptions and detailed calculations can also be found in Appendix F. In an ICE vehicle, the cabin is heated using the excess waste heat from the engine, so there is no increase in fuel consumption associated with heating (Del Duce, et al. 2013). The power consumption of the A/C system has been modelled using the maximum engine power consumed, listed in the technical specifications for the Fiat 500's A/C compressor. Fuel mass required to power the A/C unit was then calculated using the average efficiency of each engine, estimated over the NEDC. These calculations are also explained in greater detail in Appendix F.

Parameters	Fiat 500e	Fiat 500	Unit
Annual vehicle mileage in km	15000	15000	km/y
Days using max heating	92	92	Days
Days using medium heating	67	67	Days
Days without heating or air conditioning	55	55	Days
Days at medium air conditioning	55	55	Days
Days at max air conditioning	91	91	Days
Power demand of heating unit	5500	0	Watts
Power demand of air conditioning unit	6500	1260	Watts
Annual energy consumption of comfort devices	1,824,088	185,757	Wh/y
Mean energy consumption per km	**121.6**	**12.4**	Wh/km

Table 13: Parameters for calculating energy consumption of climate control systems
(Climate data is for Milan, 2005 (A.M.G. and Coauthors 2015))
(Orange cells indicate chosen LCA parameters; blue, vehicle data; and green, calculated values)

The increase in non-CO_2 tailpipe emissions associated with A/C use was estimated using the results of a National Renewable Energy Laboratory (NREL) report regarding the effect of climate control systems on internal combustion vehicles. Testing was conducted with a variety of vehicles that were subjected to the SC03 drive cycle while running with and without the air-conditioning active (Farrington and Rugh 2000). The results used as data inputs are summarised in Table 14.

	Avg. Increase
CO	+71%
NOx	+81%
Hydrocarbons	+30%

Table 14: NREL test data used to determine impact of AC use during the use phase.
Average is calculated from 7 different cars subjected to the SC03 drive cycle with and without AC active.
Air conditioning use time is assumed the same as for the electric vehicle (146 days)

The eLCAr guideline also suggests including the impact of road maintenance and non-tailpipe emissions to increase the realism of the study (Del Duce, et al. 2013). To attribute a certain amount of roadwork to each vehicle's use phase, a calculation was made for new road laid per new vehicle registered. It would also have been possible to use an alternate attribution method, such as total road area per total number of vehicles, but the new road per new vehicle method yielded the highest attribution of road area, so it represents a worst-case assumption. For the US road network an estimation of the new road area laid each year was available in online literature, however no similar numbers were found for the EU scenario. For this scenario, an estimate was made using the quoted total length of the road network in the EU, and assuming average lane widths, and the same growth rate of the road network as in the US. Full calculations and explanations can be found in Appendix G. The same quantity of roadwork was applied for all vehicles, according to the results of Viton's study that showed the majority of damage to roads to be caused by large trucks, and damage from different classes of passenger vehicles largely indistinguishable (Viton 2012). Concerning non-tail pipe emissions, emissions factors were based on the results of a literature review of the US EPA's MOVES 2014 software, and are shown in Table 15 (Office of Transportation and Air Quality 2014). Once again, emissions from different sized passenger cars are indistinguishable, so the same emissions factors have been applied in all studies. No attempt was made to classify the compounds or materials associated with these emissions, so they have only been modelled as dust particles.

	$PM_{2.5}$ *[mg/km]*	**PM_{10}** *[mg/km]*
Brake Wear Emissions	2.3	18.5
Tyre Wear Emissions	0.9	6.1

Table 15: Brake and tyre wear emission rates as used in the eLCAr simulation

5.2 Modelling in GaBi

The table in Appendix B shows a breakdown of each model created using the GaBi software. Each full life cycle is prepared by assembling four smaller simulations (referred to as "plans"), for the production, use, maintenance, and end of life phases. Individual or "black box" operations are modelled using processes, which require inputs in the form of materials or energy flows. Processes contain all necessary calculations and data for generating the environmental impacts of a certain activity, and they are scaled based on the quantity of the flows entering or exiting the process. The principle processes included for each guideline and life cycle phase are highlighted in Table 16 and further elaborated on in this section.

	PCR	**EUCAR**	**eLCAr**
Production	Raw material extraction	Raw material extraction Vehicle delivery In process recycling	Raw material extraction Vehicle delivery In process recycling
Use	Basic fuel consumption Traction battery replacement *(EV only)*	Basic fuel consumption Traction battery replacement *(EV only)*	Basic fuel consumption Traction battery replacement *(EV only)* Auxiliary fuel usage *(Climate control, lights)* Non-tailpipe emissions Roadwork
Maintenance	None	Raw material extraction	Raw material extraction End of life of used parts
End of life	None	End of life treatment Variable process for applying open-loop recycling credits	End of life treatment Shipment of waste materials Most likely EoL treatment only *(no variable credits)*

Table 16: Summary of processes modelled in each life cycle phase for each guideline

Production Phase

For the production phase, the assembly plant operations are modelled as a single process, with all vehicle materials, as well as energy, water, and supplementary materials for plant operations, flowing into the assembly process. A portion of the manufacturing phase plan for the FIAT 500, 1.2L Gasoline model is shown in Figure 18. Emissions and flows associated with the engine and gearbox assembly facilities have been modelled separately in their own plans; however the materials for these parts have been included in the regular material flows shown in the diagram. For the electric and bi-fuel vehicles however, the battery production and CNG tank production, have been modelled separately with their own materials flows because of the specialized materials used for their construction.

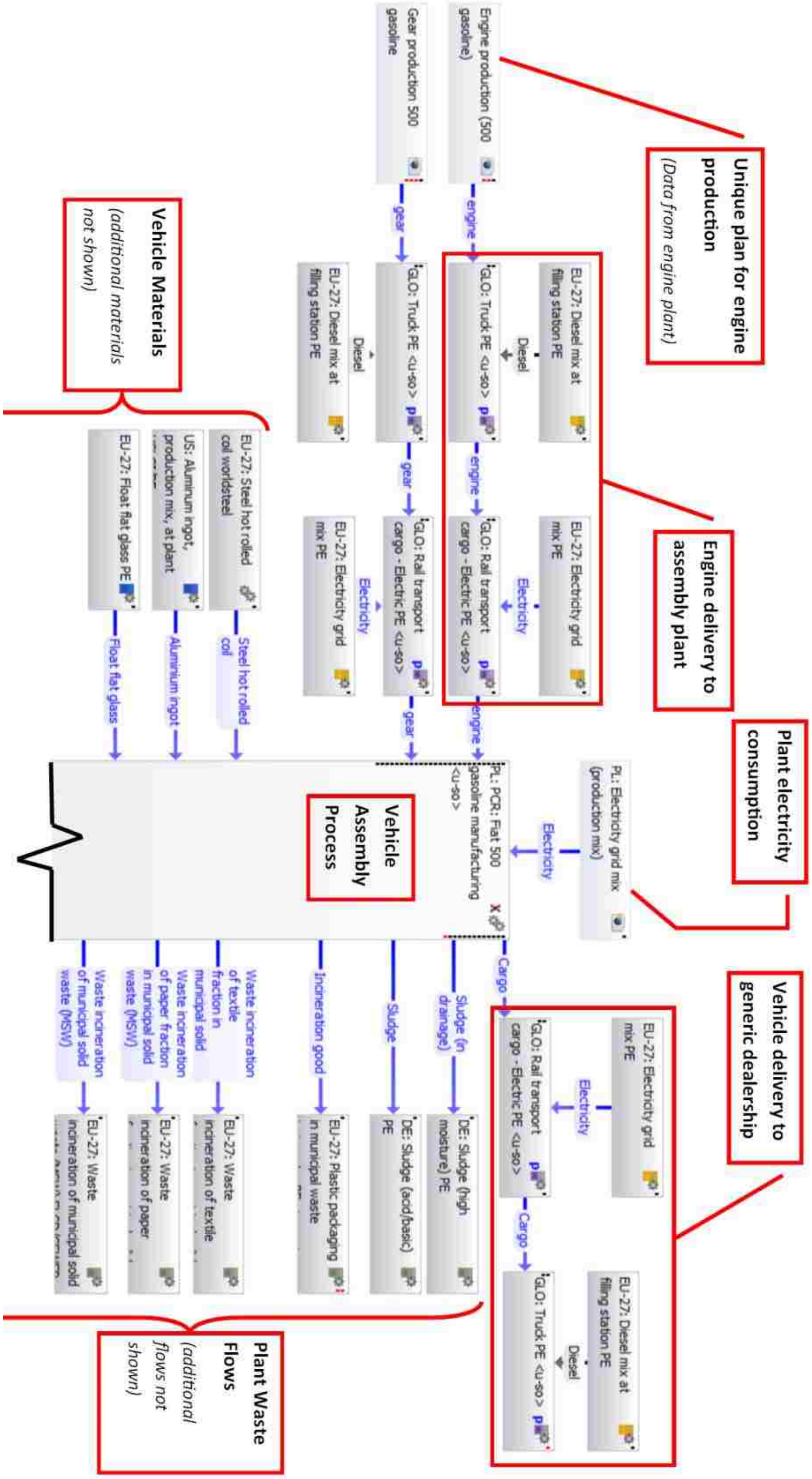


Figure 18: Production phase plan created in GaBi Software for FIAT 500, 1.2L Gasoline

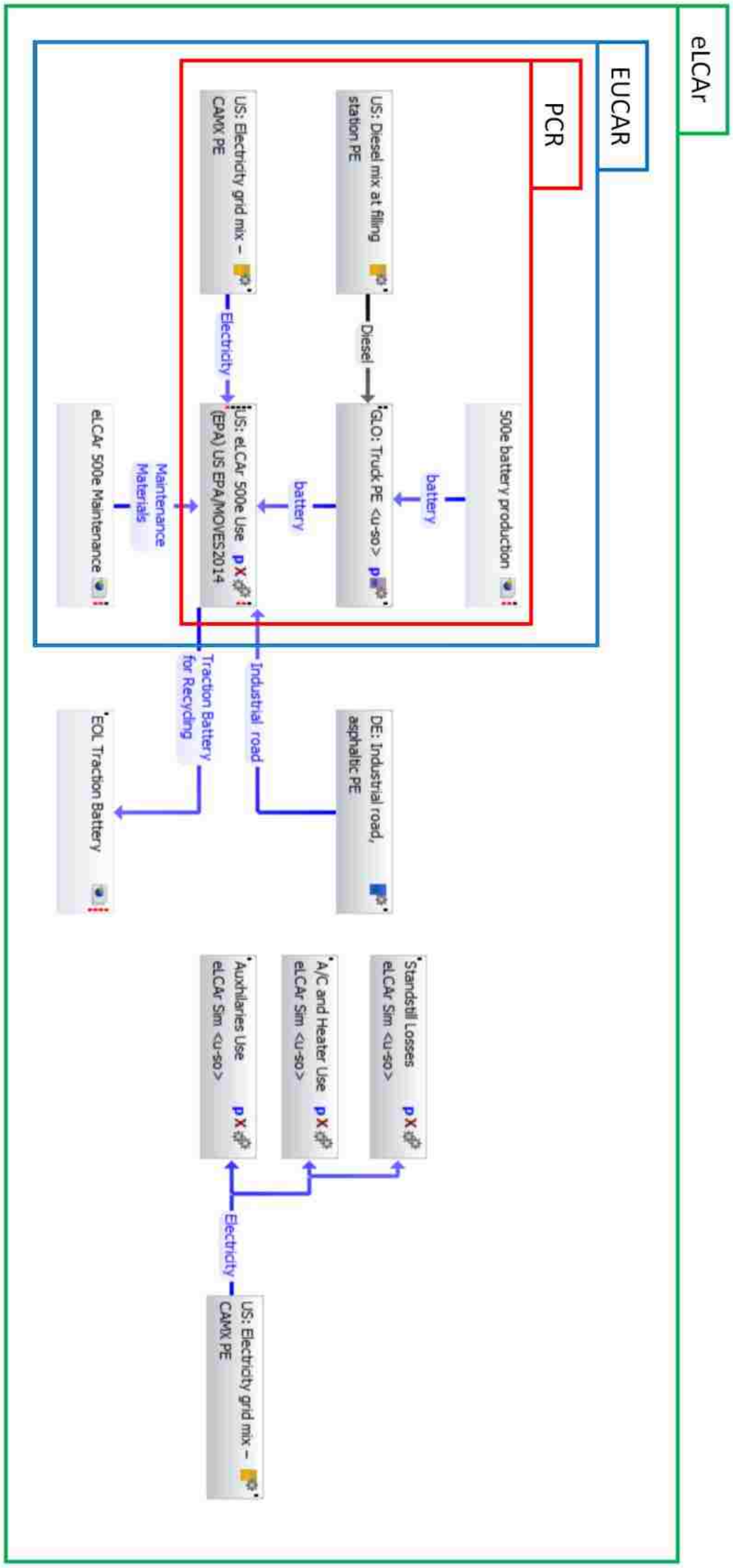


Figure 19: Comparison of use phase scope for each guideline (use phase for Fiat 500e shown)

Use and Maintenance

The use phase saw the largest differences between the recommended approach for each guideline, and therefore the GaBi plans changed considerably for each simulation. The aspects of the use phase corresponding to each of the guidelines are highlighted in Figure 19. The figure shows the use phase for the 500e model; however, the scope remains the same for the other vehicles studied, the only difference being that the electricity flow is replaced by the flow of gasoline or compressed natural gas. The PCR is the simplest, and contains only the basic electricity consumption associated with the driving cycle and the second battery for the BEV. The EUCAR guideline adds the consideration of maintenance materials and end of life treatment, while the eLCAr guideline includes all the previous parameters, plus additional electricity consumption for auxiliary components (air conditioning, headlights, etc…), the impact of road maintenance, and non-tailpipe emissions. Non-tailpipe emissions cannot be seen in Figure 19 however, as they have been modelled internally to the basic driving process, and not as their own process.

End of Life

The largest variable when modelling the end of life phase of vehicles is typically the application of – and justification of – open loop recycling credits. To simplify the guideline and reduce variability the PCR guideline foregoes any end of life considerations, while the EUCAR and eLCAr methods spend a considerable amount of time discussing them. In the studies conducted, the effect of open loop recycling was evaluated with two models. The first model is of a typical end of life scenario, as reported in the EUCAR guideline (Rover Group Ltd 1998), while the second uses a generic, parameterized recycling process that can be used to vary the amount of credit applied for all recyclable materials. Figure 20 illustrates the typical end of life scenario applied according to the eLCAr guideline. Once again, separate plans have been created for the traction battery and electric motor recycling, although this is more for convenience of modelling than necessity. For the traction battery, the structural materials have been treated similar to the vehicle's materials, and disposal of the cells has been modelled with an Ecoinvent dataset for the disposal of NiMH and Li-ion batteries. For the eLCAr model, transportation of the end of life components has also been considered; and for the battery, shipment was calculated from San Francisco to Trail, British Columbia. Trail was chosen as the most likely destination for the traction battery because Toxco, a commercial Li-ion recycler that has already been experimenting with the processing of traction batteries for EVs is located there (Gaines, et al. 2010).

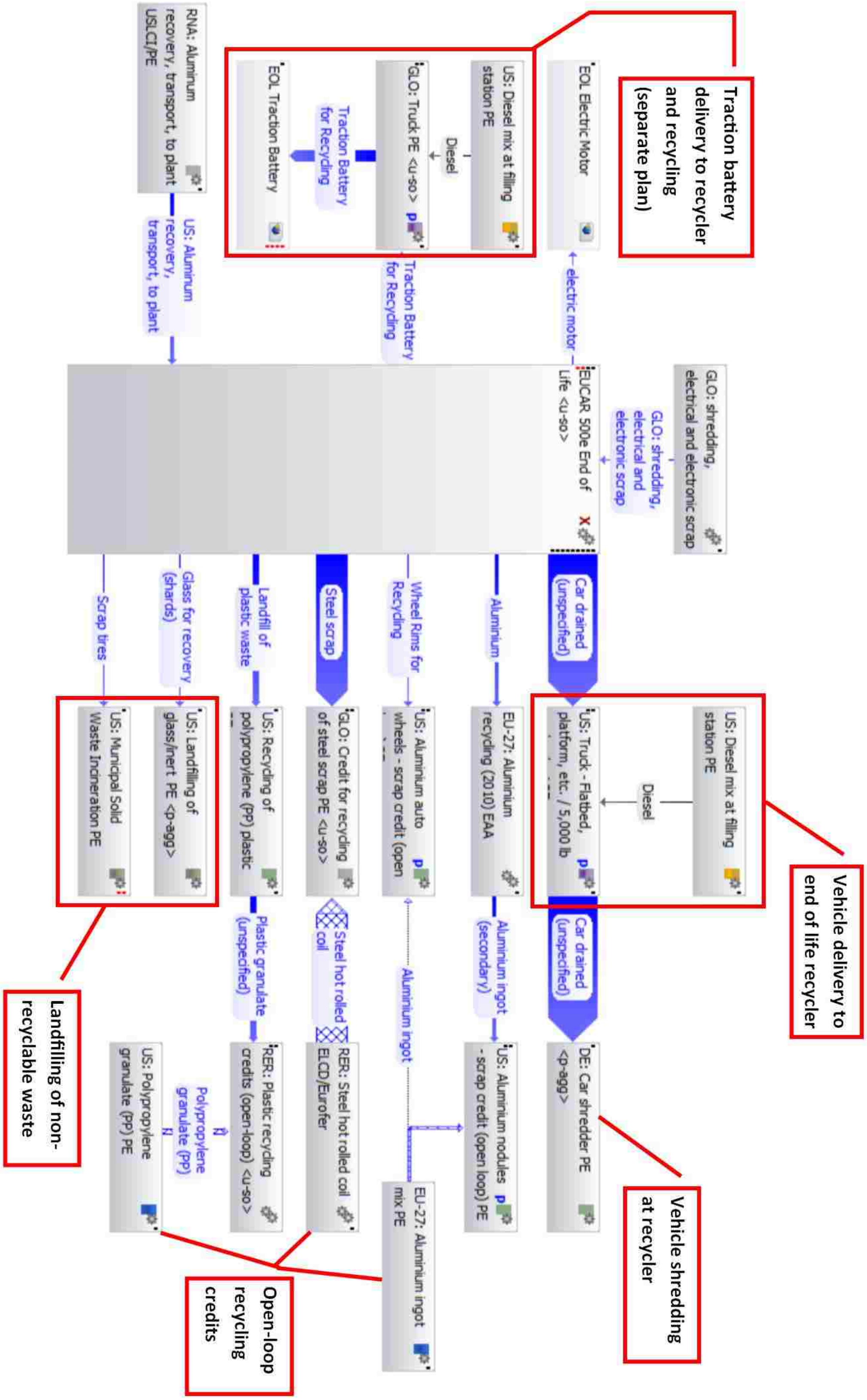


Figure 20: End of life plan for the Fiat 500e

5.3 Limitations of the Study

In order to complete the LCA, many assumptions and simplifications of the real world systems were necessary. One of the major limitations from the manufacturing phase was the discrepancy between the materials breakdown of the Fiat 500 done with the IMDS and the Fiat 500e done with the KMRS. In order to retain the original comparison between the two models, the 500 data was translated into the same material categories as the 500e data. Unfortunately, this simplification resulted in some loss of accuracy since the KRMS material categories are less detailed than the IMDS.

A study was done comparing the production of the Fiat 500 based on the IMDS materials list to that based on the KRMS and the results are presented in Table 17. The results based on the KRMS breakdown are generally lower than those from the IMDS, and for some impact categories there is a significant difference. The two human toxicity categories, however, only received an ILCD recommendation of II/III, so it is possible that these categories are overly sensitive to particular flows. For example, 82% of the Fiat 500 NP's life cycle human toxicity (cancer) impact is from the chromium steel used for the compressed natural gas tanks. The specific alloys of the other steels used in the chassis cannot be determined however, so the comparison would be between a generic group of materials and a specific alloy. It is conceivable that the same alloy of chromium steel could have been used in the chassis, but not recorded in the collected data. Therefore, the comparison would be unreliable.

	IMDS	**KRMS**	**Diff**
Global Warming Potential	4.10E+03	4.00E+03	**2%**
Ozone Layer Depletion Potential	4.25E-05	3.68E-05	**13%**
Acidification Potential	2.38E+01	1.97E+01	**17%**
Eutrophication Potential	3.65E+00	2.53E+00	**31%**
Photochem. Ozone Creation Potential	2.33E+00	2.37E+00	**2%**
Resource Depletion, fossil and mineral	1.71E+00	1.99E+00	**14%**
Marine Aquatic Ecotoxicity Pot.	2.20E+06	2.29E+06	**4%**
Human toxicity non-canc. Effects	6.41E-04	5.08E-04	**21%**
Human toxicity cancer effects	8.89E-05	1.41E-04	**59%**

Table 17: LCIA results for the Fiat 500 production, using different material breakdowns (right-hand most column indicates absolute difference)

In regards to the production phase, the other main limitations are the lack of logistics data for materials and parts going to and coming from Tier 1 suppliers, as well as lack of data from Tier 1 supplier's plants. Due to the often-complex nature of the supply chain, sometimes including Tier

2 and 3 suppliers, and the large number of parts and suppliers associated with the vehicle's production, collecting logistics and plant data can present a formidable challenge. In addition, many suppliers may not be readily willing to divulge plant operational data to the extent required for an LCA study. From the logistics data gathered however, parts shipping has a very small effect on the overall vehicle production impact. Finding suitable datasets for each material used also poses a challenge. The most notable case in this study is brake fluid. Few datasets suitable for brake fluid were found, so a generic solvent production stream was used instead. Figure 21 shows some of the impact category results for the production phase of the Fiat 500.

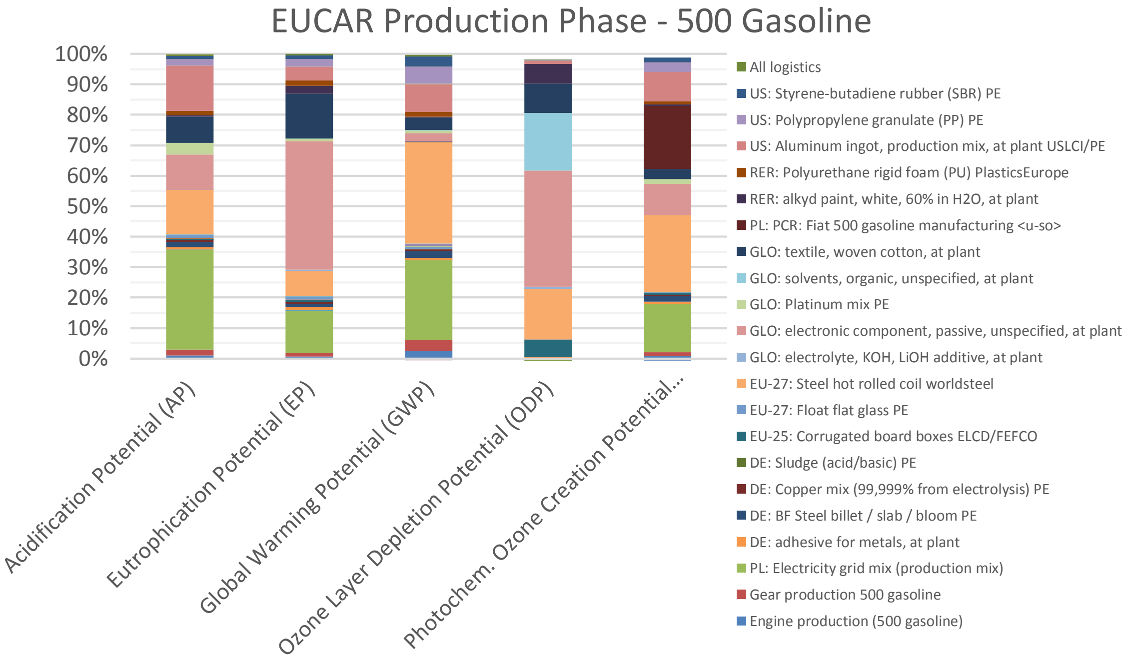


Figure 21: Production phase impacts for select impact categories, normalized for each category (Percentage is percent contribution of each material flow to the total for that category) (Bars not totaling 100% indicate the impact of in process recycling)

The *All* Logistics category in Figure 21 includes the impact of shipping the engine (80 kg, over 2000 km), the gearbox (33 kg over 1300 km), and the finished vehicle itself (942 kg over 1300 km), and yet the largest impact of the *All Logistics* category is 0.5% of the vehicle's production GWP. Given that the heaviest and largest components, which represent a worst-case scenario for the logistics impact, have a very small impact on the study, ignoring the rest of the logistics should not have a significant impact. For the Fiat 500e however, the logistics do have a significant effect in many impact categories. The impact of the logistics for the Fiat 500e is largely due to the weight and size of the battery, as well as the distance and method of shipment. The battery, which weighs approximately 200 kg, is shipped in batches of 33 batteries by truck over 3000 km. The long distance, heavy load, and inefficient mode of transport are the primary causes of the *All Logistics* impact shown in Figure 22.

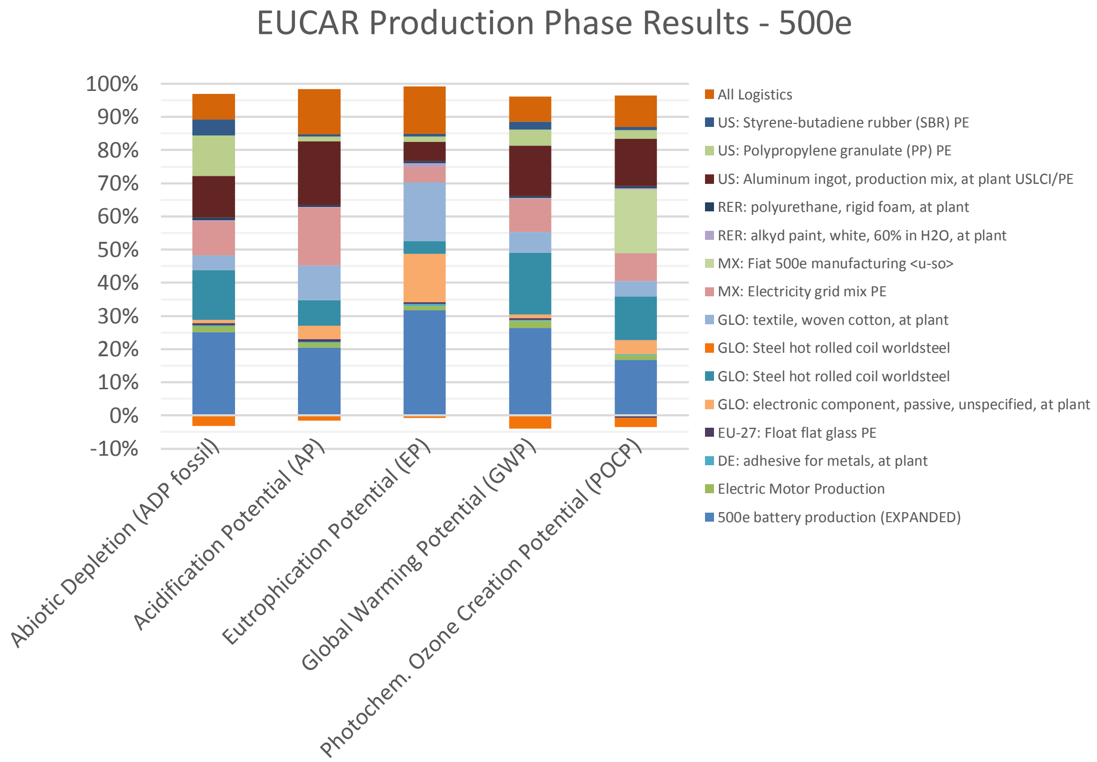


Figure 22: Breakdown of production phase for the Fiat 500e (Shipping from Toluca to Torino scenario)

Figure 21 also shows the electricity consumption of the vehicle assembly plant, engine plant, and gearbox plant, which have a significant impact in many categories. Plant operating data from Tier 1 suppliers, such as brake and steering component manufacturers, have not been included. Therefore, the study is potentially under estimating the production phase by a significant amount.

Consider the following. The Body-in-White (BIW) accounts for about ¼ of the vehicle’s mass, but the electricity consumption associated with BIW manufacturing is accounted for because it is stamped and formed within the assembly plant. The engine and gearbox account for another 12% of the vehicle’s mass and their manufacturing electricity consumption generates about 5% of the production phase GWP impact. The remaining, approximately 63% of the vehicle’s mass is manufactured by Tier 1 suppliers. If a similar electricity consumption as the engine and gearbox were assumed for manufacturing the Tier 1 supplied components, then the

GWP would increase roughly 30% over the current figure. Clearly, a 30% increase in GWP is a very crude estimate, but the exercise indicates that accounting for the electricity consumption from manufacturing each component part could have a significant impact on the study's results. Given that the production phase accounts for roughly 15% of the Fiat 500's total GWP impact, this 30% increase would result in a roughly 5% increase in total life cycle GWP emissions.

The largest limitation of the use phase is treatment of the air conditioning system, as this system has a large impact on the overall results. The eLCAr guideline recommends using the maximum power rating of the vehicles air conditioning and cabin-heating units in order to calculate the annual energy consumption. However, the guideline also cites that most heating and A/C units draw about 5000, and 1000 Watts respectively (Del Duce, et al. 2013). The Fiat 500e's A/C unit has a maximum consumed power of 6500 W, although it was not confirmed if the A/C unit actually draws this amount of power during regular use. A/C data for the Fiat 500 is more in line with typical values, so the A/C energy consumption for the ICE vehicles is much lower than that of the Fiat 500e. Therefore, the study conducted may overestimate the Fiat 500e's A/C energy consumption, increasing the 500e's use phase emissions with respect to the Fiat 500 and 500 NP. Lastly, the calculation method for all vehicles is heavily dependent on the average speed assumed for the vehicle's lifetime. For this study, the NEDC cycle was used resulting in an average speed of just 33 km/h. If a higher average speed were assumed then the annual power draw of the climate control systems could be significantly reduced.

CHAPTER 6

LIFE CYCLE IMPACT ASSESSMENT

6.1 Impact Category Results by Vehicle Life Cycle

The impact categories used to evaluate the LCI results can have a significant sway on how the study is interpreted. However, the LCIA phase is not only influenced by the methodology, but also the point of view of the LCA recipient. If the recipient's understanding of the impact categories is limited, then the LCIA phase should also present additional information to inform their interpretation. In this chapter, the impact categories shared by all guidelines are discussed in depth, as well as a selection of other categories that are also relevant to understanding the LCI results. All results presented in this subchapter are those from the eLCAr guideline based simulation, as it includes all the variables used in the EUCAR and PCR guidelines, with additional variables as well. The effect of the methodology on the results of the study is discussed in the next subchapter. Due to the inherent complexity of the characterization methods, an extensive analysis of CML or other LCIA models is beyond the scope of this thesis. Instead, focus is placed on the relevance of each impact category to the vehicle life cycle.

Global Warming Potential

Global Warming is the most widely understood and most frequently discussed environmental impact associated with passenger car use, largely because of the impacts the transportation sector has on global greenhouse gas emissions (United States Environmental Protection Agency 2013). The production and end of life phases have little impact on the overall GWP impact. For the production phase, GWP emissions result from a variety of the material flows, as well as energy generation. For ICE vehicles, the life cycle GWP is primarily a function of CO_2 emissions during the use phase. Methane (CH_4) and Nitrous Oxide (N_2O) also have strong greenhouse effects at 25 and 298 times that of CO_2 respectively. However tailpipe emissions of these gases are 3 to 4 orders of magnitude less than CO_2 (117 versus 0.01 [g/km] for CO_2 and CH_4 respectively), and thus their effect is less significant.

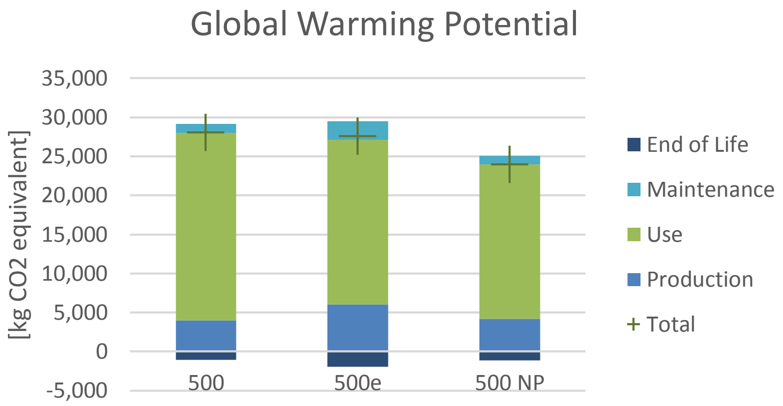


Figure 23: GWP Impact calculated in GaBi for the whole life cycle using the CML 2001 method

Figure 23 above highlights the cumulative GWP impact for each vehicle by life cycle phase, while Figure 24 shows a detailed breakdown of the use phase. From the use phase breakdown, one can see that the majority of emissions come from the basic driving emissions, although a significant portion of the Fiat 500e's emissions are due to the auxiliary systems use. For the ICE vehicles, the auxiliary usage category includes both TTW and WTT emissions from the use of climate control systems, where-as TTW and WTT emission from the primary driving cycle are displayed separately (light blue and dark red bars respectively). The additional considerations suggested by the eLCAr guideline, such as roadwork and maintenance parts, have a small impact, but little effect on the overall results.

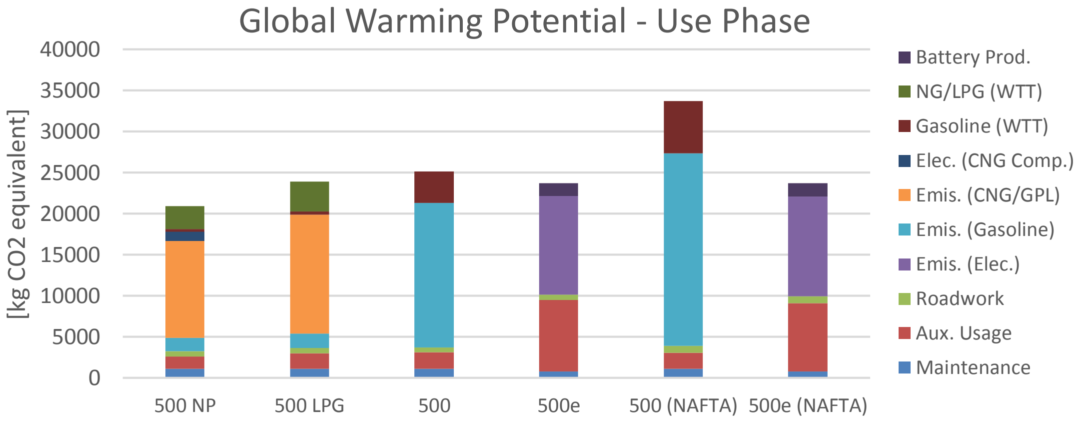


Figure 24: Use phase breakdown for all vehicles
(Low impacting emission sources have been removed for clarity)

Figure 24 also highlights the difference between the NAFTA and EMEA vehicles studied. In regards to the Fiat 500, note that the NAFTA and EMEA models use different engines, so the difference in GWP emissions is due to both the engine and the different drive test cycle. Looking at the Fiat 500e; however, the use phase GWP emissions are about the same, due to slightly reduced GWP emissions from the US electricity grid mix that offset the increased fuel consumption rating from the US EPA test cycle.

Ozone Depletion Potential

Ozone depletion refers to the destruction of ozone gas in the upper atmosphere, which is mainly attributed to the use of Chlorofluorocarbons (CFC's) in aerosol products (US Environmental Protection Agency 2010). The majority of modelled ODP emissions are generated during the manufacturing and maintenance phases (Figure 25), and come from the production of brake fluid. However, this result is uncertain because the brake fluid was modelled using a dataset for generic solvents. The electric vehicle exhibits higher ODP emissions than the conventional vehicles because of the extraction and production of Lithium Manganese Oxide, which was used as a substitute process to model producing lithium compounds inside the battery. Disposing the vehicle's used coolant fluid also has small influence on use phase ODP emissions, although this could depend on the disposal method modelled.

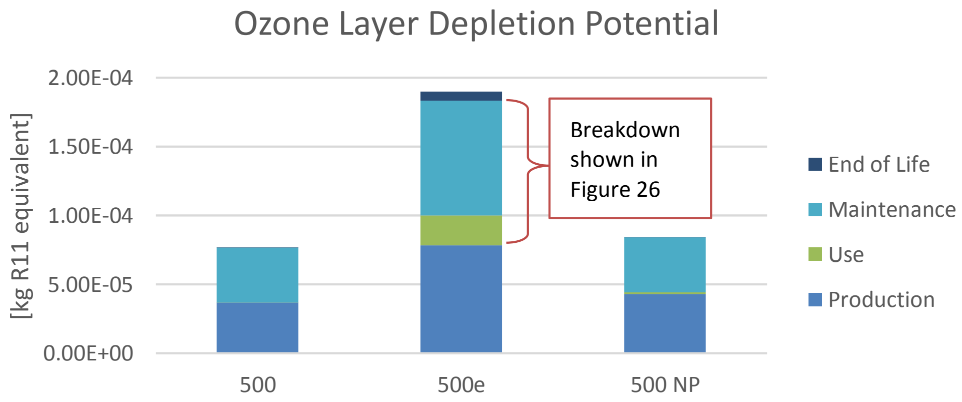


Figure 25: Life cycle ODP emissions, calculated using CML 2001 method

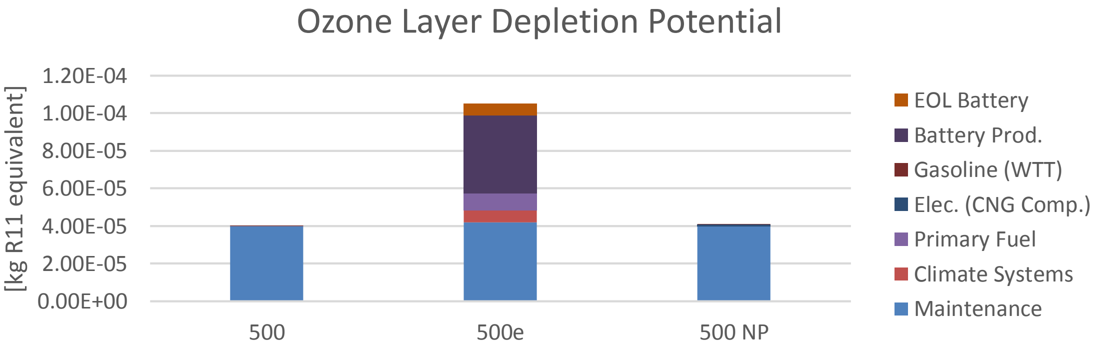


Figure 26: ODP emissions breakdown for the use phase, based on the CML method. Note the large impact of maintenance and battery production.

Acidification

Acidification Potential (AP) measures the ambient acidity of the environment resulting from emissions to the atmosphere. This leads to effects such as acid rain, and can damage the ecosystem's ability to support biodiversity (Acero, Rodriguez and Ciroth 2014). Because some ecosystems are more sensitive to acid rain than others are, some LCIA models use regionally specific factors. The CML method however, uses global factors that only account for the ability of a particular emission to form acid rain in the atmosphere (European Commission - Joint Research Center - Institute for Environment and Sustainability 2011). AP emissions are predominantly the result of electricity generation, which results in increased emissions in both the production and use phase for the electric vehicle (Figure 27).

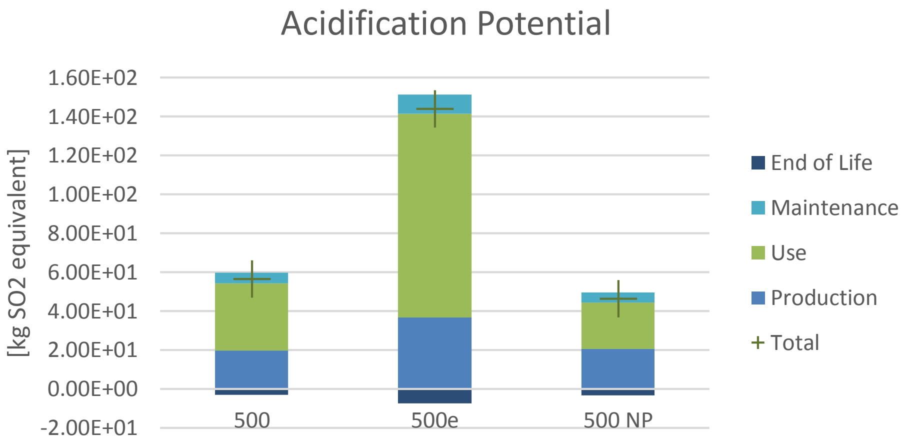


Figure 27: Life Cycle AP emissions, calculated using CML 2001 method

Eutrophication

Eutrophication is related to the artificial introduction of excess nutrients into an ecosystem, and is particularly harmful to marine ecosystems where excess nutrients can lead to algal blooms (Acero, Rodriguez and Ciroth 2014). Characterization factors can be local or global depending on the modelling method, although global factors lack the ability to precisely model impacts (European Commission - Joint Research Center - Institute for environment and sustainability 2011). The CML 2001 method used herein uses global factors. Eutrophication emissions are relatively dispersed across many of the flows, as well as across the production, use, and maintenance phases (Figure 28). The greatest emitters for the Fiat 500e are electricity generation, production of electronics for control units, and lithium extraction and processing, while for the Fiat 500 they are the WTT fuel cycle, driving emissions, and electronics production.

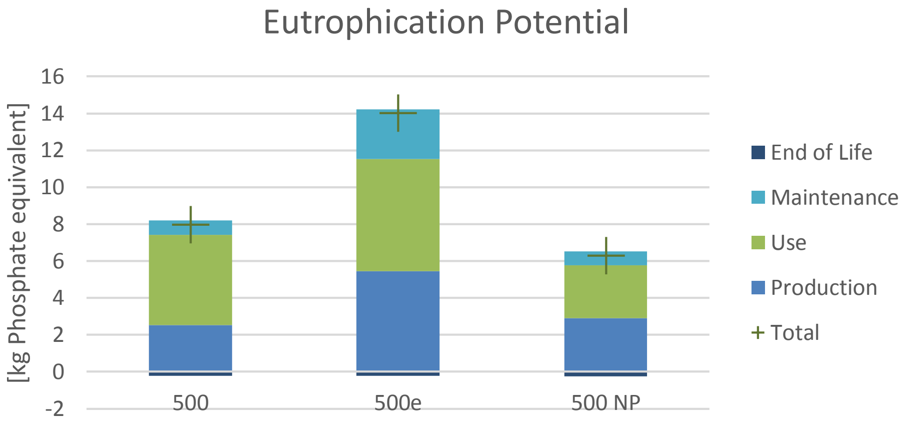


Figure 28: Life cycle EP emissions, calculated using CML 2001 method

Photochemical Oxidant Formation

Photochemical Oxidant Formation, or Photochemical Oxidant Creation Potential (POCP), relates to the generation of smog, and is particularly important for vehicles operating in urban environments due to the respiratory impacts of the emissions (Nemry, et al. 2008). An ICE vehicle operating in the city will emit POCP emissions in close proximity to the general population, and therefore have a greater human health impact than an electric vehicle, where the emissions are generated at the electricity generating plant.

In the manufacturing phase, the largest contributor to POCP is VOC emissions. In fact, the elevated POCP for the Fiat 500e manufacturing, shown in Figure 29, is mainly a result of differences between the painting areas in the assembly plants, as opposed to any differences in vehicle design. Use phase POCP emissions are mainly the result of the non-CO_2 tailpipe emissions and electricity generation; NO_x is the strongest contributor, however NMHC, CO, and CH_4 all contribute as well.

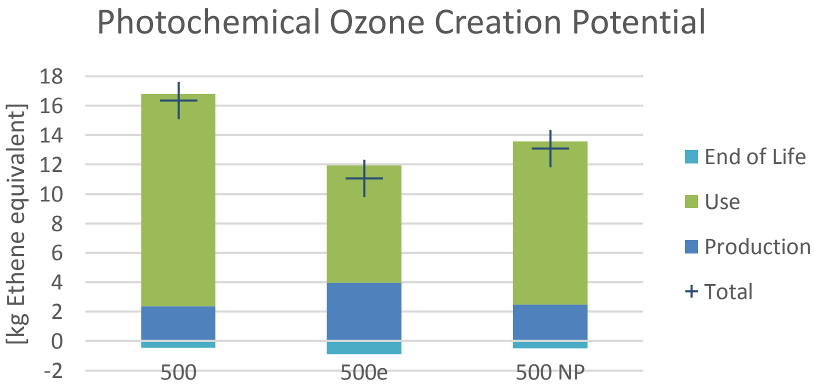


Figure 29: Life cycle POCP emissions, calculated using CML 2001 method

Resource Depletion

Resource depletion is one of the few impact categories that is almost equally discussed for all types of vehicles. Of course, the consumption of diminishing petroleum supplies is a highly discussed topic in relation to ICEV's; however, the availability of lithium for future fleets of BEV's has also been questioned in recent years. In regards to the GaBi simulation however, the 500e's increased resource depletion impact is generated by the large amounts of copper used in the vehicle's electrical components and battery (Figure 30).

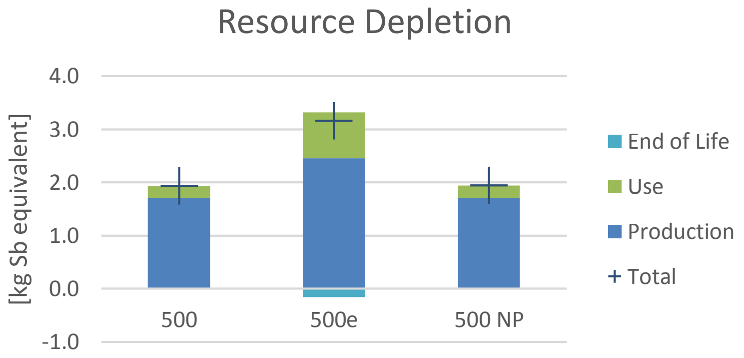


Figure 30: Resource depletion, calculated using ILCD recommended method (CML 2002)

Other Significant Impact Categories

Similar to POCP, Respiratory Inorganics (or Particulate Matter [PM]) are associated primarily with the vehicle use phase and are more damaging to human health when the emission is generated in close proximity to the general population. The major sources of PM emissions are the Well-to-Tank fuel cycle and electricity generation. Tire and brake wear also contribute to this category, however their impact is minor. In reality however, the impact of tire and brake wear may be higher due to the proximity of the emissions to the population; however, this is not modelled in the LCIA methodology.

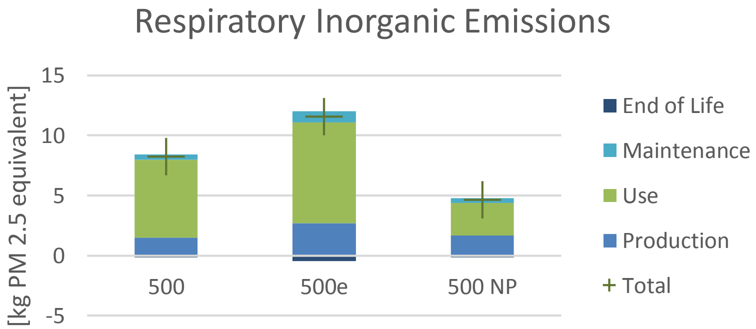


Figure 31: Respiratory inorganics, calculated using the RiskPoll methodology as recommended by the ILCD handbook

Human and environmental toxicity are recommended impact categories in both EUCAR and eLCAr guidelines, although the methodology for their measurement can vary. For Figure 32 to Figure 34, the ILCD recommended methods have been used, which divide the impacts into human (non-cancer causing), human (cancer causing), and toxicity to fresh water. The major contributing factors for the ICEVs non-cancerous toxic effect are the disposal of used engine oil, and the Well-To-Tank gasoline cycle, while the BEV's main emitters are the production of electronic components and electricity generation. The cancerous toxic effect of the 500 Natural Power is dominated by the production of Chromium Steel for the gas cylinders, which were modelled similar to the traction battery for the 500e. Ecotoxicity for all vehicles is primarily a result of the production of electronic components, raising the ecotoxicity levels for the 500e.

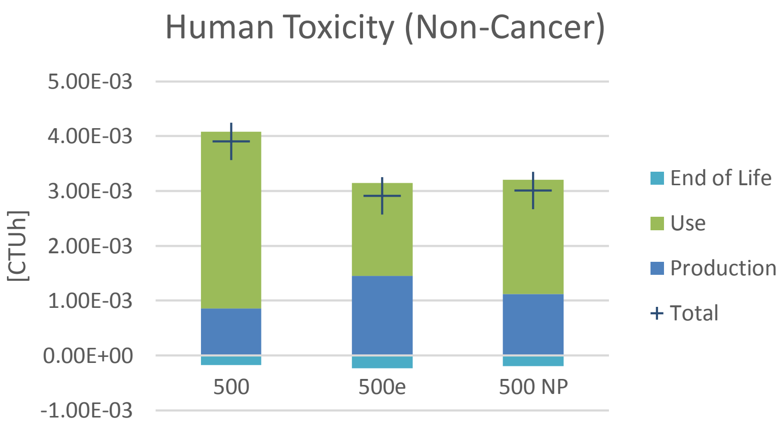


Figure 32: Non-cancer causing toxic impact, calculated using the USEtox method

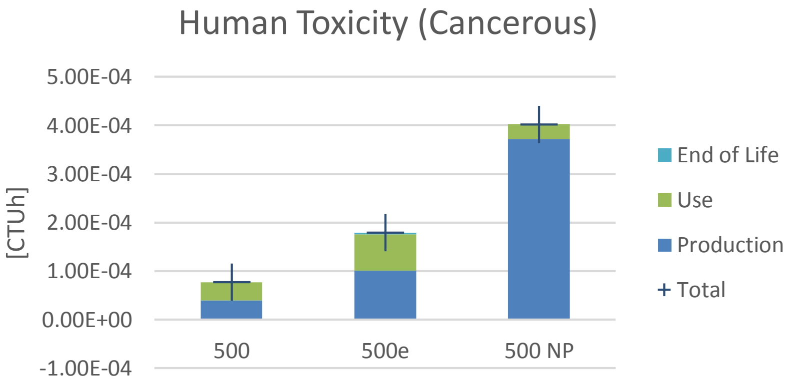


Figure 33: Cancer causing toxic impact, calculated using the USEtox method

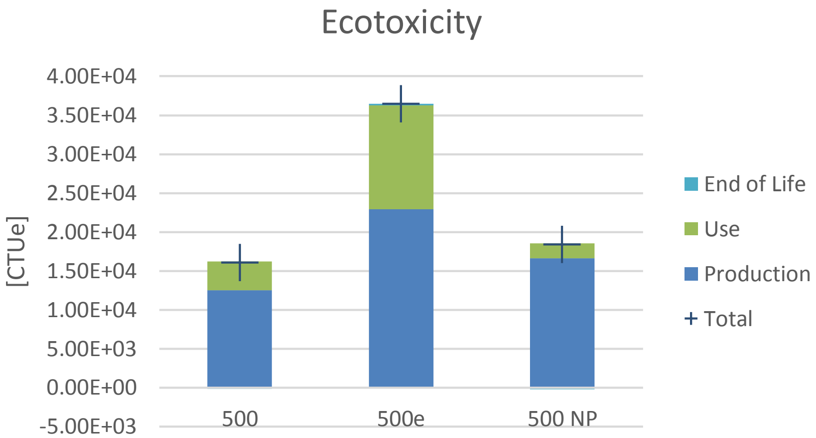


Figure 34: Ecotoxicity for aquatic fresh water, calculated using the USEtox method

Ionizing radiation is a result of releases of radioactive materials into the environment, and therefore depends on the use of nuclear energy in the chosen electricity mix. Not surprisingly, the electric vehicle impact in this category is almost 10x that of gasoline, or natural gas vehicles.

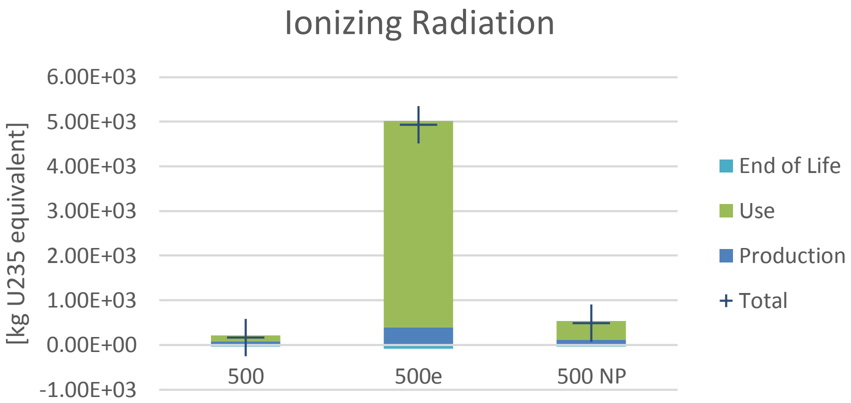


Figure 35: Ionizing radiation calculated according to the ReCiPe 1.08 Midpoint (H) method.

6.2 Comparison of Results by Guideline

The previous section outlined the various factors that contribute to the environmental impact of the vehicles studied: only the results from the model made following the eLCAr guideline were shown. This section demonstrates how the choice of the LCA guideline affects the results in some of the key impact categories. Many of the impact categories are affected by similar issues, two of which are the effects of climate control systems and vehicle maintenance. Impact categories, such as ODP, and EP, are related to the extraction of raw materials, and by including maintenance parts in the use phase these raw material flows generate additional emissions that would not have otherwise been included. Another noteworthy tendency is that many impacts are more sensitive to electricity generation than fossil fuel life cycles, leading to high emissions from the Fiat 500e. These tendencies are dependent on both the vehicle studied, and the guideline used, resulting in large variances in some impact categories between each guideline used.

The estimated Global Warming Potential, shown in Figure 36, is similar when using either the PCR or EUCAR guidelines because it depends mainly on fuel use and not maintenance materials. The eLCAr guideline shows an increase in GWP emissions when including climate control systems: this significantly decreases the performance gap between the Fiat 500e and Fiat 500. As was mentioned in the section on limitations however, the power draw of the climate system for the Fiat 500e may be overemphasized because of the larger than average A/C power draw assumed in the study. Compared to the PCR study, the eLCAr guideline yields an 11% increase in use phase emissions for the Fiat 500, but a 37% increase for the Fiat 500e. The differing effect of the climate control systems between the BEV and ICE decreases the difference in use phase emissions between the two vehicles from a 20% difference calculated using the PCR guideline, to a mere 1% using the eLCAr guideline. Similar results occur for POCP emissions, which also depend heavily on fuel consumption.

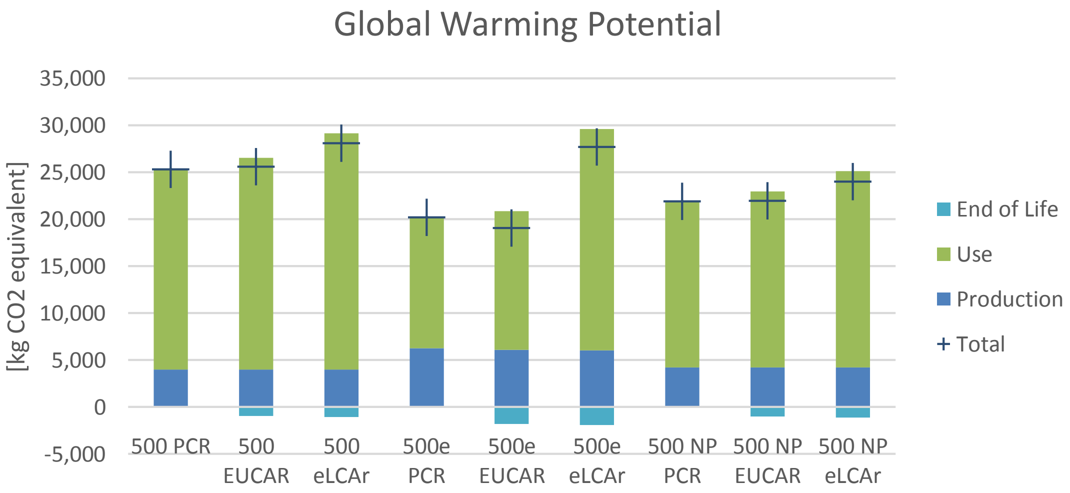


Figure 36: GWP Impact across all guidelines and vehicles studied

The ODP impact shows a steady increase depending on the guideline used, although ODP depends mainly on raw material flows and is therefore almost the same for EUCAR and eLCAr guides (Figure 37). The Use phase ODP emissions shown by the PCR guideline for the Fiat 500e are in fact due to considering the second battery, which is done for all guidelines. AP and EP impact categories also show a steady increase from PCR to the eLCAr guide, although the jump from the

EUCAR to the eLCAr results is more pronounced for the Fiat 500e because of the impact of electricity generation in both these categories (Figure 38).

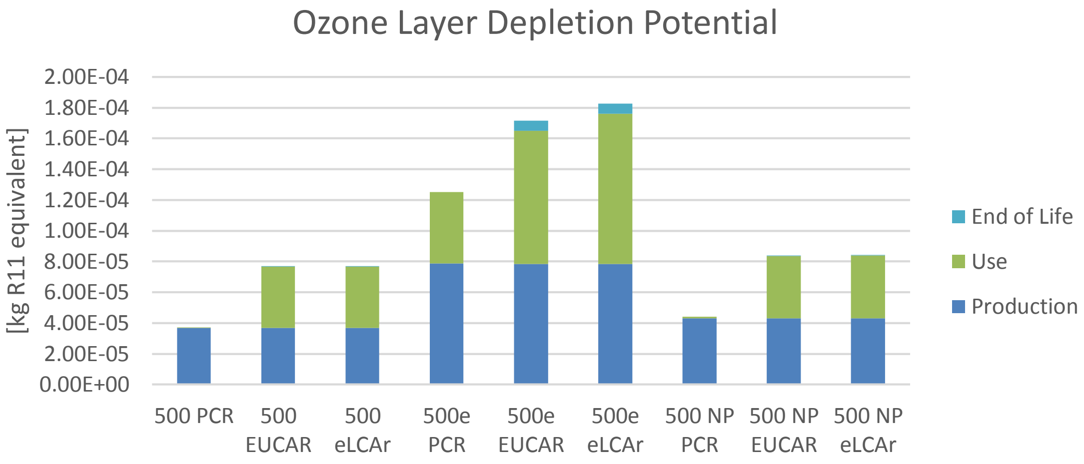


Figure 37: ODP emissions for all guidelines

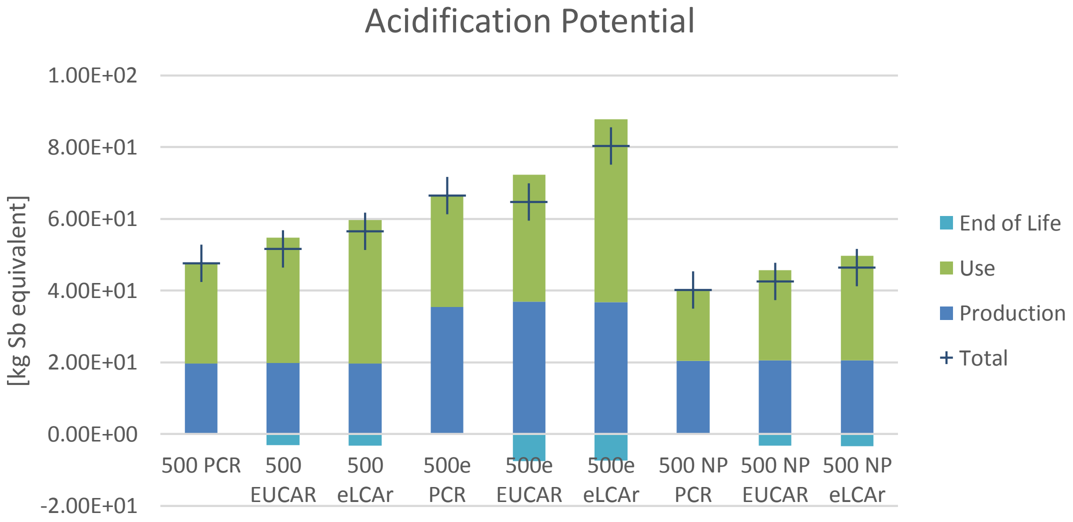


Figure 38: Acidification potential for each vehicle and guide

Resource Depletion is the only impact category that has reduced emissions when using the EUCAR and eLCAr guidelines, although this is only true for the Fiat 500e. The decrease is because of battery recycling: in the EUCAR guideline, recycling of a single battery at the vehicle end-of-life phase is included, while in the eLCAr guideline, recycling of the first and second batteries is included. For all vehicles however, the results from each guideline are much more similar for resource depletion than many of the other impact categories.

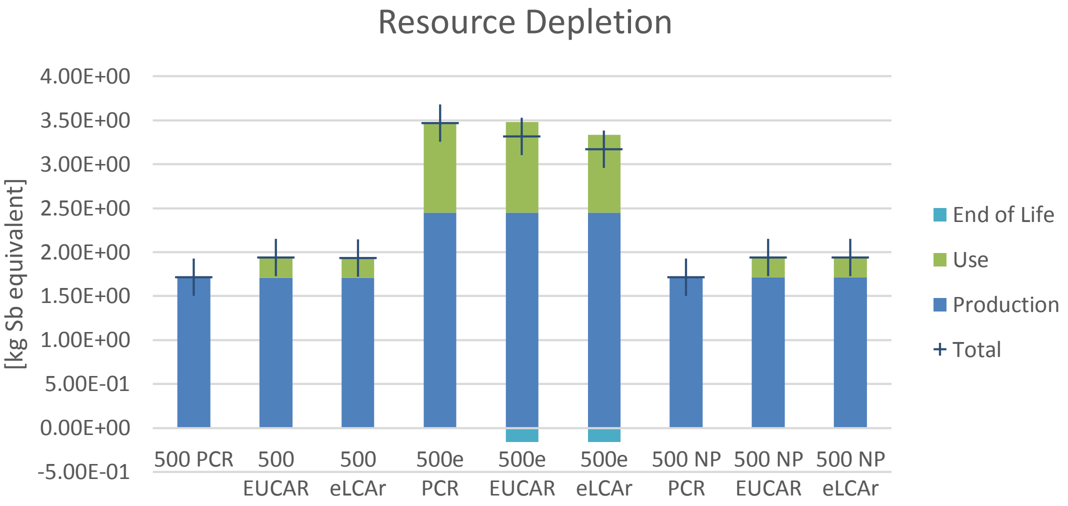


Figure 39: Resource depleting impact from all guidelines

CHAPTER 7

LIFE CYCLE INTERPRETATION

7.1 Post LCA Comparison of Guidelines

This chapter assesses the benefits and trade-offs of each guideline in detail. Because of the limitations discussed in Chapter 5, particularly those associated with the production phase, it was not possible to comply with all of the suggested practices from every guideline. Almost all of the recommendations in the PCR guideline were completed, although for parts such as the steering and brake systems, their production phase has only been considered in terms of the raw material extraction. Since these systems are supplied in whole by Tier 1 suppliers, the emissions associated with their direct production have not been considered. Table 18 provides an overview of the advantages and disadvantages of each guideline.

PCR		**EUCAR**		**eLCAr**	
Advantages	Disadvantages	Advantages	Disadvantages	Advantages	Disadvantages
Concise definition of the required functional unit Easiest to reach full compliance Simple use phase does not require any data not readily available Results should be very comparable across OEMs	Short use phase *(150,000 km)* Misses important considerations *(maintenance, climate)* No end-of-life consideration	Allows for alternative functional units *(passenger·km)* Simple treatment of in-process recycling and ELV Only requires logistics data in global scenarios Precise definition of maintenance materials for ICE vehicles	Use of alternate units could result in misleading studies Does not provide guidance specific to EVs Does not include use of climate systems	Clear direction for BEVs and use scenarios Very thorough in all life cycle phases Specific guidance on use phase assumptions Detailed guidance on end-of-life scenarios, specifically for BEVs	Limited scope makes it difficult to apply to non BEVs Some suggested considerations are difficult or impractical to include Does not provide guidance specific to ICEVs

Table 18: Comparison of advantages and disadvantages of the three guidelines

One aspect neglected by all guidelines is precise guidance on how to interpret the raw material flows, a.k.a. the material breakdown procedure, during the production phase. The PCR's concise, and easy to follow rules ensure that any study following the guideline should be comparable, but its limited scope neglects some of the important life cycle attributes included in the other guides. In contrast, the eLCAr guideline has very wide scope, and some could not be included also in this thesis; for example, charging infrastructure. The scope of the EUCAR guideline seems to be balanced between comprehensiveness and practical limitations.

Following from Table 18 a list of requirements for the new guideline is generated. Table 17 demonstrated the importance of the material breakdown procedure, so it should be covered by the new guideline. Climate control systems should also be included because of their influence on the use phase emissions of electric vehicles. To summarise Table 18, the new guideline should:

- Give a concise definition of the functional unit required for all studies
- Provide guidance for determining a vehicle's material breakdown and treatment of high impact materials
- Precisely define vehicle components to be evaluated as maintenance parts during the use phase of the vehicle
- Include auxiliary fuel consumption from use of climate control systems and give detailed guidance on making assumptions for the use pattern
- Give clear direction for making comparative studies between electric, combustion and hybrid vehicles

7.2 Analysis of Life Cycle Variables

In Table 19 the studies have been deconstructed to show the life cycle variables used in each guideline. The difference between each guideline is created mainly by which variables are included and which are not, because there is little variation in how each variable is treated by the guidelines. In the table, the *Weight* column is determined by assessing the amount that each variable contributes to the LCIA categories discussed previously. A **light weight** means that the variable contributes minimally to the majority of impact categories considered. A **medium weight** means there is a small impact in some categories but higher in others. A **heavy weight** means there is a very high impact in one or more categories. The **workload** is estimated by subjectively assessing the number of external contacts required to obtain the data, lead-time, and any assumptions that must be made.

Variable	Guidelines			Life Cycle Phase			Weight	Workload		
	PCR	EUCAR	eLCAr	Prod.	Use	EOL		PCR	EUCAR	eLCAr
Logistics	X	X	X	X	X		Light	**High**	**High**	**High**
In-Process Recycling	X	X	X	X			Light	Low	Low	Low
Raw Materials	X	X	X	X			**Heavy**	**High**	**High**	**High**
Assembly Plant Energy	X	X	X	X			Medium	Low	Low	Low
Primary Fuel Use	X	X	X		X		**Heavy**	Low	Low	Low
Maintenance Materials		X	X		X		**Heavy**	-	**High**	**High**
Roadwork			X		X		Light	-	-	**High**
Auxiliary Fuel Usage			X		X		Medium	-	-	**High**
Non-Tailpipe Emissions			X		X		Light	-	-	**High**
End of Life Processing		X	X			X	Light	-	**Med**	**High**
Open-Loop Recycling		X	X			X	Light	-	**Med**	**High**

Table 19: Analysis of life cycle variables with respect to goals of the new methodology

From Table 19 one can see that the variables with the strongest influence on the results are the primary fuel use, raw material extraction and maintenance materials (which includes battery replacement for the Fiat 500e). The highest workload variables are those that require large networks of contacts or large quantities of data not typically readily available, such as the logistics and end of life processes. Collection of raw material data is somewhat of an exception because if the data required currently exists in the IMDS, then collection is relatively easy. If it is not however, then data collection can be very time consuming, possibly requiring the disassembly of a new vehicle if suppliers are not able to update the IMDS. Likewise, collecting data for auxiliary fuel usage from A/C or other systems should be relatively easy for an OEM, but because this data is not required for any current government regulations, they are typically not recorded. This means collecting A/C consumption data could require a dedicated test by the OEM, a costly and time consuming proposition. Data for roadwork and non-tailpipe emissions pose even greater difficulty because it may be beyond the OEM's capability to measure, requiring alliances with research groups or other parties to collect the necessary data.

7.3 Case Studies

The scenarios developed in this section represent irregular or limit situations that companies conducting LCA studies may encounter. For these studies each scenario is evaluated uniquely, as opposed to comparing each guideline or using always the same guideline. The first case tests the impact of applying recycling credits and the second investigates the comparability between NAFTA and EMEA vehicle homologation procedures. The last three cases focus on reducing the GWP emissions of the use phase because increasing fuel economy and reducing CO_2 emissions are two of the most significant market forces driving the automobile design.

Open-Loop Recycling Credits

To evaluate the effect of recycling processes a study was undertaken comparing a zero recycling scenario against the scenario in which 100% of recyclable materials (steel, aluminium, plastic, copper, and glass) are recovered. All of the guidelines describe how to treat end-of-life processing, but none give precise rules on how much credit to apply. This scenario then, evaluated how much end-of-life could affect a study's outcome. The study was done following the EUCAR methodology, so the use phase only considered maintenance materials and basic driving emissions. Figure 40 displays the results for the GWP and Resource Depletion impact categories. Most impact categories have little change, similar to the GWP category (3% and 9% reductions for the Fiat 500 and Fiat 500e respectively). The Resource Depletion potential however, is heavily affected in the case of the Fiat 500e (26% reduction) because of copper recycling. Copper extraction is also the main contributor to the Resource Depletion in the production phase.

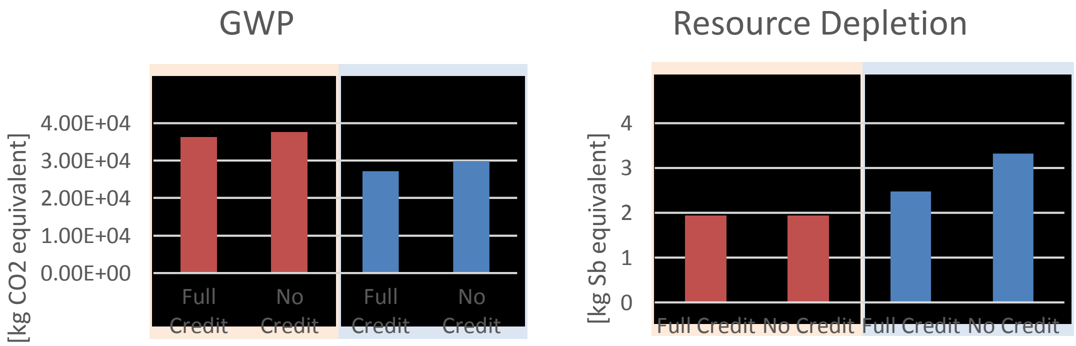


Figure 40: Comparison of GWP and Resource Depletion for recycling scenarios

Cross Market Vehicle Assessment

Global manufacturers are interested in comparing the environmental impacts of their NAFTA and EMEA vehicle models. However, none of the guidelines examined provide guidance on this type of comparison. Current guidelines often suggest using a vehicle's homologation data for calculating the use phase impacts, but this practice reduces the effectiveness of LCA studies on vehicles sold in different global markets if the homologation tests vary between them. The LCA practitioner must also assess which impact categories are based on local criteria, or global influences, and avoid any indicators that might only be valid for particular regions of the world. Figure 41 shows the GWP impact from just the primary fuel use for the Fiat 500, 1.4L gasoline model, a vehicle that was sold in the EMEA market and then imported to the NAFTA market. The NAFTA vehicle has a 15% increase in use phase GWP emissions over the EMEA model. This discrepancy is because of both structural changes that add weight to the chassis, as well as the more energy intensive US EPA driving cycle. The structural modifications add about 130 kg to the vehicle, which is estimated to increase fuel consumption by roughly 8%. The remaining 7% increase is because of the driving cycle. Because of the difference in chassis design and driving cycle, current guidelines are insufficient for manufacturers that would like to compare their NAFTA and EMEA vehicle models.

GaBi Object	GaBi Parameter	NAFTA	EMEA	Units
Fiat 500 Gasoline Use (1.4L, 16V)	CO2 Emissions	156	140	[g/km]
Fiat 500 Gasoline Use (1.4L, 16V)	Gasoline Consumption	8.1	6.1	[l/100km]
Fiat 500e Use	Electricity Consumption	180	170	[Wh/km]

Table 20: Parameters for case study on EMEA and NAFTA homologation data

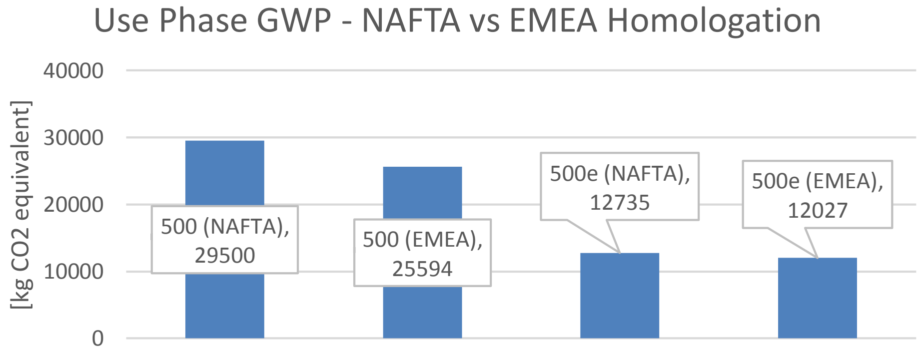


Figure 41: Comparison of GWP impact from primary fuel use based on EMEA and NAFTA homologation data

Near Future, Lightweight ICE Vehicle

For this scenario it was assumed that a substantial portion of the vehicle's mass in steel, was changed to aluminum, reducing the weight and therefore decreasing the fuel consumption. The critical parameters for the scenario are shown in Table 21, and the results for the GWP impact are presented in Figure 42. The results are those from using the PCR guideline, so only the basic driving cycle has been considered in the use phase. The aluminum production yields higher GWP emissions per unit weight than steel. However the lighter overall weight means the net effect is roughly equivalent GWP emissions for both vehicles during the production phase. The improved fuel economy reduces use phase emissions over the whole life cycle.

	Steel Mass [kg]	Aluminum Mass [kg]	Total Mass [kg]	Fuel Consumption [L/100 km]	CO_2 Emissions [g/km]
Benchmark Vehicle	643.5	52.6	**942**	**5.1**	117
Lightweight Vehicle	243.5	152.6	**642**	**4.1**	95
Delta	*-400*	*100*	*-300*	*-0.97*	*-22.36*

Table 21: Parameters for case study on vehicle lightweighting

**Fuel consumption delta based on Fuel Reduction Value of 0.6 (as suggested by EUCAR guideline)*

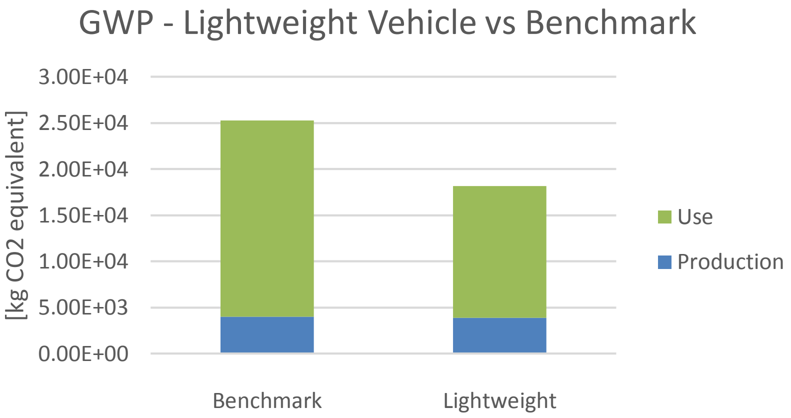


Figure 42: GWP impact of Fiat 500 1.2L (benchmark) vs hypothetical lightweight vehicle

Green Energy Mix

Often considered for LCA studies on BEVs, green energy mixes can substantially reduce the vehicle's lifecycle GHG emissions. As opposed to the previous case study however, a green energy mix can reduce the use phase GWP emissions to the point of becoming less than the production phase emissions (Figure 43). Reducing use phase emissions of this magnitude should shift the focus of the LCA study from the use phase to the production phase, thereby placing increased importance on correct modelling of the production phase. At this point, the LCA practitioner should begin to work with an increased number of suppliers, to collect LCA data on component production and logistics. Lastly, depending on the energy mix, acids and other emissions from energy production facilities can also be significantly reduced.

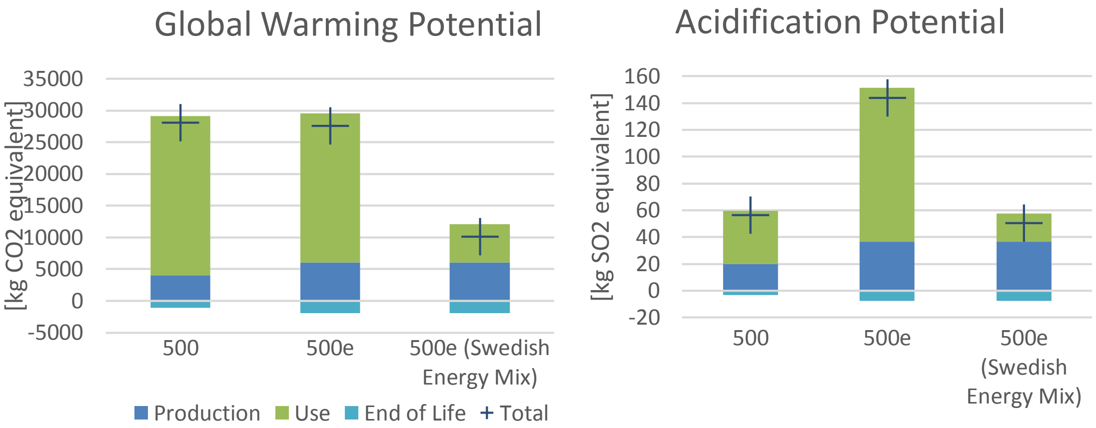


Figure 43: GWP and AP of Fiat 500e using EU-27 Energy mix and Swedish Energy Mix
Refer to Figure 9 for description of EU-27 and Swedish energy mixes

Bio-Methane for Use in Bi-Fuel Vehicle

This case study represents a potential future scenario given that production and use of bio-methane is very limited. As previously discussed in the literature review, only small amounts of bio-methane are currently being produced globally, and their distribution networks are limited (DENA 2010). Nonetheless, the use of bio-methane presents the opportunity to significantly decrease vehicle emissions while still using conventional, ICE technology. Figure 44 shows the use phase GWP impact for two forms of bio-methane (grass and waste) as well as traditional natural gas. Although not as drastic as the low GWP energy mix, bio-methane from grass has the potential to significantly reduce the use phase GWP emissions.

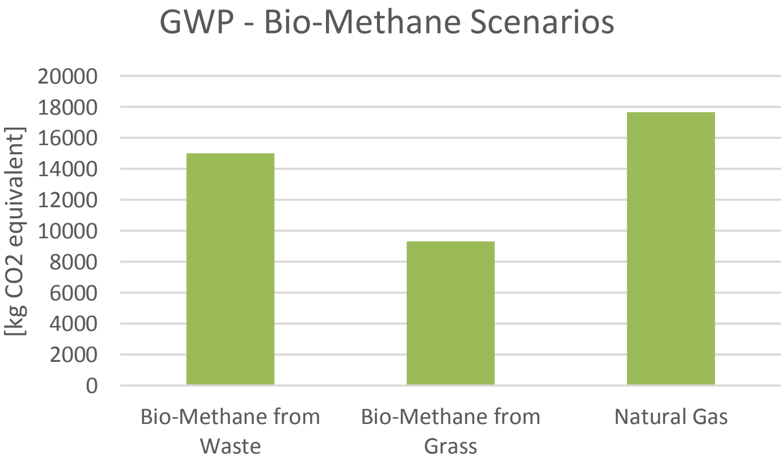


Figure 44: Use phase, basic driving emissions from two forms of Bio-Methane and CNG

CHAPTER 8

A NEW GUIDELINE

From the previous comparison of the three guidelines, it is evident that each guideline provides unique advantages and disadvantages. The eLCAr guideline is broad and covers many details in depth, but requires significant amounts of data and includes many factors that are insignificant compared to the whole. By contrast, the PCR is straightforward and simple to follow, but neglects critical aspects of the lifecycle that can affect the interpretation of the study. The case studies also showed that there are some common scenarios where all of the guidelines fail to provide the necessary guidance. Consequently, a new guideline was developed.

8.1 Goal and Scope Definition

The goal of the new guideline is to identify which aspects of the vehicle life cycle have the most significant contribution to its overall impact, while trying to reduce the overall workload and provide clear guidance for OEM's. Because most LCAs are primarily intended to compare one option against another, the guideline focusses on those variables which can be used to distinguish one vehicle from another, instead of variables that are more or less the same for all vehicle models. The guideline will also enhance comparability, and decrease the time to implement LCA studies by eliminating variables that increase uncertainty. Enhancing comparability between studies and providing a clear methodology also makes the LCA study easier to communicate to an unfamiliar audience. In addition, the straightforward guideline can be more easily integrated into the product development process. The following sections are written as "to-do" series of actions for the LCA practitioner, and at the end of each subchapter, a checklist summarises the key aspects and decisions in each LCA phase. The checklist below gives an example for the goal and scope definition phase.

Goal and Scope Checklist

Goal of the Study	*Compare environmental advantages and disadvantages of electric, natural gas, and gasoline vehicles*
Market Scenarios	NAFTA ☐ EMEA ☒ LATAM ☐ APAC ☐ Other ☐
Cross Market Analysis	YES ☐ YES, but without direct comparison ☐ No ☒
Vehicle Models	*Fiat 500e (electric)* *Fiat 500 Natural Power (CNG)* *Fiat 500 1.2L (gasoline)*

8.2 Life Cycle Inventory Phase

Manufacturing Phase

In regards to the manufacturing phase, the most critical data pertain to the raw materials used in the vehicle. Prior to collecting material data the LCA practitioner should:

- Identify any materials or processes that may have abnormally high environmental impacts (ie. Lithium compounds, synthetic materials such as graphite, rare metals such as platinum, and highly alloyed metals like chromium steels). For the breakdown of regular materials, the IMDS materials categories are recommended, if possible.
- In regards to BEVs, copper and electronic equipment should be modelled as high impact materials.
- Vehicle fluids filled in the assembly plant should also be included.
- At least 95% of the vehicle's mass should be accounted for in the raw material breakdown, excluding the inclusion of high impact materials.

For manufacturing and assembly plant operations:

- It is sufficient to only record data on VOC emissions and electricity consumption. It is not necessary to account for normal plant refuse or in-process recycling of raw material.
- In all cases, the mass of materials modelled entering the plant should be equal to the total mass products produced. Allocation by number of products is acceptable in cases where a plant produces a similar range of products/vehicles. If a plant produces many different products that vary significantly in size, weight, or energy intensity, then allocation by another means should be used.
- If an assembly plant receives a large number of pre-assembled component parts from third party suppliers, the supplier's plant energy consumption should be included in the LCI for any assemblies accounting for more than 5% of the vehicle's total mass.
- When analysing future automotive scenarios with low use phase emissions, it is recommended that a higher degree of supplier cooperation be used to reduce the uncertainty in the study.
- For supplied parts, production energy and emissions of individual components as little as 2% of the vehicle's total mass should be accounted for.

- Logistics data for delivering supplied parts to assembly facilities can generally be neglected, except in cases where exceptionally long distance transport is required for very large, or heavy components (such as the delivery of traction batteries).

Life Cycle Inventory – Production Phase Checklist

Raw materials ☐
(>95% of vehicle mass)

High impact materials identified ☐

Production Materials:
ie, Oils and hydraulic fluids
Solvents,
Lacquers,

Vehicle Materials:
ie, Lithium compounds
Rare metals
Highly alloyed or specialty metals
Electronics
Copper and copper alloys
Composites or other synthetic materials

IMDS breakdown used ☐

Vehicle fluids included ☐

Production electricity consumption ☐

VOC emissions ☐

Allocation method used *ie, Number of products*

Energy consumption of Tier 1 suppliers ☐
Indicate to what level of detail *ie, Battery, IC engine, gearbox*

Logistics data in necessary cases ☐
Indicate cases *ie, Battery to assembly plant*

Use Phase

The variable with the greatest use phase impact is the driving cycle. There is still significant debate as to which regulatory cycles are the best suited to recreate real world use. This guideline does not recommend a specific cycle to use; however, in the case of comparative studies, all vehicles in the study should be compared using the same driving cycle and data collection methods. If possible:

- Real world or simulated data should be collected for non CO_2 tailpipe emissions, but regulatory limits can be used if this data is unavailable.

- Should real world or simulated data be collected, it should be done in accordance with the regulated testing methods.
- Cross market comparisons with different regulated tailpipe emissions are not recommended, due in part to the effect of the driving cycle on fuel consumption, as well as the effect of non CO_2 tailpipe emissions on the POCP impact category.
- Should a cross market comparison be desired, then only fuel consumption and CO_2 tailpipe emissions should be considered, and the POCP impact category should not be included in the study.

The use of climate control systems can have a large impact on use phase emissions as well as the interpretation of the study. Modelling their use however requires a number of assumptions and can fluctuate depending on regional weather profiles and customer behaviours. The optimal solution would be to collect real fuel consumption data by completing regulated driving cycles while using the climate control systems, with one full driving cycle conducted for each climate setting. Should this level of testing not be possible, then the eLCAr method (described in Chapter 5 detailed in Appendix F) should be used. Any usage pattern may be assumed, and climate data from the European Climate Assessment and Dataset project are recommended. All assumptions and climate data used should be made available if the study is published.

Modelling roadway maintenance and non-tailpipe vehicle emissions also require a number of assumptions and external data. These however have little impact on the study outcome, especially since current data cannot distinguish between the emissions and subsequent effects of different passenger vehicles (Viton 2012) (Office of Transportation and Air Quality 2014). Including roadway maintenance and non-tailpipe emissions is, therefore, not recommended.

Maintenance materials, including the consideration of a second battery for BEVs, is the third most influential variable for use phase GWP emissions: in many other impact categories it is the most influential. It is recommended that manufacturers use their dealer, or registered maintenance center networks to collect data on the lifetimes of components covered in Appendix 9 of the EUCAR guideline (also shown in Appendix D of this document), as well as the lifetime of traction batteries, motors, and high power electronics for BEVs. Should this data not be available, then using the data from Appendix 9 of the EUCAR guideline is recommended. Logistics data for the delivery of replacement parts need not be included. End of life processing of used engine oil and used coolant fluid is also not required because of their low impact if properly disposed of.

Life Cycle Inventory – Use Phase Checklist

Driving cycles NEDC ☐ US EPA ☐ WLTC ☐ CADC ☐ Other _______

Non CO_2 tailpipe emissions Measured ☐ Regulatory Limits ☐ Other _______

Climate control systems Measured ☐ Calculated ☐

If measured, describe test details: *Drive cycle, # of cycles, climate settings used*

Climate data used: *City and Year*

Usage pattern: *Temperature limits for climate settings,*
driving routine

Maintenance materials EUCAR Data ☐ Service Manual ☐ Other _______

High Impact Materials: *ie, Engine Oil*
Ie, Brake Fluid

End of Life Phase

The vehicle end of life phase was shown to have very little impact in all environmental impact categories examined, while also being highly subjective in its modelling method and allocation of open loop recycling credits. To reduce the modelling effort required for the LCA, it is recommended that no end of life processes be included in the life cycle modelling of passenger vehicles. This will also enhance the clarity and comparability between studies, by reducing the assumptions required. The previous statements do not, however, mean that the vehicle end-of-life management is not important, but in the context of this analysis their significance is limited.

8.3 Life Cycle Impact Assessment Phase

This guideline recommends specific impact categories that should be evaluated, however, it leaves the choice of impact modelling technique to the practitioner. The highest recommended impact categories are Global Warming Potential, Ozone Depletion Potential and Respiratory Inorganics. These categories have been chosen as they are based on simple, well understood and globally applicable models, all of which are recommended for use by the International Life Cycle Database. GWP, ODP, and Respiratory Inorganics also present a diverse range of impacts that highlight the unique benefits of different alternative fuels. Acidification, eutrophication, resource depletion, and photochemical oxidant creation are recommended by all guidelines examined in this study, and are also recommended by this guideline. In the case of acidification, and eutrophication, the practitioner used should verify if local or global characterisation factors are used, and make sure that the method is applicable for the study. Human and ecological toxicity categories received low scores from the International Life Cycle Database evaluation, and have been shown to be highly sensitive to specific material flows; their use is not recommended. Finally, in the case of studies involving electric vehicles, ionizing radiation is recommended. To enhance the clarity of the results, each impact category should be shown as the sum of its production and use phase emissions, with the effect of maintenance materials and climate control systems highlighted separately.

Impact Category	**Recommendation**
Global Warming Potential	Recommended
Ozone Depletion Potential	Recommended
Respiratory Inorganics	Recommended
Photochemical Oxidant Creation	Recommended
Resource Depletion	Recommended
Acidification	Recommended, only with validation of LCIA method
Eutrophication	Recommended, only with validation of LCIA method
Ionizing Radiation	Recommended, only for studies involving electric vehicles

Table 22: Summary of recommended impact categories

Life Cycle Impact Assessment Phase Checklist

Geographic Scope Global ☐ North America ☐ Europe ☐ Other _____

LCIA Methodology CML ☐ TRACI ☐ ReCiPe ☐ ILCD ☐ Other _____

LCIA Impact Categories:

Global Warming Potential ☐ Respiratory Inorganics ☐

Ozone Depletion Potential ☐ Resource Depletion ☐

Photochemical Oxidant Creation ☐ Ionizing Radiation ☐

Acidification ☐ Validation of LCIA method ☐

Eutrophication ☐ Validation of LCIA method ☐

CHAPTER 9

EVALUATION OF THE NEW GUIDELINE

The proposed guideline was evaluated by re-running the prior simulation to validate its integrity and effectiveness. The first check was comparing the results of the new guideline against those from the currently published guidelines, and then to compare the results of this study with those from other automakers. Comparing the new guideline against the previously conducted studies tested if, given the assumptions considered for this analysis, the new guideline captured all significant environmental impacts and still highlighted the main advantages and disadvantages of the alternative fuel options studied. By further analysing the results with respect to the LCA studies performed by other automakers, any omissions or differences inherent to the modelling technique were exposed. Finally, the potential for the new guideline to be used as a starting point for LCA based regulations was examined, and any potential alterations or additions suggested.

9.1 New Results Compared to Previous Guidelines

The new guideline has been verified against the published guidelines using the five recommended impact categories from Table 22. AP and EP impact categories have been included in Appendix J, but were not discussed in detail here. Neither of the impact categories were affected significantly by end of life processing. As a result, the new guideline results are very similar to those from the eLCAr guideline. Ionizing radiation has also been ignored since it is only dependent on electricity use. Looking at Figure 45 one can see the effect the new guideline (labelled as “KC-15” in the figure) has on the interpretation of the vehicle’s GWP impact. Since the Fiat 500e is more affected by both A/C use and ELV treatment than the ICE vehicles, it became the highest GWP emitter in the study. The difference from the eLCAr study is minimal though, going from a 2% reduction to a 3% increase when comparing the Fiat 500e to the Fiat 500. As well, it should be noted again that the assumptions used to calculate the A/C impact favored the ICE vehicles, and in reality the GWP impact of the 500e is suspected to be closer to that of the Fiat 500 NP.

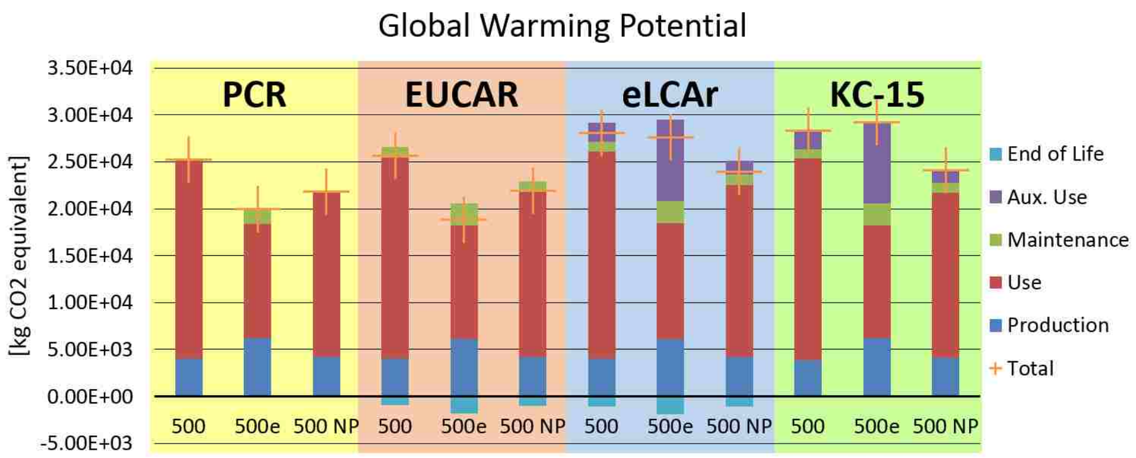


Figure 45: GWP impact compared against all vehicles and guidelines studied.

Looking to the Ozone Depletion Potential, compared in Figure 46, one can see that the production phase emissions remain unchanged across all guidelines. The KC-15 guideline underestimates the ODP compared to the eLCAr, and even EUCAR guidelines, but only by a small percentage. This difference is predominantly because of not including a disposal method for the vehicle's coolant fluid during the maintenance and end-of-life phases. Because different processing methods could have different environmental impacts, these emissions could fluctuate from study to study.

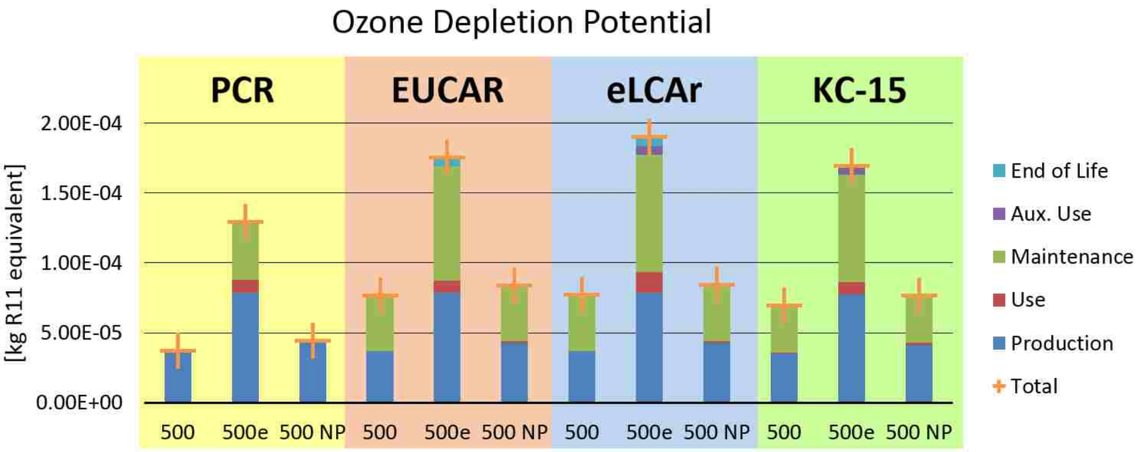


Figure 46: Ozone Depletion Potential compared for all vehicles and guidelines studied

The eLCAr guideline yields the highest PM emissions for all vehicles because it includes non-tailpipe emissions. This emission is equivalent for all vehicles however, so not including it has little effect on the overall interpretation of the study. With respect to the eLCAr guideline, the KC-15 guideline increases the performance gap between the Fiat 500e and Fiat 500 because end-of-life processes are omitted. The best performing vehicle is the Natural Power model, which has far less use phase emissions than the others due to the relatively clean WTT cycle for natural gas.

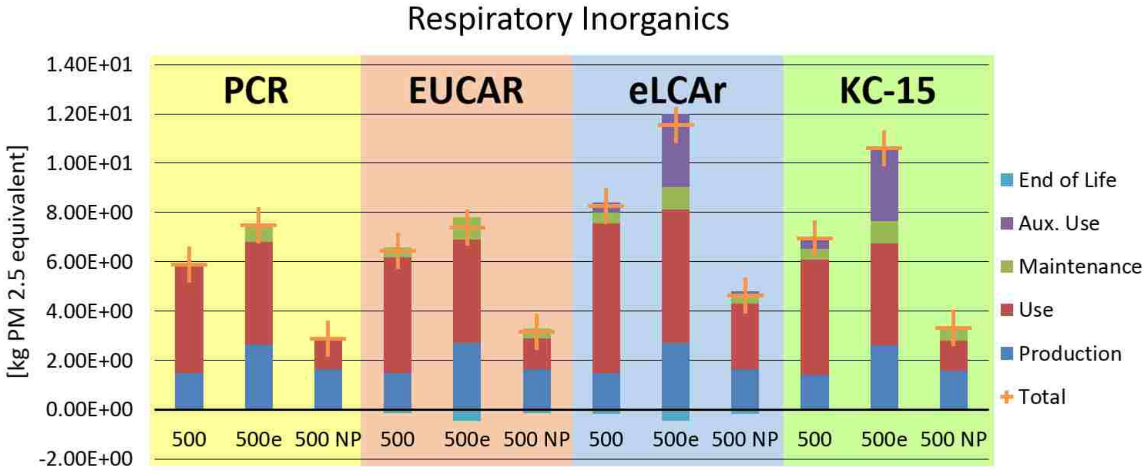


Figure 47: Emissions of respiratory inorganics for all vehicles and guidelines.

POCP emissions are mainly a function of the use phase emissions from the non CO_2 tailpipe emissions, and Well-To-Tank cycle, but are significantly increased in the ICE vehicles by the use of air conditioning (Farrington and Rugh 2000). The performance gap between the Fiat 500 and Fiat 500e is reduced when comparing the KC-15 guideline to the eLCAr results: going from a 32% reduction in emissions to 30%. Once again, it would be ideal for the non-tailpipe emissions to be measured for both A/C on and off, in order to confirm these findings.

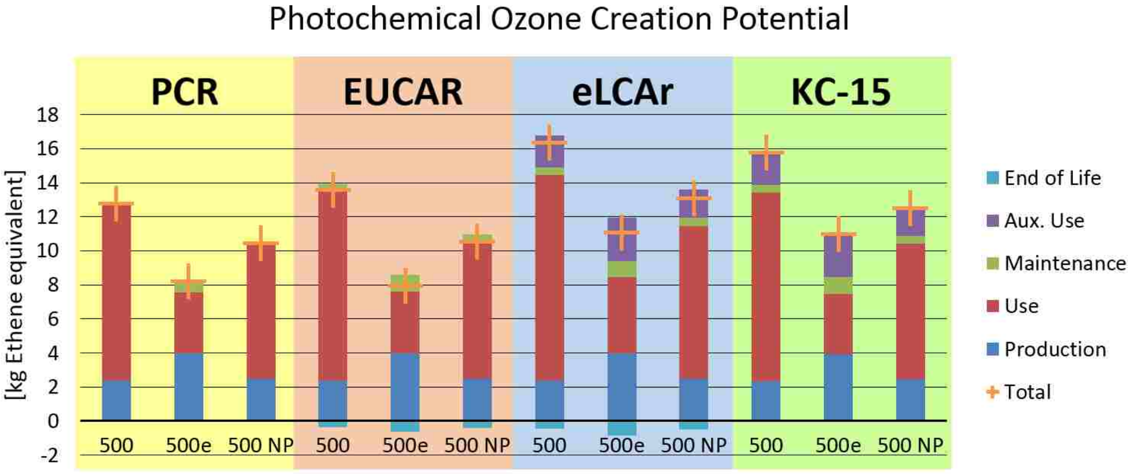


Figure 48: POCP emissions for all vehicles and guidelines

The most stable of all impact categories – resource depletion – depends on only a few raw material flows, and therefore changes little across all guideline. The end of life phase has the greatest impact in this category, since any recycled material can directly substitute virgin raw material. Neglecting the end of life, therefore, increases the Fiat 500e's resource depletion impact, although it is a minimal reduction and does not change significantly the relative impacts between fuel types.

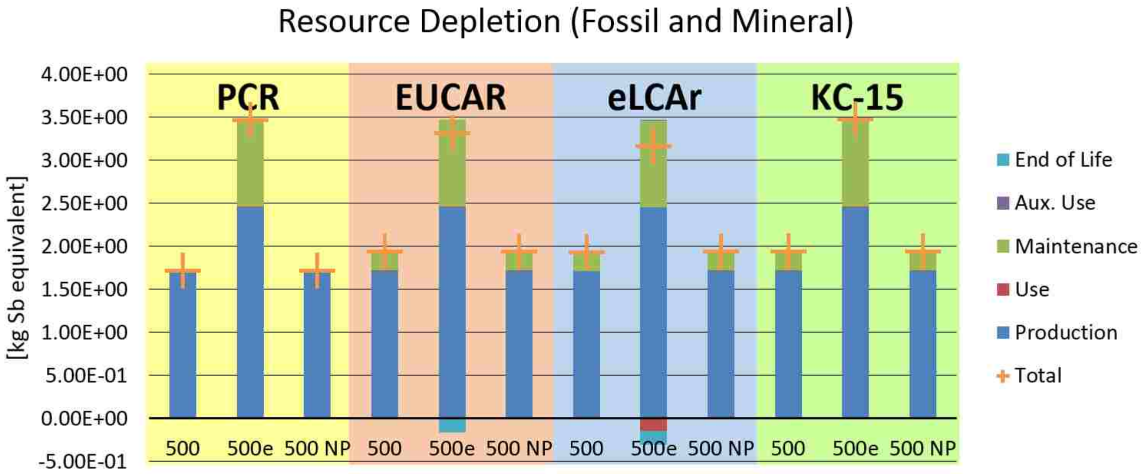


Figure 49: Resource depletion for all vehicles and guidelines

9.2 Comparison to Other Manufacturer's Studies

The most prevalent LCA studies comparable with the studies in this thesis are those by Volkswagen, Renault, and Ford. Each of these manufacturer's has their own methodology for completing LCA studies. However, the basis for each remains quite similar, and many are using GaBi Life Cycle software similar to the version used for this thesis. The table in appendix I displays the similarities and differences across the studies collected. One of the biggest differences, which could have significant impacts on the study results is the variance in material data collection systems. Both Renault and Volkswagen are using in-house developed systems. Volkswagen's Life Cycle Inventory data collection system is, in fact, so well-coordinated with their operating processes that they are able to account for the material impact of machine tool and mold use (Schweimer and Levin 2000). Despite this increased level of detail however, most environmental impacts reported are within the same range as those found in this study, and those of the other OEMs. Figure 50 highlights the GWP impact declared for the studies examined in detail. One can see that most of the results fall within the range of 20 – 35 metric tonnes of CO_2 per vehicle. VW and Renault both declare that their EV models are less emitting than their ICE counterparts. However, the new guideline and Ford's studies show the EVs produce the same or more emissions than their ICE counterparts. Similar to the new guideline, Ford has also considered air conditioning in their studies, so this could point to the impact of climate control systems on the LCA study.

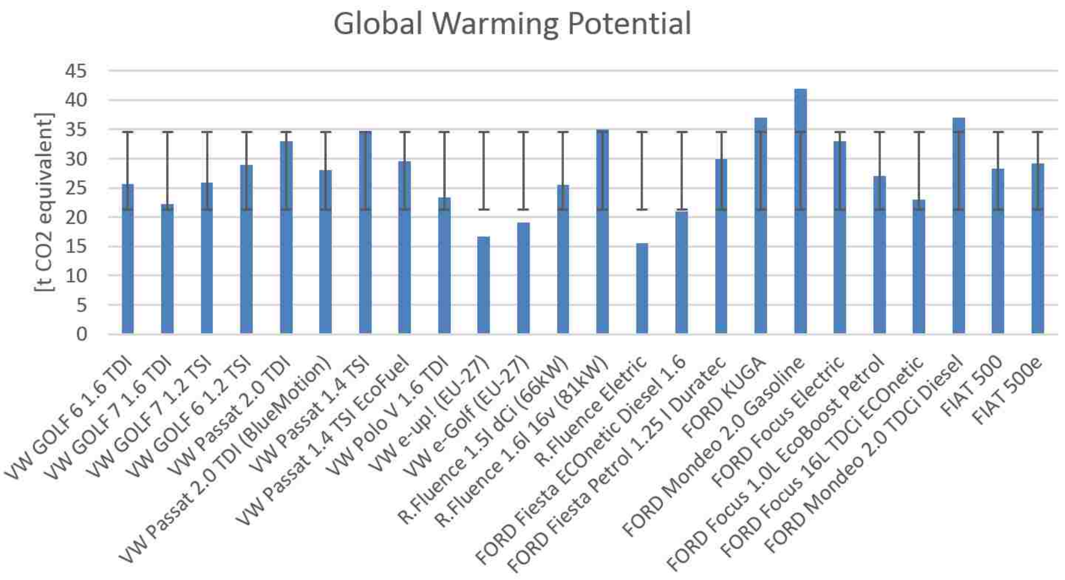


Figure 50: Global Warming Potential from other OEM LCA studies. Error bars indicate +/-1 standard deviation from the average value.

Volkswagen was the only other OEM to declare ODP emissions; however, their results are significantly larger than those declared in the studies by FCA are. This is most probably due to a material flow accounted for in their data system that was omitted from the FCA studies. ODP emissions in the FCA study were mostly resulting from solvents and lithium extraction, so it is possible that VW's superior data collection during the production phase has captured the use of increased solvents or waste fluids. This loss of data is tolerable though, since even VW cites that their reported ODP emissions are small when compared to the average ODP impact attributable to a single person in the EU-15 (Volkswagen AG 2008).

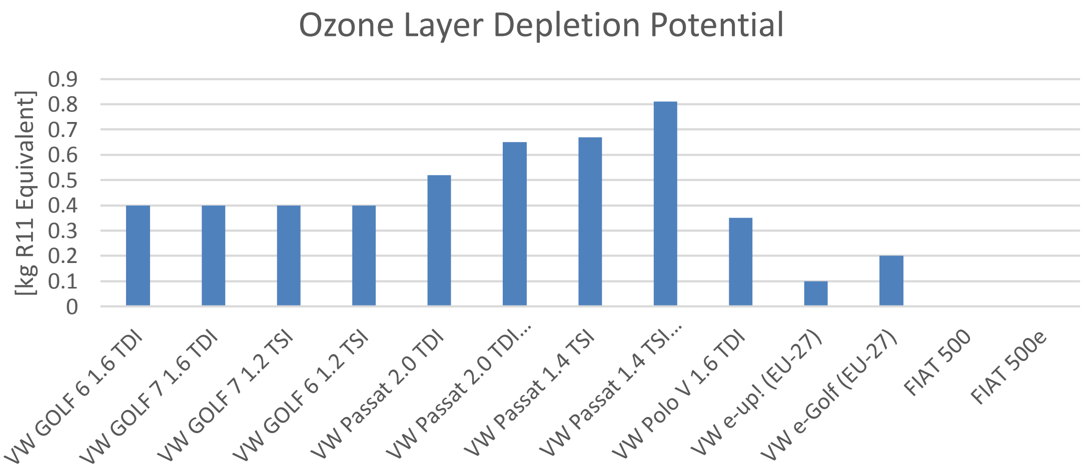


Figure 51: ODP emissions declared by VW are significantly higher than those by the FCA studies

The declared POCP emissions fall within a close grouping, similar to the results for GWP: most likely a function of both POCP and GWP being highly dependent on the use phase. The studies by Ford, however, stand out as being significantly higher than the other studies examined. This is potentially because Ford's LCI data was derived by internal testing that included the use of air conditioning systems (Ford of Europe 2007). With the exception of the studies by Ford then, most POCP results are similar to those found by the studies herein.

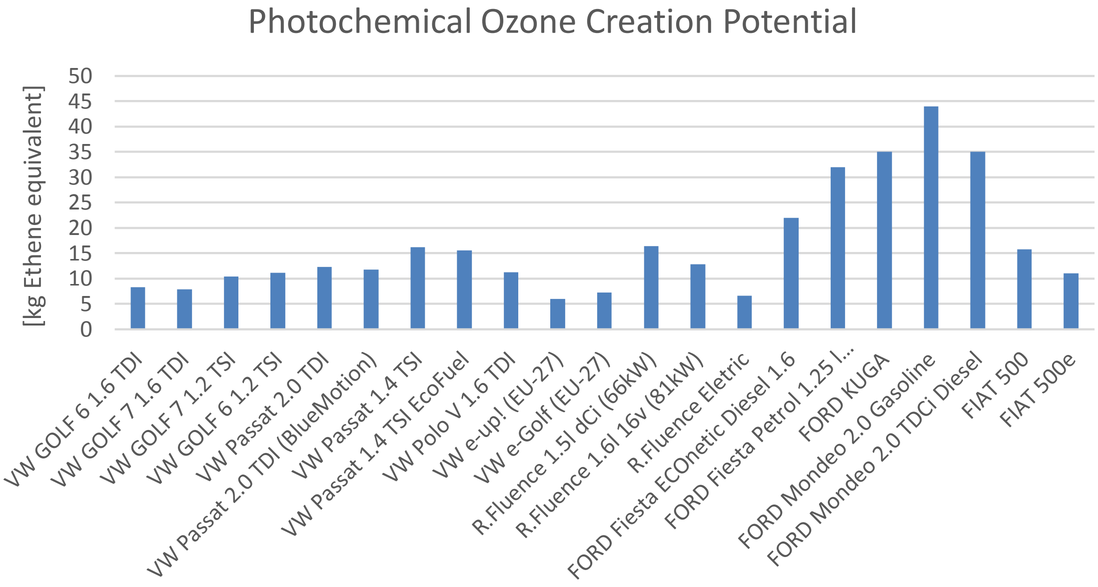


Figure 52: POCP Emissions found by VW and Renault are similar to those of the FCA studies

9.3 Relationship with Potential LCA Based Legislation

Competing requirements make it difficult for an LCA guideline to be both flexible enough for use in many situations, as well as rigid enough to be used as an industry standard for comparison. The most significant influence that has not been directly addressed by the KC-15 guideline is the length of the use phase, which can scale up the use phase emissions significantly. All studies in this thesis considered a use phase of 150,000 km. This lifetime is commonly used by OEMs since it was first recommended by the EUCAR guideline, but the eLCAr guideline suggests 200,000 km and even 250,000 km. In the U.S., the average age of roadworthy passenger vehicles has been estimated to be near 260,000 km (Tuttle 2012), which suggests that future LCA studies should consider a use phase length of at least 250,000 km. In regards to GWP, POCP, and PM emissions, increasing the use phase length would have the effect of magnifying the use phase's importance, and diminishing the impact of the other phases. If an LCA based regulation were to come into force, it would have to specify a use phase length and set time interval. For the other impact categories, resource depletion, AP, EP, and ODP, which depend on the production and maintenance, a set of rules should be drafted regarding the collection of data on maintenance parts.

Another important variable in the use phase that would require agreement is the treatment of air conditioning. In particular, climate data and the usage pattern would need to be set for all OEM's because this can change both the magnitude of the GWP impact, and the difference between fuel types. Since ICE vehicles only have to power the A/C unit, and not the heater, colder climates could skew the analysis towards an ICE vehicle. The climate data used in this study had almost equal use of A/C and heating, so it could be a sufficient starting point. It is suspected however, that the method used to calculate the annual energy consumption of the A/C system on the Fiat 500e has overestimated its consumption. Requiring OEM's to follow this method if they cannot produce test results could, therefore, push them to begin more road testing with climate control systems.

For collecting vehicle materials data the IMDS system is recommended. The IMDS has already gained wide acceptance and is in use by both OEM's and Tier 1 suppliers. Unfortunately, materials data collection can still be problematic if IMDS data is not yet available for new model products. Electricity consumption and VOC emissions data should be readily available for all assembly plants. Some variance could be found in the identification of high impact materials, and so a more detailed list of specific materials to be included should be drafted. High impact materials should be identified for not only the vehicle mass, but also for materials or chemicals associated with the production phase. For instance, one potentially high impact material that has not been included in these studies was the permanent magnetic material used in the Fiat 500e's electric motor; for future studies, it is recommended that this type of material be addressed.

The LCIA method chosen for the study can have a significant impact on the results; however, it can also depend on the scope of the study and location where impacts are to be considered. The ILCD handbook, composed by the JRC, has already covered in detail the majority of LCIA methods within a European context, and presented a list of recommended LCIA methods. For legislation within Europe then, following the ILCD recommendations would be advised. Outside of Europe, the LCIA methods should be verified for having characterization factors that are appropriate to the location of interest. Although this is less applicable for global impact models, it is critical for models with local effects (AP and EP).

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The primary objectives of this thesis were to answer the questions being asked about multiple LCA methodologies, and to find or develop an LCA guideline that would be straightforward and robust while still capturing the major life cycle impacts of passenger vehicles. By comparing the PCR, EUCAR, and eLCAr guidelines, as well as a set of case studies, the need for a new guideline was established, and the new guideline was developed.

The highest impact life cycle inputs were identified to be the raw material flows, the vehicle's primary fuel use, use of climate control systems, and the maintenance materials used throughout the vehicle's life time. The raw material flows, were responsible for the majority of the production phase impacts, with many impact categories dominated by a few flows. Likewise, the raw material flows used to represent the maintenance parts had large impacts for the use phase in the ODP, AP, and EP impact categories. Unfortunately, this sensitivity to particular flows creates uncertainty in the results and the modelling technique used. One solution to address this uncertainty would be for each LCA practitioner to use the same material breakdown system and life cycle datasets for each model created, although this solution may be unrealistic. All studies included the use of a second battery throughout the Fiat 500e's life cycle, despite being impractical given the cost of the battery and amount of vehicle teardown that would be required for replacement. The current warranty offered on the Fiat 500e battery is 8 years and 150,000 km, so replacement within the timeframe considered for these studies (10 years, 150,000 km) is debatable; however, increasing the use phase up to 250,000 km has been suggested. If the lifetime of the vehicle were to be increased, then to compare a BEV to a conventional ICE, either battery replacement, or the partial life cycle of a second BEV would need to be considered. Some of the additional life cycle considerations recommended by the eLCAr guideline, such as non-tailpipe emissions and road maintenance, were found to have small impacts, but required many assumptions and were difficult to evaluate for a particular vehicle. Climate control systems, although difficult to model, were found to have a significant impact on the use phase and to potentially change the interpretation of the study.

The goals of the new guideline were to balance the work required to complete LCA studies, while still capturing the most important aspects of the vehicle life cycle. The new guideline has managed to identify aspects of the vehicle's life cycle that have typically been overlooked in LCA studies by automakers, such as the use of climate control systems and inclusion of maintenance parts, although including these systems does present a greater difficulty to complete the LCA study. The increase in use phase detail has been balanced by suggesting that the end-of-life treatment of the vehicle be omitted, because of the difficulty in defending the modelling method and the relatively low impact on the recommended impact categories.

The guideline that was created focused on yielding a basic overview of environmental impacts, promoting external communications of product qualities, and supporting design decisions. In order to provide completely comparable LCA studies however, industry wide agreement is required on the treatment and application of specific LCI data, such as the product lifetime and distance, and the modeling method for raw material flows and climate control systems use. Within the guideline, recommendations have been given regarding which data to collect, and certain cases that require more or less complexity to treat. The sacrifices made to reduce the complexity of the analysis have had a small impact, but may also inhibit the guidelines further use should infrastructure or technological improvement result in large changes to the vehicle's life cycle in the near future. For this reason the guideline presented should be considered valid only for the current state of the automotive industry, and should be re-evaluated as new technologies and processes are introduced.

It is also important to recall the uncertainty in the production phase, so future studies should target Tier 1 suppliers to obtain more comprehensive knowledge about the production supply chain. There is also uncertainty in the use phase, since the EU regulatory limits were used for non CO_2 tailpipe emissions, as opposed to measured values. These emissions can also vary depending on climatic conditions and the state of the vehicle's catalytic converter. Furthermore, use phase emissions ultimately depend on the driver, so real vehicle emissions can vary significantly from the figures presented here. However, uncertainty regarding the user is difficult to quantify. Conversely, any such uncertainty may be equally applicable to any of the vehicles studied. Therefore, while uncertainty can impact an LCA study, if it is a relative error, it may have less effect on the study outcome than expected.

Evaluating the results of the new guideline against those from other manufacturers reinforced the relationships found throughout the study. For studies with the same lifetime and distance, impact categories dependent on use phase emissions showed consistent results, albeit with a high standard deviation, while impact categories dependent on production phase data or raw material flows varied significantly.

Recommendations

Following the results from the work presented herein, the largest recommendation put forward to improve the state of LCA in the automotive industry is the need for agreement on common parameters and methodology between manufacturers. Unfortunately, this is difficult both technically and politically. Politically, manufacturers may fear that unanimous agreement on LCA methodologies would increase the likelihood of LCA based regulations, presenting yet another normative with which to comply. Technically, for manufacturers operating in different parts of the world with differing processes and varying access to life cycle data, coming to an agreement may limit the usefulness of the methodology. The guideline presented here offers a basic level of LCA study that could be equally applied by any OEM.

Automakers operating on a global scale may be interested in comparing similar models sold in different markets. This type of comparison is not recommended, unless the goal of the study is to evaluate the differences between the markets themselves or if the data and the modelling can be adjusted to account for significant differences. As was shown for the Fiat 500, 1.4L gasoline, the structural modifications required for the different crash test regulations, combined with the different driving cycle, significantly change the emissions of the vehicle.

Summary of Thesis Contributions

This thesis has contributed to the state-of-the-art of life cycle assessment by presenting a comprehensive comparison of similar LCA guidelines. To the author’s knowledge no similar comparisons have been previously conducted, although some studies have evaluated the impact of changing certain life cycle parameters (the energy grid mix of an electric vehicle for example). Additionally, the thesis has highlighted the importance of several aspects of the LCA previously overlooked, most notable the vehicle’s maintenance, and use of climate control systems. The guideline developed offers a streamlined approach to vehicle LCA, using existing elements from known life cycle approaches. The new guideline is different from previous guidelines and will allow automakers to focus on improving key areas of their LCA programs. If followed, the new guideline should create higher confidence in the results of LCA studies and make the LCA process more efficient.

Further Work

Future work would include completing the same or similar studies using a different LCI database to validate equivalency across databases. This thesis compared different material breakdowns, demonstrating the variability resulting from selection of raw material flows. It would be interesting to explore these effects further, using different GaBi datasets for each of the identified material groups. Ideally, more data should also be collected regarding typical use of climate control systems and the precise power consumption of these devices during use.

Regarding electric vehicles, this study and others have shown that their life cycle emissions are highly dependent on the method of electricity generation. It is clear that while electric vehicles have the potential for reducing global warming and other climate impacts, this potential has not yet been realized. Therefore, further research should focus on developing green energy sources worldwide, as well as improving the consumer appeal of the vehicles. Finally, in the coming years many of the new BEV’s on the market will be reaching the rated lifetime of their batteries, so it will be interesting to see the end of life methods developed to deal with these new wastes; as well as, if in fact the batteries are capable of reaching their rated lifetimes.

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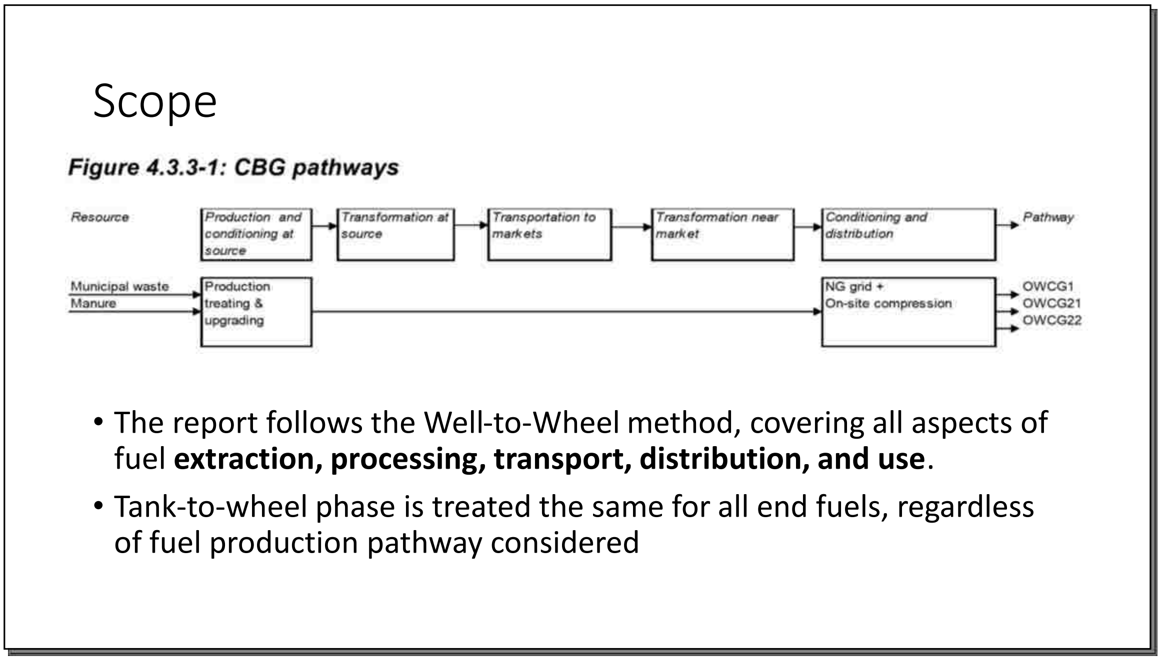
Appendix A

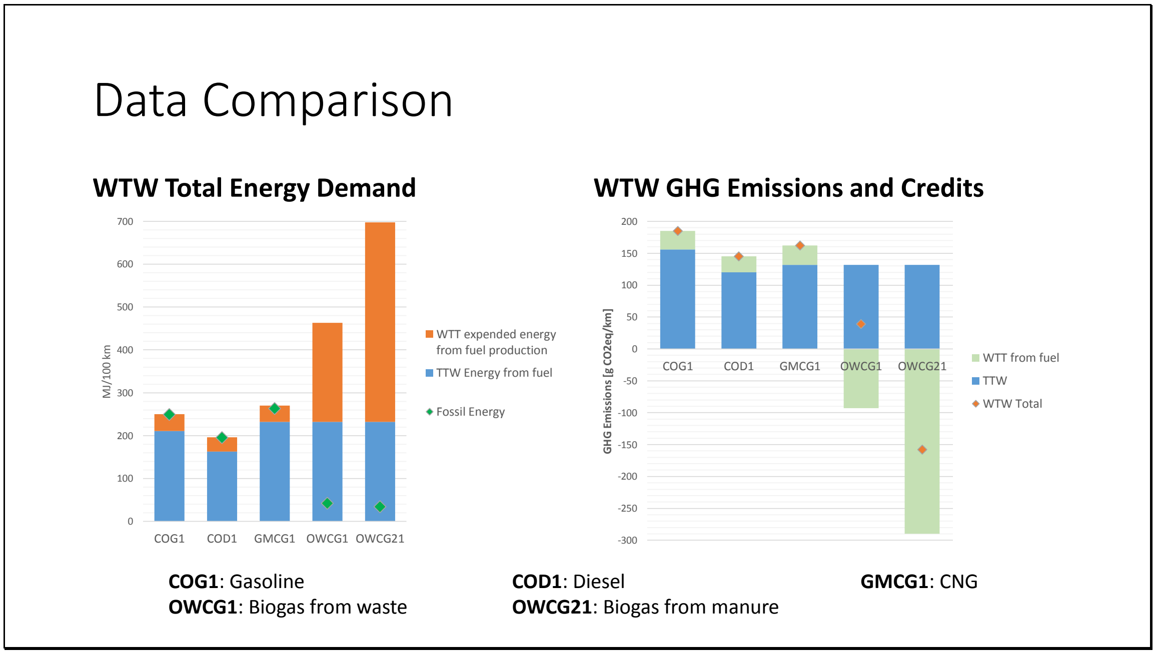
Review of JRC Report: Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context



Scope

Figure 4.3.3-1: CBG pathways

- The report follows the Well-to-Wheel method, covering all aspects of fuel **extraction, processing, transport, distribution, and use**.
- Tank-to-wheel phase is treated the same for all end fuels, regardless of fuel production pathway considered



Data Comparison

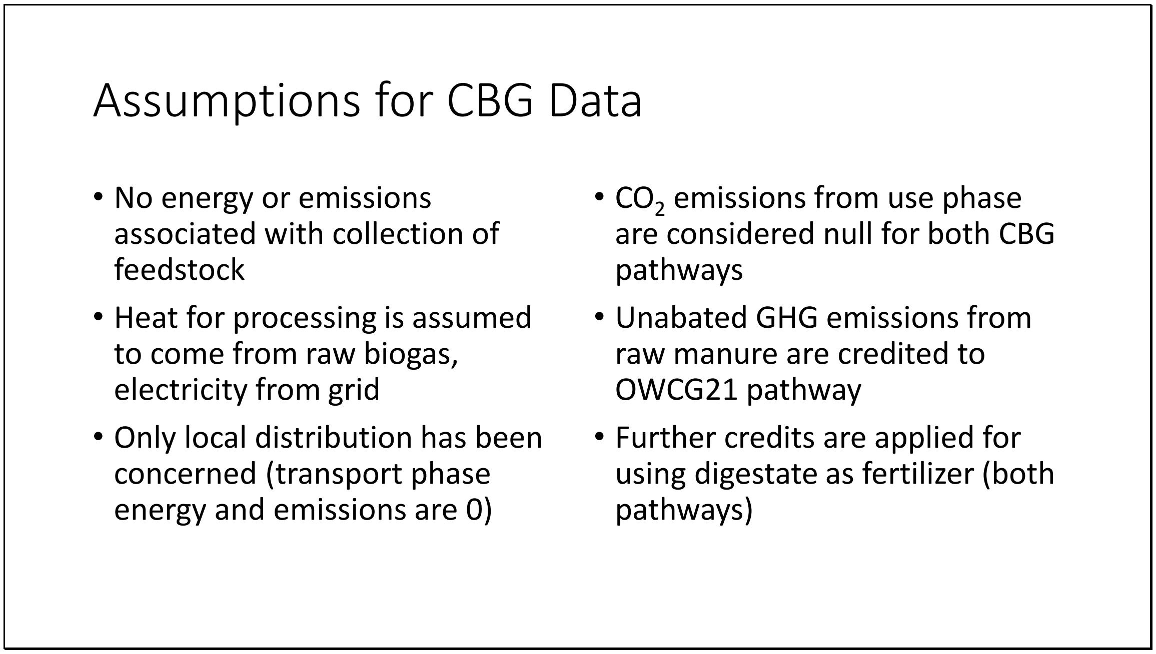
WTW Total Energy Demand

WTW GHG Emissions and Credits

COG1: Gasoline
OWCG1: Biogas from waste

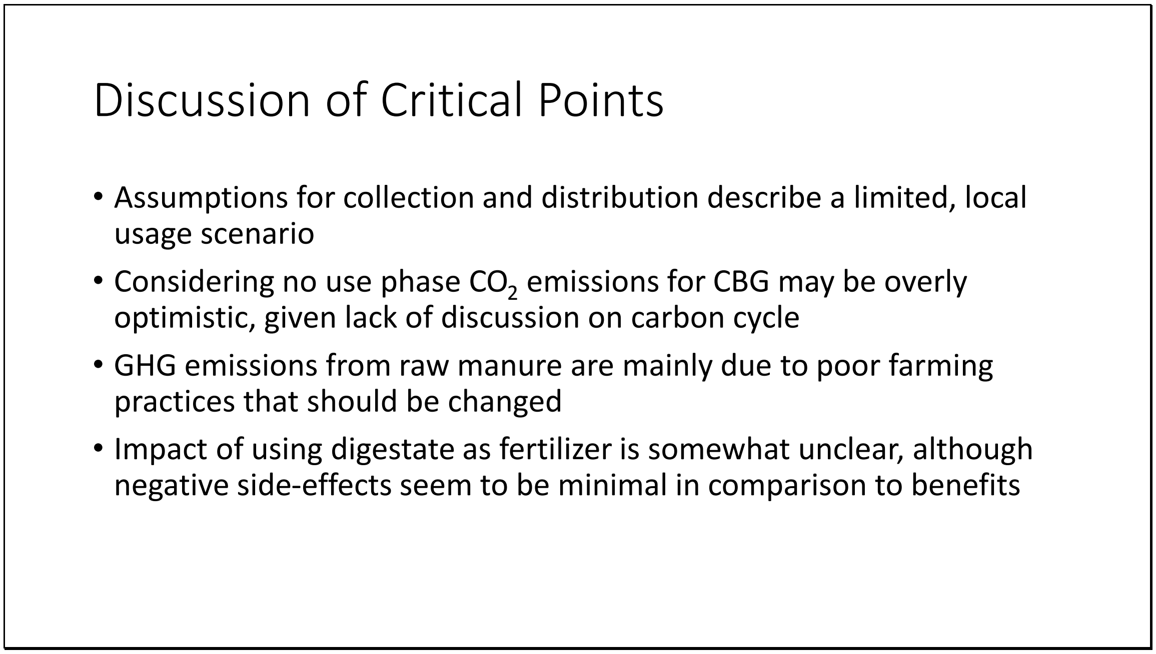
COD1: Diesel
OWCG21: Biogas from manure

GMCG1: CNG



Assumptions for CBG Data

- No energy or emissions associated with collection of feedstock
- Heat for processing is assumed to come from raw biogas, electricity from grid
- Only local distribution has been concerned (transport phase energy and emissions are 0)
- CO_2 emissions from use phase are considered null for both CBG pathways
- Unabated GHG emissions from raw manure are credited to OWCG21 pathway
- Further credits are applied for using digestate as fertilizer (both pathways)



Discussion of Critical Points

- Assumptions for collection and distribution describe a limited, local usage scenario
- Considering no use phase CO_2 emissions for CBG may be overly optimistic, given lack of discussion on carbon cycle
- GHG emissions from raw manure are mainly due to poor farming practices that should be changed
- Impact of using digestate as fertilizer is somewhat unclear, although negative side-effects seem to be minimal in comparison to benefits

Reference: (Edwards, et al. 2014)

Appendix B

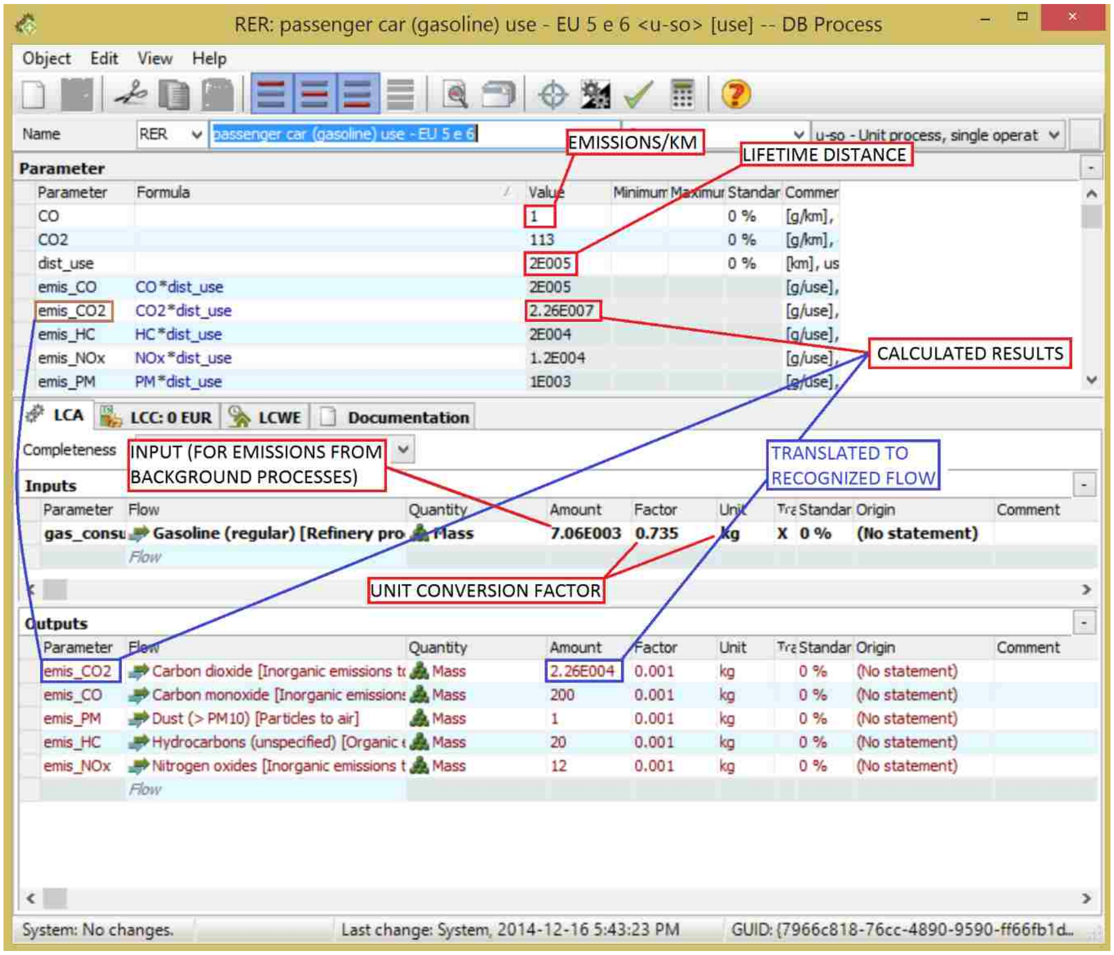
Matrix of all Studies Performed

>>> Vehicle >>>	**500 1.2L Gasoline**			**500 1.4L Gasoline**			**500 0.9L CNG** (Simulated Vehicle)		
>>> Market >>>	**EMEA**			**NAFTA**			**EMEA**		
Production	PCR	EUCAR	eLCAr				PCR	EUCAR	eLCAr
Use	PCR	EUCAR	eLCAr	PCR	EUCAR	eLCAr	PCR	EUCAR	eLCAr
ELV	PCR	EUCAR	eLCAr				PCR	EUCAR	eLCAr
Maintenance	PCR	EUCAR	eLCAr				PCR	EUCAR	eLCAr

>>> Vehicle >>>	**500 1.2L GPL**			**500e**					
>>> Market >>>	**EMEA**			**NAFTA**			**EMEA**		
Production				PCR	EUCAR	eLCAr			
Use	PCR	EUCAR	eLCAr	PCR	EUCAR	eLCAr	PCR	EUCAR	eLCAr
ELV				PCR	EUCAR	eLCAr			
Maintenance				PCR	EUCAR	eLCAr			

Appendix C

Explanation of GaBi Process for FIAT 500, 1.2L Gasoline



Name: RER | passenger car (gasoline) use - EU 5 e 6 | u-so - Unit process, single operat

Parameter

Parameter	Formula	Value	Minimum	Maximum	Standar	Commer
CO		1			0 %	[g/km],
CO2		113			0 %	[g/km],
dist_use		2E005			0 %	[km], us
emis_CO	CO*dist_use	2E005				[g/use],
emis_CO2	CO2*dist_use	2.26E007				[g/use],
emis_HC	HC*dist_use	2E004				[g/use],
emis_NOx	NOx*dist_use	1.2E004				[g/use],
emis_PM	PM*dist_use	1E003				[g/use],

Completeness

Inputs

Parameter	Flow	Quantity	Amount	Factor	Unit	Tra	Standar	Origin	Comment
gas_consu	**Gasoline (regular) [Refinery pro**	**Mass**	**7.06E003**	**0.735**	**kg**	**X**	**0 %**	**(No statement)**	
	Flow								

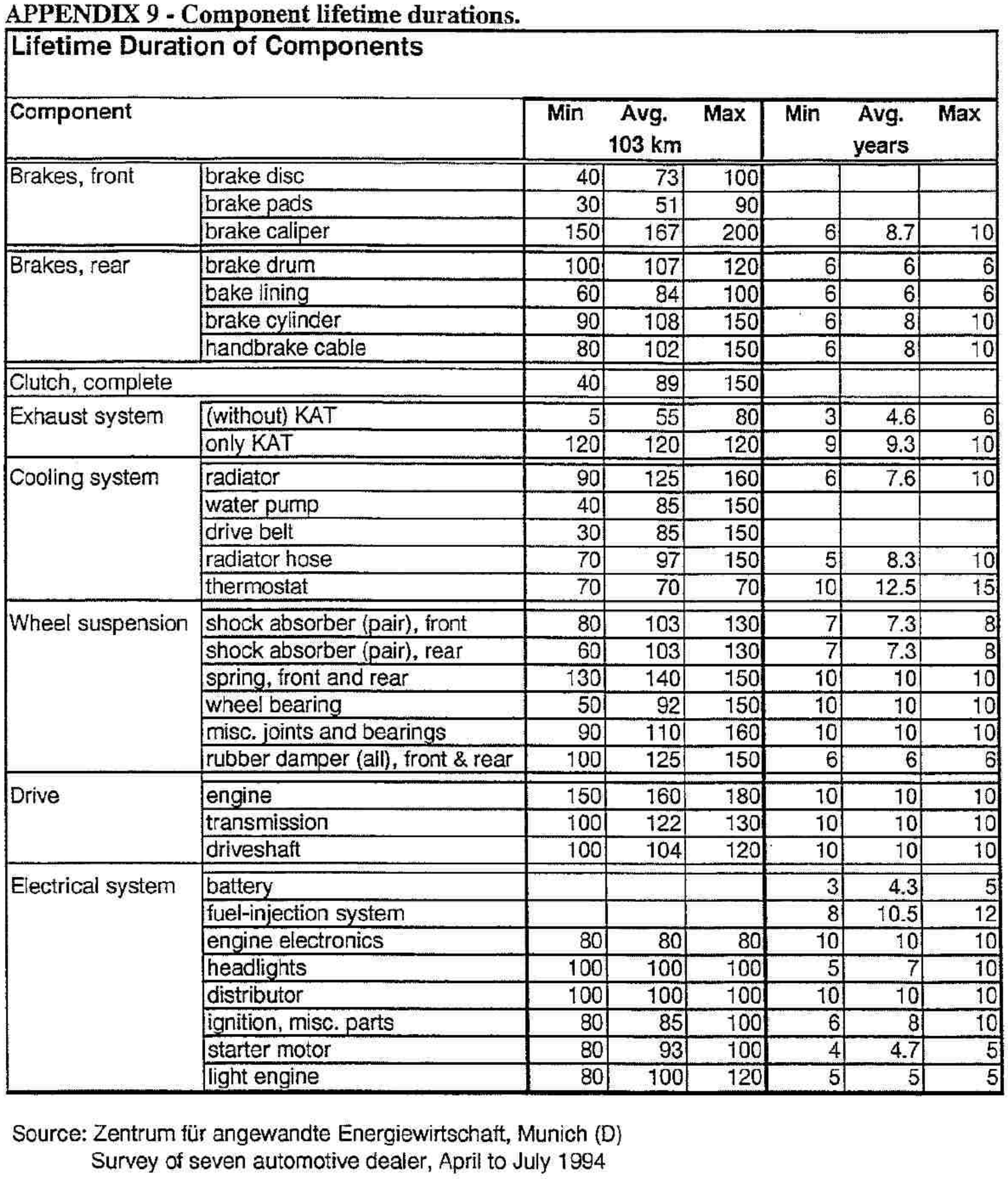
Outputs

Parameter	Flow	Quantity	Amount	Factor	Unit	Tra	Standar	Origin	Comment
emis_CO2	Carbon dioxide [Inorganic emissions t	Mass	2.26E004	0.001	kg		0 %	(No statement)	
emis_CO	Carbon monoxide [Inorganic emission	Mass	200	0.001	kg		0 %	(No statement)	
emis_PM	Dust (> PM10) [Particles to air]	Mass	1	0.001	kg		0 %	(No statement)	
emis_HC	Hydrocarbons (unspecified) [Organic	Mass	20	0.001	kg		0 %	(No statement)	
emis_NOx	Nitrogen oxides [Inorganic emissions t	Mass	12	0.001	kg		0 %	(No statement)	
	Flow								

System: No changes. Last change: System, 2014-12-16 5:43:23 PM GUID: {7966c818-76cc-4890-9590-ff66fb1d...

Appendix D

Component Lifetimes for Vehicle Maintenance



APPENDIX 9 - Component lifetime durations.

Lifetime Duration of Components

Component		Min	Avg. 103 km	Max	Min	Avg. years	Max
Brakes, front	brake disc	40	73	100			
	brake pads	30	51	90			
	brake caliper	150	167	200	6	8.7	10
Brakes, rear	brake drum	100	107	120	6	6	6
	bake lining	60	84	100	6	6	6
	brake cylinder	90	108	150	6	8	10
	handbrake cable	80	102	150	6	8	10
Clutch, complete		40	89	150			
Exhaust system	(without) KAT	5	55	80	3	4.6	6
	only KAT	120	120	120	9	9.3	10
Cooling system	radiator	90	125	160	6	7.6	10
	water pump	40	85	150			
	drive belt	30	85	150			
	radiator hose	70	97	150	5	8.3	10
	thermostat	70	70	70	10	12.5	15
Wheel suspension	shock absorber (pair), front	80	103	130	7	7.3	8
	shock absorber (pair), rear	60	103	130	7	7.3	8
	spring, front and rear	130	140	150	10	10	10
	wheel bearing	50	92	150	10	10	10
	misc. joints and bearings	90	110	160	10	10	10
	rubber damper (all), front & rear	100	125	150	6	6	6
Drive	engine	150	160	180	10	10	10
	transmission	100	122	130	10	10	10
	driveshaft	100	104	120	10	10	10
Electrical system	battery				3	4.3	5
	fuel-injection system				8	10.5	12
	engine electronics	80	80	80	10	10	10
	headlights	100	100	100	5	7	10
	distributor	100	100	100	10	10	10
	ignition, misc. parts	80	85	100	6	8	10
	starter motor	80	93	100	4	4.7	5
	light engine	80	100	120	5	5	5

Source: Zentrum für angewandte Energiewirtschaft, Munich (D)
Survey of seven automotive dealer, April to July 1994

Taken from Appendix 9 of EUCAR, Life Cycle Analysis Data and Methodologies (Rover Group Ltd 1998)

Appendix E

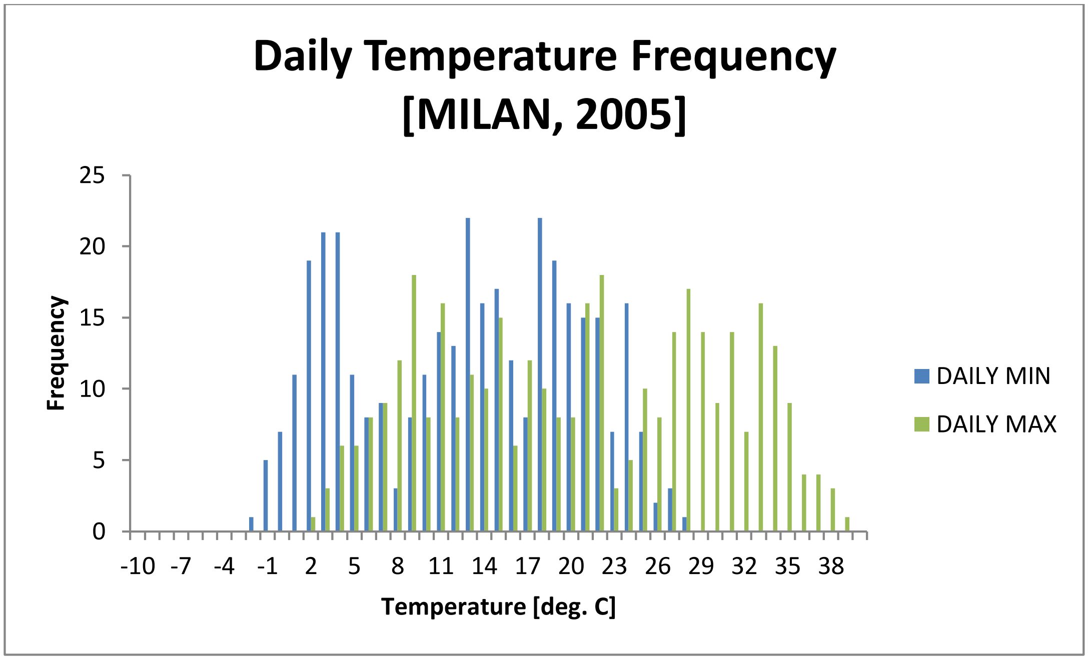
Material Codes for IMDS

Material Code	**Description**
1	**Steel and iron materials**
1.1	Steel / cast steel / sintered steel
1.1.1	unalloyed, low alloyed
1.1.2	highly alloyed
1.2	Cast iron
1.2.1	Cast iron with lamellar graphite / tempered cast iron
1.2.2	Cast iron with nodular graphite / vermicular cast iron
1.2.3	Highly allowed cast iron
2	**Light alloys, cast and wrought alloys**
2.1	Aluminium and aluminium alloys
2.1.1	Cast aluminium alloys
2.1.2	Wrought aluminium alloys
2.2	Magnesium and magnesium alloys
2.2.1	Cast magnesium alloys
2.2.2	Wrought magnesium alloys
2.3	Titanium and titanium alloys
3	**Heavy metals, cast and wrought alloys**
3.1	Copper (e.g. copper amounts in cable harnesses)
3.2	Copper alloys
3.3	Zinc alloys
3.4	Nickel alloys
3.5	Lead
4	**Special metals**
4.1	Platinum / rhodium
4.2	Others
5	**Polymer materials**
5.1	Thermoplastics
5.1.a	filled Thermoplastics
5.1.b	unfilled Thermoplastics
5.2	Thermoplastics elastomers
5.3	Elastomers / elastomeric compounds
5.4	Duromers
5.4.1	Polyurethane
5.4.2	Unsaturated polyester
5.4.3	Others
5.5	Polymeric compounds (e.g. inseparable laminated trim parts)
5.5.1	Plastics
5.5.2	Textiles
6	**Process polymers**
6.1	Lacquers
6.2	Adhesives, sealants
6.3	Underseal
7	**Other materials and material compounds (scope of mixture)**
7.1	Modified organic natural materials (e.g. leather, wood, cardboard, …)
7.2	Ceramics / glass
7.3	Other compounds (e.g. friction linings)
8	**Electronics / electrics**
8.1	Electronics (e.g. pc boards, displays)
8.2	Electrics
9	**Fuels and auxiliary means**
9.1	Fuels
9.2	Lubrificants
9.3	Brake fluid
9.4	Coolant / other glycols
9.5	Refrigerant
9.6	Washing water, battery acids
9.7	Preservative
9.8	Other fuels and auxiliary means

Appendix F

Assumptions and Calculations for Climate Control Systems

Temperature Profile



Minimum and maximum daily temperatures, recorded for Milan, 2007 (A.M.G. and Coauthors 2015)

Heating and air conditioning usage profile

		Occurrences at daily min	Occurrences at daily max
Heating @ max power:	**ambient temperature < 10 °C**	135	71
Heating @ med power:	**10 °C < ambient temperature < 15 °C**	82	60
No heating or A/C:	**15 °C < ambient temperature < 20 °C**	77	44
A/C @ med power:	**20 °C < ambient temperature < 25 °C**	60	52
A/C @ max power:	**25 °C < ambient temperature**	6	133
Distribution of daily driving:	**1/3 of trips at daily minimum** **2/3 of trips at daily maximum**		

Assumptions for air conditioning and heating usage pattern. Medium power is assumed to be ½ of max power. Use of anti-fog systems has not been considered.

Calculations for energy consumption of climate systems

Total annual vehicle operation time in hours	$t_{annual} = d_{annual}/v_{mean}$
Days at max heating	$t_{Hmax} = {}^{1}/_{3}\, Daily \min occurrences \times {}^{2}/_{3}\, Daily \max occurrences$
Annual consumption of heater (@max power)	$E_{ann.Hmax} = P_{Hmax} \times t_{Hmax}/360 \times t_{annual}$

Calculations used for completing the table on the following page. Calculations are repeated for each device and each power setting (medium or maximum).

Parameters		Fiat 500e	Fiat 500	Unit
Annual vehicle mileage in km	d_{annual}	15000		km/y
Mean cycle speed of the specific cycle	v_{mean}	33.3		km/h
Total annual vehicle operation time in hours	t_{ann}	450		h
Days at max heating	t_{Hmax}	92		Days
Days at medium heating	t_{Hmed}	67		Days
Days without heating or cooling	$t_{no\ clima}$	55		Days
Days at medium A/C	t_{ACmed}	55		Days
Days at max A/C	t_{ACmax}	91		Days
Power demand of heating in W	P_{Hmax}	5500	0	W
Power demand of air conditioning in W	P_{ACmax}	6500	1260	W
Annual energy consumption of heater (max power)	$E_{ann.Hmax}$	634474	0	Wh/y
Annual energy consumption of heater (med power)	$E_{ann.Hmed}$	231343	0	Wh/y
Annual energy consumption of A/C (max power)	$E_{ann.ACmax}$	736299	142729	Wh/y
Annual energy consumption of A/C (med power)	$E_{ann.ACmed}$	221972	43028	Wh/y
Annual mean energy consumption of comfort devices		**1824088**	**185757**	Wh/y
		121.6	**12.4**	Wh/km

Calculations for fuel consumption of ICE vehicle attributed to A/C use

$$ICE\ Fuel\ Consumption\ [kg] = \frac{E_{AC}\left[\frac{Wh}{km}\right] \times lifetime[km]}{IC_{eff.NEDC}} \Big/ E_{dens.fuel}\left[\frac{Wh}{kg}\right]$$

Where:

$$IC_{eff.NEDC} = \frac{E_{cons.NEDC}\left[\frac{Wh}{km}\right]}{FE_{NEDC}\left[\frac{L}{km}\right] \times E_{dens.fuel}\left[\frac{Wh}{L}\right]}$$

$$lifetime = vehicle\ lifetime\ considered\ in\ the\ study = 150{,}000\ km$$

$$E_{dens.fuel} = Energy\ density\ of\ fuel\ (using\ appropriate\ units\left[\frac{Wh}{L}\right] or \left[\frac{Wh}{Nm^3}\right]$$

$$E_{cons.NEDC} = calculated, theoretical\ energy\ demand\ over\ NEDC\ per\ kilometer^{*}$$

*Calculated based on vehicle weight, drag, and rolling resistance

ICE efficiency data and calculation results

	500		**500 NP**		**500 GPL**	
FE rating	5.1	L/100km	4.8	m^3/100km	6.6	L/100km
Weight	900	kg	1080	kg	865	kg
Drag coefficient	0.23		0.23		0.23	
Cross-sectional area	2.058	m^2	2.058	m^2	2.058	m^2
Rolling resistance coefficient	0.007		0.007		0.007	
Theoretical required energy for NEDC	119.78	Wh/km	126.29	Wh/km	118.52	Wh/km
Fuel	**Gasoline**		**Methane**		**Propane**	
Sourced energy content			50	MJ/kg	46.4	MJ/kg
Conversion factors			277.8	Wh/MJ	277.8	Wh/MJ
			0.72	kg/m^3	0.55	kg/L_{LPG}
Fuel energy content	8.76	kWh/L	13889	Wh/kg	12889	Wh/kg
CO2 emissions factor	2340	$g_{CO2}/L_{gasoline}$	2400	$g_{CO2}/kg_{methane}$	1665	g_{CO2}/L_{LPG}
Fuel energy provided	446.76	Wh/km	480.00	Wh/km	467.87	Wh/km
ICE Efficiency$_{NEDC}$	**26.8%**		**26.3%**		**25.3%**	

Appendix G

Calculations and Data for Roadwork Attributable to a Single Vehicle

United States Road Network Data (American Road & Transportation Builders Association 2015)			
Miles of road (Total)	4,090,000	Square miles of new road / year (Average, 2000-2012)	66.3
US Vehicle Registrations			
Number of vehicles registered (International Council on Clean Transportation 2013)	231,000,000	New vehicle registrations / year (Average, 2008-2012) (The Economist Intelligence Unit 2013)	12,465,400
Square meters of new road attributable to one new vehicle	**14**	$\frac{square\ miles\ of\ new\ road/year}{New\ vehicle\ registrations/year} \times \frac{meters}{mile}$	
European Union Road Network Data			
EU-27 Paved roads + Motorways (Total, km) (European Commission 2012)	5,066,700	km^2 of new road / year (Assuming same growth rate as US and 7m wide roads on average)	125
EU-27 Vehicle Registrations (International Council on Clean Transportation 2013)			
Number of vehicles registered	239,000,000	New vehicle registrations / year (2012)	12,000,000
Square meters of new road attributable to one new vehicle	**10.5**	$\frac{square\ km\ of\ new\ road/year}{New\ vehicle\ registrations/year} \times 1000^2$	

Appendix H

New Guideline Completion Checklist

Goal and Scope Definition

Goal of the Study ______________________________

Market Scenarios NAFTA ☐ EMEA ☐ LATAM ☐ APAC ☐ Other ☐

Cross Market Analysis YES ☐ YES, but without comparison ☐ No ☐

Vehicle Models ______________________________

____

____

____

Life Cycle Inventory Phase – Production

Raw materials
(>95% of vehicle mass) ☐

High impact materials identified ☐

Production Materials:	Vehicle Materials:
______________________________	______________________________
______________________________	______________________________
______________________________	______________________________
______________________________	______________________________
______________________________	______________________________
______________________________	______________________________

IMDS breakdown used ☐

Vehicle fluids included ☐

Production electricity consumption ☐

VOC emissions ☐

Allocation method used ______________________________

Energy consumption of Tier 1 suppliers ☐
Indicate to what level of detail ______________________________

____

Logistics data in necessary cases ☐
Indicate cases ______________________________

Life Cycle Inventory Phase – Use

Driving cycles NEDC ☐ US EPA ☐ WLTC ☐ CADC ☐ Other __

Non CO_2 tailpipe emissions Measured ☐ Regulatory Limits ☐ Other __

Climate control systems Measured ☐ Calculated ☐

If measured, describe test details: ____________________

Climate data used: ____________________

Usage pattern: ____________________

____

Maintenance materials EUCAR Data ☐ Other Data Source ☐

Life Cycle Impact Assessment Phase

Geographic Scope Global ☐ North America ☐ Europe ☐ Other __

LCIA Methodology: CML ☐ TRACI ☐ ReCiPe ☐ ILCD ☐ Other __

Global Warming Potential ☐

Ozone Depletion Potential ☐

Respiratory Inorganics ☐

Photochemical Oxidant Creation ☐

Resource Depletion ☐

Acidification ☐ Validation of LCIA method ☐

Eutrophication ☐ Validation of LCIA method ☐

Ionizing Radiation ☐

Appendix I

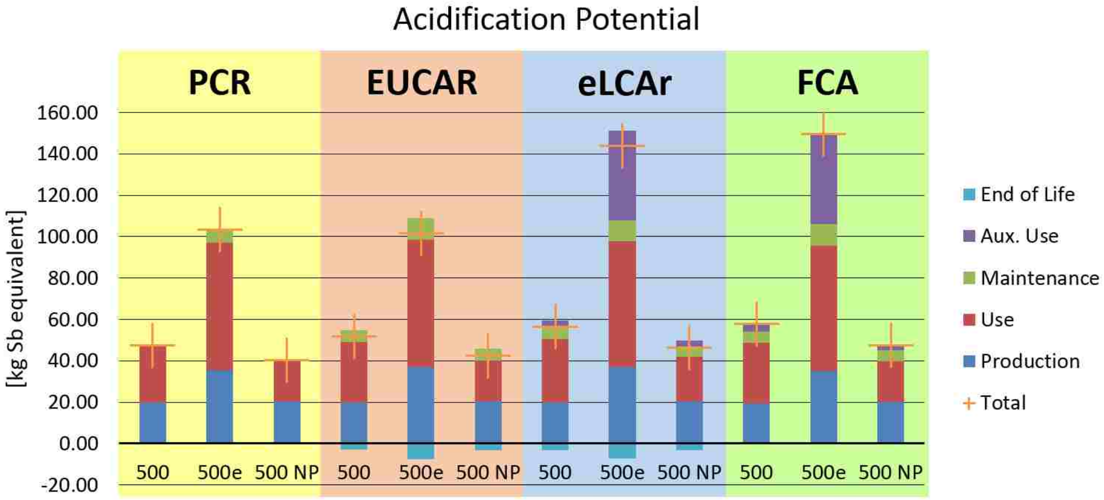
Comparison of LCA studies by other manufacturers

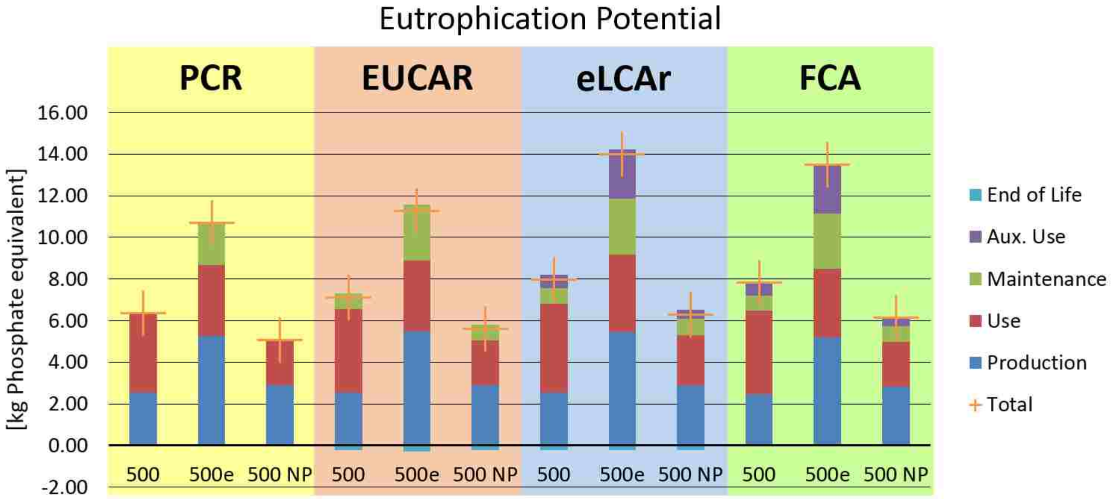
	Renault	**VW**	**Ford**	**FCA**
diesel	x	x	x	
petrol	x	x		x
electric	x		x	x
CNG		x		x
	GaBi4.4	GaBi5/GaBi6	GaBi	GaBi ts 7.0
150000 kms	x	x		x
160000 kms				
200000 kms				
Materials Data	Internal	MISS		
Vehicle	x	x		x
Engine / transmission	x	x		x
battery	x	-		x
Fuel consumption	x	x		x
Electric consumption	x	-		x
CO_2 [g/km]	x	x		x
Tailpipe Emissions	EURO 5	EURO 3/ 4 /5	EURO 5	EURO #
Vehicle Maintenance	available	not included		EUCAR guideline
Tier 1 suppliers	included			Battery
From plant to dealer	included			
Recycling phase	Literature / recycling center	VW SiCon		

References: (Ford of Europe 2007), (Schweimer and Levin 2000), (Renault 2011)

Appendix J

Acidification and Eutrophication Potential for All Guidelines





Appendix K

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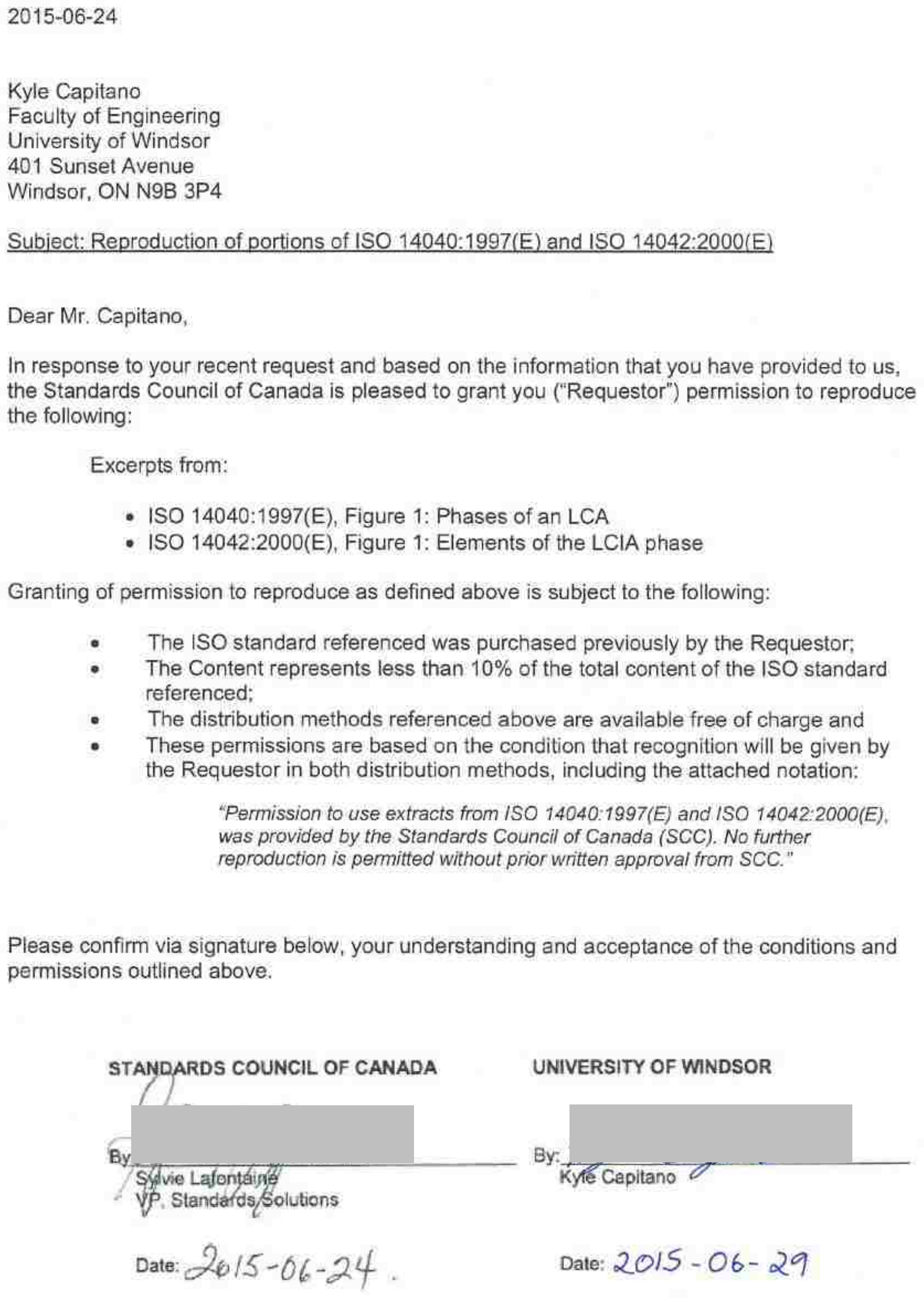

2015-06-24

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Kyle Capitano

Date: 2015-06-29

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Kyle Capitano was born in 1990 in London, Ontario. He graduated from Catholic Central High School in 2008. From there he went on to the University of Western Ontario where he obtained a B.Sc. in Mechanical Engineering in 2013. He is currently a candidate for the Master's degree in Automotive Engineering at the University of Windsor and hopes to graduate in Fall 2015.