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Life Cycle Assessment of Road Vehicles for Private and Public Transportation

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MASTER THESIS

for

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Life Cycle Assessment of Road Vehicles for Personal and Public Transportation
Livsløpsanalyse av kjøretøy for privat og offentlig transport

Background

In order to mitigate the climate impacts of the transport sector, substantial effort is currently being devoted to the development of novel car and fuel technologies. At the same time it is also well understood that the size and weight of different vehicles are significant for their overall environmental performance. Larger vehicles have higher impacts from manufacturing and higher energy requirements in operation, regardless of drivetrain technology. Understanding the overall environmental performance of different alternatives requires assessment that captures differences in manufacturing, fuel cycle, operation and end-of-life phases across different drive train technologies and vehicle classes and sizes. Development of policies, research priorities and investment decisions relies on insights from such analyses.

Aim

The primary objective of this work is to analyze the environmental performance of different road vehicles for personal and public transportation. Emphasis will be on assessing the importance of size and weight seen in conjunction with passenger capacity. The secondary objective will be on assessing how these different alternatives perform under different occupancy factors.

The analysis should include following elements:

1) Development of life cycle inventories for different vehicle classes.
2) Development of different benchmarking comparisons, including alternative functional units.
3) Comparative life cycle assessment of the different cases.
4) Analysis and discussion.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

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☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 1. February 2013

Olav Bolland

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Abstract

Ever increasing prosperity and global civilization heralds an increasing demand for communication and transport. The transport sector alone accounts for one quarter of global human greenhouse gas emissions. In the transport sector, road transport alone is responsible for 70%. To help mitigate these emissions, people are advised to take advantage of public transportation systems, on the argument that public transit is more environmentally friendly than private transport.

To assess the environmental benefits of public transit contra private transport, a process life cycle analysis is performed on three private vehicles and three transit vehicles. The private vehicles are composed of a Sports Utility Vehicle (SUV), a hatchback family car and a smaller subcompact car. The transit buses consist of two intercity buses with different motors: one bus powered by diesel and one powered by compressed natural gas. A third bus, a long distance diesel coach, is also analyzed.

The results from the LCA are addressed and the emissions associated with the passenger kilometres travelled are benchmarked and analyzed.

Sammendrag

Økende velstand og global sivilisasjon bringer med et økende behov for kommunikasjon og transport. Transportsektoren alene står for en kvart av globale menneskelige drivhusgassutslipp. Innen transportsektoren står veitransport alene for 70% av utslippene. For å hjelpe til å minke disse utslippene er folk rådet til å ta i bruk offentlig transport, på bakgrunn av argumentet at offentlig transport er mer miljøvennlig enn privat transport.

For å adressere miljøgevinsten av å bruke offentlig transport kontra privat transport blir en livssyklusanalyse gjennomført på tre private kjøretøy og tre busser. De private kjøretøyene består av et sport- og nyttekjøretøy (SUV), en familebil (hatchback) og en litt mindre bil (subcompact). Bussene består av to bybusser med forskjellige motorer: en som kjører på diesel og en som kjører på komprimert naturell gas. En tredje buss, en langdistanse dieselbuss, blir også analysert.

Resultatene fra livssyklusanalysen blir adressert og utslippene forbundet med passasjerkilometer reist blir sammenliknet og analysert.

Contents

Note on the use of the comma

Although this thesis is written in English, the format of the numbers will follow the Norwegian standard due to software limitations and convenience. The comma will thus represent a decimal separator, equivalent to the English decimal point.

Tables

Figures

Charts

Abbreviations

Ckm –Capacity Kilometre
CNG – Compressed Natural Gas
GHG – Greenhouse Gas
Indecol – Industrial Ecology
LCA – Life Cycle Analysis
LCI – Life Cycle Inventory
Pkm – passenger/person kilometre
Sub – Subcompact (Vehicle)
SUV – Sports Utility Vehicle

1. Introduction

1.1 Background

The last few centuries have witnessed humanity grow from region-bound communities into a global society. This development is owed to advances in communication and transport, allowing us to rapidly cross the distances separating us. The global civilization has come to rely entirely on transport – the transport sector alone is responsible for one quarter of human greenhouse gas emissions, and is the sector seeing the most rapid growth in emissions. The road transport sector alone accounts for 70% of the transport emissions. Ever increasing prosperity in several parts of the world brings along an increasing demand for private transportation; the current world population of light motor vehicles is 750 million, and is projected to rise by a factor of 2 by 2030 and a factor of 3 by 2050. (Houghton 2009, Simonsen 2012)

Over the last few decades, environmental issues have been getting increased attention. Climate change as a consequence of human consumption has rapidly been accepted as fact, and an increased awareness for anthropological emissions and resource use has emerged. In an effort to combat increasing emissions, government regulations are moving towards "life-cycle accountability"; the approach that the manufacturer is responsible for both direct emissions and emissions associated with inputs, use, transport and disposal (Srinivas) One of the tools used to assess environmental impacts from a products whole life cycle, from "cradle-to-grave", is Life Cycle Analysis – LCA.

The ever-increasing demand for private mobility heralds an increase in resource use and emissions - the rapidly growing CO_2 emissions from automobile use has become a global challenge. The use of public transport, before considered mostly as conveyances of convenience, now also carries with it an environmentally beneficent element. Compared to a private vehicle, the construction and operation of public transport vehicles is a more resource intensive and polluting at every turn. However, the transit vehicles have one drastic advantage – they have the capacity to carry drastically more passengers.

1.2 Research objectives

For this project, a comparative life cycle assessment of several different vehicles will be performed. Inventories for three different private vehicle of varying size and three different transit vehicles of varying use and/or technology will be made. An SUV, the GLK220, represents the largest of the private vehicles. A hatchback Mercedes A150 serves as a typical family car. A Volkswagen Polo is the smallest private vehicle evaluated. For the transit vehicles, two intercity buses are analyzed: a Volvo 8500 diesel bus and a Solaris CNG bus. These are compared with a third transit vehicle: The Volvo 9700 serves as a coach, driving long distances cross county and between cities. Based on these six real life vehicles, model vehicle inventories are assembled, and an LCA is performed.
A contribution analysis will be undertaken and key emissions from all parts of the vehicles' lifetimes will be presented and analyzed. The different modes of transportation will be benchmarked in context of lifetime emissions and emissions on a per passenger kilometre basis.

1.3 Work Structure

Chapter 2 presents LCA how its method is used in this study. The LCA methodology and mathematical framework is presented, and the Ecoinvent database and ReciPe framework is explained.

Chapter 3 describes the system case, including the goal and scope of the project. The inventories of the vehicles are presented, and passenger load factor is explained.

Chapter 4 presents the results from the performed life cycle analysis. Total climate change potential and climate change in the context of vehicle lifetime is shown. Contribution analysis of key impact potential categories is presented, followed by climate change per passenger kilometre travelled.

Chapter 5 discussed the results from the life cycle analysis, and addresses the goal of the study and whether it was completed. Key assumptions and limitations are shown, and suggestions for further work presented.

Chapter 6 concludes the study with the conclusion, presenting key points from the study.

2. Method and Model Description

2.1 Method

LCA addresses environmental aspects and potential impacts throughout the life cycle of a product - from the acquisition of raw materials through production, use, end-of-life treatment and disposal. (International Organisation for Standardisation (ISO) 2006) . With LCA one can gather information and make comparisons between competing products to evaluate the more environmentally friendly product or manufacturing process. One can also identify and locate where in a products lifetime emissions occur, and address these emissions where they occur

The inventory compiled in this project is intended to be used according to the Life Cycle Assessment methodology (LCA). According to the ISO 14040 (International Organisation for Standardisation (ISO) 2006) LCA is performed over four distinct phases – Goal and Scope, Inventory Analysis, Impact Assessment and Interpretation. These four phases are often interdependent; the results of one phase will affect the completion of the other phases. (Figure 1)

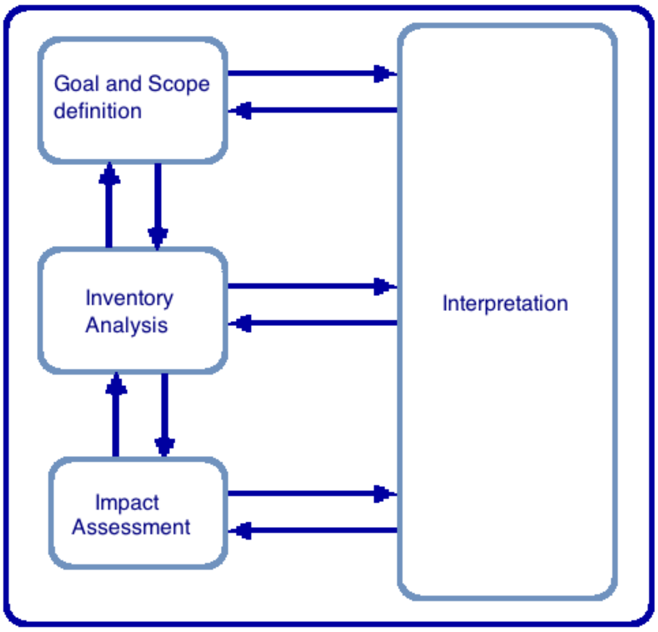


Figure 1 LCA phases, after ISO 14040

2.2 Goal and scope definition

An LCA should start with an explicit definition of the goal and scope of the study, as clear and concise as possible. The context is set out and methodological choices are made. The final goal of the study is decided, as well as how and to whom the final results are to be reported. The goal and scope definition includes technical details that affect and guide the subsequent phases. The functional unit defines and is representative of what is being studied. The boundaries of the system are defined, specified across several dimensions, e.g. time restrictions, technical limits, natural or social limitations and downstream process limitations. Impact categories are chosen and allocation methods for partitioning environmental loads between these categories are decided.

2.3 Inventory Analysis – Life Cycle Inventory

The second phase of an LCA is the Life Cycle Inventory and its analysis. An inventory of flows to and from nature through a production system is constructed, within the system boundaries and scope. The data is often represented in charts and flowcharts, and data entries can number in hundreds or thousands, depending on the scope of the study. The inventory contains not only the actual physical components that are used in the construction of, for instance, a car – but also include inputs like energy and other ancillary inputs.

2.4 Life Cycle Impact Assessment (LCIA)

When the scope and goal have been defined and the inventory assembled, an impact assessment is performed. At this phase, one attempts to evaluate potential environmental impacts based on the environmental loads of the Life Cycle Inventory results. The purpose of LCIA is to provide additional information in order to help assess a production system, to better understand the environmental significance of its inventory flows. (International Organisation for Standardisation (ISO) 2006)

The Life Cycle Impact Assessment consists of several mandatory elements: (Baumann and Tillman 2004)

- A manageable selection of impact categories and resource usage.
- Classification of parameters, assigning them to impact categories.
- Characterization of the LCI flows, measuring the environmental impacts of the system.

Evaluating and weighing the system can introduce subjectivity to the study. The ISO14040 guidelines thus encourages high level of transparency when performing this step of the LCA (Gryczon 2008)

2.5 Interpretation

Interpretation is the final, and perhaps most important, stage of the LCA. The preceding phases of the LCA produce an impressive amount of numbers. The LCA practitioner must make sense of these numbers, especially in connection to the quality of the data and other input provided. This phase is intended as a systematic place to analyze and discuss the previous results. An important aspect, also for this phase, is a transparent and comprehensive reporting of input data, assumptions, choices, and drawn conclusions. (Reinout Heijungs and Helge Brattebø 2007)

2.6 LCA calculations and methodology

The calculations used to model interdependencies between processes in LCA are normally modeled as a linear system, using matrices and linear algebra (Strømman 2010).

Total output of processes is given as

$$x = (I - A)^{-1}y$$

Where A is the requirements matrix, describing intermediate demand. X is the total output and y is external demand. $(I - A)^{-1}$ is also known as L, the Leontief Inverse, after Wassily Leontief.

For the sake of convenience, LCA practitioners often distinguish between a foreground and a background system in the A matrix. The foreground processes are defined in the study to be conducted, and the background system are from a generic database.

$$A = \begin{vmatrix} A_{ff} & o \\ A_{bf} & A_{bb} \end{vmatrix}$$

The components of the A matrix are defined in Table 1

Table 1 Components of the A matrix

A_{ff}	$Foreground\ process\ requirements\ matrix$
A_{bf}	$Upstream\ inputs\ of\ background\ processes\ to\ foreground\ system$
A_{bb}	$Background\ processes\ requirements\ matrix$

(Strømman 2010)

The generated stressors are found by multiplying a stressor matrix S that lists stressors by processes, with output x:

$$e = Sx = SLy$$

It's favorable to distinguish between materials used in the production phase, and materials actually ending up in the final product – as there might often be a significant material use associated with secondary production processes.

2.6 Ecoinvent and ReCiPe

The software Arda has been used to perform the LCA in this study. Arda is a program written and developed by Guillaume Majeau-Bettez, of the Industrial Ecology program at NTNU. Arda takes in a foreground inventory made by the user, and performs calculations by connecting the foreground inventory to a background inventory. The background inventory used by Arda is known as Ecoinvent Database. Ecoinvent is the world's leading supplier of a consistent and transparent life cycle database. (Ecoinvent, 2010).The database used for this study is the Ecoinvent V2.2 database, although it is worth mentioning that at the time of writing, Ecoinvent have recently released their V3 database. The Ecoinvent databases provides several thousand industrial life cycle inventory datasets, containing a plentiful range of processes and stressors.

The ReCiPe framework is a method to convert the emission of hazardous substances into impact category indicators. (Mark Goedkoop, Reinout Heijungs et al. 2009)
The framework, shown in Figure 2, contains 18 midpoint level impact categories that are aggregated to 3 endpoint level categories.

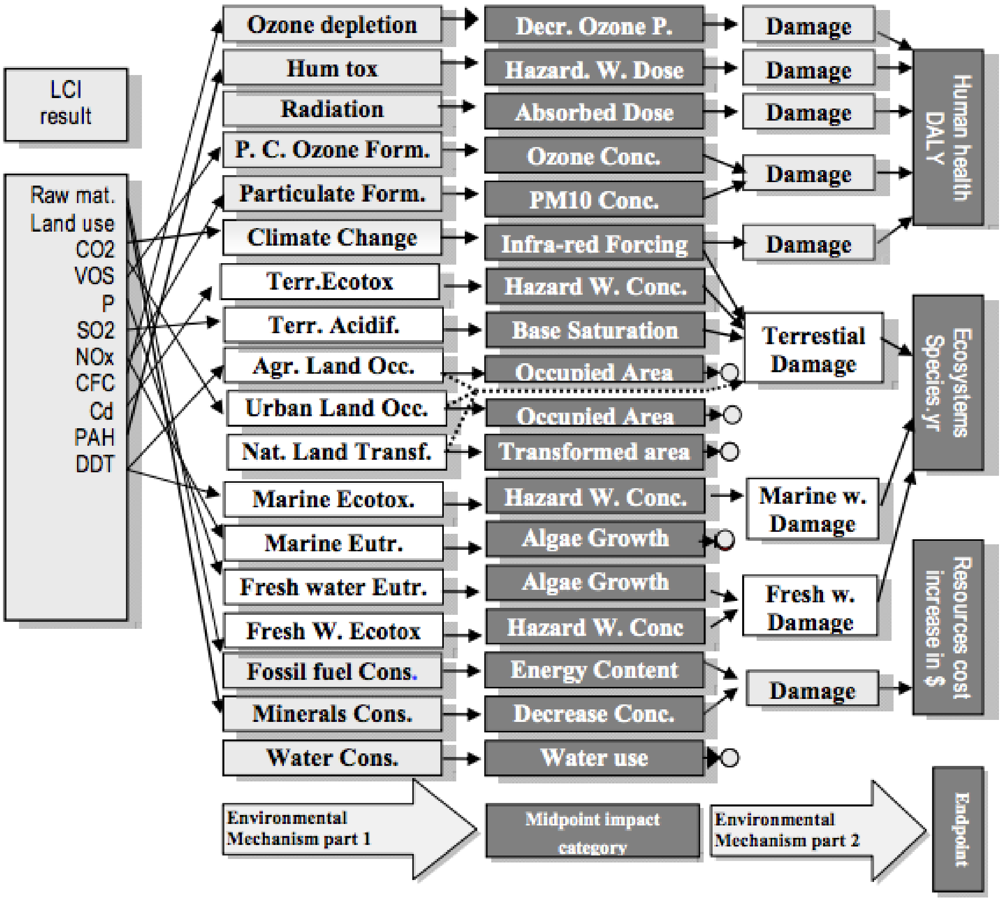


Figure 2 Recipe Framework
(Goedkoop, Heijungs et al, 2009)

The life cycle inventory results are shown on the left. The stressors presented in the results correspond to environmental mechanisms that further correspond to the 18 midpoint impact categories in the middle. These 18 impact categories can be further aggregated through assessment of their environmental mechanisms to three endpoint level categories, on the right hand side. These aggregations are performed from three different perspectives: individualist, hierarchist and egalitarian. These perspective differ mainly in timeframe: individualist timeframe considers 20 years, hierarchist considers 100 years and egalitarian has an infinite timeframe. For this thesis, the hierarchist perspective is used.

3. Case Description

The objective of this thesis is to analyze the environmental performance of several different transport vehicles. The impact potential of the lifetime of the vehicles will be analyzed, benchmarked and assessed under varying occupancy factors and driving distances. Two distinct vehicle types are analyzed in this thesis: Bus transit vehicles and private vehicles, summarized in Table 2.

Table 2 Modelled Vehicles
An overview of the modelled and analyzed vehicle types.

Vehicle Type	Model vehicle based on:	Short:
Intercity Diesel Bus	B12BLE chassis / Volvo 8500	Diesel Bus
Coach Diesel Bus	B12B chassis / Volvo 9700	Coach
Compressed Natural Gas Bus	Solaris Urbino 12 CNG	CNG Bus
Sports Utility Vehicle - SUV	Mercedes-Benz GLK220	SUV
Hatchback private vehicle	Mercedes-Benz A150	Hatchback
Subcompact private Vehicle	Volkswagen Polo 1.2 TDI BM	Sub

The vehicles were modelled to represent vehicles commonly found in the Trondheim fleet, and were based on existing vehicles. The B12BLE chassis and Solaris Urbino 12 CNG are chassis types currently deployed in Trondheim by AtB – the company currently responsible for public transport in Sør-Trøndelag. These chassis types number among the most commonly deployed in the Trondheim city central area. (Krokstad 2013) The Volvo 9700 is a bus employed by both Værnes-Ekspressen and Flybussen Trondheim – two competing coach service companies in Trondheim. The Mercedes-Benz A150 was chosen as a basis for the modeled hatchback vehicle as existing life cycle information for this vehicle is plentiful – the Industrial Ecology Group at NTNU have developed an extensive and highly detailed A150 inventory covering all of its life cycle phases. The SUV and Sub vehicles were chosen to represent size outliers, representing a larger and smaller private vehicle respectively. The GLK220 and Polo 1.2 were specifically chosen as their companies have released assessments of their respective environmental impacts. (Mercedes-Benz 2009, Volkswagen 2010)

3.1 Goal and Scope

The intention of the performed study is to find emissions associated with the manufacture, operation and disposal of the six modelled vehicles. Life cycle inventories are developed for each step of the vehicles life cycles, presented in **Error! Reference source not found.**. For the production phase, material use and manufacture emissions are taken into consideration. The operation phase is calculated based on maintenance input, fuel use and production and road abrasion and tire wear. The final step of the vehicle life time, the disposal phase, takes end of life treatment and recycling into account.

A process life cycle impact assessment, following ISO14040 guidelines, is performed. Key impact potentials of the vehicles are discussed and benchmarked, and a comparative assessment is performed on the vehicles climate change – based on factors such as vehicle lifetime and passenger load factor.

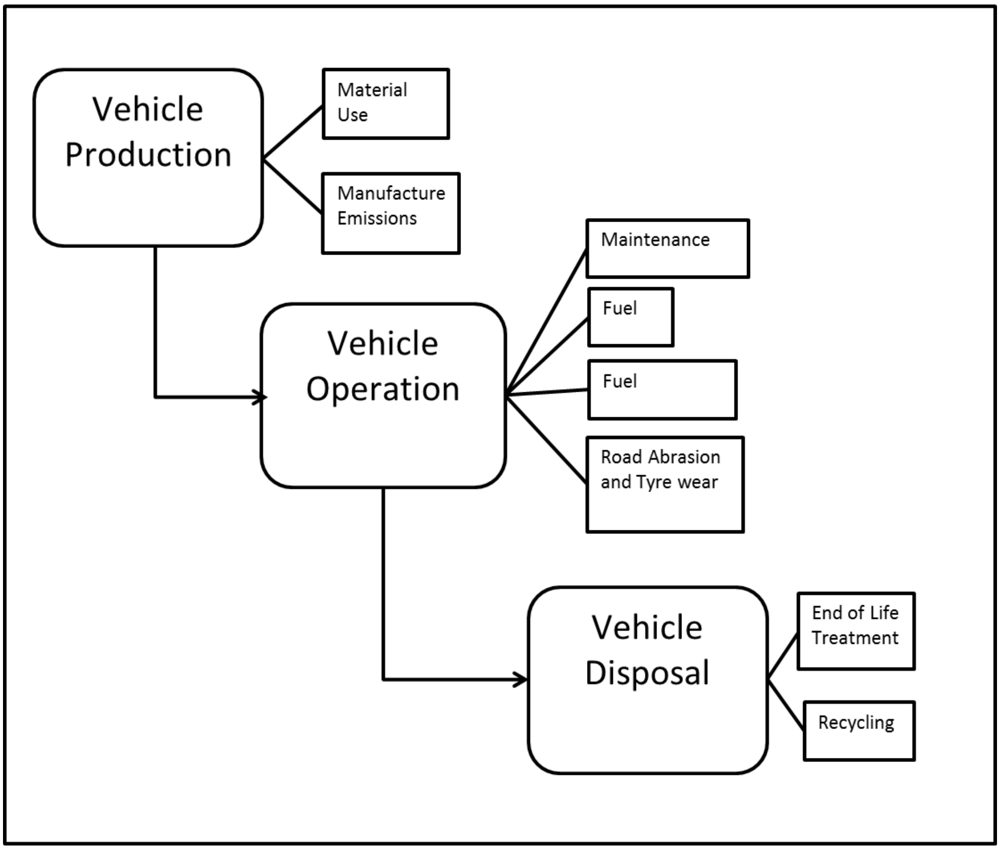


Figure 3 Vehicle Life Cycle
The life cycle phases and steps that are analyzed.

3.2 Transit Vehicle Inventories

As focus was intended to be on the operational phase of the transit vehicles, the three basis transit vehicles that the inventories were modelled after were chosen to be as similar as possible, but still representative of their bus category. The intercity diesel bus is based on the Volvo 8500, a common and widely popular intercity bus. An intercity bus is driven in a mostly urban traffic environment, entailing frequent starts and stops, a low average speed and a high idle time. The coach, modelled after the Volvo 9700, is driven in highway traffic with high average speeds and infrequent stops. The Compressed Natural Gas Bus, CNG Bus, drives in the same environments as the Intercity Diesel Bus. In Trondheim, AtB covers their routes arbitrarily with either a CNG bus or a Diesel bus – and the driving pattern of the CNG bus and the Diesel bus are thus treated as identical for the operational phase of the modelling. For a more detailed look at the specific input data used for the transit vehicles LCA, not shown explicitly in the text, refer to the inventories in appendix A.

3.2.1 Transit Vehicle Production

The three transit vehicles considered for analysis are modelled quite similar in manufacture: The vehicles consist of two main components: A stainless steel frame, covered in stainless steel and aluminum panels forms the body frame. The cabin is mounted on two axle chassis made of stainless steel, with a rear mounted engine. All three vehicles are approximately 12 meters long and 2.55 meters wide. Key vehicle dimensions are listed in Table 3.

Table 3 Key specifications, transit vehicles

Vehicle	Height [m]	Length [m]	Width [m]	Kerb Weight [ton]	Reference
Diesel Bus	3,115	11,990	2,55	10,900	a,b,c,h
Coach	3,590	12,29	2,55	13,130	c,d,e
CNG Bus	2,850 (3.430*)	12	2,55	11,350	f,g,h

* Including height of gas tanks on roof
a: Volvo 8500 range, Volvobuses b: Volvo 8500 Energi og Utslippsvirkninger av produksjon av Volvo 8500 busser, Morten Simonsen
c: Volvo B12 Range, Volvobuses d: Research on the weight of buses and touring coaches Final Report, J.T. Schoemaker
e: Volvo 9700 range g: Solaris Urbino Range, Solaris h: Correspondence with Einar Krokstad, AtB

The manufacture inventory for the regular intercity bus was based on the life cycle inventory tables created by EcoInvent. The EcoInvent inventory was created from the Environmental Product Declaration for the Volvo 8500 released by Volvo buses in 2004, now no longer available to the public. The production inventory for the coach and CNG bus were then scaled from this inventory as a starting point. Table 4 summarizes the material composition used for the three modeled vehicles.

Table 4 Material composition of transit vehicles

Material composition [kg]	Model Diesel Bus	Model Coach	Model CNG Bus
Iron/steel	6796	8155	6830
Aluminum	1666	1999	1700
Lead	90	108	90
Copper	112	134	112
Thermoplastics	553	663	553
Rubber	405	486	405
Glass	490	588	490
Wood	396	475	396
Paint	30	36	30
Bitumen	54	64	54
Composite materials	0	0	450

The diesel bus inventory is modelled after the Volvo 8500 body frame, mounted on a B12B Low Entry chassis. Being low entry, the floor of the bus has been lowered to accommodate for easier accessibility for the passengers. Only the rear section of the bus is raised, to fit powertrain components. The low floor height is achieved by making the front wheels independent, and having a rear engine rear wheel drive. The front and rear wheel sets are not connected by a central axle. Both the B12B coach and the B12BLE bus have rear mounted 6 cylinder 12-litre diesel engines with a 250 kW output. The CNG bus has a rear mounted Cummins ISLG 320 natural gas engine, with a 234.8 kW output. With regards to material composition and weight, there is little difference between the diesel engine and the natural gas engine: 90% of the materials used in the CNG engine is also used in the Diesel engine. For the sake of manufacture inventory for the model buses, the engines are thus assumed to be similar.

The CNG bus is modelled to be as similar to the regular bus as possible, with the only major difference being the fuel type and the corresponding fuel tanks. The CNG Solaris chassis is low entry, and its material composition is assumed to be similar to the B12BLE chassis. The body frame of the CNG bus is similarly assumed to be almost equal to the 8500 bus body frame. Much, if not most, of the additional weight of the CNG vehicle comes from the addition of six 214 L CNG cylinders on the roof, and its corresponding housing. The CNG vehicle, with regards to material composition, is modelled exactly like the regular low entry bus – but with added natural gas fuel tanks rather than a diesel fuel tank. The six fuel tanks of the CNG model vehicle are made of composite materials, with the same material composition as battery grade graphite for modelling purposes. DyneCell composite cylinders at 250 bar / 3600 psi (Dynatek Industries 2006) were used, and scaled slightly by volume – each tank weighing 75 kg and housing approximately 80 liters of compressed natural gas.

The B12B chassis is a step entrance variant of the B12BLE chassis, used for coaches. The floor is not lowered, making the B12B chassis slightly heavier and more solid than the low entry variant, but allowing more room for luggage and passenger seats. For the model coach, a Volvo 9700 body frame is assumed to be mounted on the B12BLE chassis. The coach body frame is 0.475 meters taller than the bus body frame, and approximately 2.5 tons, or 20%, heavier. The material composition of the coach is scaled from the diesel bus inventory using linear approximation.

Manufacture emissions to the environment were similarly based on Ecoinvent transport inventories. The data comes from MAN production sites in Germany and comprises final assembly and engine and metal parts manufacturing. These emissions were scaled between the three vehicles using linear approximation.

3.2.2 Transit Vehicle Operation

The operation phase inventories are based on numbers from Ecoinvent (Ecoinvent 2007) modified to represent the Trondheim vehicle fleet using specifications and data from AtB (Krokstad 2013). Volvo (Simonsen 2012) operate with a bus lifetime of 1 000 000 km for their Environmental Product Declaration. AtB Trondheim aim to operate their buses at approximately xxx km per year over 8 – 9 years before decommissioning them, giving a service life of approximately 500 000 km. Three different lifetime scenarios were thus analyzed for the buses: 500 000 km, 750 000 km and 1 000 000 km.

Fuel use per distance travelled varies depending on multiple factors. Fuel consumption varies with motor efficiency, the weight of the vehicle, average speed and usage pattern. The repeated starts and stops associated with city traffic consumes more fuel than the more stable driving associated with highway driving– with higher maximum speed and less stops. The difference in fuel consumption between city traffic (33% idle and average speed of 19 km/h) and commuter traffic (20% idle and average speed of 40 km/h) can be as high as 36% (Jobson 2008). The fuel consumption of each model vehicle is summarized in Chart 1.

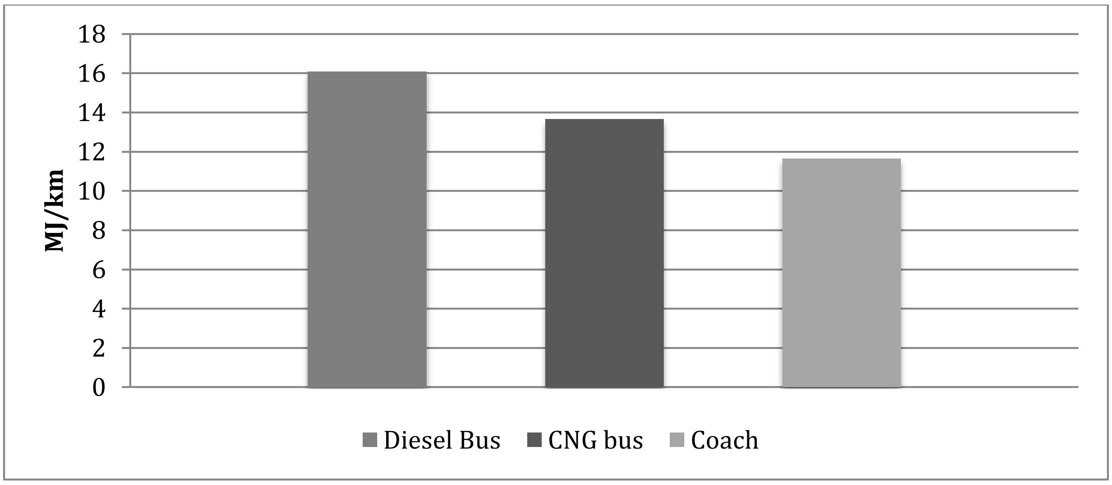


Chart 1 Fuel consumption, transit vehicles
Diesel bus and CNG consumption from AtB (Krokstad, 2013). Coach fuel consumption from Ecoinvent.

The emissions associated with vehicle operation are split between two categories: Tail pipe emissions and non-exhaust emissions. Tail pipe emissions are emissions associated with the combustion of fuel and motor operation, and is expelled through the tail pipe as exhaust gas. Non-exhaust emissions are produced mainly from tire abrasion, break wear and road abrasion. The tail pipe emissions are calculated from fuel consumption and the Ecoinvent inventory for Swiss diesel buses(Ecoinvent 2007). The non-exhaust emissions are scaled linearly between the vehicles by total weight. The total emissions associated with driving one kilometre is shown in Table 5

Table 5 Operation emissions, transit vehicles
Stressor emissions from both tail pipe and abrasion, per vehicle kilometre driven.

Stressor	Diesel Bus	Coach	CNG Bus	Unit
Carbon Dioxide, Fossil	9,47E-01	7,99E-01	6,47E-01	kg
Sulfur Dioxide	3,00E-05	2,53E-05	3,68E-06	kg
Cadmium	3,71E-09	2,74E-09	2,00E-09	kg
Copper	9,86E-07	8,20E-07	3,00E-08	kg
Chromium	2,33E-08	1,84E-08	1,80E-08	kg
Nickel	2,95E-08	2,27E-08	1,60E-08	kg
Zinc	7,45E-07	6,48E-07	1,61E-06	kg
Lead	2,83E-08	2,83E-08	9,99E-09	kg
Selenium	3,50E-09	2,53E-09		kg
Mercury	7,00E-12	5,05E-12		kg
Chromium VI	3,50E-11	2,53E-11		kg
Carbon Monoxide	2,75E-03	1,44E-03	1,68E-03	kg
Nitrogen Oxides	1,10E-02	8,72E-03	7,75E-05	kg
Particulates, <2.5 µm	3,81E-04	2,59E-04	3,37E-06	kg
Particulates, > 10 µm	5,66E-05	5,66E-05	7,80E-05	kg
Particulates, >2.5 µm and < 10 µm	6,16E-05	6,16E-05	1,34E-05	kg
NMVOC	6,42E-04	3,60E-04	3,95E-05	kg
Methane, Fossil	1,93E-05	1,08E-05	1,70E-04	kg
Benzene	2,57E-06	1,44E-06	2,87E-06	kg
Toluene	1,35E-05	7,53E-06	1,98E-05	kg
Xylene	6,44E-06	3,61E-06	2,03E-05	kg
Formaldehyde	6,60E-05	3,70E-05		kg
Acetaldehyde	3,59E-05	2,01E-05		kg
Ammonia	4,29E-06	5,00E-06	1,30E-04	kg
Dinitrogen Monoxide	1,13E-05	1,32E-05	3,26E-06	kg
PAH	3,43E-10	4,00E-10	4,03E-09	kg
Zinc, Ion	5,02E-06	5,02E-06	4,53E-06	kg
Copper, Ion	1,19E-07	1,19E-07	8,45E-08	kg
Cadmium, Ion	1,78E-09	1,78E-09	5,64E-09	kg
Chromium, Ion	8,48E-09	8,48E-09	5,07E-08	kg
Nickel, Ion	2,30E-08	2,30E-08	4,51E-08	kg
Lead	7,31E-08	7,31E-08	2,13E-08	kg
Zinc	5,02E-06	5,02E-06	4,53E-06	kg
Copper	1,19E-07	1,19E-07	8,45E-08	kg
Cadmium	1,78E-09	1,78E-09	5,64E-09	kg
Chromium	8,48E-09	8,48E-09	5,07E-08	kg
Nickel	2,30E-08	2,30E-08	4,51E-08	kg
Lead	7,31E-08	7,31E-08	2,81E-08	kg
Heat, Waste	1,58E+01	1,14E+01	1,28E+01	MJ

3.2.3 Transit Vehicle Maintenance and Disposal

Maintenance inventories for the diesel bus were based on Ecoinvent data, derived from expert estimates and calculations, using figures from service garages in Berne and Zurich. Maintenance and replacement of bus hardware was assumed to scale between the buses linearly with weight. Service fluid use was scaled linearly with oil-change intervals for the engine: The CNG bus must change oil every 24 000 km (Cummins Westport 2013) while the Diesel bus and Shuttle bus need to change oil every 40 000 km and 100 000 km respectively (Volvo 2005). Although the impact from this is negligible, it should be noted that energy use associated with more frequent oil change is not taken into account.

Table 6 Maintenance inventory, transit vehicles

Name	CNG	Bus	Shuttle	Unit
Reinforcing Steel, at plant	57	55	66,3	kg
polyethylene, HDPE, granulate, at plant	3	1,4	1,7	kg
synthetic rubber, at plant	208	133	160,2	kg
natural gas, burned in industrial furnace >100kw	42068	40400	48665,3	MJ
electricity, low voltage, at grid	70599	67800	81671	kWh
light fuel oil, burned in industrial furnace 1MW, non-modulating	42068	40400	48665,3	MJ
tap water, at user	503982	484000	583020,2	kg
lubricating oil, at plant	1351	824	329,6	kg
lead, at regional storage	19	17,9	21,6	kg
paper, woodfree, uncoated, at regional storage	3	3,2	3,8	kg
transport, freight, rail	216	207	249,3	tkm
disposal, used mineral oil, 10% water, to hazardous waste incineration	1351	824	329,6	kg
disposal, plastics, mixture, 15.3% water, to municipal incineration	104	55	66,3	kg
treatment, sewage, to wastewater treatment, class 1	794	484	193,6	m3
transport, lorry 28t	54	51,7	62,3	tkm
heat, waste	254073	244000	293919,3	MJ

Disposal inventories were similarly based on Ecoinvent data. Bulk material used in the vehicle is taken into account, and steel, aluminum and copper are assumed to be fully recycled. 50% of all tires are assumed to be used as secondary fuel in cement works. The CNG tanks have a lifetime of 15 to 20 years, CNG cylinder tank maintenance will thus not be taken into account. CNG cylinders are however not to be directly recycled at end of life. After 20 years the composite materials have atrophied to the point of not being safe for further use – and must be destroyed separate from the vehicle (Clean Vehicle Foundation). Due to lack of better process options in the EcoInvent database, the composite materials will be represented by aluminum. The remainder of the disposal inventory was scaled on weight across all vehicles, summarized in Table 7.

Table 7 Disposal inventory, transit vehicles

Name	Bus	Coach	CNG	Unit
disposal, plastics, mixture, 15.3% water, to municipal incineration	5,5E+02	6,7E+02	6,9E+02	kg
transport, lorry 28t	1,4E+01	1,7E+01	1,8E+01	tkm
disposal, glass, 0%water, to municipal incineration	1,2E+02	1,4E+02	1,4E+02	kg
disposal, emulsion paint, 0% water, to municipal incineration	1,2E+01	1,4E+01	1,5E+01	kg
disposal, used mineral oil, 10% water, to hazardous waste incineration	2,5E+01	3,0E+01	3,2E+01	kg
disposal, aluminum, 0% water, to municipal incineration/ CH/ kg	0	0	4,5E+01	kg

3.3 Private Vehicle Inventories

The three basis private vehicles used for modelling and benchmarking were chosen based on data availability and representativeness of their respective car categories. The Mercedes-Benz A150 class is a hatchback family car. As one of Mercedes-Benz' flagship family car series, it functions as a good representation of the "common family car". The Industrial Ecology group at NTNU have compiled a highly detailed production inventory for the A150, making it a good starting point for modelling and scaling. In a similar vein, the Mercedes-Benz GLK series and the Volkswagen Polo are well known and widely used series, and are good representations of an SUV and a Subcompact, respectively. For a more detailed look at the specific input data, not shown explicitly in the text, used for the private vehicles LCA refer to appendix A.

3.3.1 Private Vehicle Production

For the private vehicles, the Mercedes-Benz A150 hatchback car was used as a basis model, scaled to represent the SUV and Sub inventories. The inventory used for the A150 is a multi-vehicle inventory developed by the NTNU Industrial ecology group (Hawkins, Singh et al. 2012). The inventory details the manufacture of the Mercedes-Benz A150, defined by 12 major components and processes, shown in Table 8:

Table 8: Major Components and processes, A150 inventory

Major Components/Processes					
Body & Doors	Brakes	Chassis	Engine	Final Assembly	Fluids, ICEV and EV
Interior and Exterior	Powertrain components	Tires and Wheels	Transmission	Batteries	Fluids, ICEV only

The major components and processes are composed of a multitude of subcomponents and subprocesses that in turn are defined by a mass and material compositions. Table 8 shows non-assembly aggregated material composition for the major components, modified to take into account industry numbers. For a disaggregated overview, refer to appendix A.

Table 9: Material composition, A150 Inventory
The material composition and mass of the A150 vehicle major components [kg]

Major Component	Steel/Iron	Light Alloys	Non-Ferrous Metals	Polymers	Service Fluids	Composites and Others	Special Metals
Body and Doors	389,0		0,2	0,2		28,8	
Brakes	28,8					2,3	
Chassis	172,5	3,3	4,1	7,0			
Engine	118,3	29,8		2,5			
Interior and Exterior	70,6	18,7	12,4	121,9			
Tires and wheels	46,9		0,3	20,0			
Powertrain components	53,1		6,5	29,7		2,9	0,01
Transmission	18,0	11,0	0,2	4,0			
Battery			11,4				
Vehicle Fluids					52,6		

It should be noted that the material composition in the Indecol vehicle inventory has a higher steel/iron content, and correspondingly lower light alloy content, than industry reports. The iron/steel content is 70% for the Indecol inventory versus 62% reported in the Mercedes-Benz A Class Environmental Certificate. The consequence of this is that the three modeled vehicles will have a slightly higher iron content and lower aluminum content than the real life vehicles which they are based on.

The A150 inventory is scaled to represent the Sub and SUV inventory on major component level. To perform this scaling, an assumption is made: The material ratios for each separate major component are constant, regardless of vehicle. This means that the ratio, for instance, between steel and aluminum in the engine remains the same across the different vehicles, although their mass naturally is not the same. Using the material composition for the A150 inventory, shown in Table 9, the material ratio of each major component is found and presented in Table 10.

Table 10 Material Ratio of Private Vehicles
The material ratio of the SUV, Car and Sub, assumed to be constant across vehicles.

Major Component	Steel/Iron	Light Alloys	Non-Ferrous Metals	Polymers	Service Fluids	Composites and Others	Special Metals
Body and Doors	93%		0,05 %	0,05 %		6,9 %	
Brakes	92,7 %					7,3 %	
Chassis	92,3 %	1,8 %	2,2 %	3,7 %			
Engine	78,5 %	19,8 %		1,7 %			
Interior and Exterior	31,6 %	8,4 %	5,6 %	54,5 %			
Tires and wheels	69,8 %		0,45 %	29,8 %			
Powertrain components	57,6 %		7 %	32,2 %		3,1 %	0,01 %
Transmission	54,3 %	33,2 %	0,5 %	12, %			
Battery			94,5 %	5,5 %			
Vehicle Fluids					100%		

Operating under the assumption that the material ratio of the major components are constant across the vehicles, industry given material compositions are then used to linearly scale the major components between vehicles. Table XYZ shows *industry* given material composition and weight of the three basis vehicles, as well as the ratio between the Polo1,2 /GLK220 and the A150. (Mercedes-Benz 2008, Mercedes-Benz 2009, Volkswagen 2010)

Table 11 Industry given material composition [kg]

Vehicle	Steel/Iron	Light Alloys	Non-Ferrous Metals	Polymers	Service Fluids	Composites and Others	Special Metals
A150	789	95	27	199	62	46	0,24
GLK220	1092	182	35	327	83	44	0,18
Polo 1,2	724	117	28	212	54	43	0,03
Ratio| Polo 1,2/A150	0,918	1,225	1,054	1,068	0,873	0,923	0,139
Ratio| GLK220/A150	1,384	1,916	1,319	1,647	1,337	0,954	0,725

Multiplying a ratio row from Table 11 with the material ratio row of any major component from Table 10 gives the corresponding scaled material composition of said major component.

Defining the coefficients of Table 10 as a 10x7 matrix C and the ratio rows from Table 11 as vectors r_{Sub} and r_{Suv}, an expression for the vector of scaling constants k is given as:

$$k_n = C * r_n^T$$

Where n = Sub, SUV and T = transpose

For example:

The scaling constant for the Body and Doors major component for the SUV becomes:

$$k_{body\&doors(SUV)} = 93\% * 1{,}384 + 0{,}05\% * 1{,}319 + 0{,}05\% * 1{,}647 + 6{,}89\% * 0{,}95$$

$$k_{body\&doors(SUV)} = 1{,}354$$

The scaling constant for all major components for both vehicles are presented in

Table 12 Scaling constants, private vehicles

Major Component	Hatchback	SUV	Sub
Body and Doors	1	1,350	0,920
Brakes	1	1,349	0,920
Chassis	1	1,398	0,934
Engine	1	1,491	0,984
Interior and Exterior	1	1,569	1,035
Tires and wheels	1	1,460	0,965
Powertrain components	1	1,449	0,977
Transmission	1	1,591	1,042
Battery	1	1,338	1,051
Vehicle Fluids	1	1,340	0,870

The scaling constants are used as input data for the production phase in the inventory, scaled linearly with the Hatchback as a baseline. Manufacture input is scaled linearly with weight.

The final kerb weights for the model vehicles are summarized in Table 13.

Table 13 Kerb weight, private vehicles

Vehicle	Kerb Weight [ton]	Reference
Hatchback	1250	Mercedes-Benz 2008
SUV	1770	Mercedes-Benz 2009
Sub	1150	Volkswagen 2010

3.3.2 Private Vehicle Operation

The operation phase inventories are based on default vehicle numbers from Ecoinvent (Ecoinvent 2007) modified to better represent the specific chosen private vehicles based Environmental Product Declarations (Mercedes-Benz 2008, Mercedes-Benz 2009) and Commendation Background Reports (Volkswagen 2010). An operation lifetime of 200 000 km was used for the private vehicles.

Several factors have an impact on fuel consumption per kilometre driven, as for the transit vehicles. Fuel use depends on the efficiency of the motor, the vehicle weight and the driving pattern of the vehicle. City traffic usually consumes more fuel than highway commuting. For the private vehicles, a mix of gas guzzling city driving and more stable and less fuel consuming highway traffic is assumed. The fuel consumption used for the private vehicles is shown in Chart 2

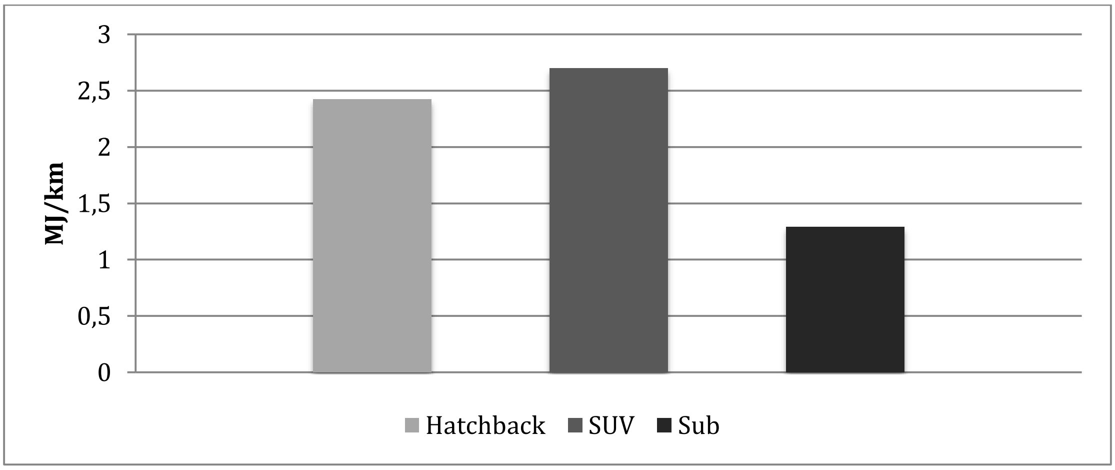


Chart 2 Fuel consumption, private vehicles

As for the transit vehicles, the emissions from vehicle operation are split into two categories: Tail pipe emissions and non-exhaust emissions. Tail pipe emissions are emissions associated with the combustion of fuel, expelled through the tail pipe as exhaust gas. The sources of non-exhaust emissions are mainly tire abrasions, break wear and road wear. The tail pipe emissions are calculated from fuel consumption and the Ecoinvent inventory for Swiss diesel cars (Ecoinvent

2007). The non-exhaust emissions are scaled linearly by vehicle weight. The emissions associated with driving one vehicle kilometre are shown in Table 14.

Table 14 Operation emissions, private vehicles
Stressor emissions from both tail pipe and abrasion, per vehicle kilometre driven.

Stressor	Hatchback	SUV	Sub	Unit
Carbon Dioxide, Fossil	1,48E-01	2,08E-01	8,70E-02	kg
Sulfur Dioxide	5,81E-06	6,47E-06	3,09E-06	kg
Cadmium	6,78E-10	9,60E-10	6,24E-10	kg
Copper	4,79E-07	6,78E-07	4,41E-07	kg
Chromium	8,13E-09	1,15E-08	7,48E-09	kg
Nickel	7,69E-09	1,09E-08	7,07E-09	kg
Zinc	1,99E-07	2,82E-07	1,83E-07	kg
Lead	2,46E-08	3,48E-08	2,26E-08	kg
Selenium	5,51E-10	7,80E-10	5,07E-10	kg
Mercury	1,10E-12	1,56E-12	1,01E-12	kg
Chromium VI	5,51E-12	7,80E-12	5,07E-12	kg
Carbon Monoxide	2,47E-04	2,75E-04	1,31E-04	kg
Nitrogen Oxides	3,89E-04	4,33E-04	2,07E-04	kg
Particulates, <2.5 µm	3,02E-05	3,82E-05	2,19E-05	kg
Particulates, > 10 µm	1,19E-05	1,69E-05	1,09E-05	kg
Particulates, >2.5 µm and < 10 µm	1,35E-05	1,91E-05	1,24E-05	kg
NMVOC	4,00E-05	4,45E-05	2,13E-05	kg
Methane, Fossil	1,20E-06	1,34E-06	6,39E-07	kg
Benzene	1,57E-07	1,75E-07	8,36E-08	kg
Toluene	7,59E-07	8,45E-07	4,04E-07	kg
Xylene	4,00E-07	4,45E-07	2,13E-07	kg
Formaldehyde	4,09E-07	4,55E-07	2,18E-07	kg
Acetaldehyde	2,21E-06	2,46E-06	1,18E-06	kg
Ammonia	1,00E-06	1,11E-06	5,32E-07	kg
Dinitrogen Monoxide	5,51E-06	6,13E-06	2,93E-06	kg
PAH	4,00E-10	4,45E-10	2,13E-10	kg
Zinc, Ion	2,70E-07	3,82E-07	2,48E-07	kg
Copper, Ion	6,39E-09	9,05E-09	5,88E-09	kg
Cadmium, Ion	9,55E-11	1,35E-10	8,79E-11	kg
Chromium, Ion	4,55E-10	6,44E-10	4,19E-10	kg
Nickel, Ion	1,23E-09	1,74E-09	1,13E-09	kg
Lead	3,93E-09	5,56E-09	3,62E-09	kg
Zinc	2,70E-07	3,82E-07	2,48E-07	kg
Copper	6,39E-09	9,05E-09	5,88E-09	kg
Cadmium	9,55E-11	1,35E-10	8,79E-11	kg
Chromium	4,55E-10	6,44E-10	4,19E-10	kg
Nickel	1,23E-09	1,74E-09	1,13E-09	kg
Lead	3,93E-09	5,56E-09	3,62E-09	kg
Heat, Waste	2,62E+00	3,71E+00	2,41E+00	MJ

3.3.3 Private Vehicle Maintenance and Disposal

Maintenance inventories for the private vehicles were based on Ecoinvent data, derived from expert estimates and calculations. Maintenance and replacement of vehicle hardware was assumed to scale linearly with weight.

Table 15 Maintenance inventory, private vehicles

Name	Hatchback	SUV	Sub
steel, low-alloyed, at plant	2,20E+01	3,25E+01	2,33E+01
copper, at regional storage	3,00E+01	4,43E+01	3,18E+01
polyethylene, HDPE, granulate at plant	1,00E+01	1,48E+01	1,06E+01
polypropylene, granulate, at plant	1,20E+01	1,77E+01	1,27E+01
synthetic rubber, at plant	2,33E+02	3,44E+02	2,47E+02
electricity, low voltage, production UCTE, at grid	8,47E+03	1,25E+04	8,98E+03
lead, at regional storage	1,30E+01	1,92E+01	1,38E+01
ethylene, average, at plant	3,80E+01	5,61E+01	4,03E+01
ethylene glycol, at plant	2,00E+00	2,95E+00	2,12E+00
sulphuric acid, liquid, at plant	1,40E+00	2,07E+00	1,48E+00
transport, lorry 32t	3,18E+01	4,69E+01	3,37E+01
transport, freight, rail	6,37E+01	9,40E+01	6,75E+01
heat, waste	3,05E+04	4,50E+04	3,23E+04

Disposal inventories were based on Ecoinvent data. Bulk material used in the vehicle is taken into account, and steel, aluminum and copper are assumed to be fully recycled. 50% of all tires are assumed to be used as secondary fuel in cement works. The inventory was scaled on weight across all vehicles, summarized in Table 16.

Table 16 Disposal inventory, private vehicles

Name	Bus	Coach	CNG	Unit
disposal, plastics, mixture, 15.3% water, to municipal incineration	5,5E+02	6,7E+02	6,9E+02	kg
transport, lorry 28t	1,4E+01	1,7E+01	1,8E+01	tkm
disposal, glass, 0%water, to municipal incineration	1,2E+02	1,4E+02	1,4E+02	kg
disposal, emulsion paint, 0% water, to municipal incineration	1,2E+01	1,4E+01	1,5E+01	kg
disposal, used mineral oil, 10% water, to hazardous waste incineration	2,5E+01	3,0E+01	3,2E+01	kg

3.4 Passenger load

The passenger load factor is a measure of how much of total available passenger capacity is utilized. The definition of load factor varies: in some industries the load factor is only indicative on utilization of seating capacity. For the purposes of this thesis both standing and seating capacity will be taken into account - a load factor of 100% indicates that both standing capacity and sitting capacity is fully utilized.

Table 17 Vehicle passenger loads

Vehicle	Standing Capacity	Sitting Capacity	Total
Intercity Diesel Bus	37	37	74
Coach Diesel Bus	0	50	50
Compressed Natural Gas Bus	37	37	74
Sports Utility Vehicle - SUV	0	5	5
Hatchback private vehicle	0	5	5
Subcompact private Vehicle	0	5	5

It's worth noting that, while the coach has capacity for standing passengers, it is considered unsafe and illegal at high speeds. As a result of this, coach services in Norway generally do not utilize the standing capacity of the bus at any point in its journey. The standing capacity of coaches will thus be considered to be 0 for this analysis. For vehicles with capacity for standing passengers, the industry standard for crowding is at 125% of the sitting capacity. For the considered vehicles, this would correspond to a passenger load of 75% (47 passengers) for the Diesel and CNG intercity buses. At these passenger loads, additional service may have to be deployed to sufficiently cover peak loads. (MacKechnie 2013)

Statistics Norway has data on Capacity Kilometres (ckm) and Passenger Kilometres (pkm) for transit vehicle in Trondheim and across county borders. (Statistisk Sentralbyrå 2012) Using these two factors, a mean passenger load can be found by dividing pkm on ckm, as shown in Table 18. Passenger kilometre represents the distance travelled by passengers, determined by multiplying the amount of passengers with the driven distance. A bus with 50 passengers would drive 50 passenger kilometres per kilometre. Capacity kilometres represents the maximum amount of passenger kilometres a bus can drive. For instance: a bus with 47 seats and room for 47 standing passengers (total capacity: 94) would drive 94 capacity kilometres per kilometre.

Table 18 Driving distances, transit vehicles.
Lists yearly total pkm and ckm in 1000 km.

Area	Pkm (1000 km)	Ckm (1000 km)	Average passenger load
Trondheim (2009)	133 823	693 614	19,3%
Trondheim (2010)	144 281	704 402	20,5%
Trondheim (2011)	154 499	753 950	20,5%
Cross county (2009)	733 772	2 206 551	33,3%
Cross county (2010)	654 967	2 142 274	30,6%
Cross county (2011)	630 141	2 148 295	29,3%

This gives an approximate total average passenger load of 20% for the intercity buses and 31% for the coach service.

Statistics Norway has data on passenger load for private vehicles as well, but do not differentiate by vehicle size. The average amount of passengers lie between 1,3 and 2,1 – depending on the length of the journey. Longer journey tend to have a higher amount of passengers. (Toutain, Taarneby et al. 2008)

4. Results and Analysis

In this section, the main results from the LCA performed on the model vehicles will be briefly presented, along with a contribution analysis of the main impact potentials associated with the lifetime of both cars and buses. Climate change potential will then be further analyzed: Climate change potential as a function of passenger kilometres travelled will be discussed and benchmarked.

4.1 Climate Change Potential

In order to compare the effects of different greenhouse gases, they are collectively converted to CO^2-equivalents. The greenhouse gases have different atmospheric lifetimes, giving varying profiles of future radiative forcing. The Climate Change index (CC) takes the ratio of the time-integrated radiative forcing from the release of 1 kg of a given gas compared to 1 kg of CO^2 (Houghton 2009, Ellingsen 2011). For this LCA, the CC-100 has been used – giving a time horizon of 100 years. Table 19 shows the climate change potential for the different vehicles, illustrated in

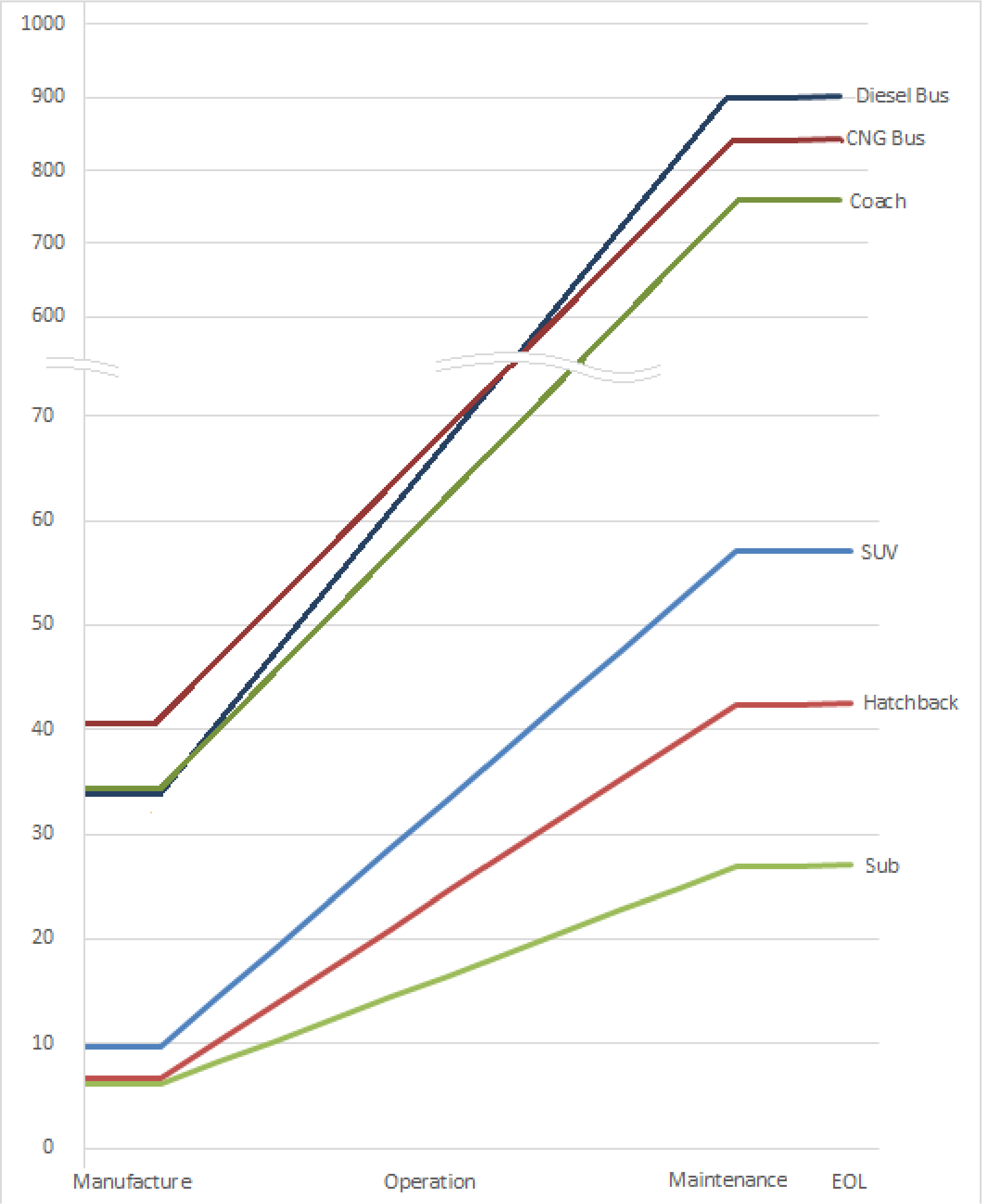


Figure 4 Lifetime climate change potential
– assuming a lifetime of 200 000 km and 750 000 km for the private vehicles and the transit vehicles, respectively.

Table 19 Climate change potential
Climate change potential over lifetime [ton CO^{2}-eq]

Vehicle	Materials	Manufacture	Operation	Maintenance	Disposal	Sum
Hatchback	5,22	1,41	35,45	0,32	0,17	42,58
SUV	6,70	1,72	48,12	0,46	0,15	57,14
Sub	4,80	1,29	20,52	0,30	0,17	27,08
Diesel Bus	27,20	7,01	850,40	15,32	1,39	901,33
Coach	32,64	8,42	701,55	16,36	1,67	760,65

CNG Bus	27,24	7,99	789,35	16,02	1,74	842,34

As illustrated in

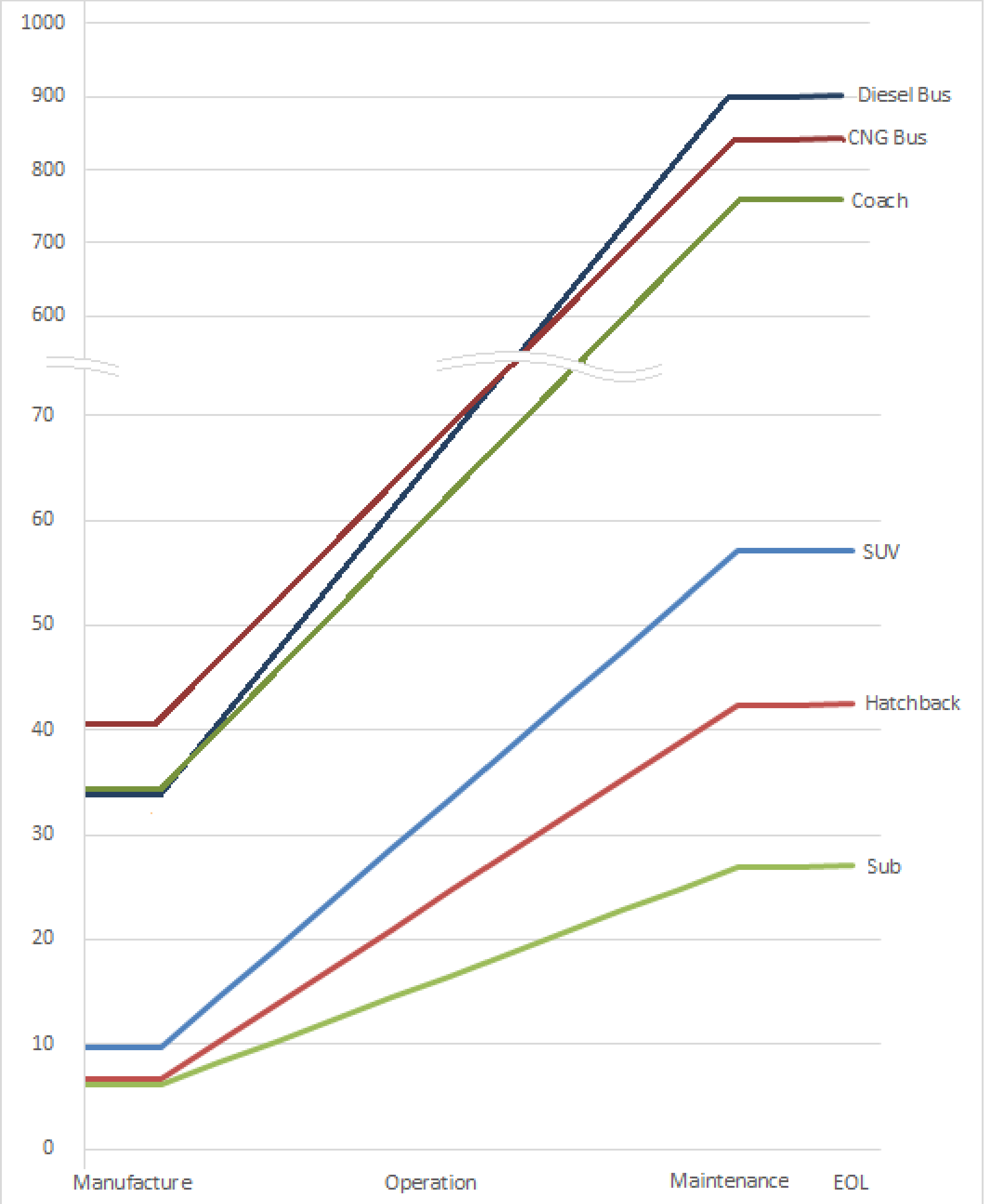


Figure 4 Lifetime climate change potential

, the operation phase uniformly contributes the most to climate change for all the vehicles. Operation alone accounts for between 76% and 84% for the private vehicles and between 92% and 94% for the transit vehicles, of lifetime emissions. A longer lifetime for the transit vehicles means that the impact potentials associated with driving, operation and maintenance accounts for a higher part of total lifetime potentials.

Maintenance and disposal emissions contribute less than 3% to total climate change impact. For the maintenance phase, greenhouse gases are mostly emitted through the burning of light fuel oil and natural gases, used in maintenance processes. The oil change frequency has, in the big picture, low to negligible impact. For the end of life treatment, disposal of plastics, used mineral oil and emulsion paint are the greatest contributors.

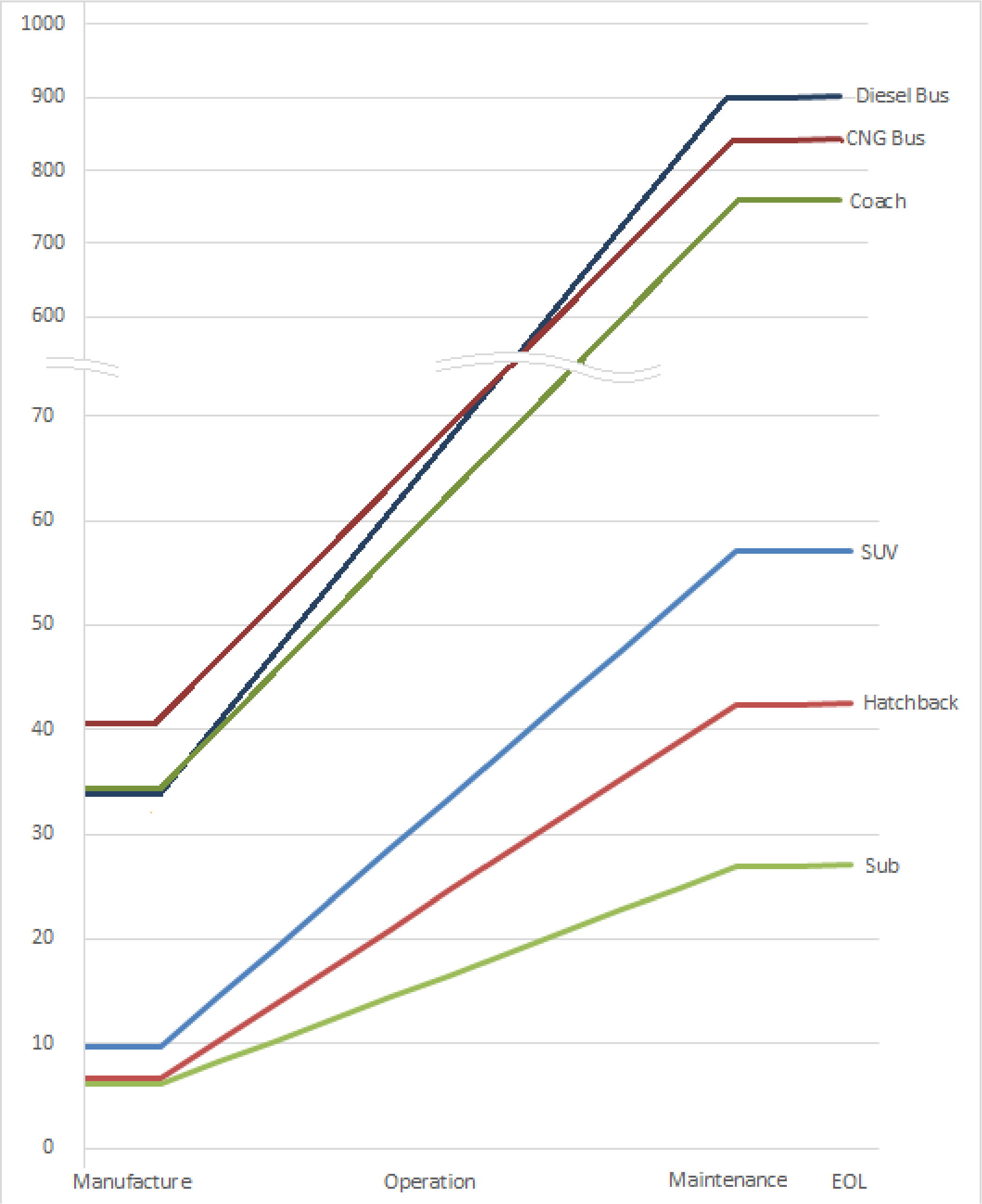


Figure 4 Lifetime climate change potential

4.1.1 Production phase

The production phase accounts for between 3,7% to 5,4% (transit vehicles) and 14,7% to 22,5% (private vehicles) of total lifetime emissions. Due to the shorter lifetime of the private vehicles, the production phase accounts for a higher share of total impact potential for these vehicles. The climate change potential from the materials is largely due to primary aluminum and iron use – the two main materials used in all the vehicles. The environmental impact from materials is proportional to the material intensity of the vehicle – the heavier vehicles have a higher environmental impact from material use. **Error! Reference source not found.** shows the climate change potential impact from the production phase, as well as emission intensity – the emissions of CO2 per vehicle weight.

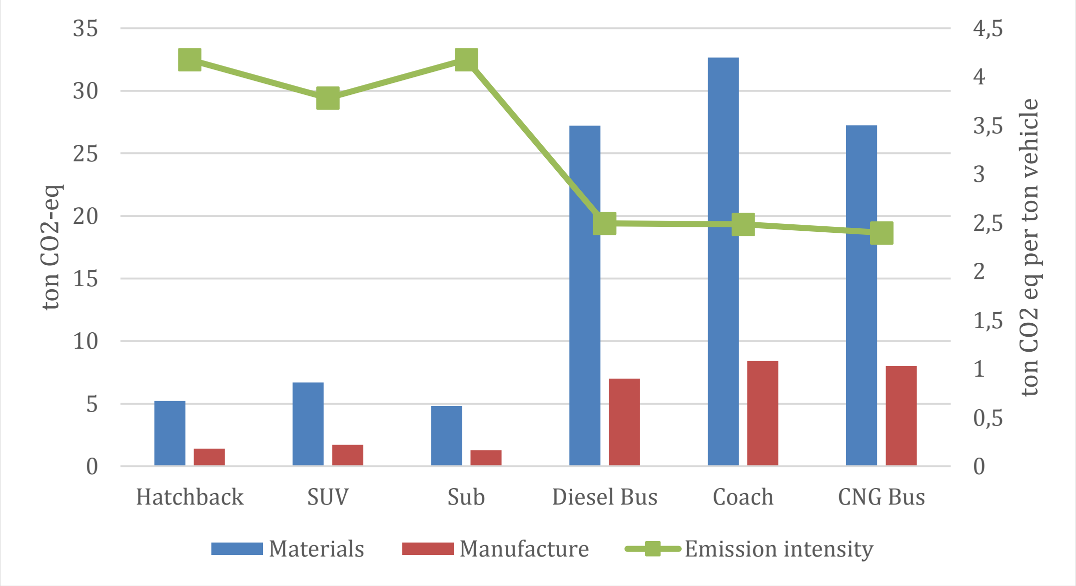


Chart 3 Climate change potential from production phase
Left axis shows ton CO2-eq from materials and manufacture. Right axis displays emission density – CO2-eq emissions per vehicle weight.

It should be noted that the emission intensity of the transit vehicles is higher than for the private vehicles. This is addressed in the discussion. For emissions associated with manufacturing in the production phase, the burning of natural gas, lignite and coal in industrial furnaces accounts for the majority of the impact.

4.1.2 Operation phase

The operation phase is responsible for the majority of the climate change potential for all the vehicles – accounting for between 76% and 84% for the private vehicles and between 92% and 94% for the transit vehicles. Climate change potential from operation is split between two distinctive sources: tailpipe emissions from fuel use and emissions from fuel production, shown in **Error! Reference source not found.**.

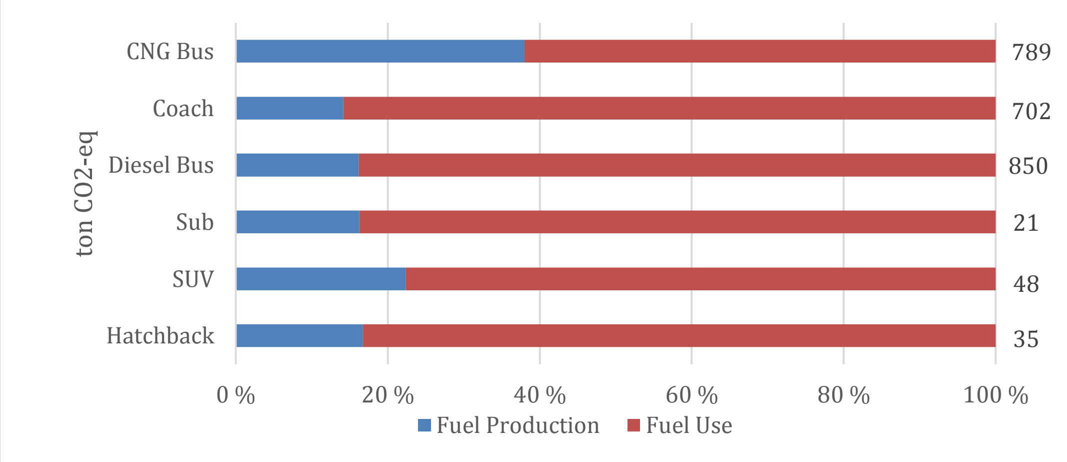


Chart 4 Operation phase, climate change potential

Tailpipe emissions occur as a result of fuel combustion in the vehicles engine and are emitted from the exhaust system. As shown in **Error! Reference source ot found.**, the tailpipe emissions from fuel use are responsible for the majority of the climate change potential from the operation phase. Between 78% and 86% of CO2-eq emissions for the diesel vehicles are from fuel use alone, compared to 62% for the CNG bus.

Natural gas has a lower carbon content than diesel, and thus burns cleaner – emitting CO_2 and CO - compared to the Diesel bus, operating with the same driving profile, the CNG bus has 20% lower emissions of CO_2 equivalents. Operation emissions, however, are only 7% lower in total. This is because the production of CNG fuel emits 3 times the CO_2-equivalents of the diesel production. Production of CNG emits almost 9 times more methane than the production of diesel.

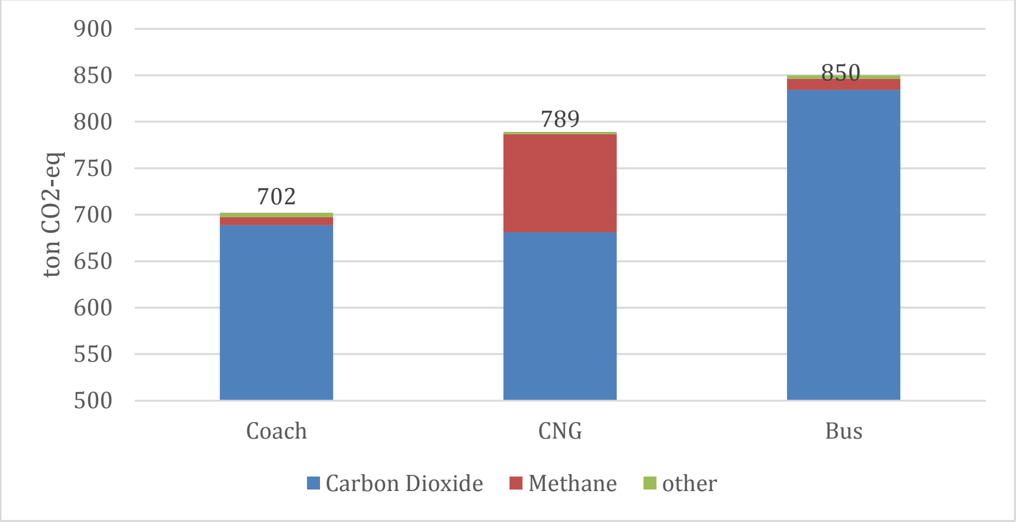


Chart 5 Climate change potential by stressor

98% of the diesel buses' climate change potential stems from carbon dioxide emissions. For the CNG bus, 86% of the emission potential comes from carbon dioxide emissions, with 13% owing to methane emissions.

The increased methane emissions prove to be significant when, using CC-100, the emissions of 1kg of methane calculates at 25 times the climate change potential of 1 kg of CO_2. For the CNG bus the greenhouse gases associated with the operation phase are thus shifted from fuel use to fuel production, farther away from the end user.

4.1.3 Lifetime scenarios

All impact potentials thus far have been calculated based on a lifetime of 750 000 km for each bus. Volvo perform their calculations with a lifetime of 1 000 000 km (Simonsen 2012). AtB Trondheim plan to use their buses for 7 to 9 years, expecting to drive them for 70-80 000 km – giving an approximate lifetime of 500 000 km. Chart 6 illustrates the implications of a varying lifetime.

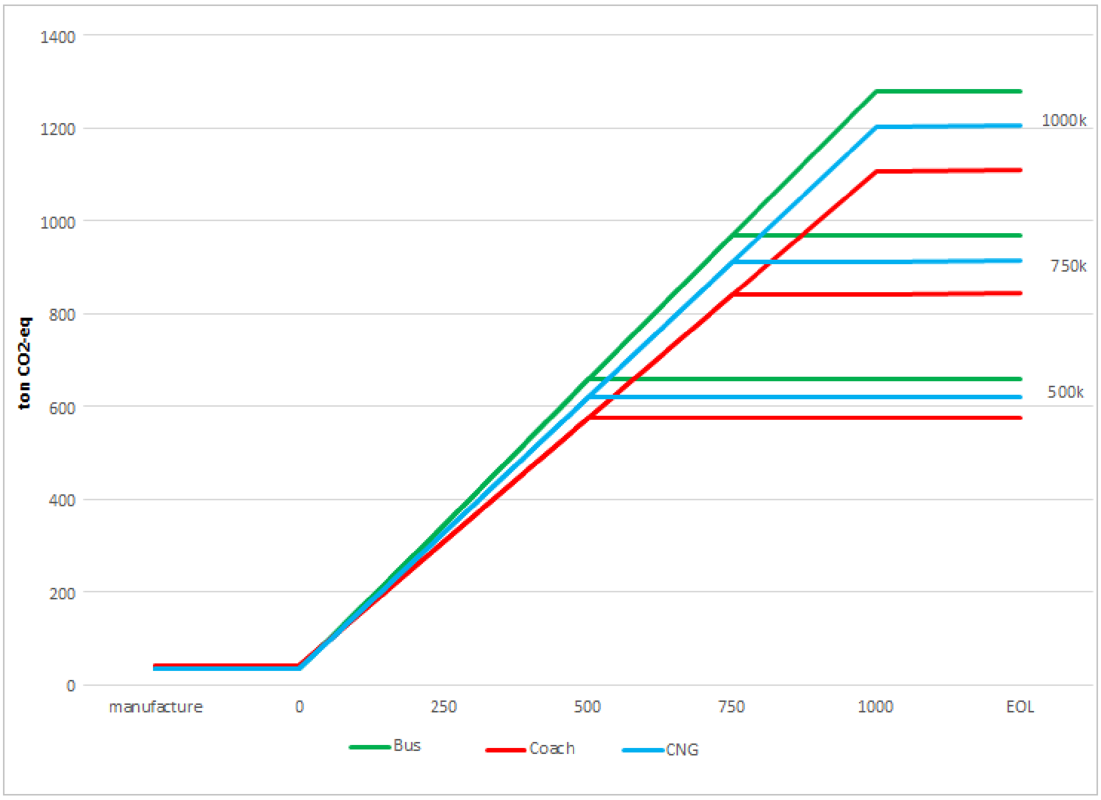


Chart 6 Lifetime CO2 Scenarios

The way the vehicles have been modeled, a longer vehicle lifetime has no impact on disposal and production emissions. Only maintenance and operation emissions scale with lifetime. As the operation phase on average accounts for 93% of the vehicles greenhouse gas emissions, an increase in lifetime yields an almost similar increase in total greenhouse gases, percent wise. This assumes that maintenance costs scale linearly over the vehicles lifetime, which might not be a realistic scenario – maintenance costs may have a tendency of increasing as a vehicle grows older.

4.2 Contribution Analysis

4.2.1 Transit vehicles

Table 20 shows some key chosen impact potentials for the different transit vehicles, illustrated and disaggregated in chart

Table 20 Impact contribution, transit vehicles
Assuming a lifetime of 750 000 km

Impact category	Bus	Coach	CNG	unit
fossil depletion	353656	262682	708507	kg oil-Eq
human toxicity	73710	71165	62436	kg 1,4-DCB-Eq
marine eutrophication	1202	954	177	kg N-Eq
particulate matter formation	2646	2092	538	kg PM10-Eq
Metal Depletion	18 732	20 828	21 206	Kg Fe-Eq
photochemical oxidant formation	9981	7759	1580	kg NMVOC
terrestrial acidification	6259	4952	1548	kg SO2-Eq

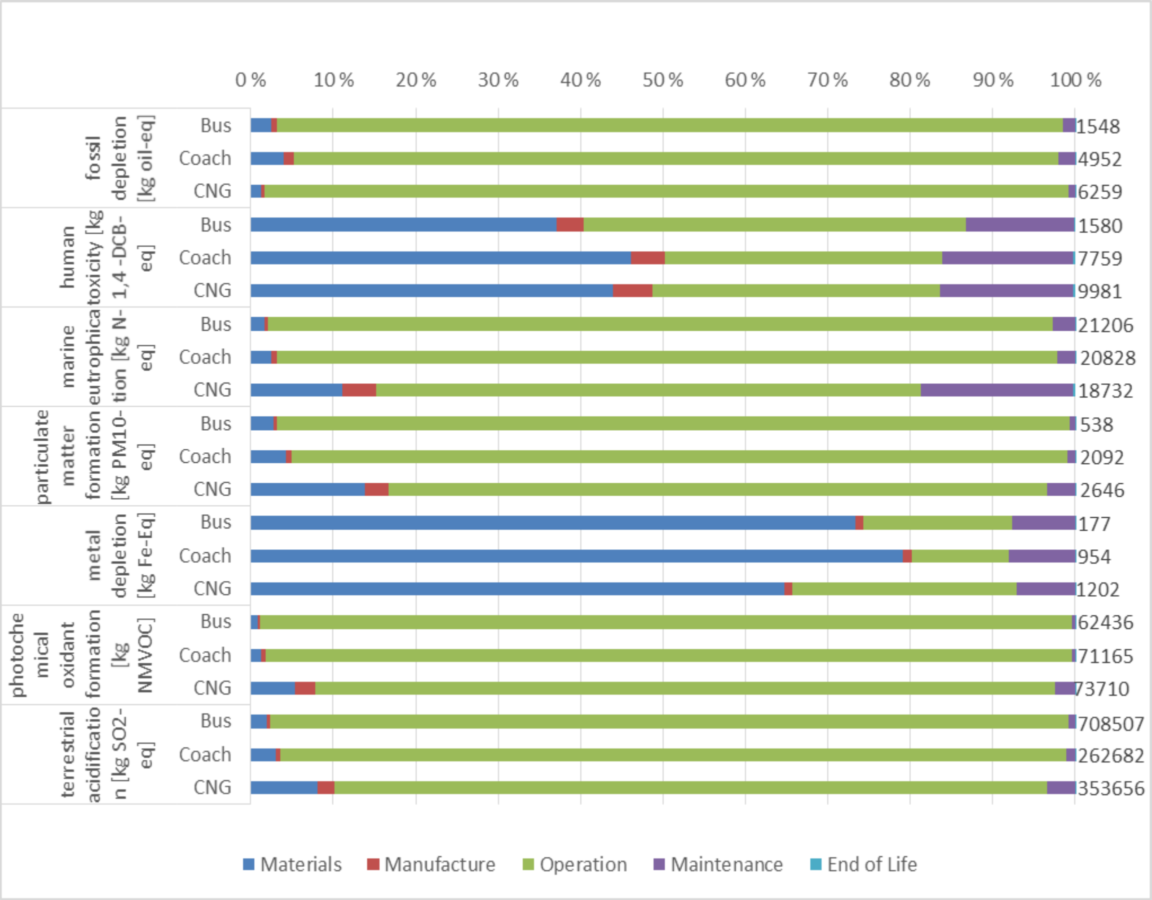


Figure 5 Impact contribution disaggregated, transit vehicles

The impact potentials of the buses across all categories are dominated by the vehicle body and operation phase. The maintenance phase, however, plays a more significant role for the buses, compared to the cars. The vehicle body materials, conversely, account for a smaller percentage of lifetime impact potential.

Fossil depletion impact potential comes largely from bus operation, with 84%, 89% and 94% of the potential coming from operation of the Coach, Diesel bus and CNG bus respectively. For the diesel bus and the coach, both running on diesel, the fossil depletion comes from crude oil extraction at both offshore and onshore locations. For the CNG bus, the fossil depletion stems from natural gas extraction. The fossil depletion impact for the CNG bus is 64% and 49% higher than the impact for the coach and diesel bus, respectively – as the ReCiPe characterization method for fossil depletion impact potential yields higher impact for natural gas, compared to diesel, per energy content.

Human toxicity potential have relatively high contribution from all steps of the vehicles lifetimes. Between 37% and 46% come from material use, whereas Operation accounts for between 34% and 46%. For all of the vehicles lifetimes processes, most of the human toxicity potential is due to spoil from the mining of coal and lignite, used for steam-electric power generation. For the CNG bus, however, 12% of the operation human toxicity potential comes from disposal of uranium tailings as non-radioactive emissions.

Marine eutrophication potential is mostly connected to the vehicles operation phase, accounting for around 94-95% for the diesel bus and coach, and 66% for the CNG bus. The diesel bus and coach respectively have 6.8 and 5.4 times higher marine eutrophication potential than the CNG bus. This is explained by their differing emission profiles: the marine eutrophication potential from bus operation stems from process specific tailpipe emissions of nitrogen oxide and ammonia. Driving the CNG bus emits roughly 140 times less nitrogen oxide and 3.5 times less dinitrogen monoxide than the bus. This is balanced somewhat, however, by increased ammonia emissions: the CNG bus emits 30 times more ammonia than the diesel bus per km. Nitrogen oxide is also an important source of photochemical oxidant formation and terrestrial acidification potential. The diesel vehicles emit several factors more nitrogen oxide than the CNG bus, giving the diesel bus and coach higher impact potentials than the CNG bus.

Particulate matter formation potential comes above all from the vehicle operation phase, where sources of particulates are tailpipe emissions as well as abrasion and wear. While abrasion and wear add to particulate matter formation potential in the form of particulates larger than 2.5 μm, their contribution is largely overshadowed by particulates smaller than 2.5 μm, released as tailpipe exhaust. The three buses have essentially similar wear and abrasion profiles, but the diesel vehicles emit significantly more tailpipe particulates than the CNG bus – giving the CNG bus a drastically lower particulate matter formation impact potential. Chart 7 illustrates the numbers shown in Table 20. It is evident that for many areas of impact, the CNG engine has as low as 15% of the impact of the diesel vehicles.

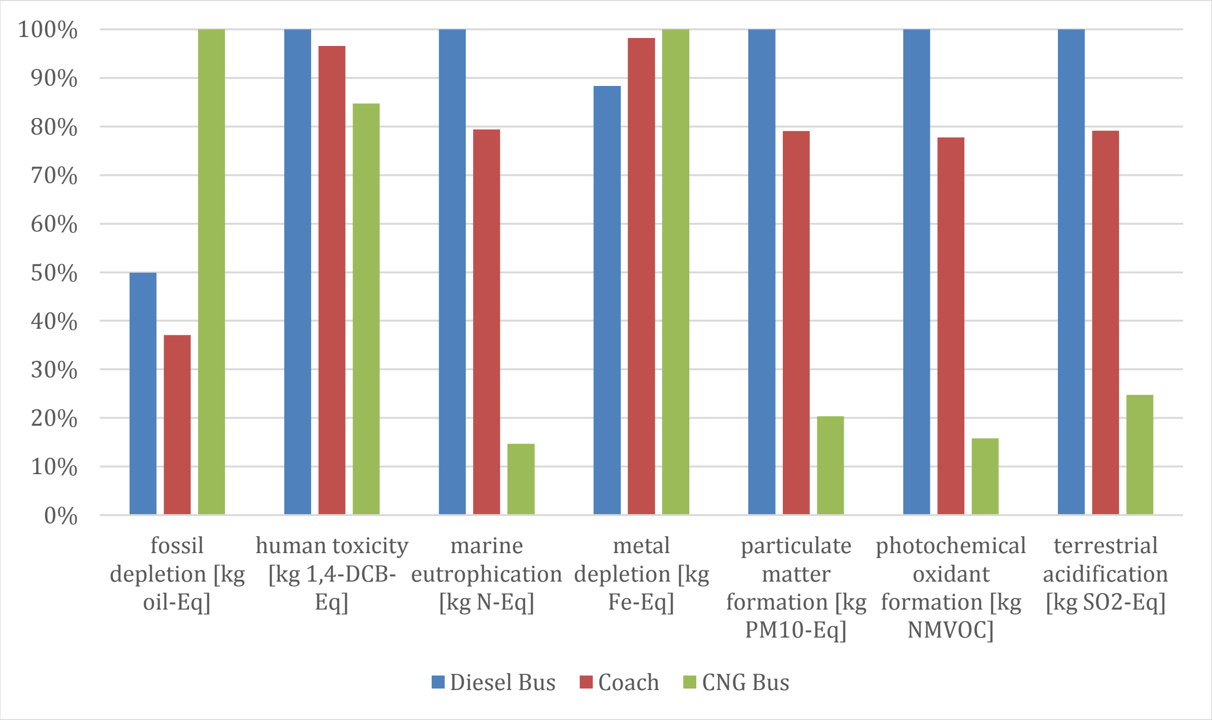


Chart 7 Normalized impact potentials, transit vehicles

4.2.2 Private vehicles

Table 21 shows impact potentials of the different private vehicle technologies, illustrated and disaggregated in Figure 6. Due to the scaling and similarity in material composition of the modelled vehicles, their respective impact distributions within each category are quite similar, as is reflected in the chart.

Table 21 Impact contribution, private vehicles
Assuming a lifetime of 200 000 km

Impact category	SUV	Car	Sub	unit
fossil depletion	18 306	16 098	9 566	kg oil-Eq
human toxicity	10 897	8 260	7 177	kg 1,4-DCB-Eq
marine eutrophication	24	20	14	kg N-Eq
particulate matter formation	75	63	44	kg PM10-Eq
Metal depletion	5378	4241	3850	Kg Fe-Eq
photochemical oxidant formation	169	149	88	kg NMVOC
terrestrial acidification	193	167	114	kg SO^{2}-Eq

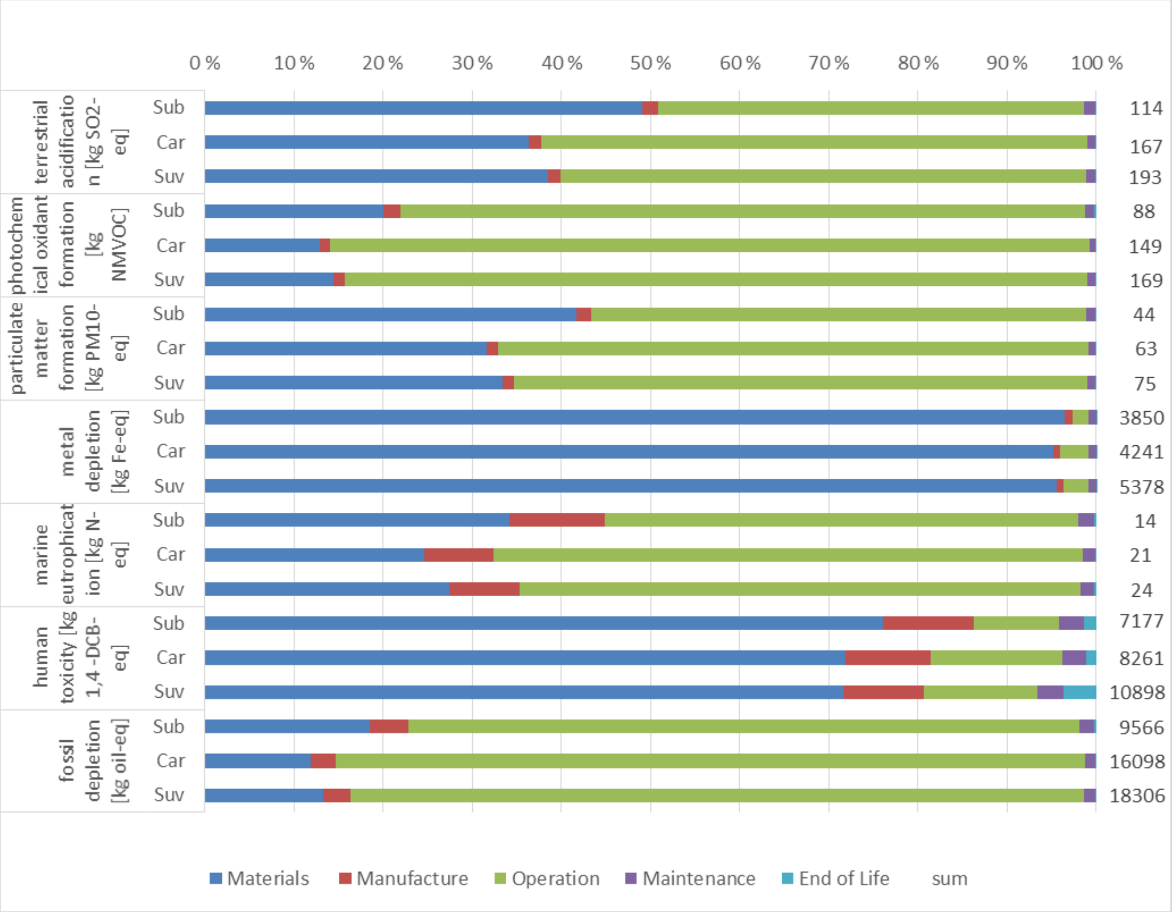


Figure 6 Impact contribution disaggregated, private vehicles

The vehicle body and the operation phase dominate the impact potential, accounting for over 90% of the potential across all the vehicles. The impact potential in all categories are, perhaps unsurprisingly, lowest for the Sub and highest for the SUV. A general noticeable trend across most of the impact potentials is that the impact from the Sub body is higher relative to its total impact potential, compared to the SUV and hatchback. This is because it has a noticeably lower emissions profile for the operational phase, compared to the other vehicles – while the manufacturing phase is more similar. In the same vein: the operational impact of the Car, compared to the SUV, is higher relative to total impact potential, across most of the impact potentials. This is because the SUV is more material intensive than the hatchback, making the body of the SUV account for a higher percentage of its lifetime impact compared to the hatchback. This is despite the fact that the SUV has a more energy demanding driving profile, needing more fuel per km driven.

75% to 85% of the fossil depletion impact potential stems from the operational phase of the vehicle lifetime, from extracting crude oil to be used for fuel production. The fossil depletion associated with the manufacture phase is due to gas, oil and coal extraction necessary for manufacture processes and material fabrication.

The operation phase, including manufacture emissions and materials used for vehicle body, accounts for between 80% and 90% of the human toxicity potential. Around 60% of this potential is due to disposal: disposal of sulfidic tailings as well as spoil from lignite and coal mining release manganese and arsenic into ground water, and mercury into the air.

Between 24% and 34% of the marine eutrophication potential comes from material use, mostly from spoil disposal from lignite and coal mining. Between 7% and 11% of the potential is due to emissions from the manufacturing process – from sewage sent to wastewater treatment. From the operation phase, covering between 53% and 63%, most of the potential comes from nitrogen in the exhaust.

The particulate matter formation impact potential is fairly low for the private vehicles. For the operational phase, covering 55% to 65% of the impact potential, the majority of the potential comes from the burning of fuel, with negligible impact from road and tire abrasion. For the materials used in the car, covering between 31% and 41%, much of the potential comes from palladium and other noble metals, as well as iron substances: iron ore, ferrochromium, ferronickel and sintered iron.

For photochemical oxidant formation, between 12% and 20% comes from body materials, while between 77% and 85% of the impact is from fuel production and consumption. The photochemical oxidant formation potential associated with body materials stem from palladium and other noble metals used in the vehicles catalytic converter and from fuel burned as a step in the manufacturing process: diesel, hard coal, lignite and natural gas.

Between 37% and 50% of the terrestrial ecotoxicity impact is due to materials used in the body of the vehicles. This impact stems mostly from palladium and rhodium used in the vehicles catalytic converter. Operation accounts for between 48% and 62% of terrestrial ecotoxicity, almost entirely from fuel production and consumption.

4.3 Climate change and passenger load

It has been shown that the total climate change potential is significantly higher for the transit vehicles, compared to the private vehicles – on average total greenhouse gas emissions are 20 times higher. Taking only emission numbers into account, it is evident that one private vehicle is more environmentally benign than one transit vehicles.

One important factor to take into account, however, is the seating capacity of the two different vehicle types. The transit vehicles are designed to carry significantly more passengers than the private vehicles. A way to factor the increased passenger capacity of the transit vehicles is to calculate the environmental impact per passenger kilometre travelled. This shows how much climate change potential is associated with the transport of one passenger. Passenger vehicles are primarily designed for human transport, with the end goal of moving humans from one point to another. Climate change per passenger kilometre travelled thus serves as a good standard on which to judge the environmental efficiency of a vehicle.

The average passenger loads of the transit vehicles are 31% for the coach and 20% for the diesel and CNG buses. The private vehicles have a passenger load of approximately 30%, varying with distance. Calculating based on lifetime greenhouse gas emissions, average load factor and lifetime, one can then find the average climate change impact per person kilometre driven – illustrated in **Error! Reference source not found.**. Based on the functional unit of emissions er pkm, the transit vehicles come across as the more environmentally optimal choice. The SUV and Hatchback emit on average approximately twice the amount of greenhouse gases per pkm. Only the Subcompact comes close to matching the pkm emissions of the transit vehicles.

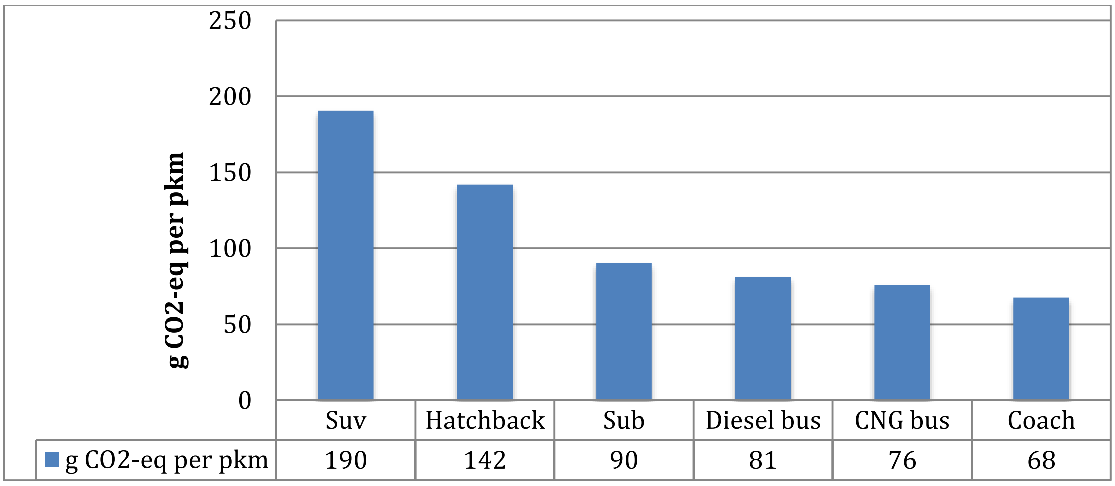
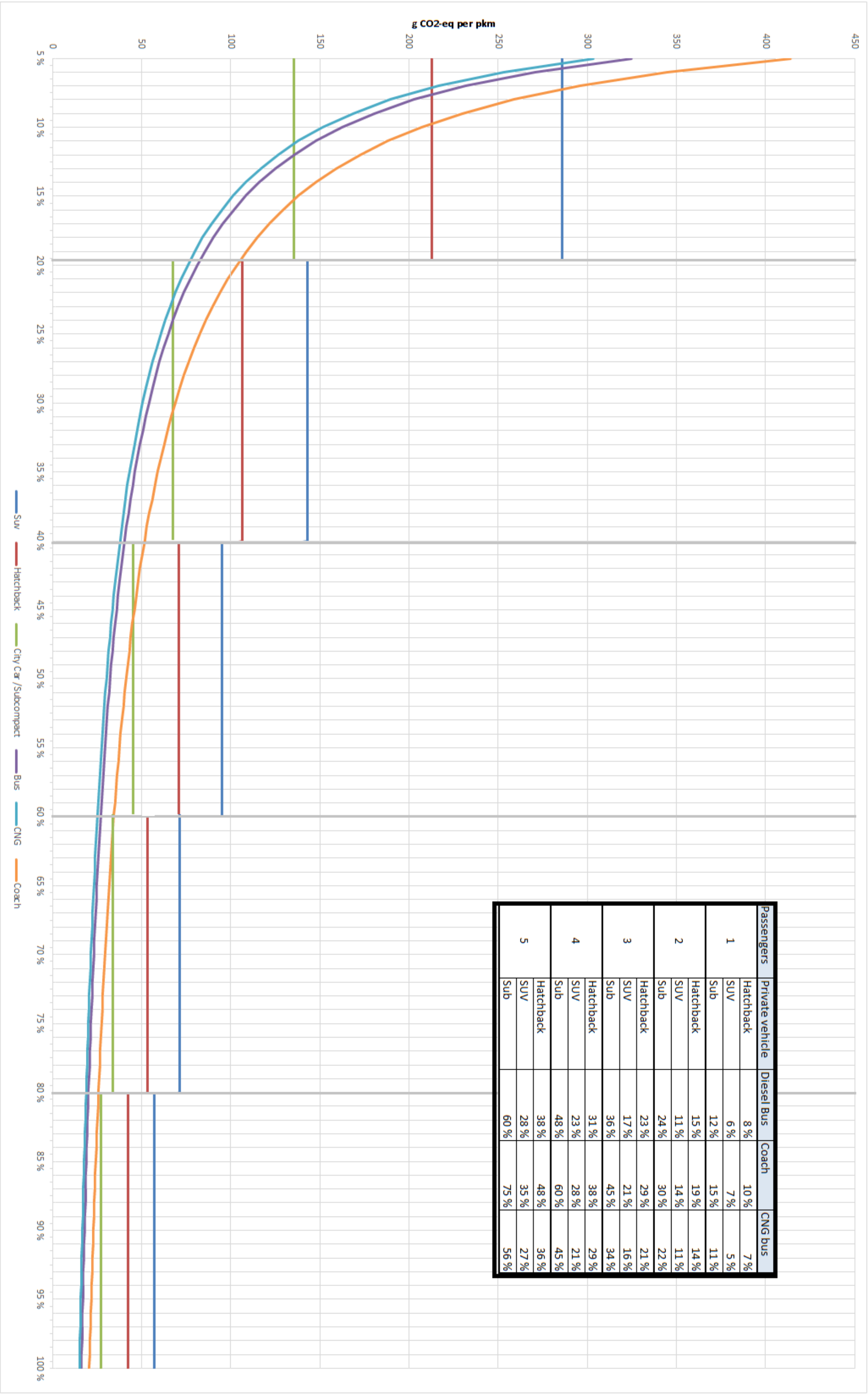


Chart 8 Average CO2-eq per pkm

It should be mentioned that the average load factor is just that – *average*. The amount of passengers a vehicle transports at any given time varies over the day and the year – doubly true for the transit vehicles. The difference in passenger load between the summer season and the winter season can be quite stark: an average winter passenger load of twice or triple that of the summer passenger load is not unheard of (Krokstad, 2013).

The load factor varies during the day, peaking at prime times over the day – typically at the beginning and end of the work day, and the evening at weekends. At these peak passenger times, the bus transit company must consider whether additional service deployment is necessary or not, in order to satisfactorily cover passenger demands.

The emissions per pkm varying as a function of load factor is shown in Figure 7. Transit vehicle passenger load is modeled as a continuous curved graph, due to their high passenger capacity. The private vehicles are represented linear functions with five distinct separate sections, corresponding to one, two, three, four and five passengers at 20, 40, 60, 80 and 100% capacity respectively.



Passengers	Private vehicle	Diesel Bus	Coach	CNG bus
1	Hatchback	8 %	10 %	7 %
	SUV	6 %	7 %	5 %
	Sub	12 %	15 %	11 %
2	Hatchback	15 %	19 %	14 %
	SUV	11 %	14 %	11 %
	Sub	24 %	30 %	22 %
3	Hatchback	23 %	29 %	21 %
	SUV	17 %	21 %	16 %
	Sub	36 %	45 %	34 %
4	Hatchback	31 %	38 %	29 %
	SUV	23 %	28 %	21 %
	Sub	48 %	60 %	45 %
5	Hatchback	38 %	48 %	36 %
	SUV	28 %	35 %	27 %
	Sub	60 %	75 %	56 %

Figure 7 Climate change potential per passenger as a function of load factor

The intersections of the various graphs show emission break even points, where the passenger load and emissions per pkm for the intersecting vehicles are equal. One can see then, at which passenger loads it is more environmentally beneficent to use one form of transport over the other. The diesel and CNG buses have the same capacity and average passenger load, and their lines are therefore close to each other on the figure. The coach function is on average higher, even though total greenhouse gas emissions are lower, because the coach has no capacity for standing passengers.

The table in **Error! Reference source not found.** shows the break even passenger loads of the transit vehicles, compared to the private vehicles. There are 5 distinct horizontal rows, each representing amount of passengers in the personal vehicles. The columns shows break even points for the columns bus. The private vehicles release less greenhouse gases per pkm than the transit vehicles, up until the transit vehicles have passengers equal to or above the break even passenger load.

A diesel bus with a load of 8% (~3 passengers) has approximately the same greenhouse gas emissions per pkm as a hatchback with only one passenger (the driver, presumably). Any passengers beyond 3 in the diesel bus will serve to lower the emissions per pkm, while any fewer will make it emit more emissions per pkm than the hatchback. Similarly, a hatchback with 2 passengers has the same emissions per pkm as a diesel bus with 6 passengers.

The most efficient private vehicle scenario in this case is 5 passengers all sharing a subcompact. The transit vehicles needs to have 23, 19 and 21 passengers for the diesel bus, coach and CNG bus respectively to achieve the same low environmental impact per person kilometre.

According to Statistics Norway, a private car has between 1 and 2 passengers on average. 1 to 2 passengers in the private vehicle corresponds to between 3 and 6 public transport passengers for the hatchback and SUV, and between 4 and 9 passengers for the Subcompact, in regards to greenhouse gas emissions per pkm. The average passenger load for transit vehicles lie between 7 and 8 passengers.

Based on average numbers alone, this shows that from an environmental perspective, a transit vehicle is always more effective than an SUV and hatchback. The Subcompact on the other hand has the capacity to be more efficient than the transit vehicles on average.

It is worth mentioning the effect of total vehicle lifetime with regards to greenhouse gases per pkm. As already established, in the modeled scenario, on average 93% of the greenhouse gases are emitted in the operation phase. Lifetime climate change thus scales close to directly with vehicle lifetime, whereas lifetime passenger kilometres do scale directly 1 to 1 with vehicle lifetime. In the context of emissions per pkm, an increased or decreased lifetime thus has almost negligible impact. Increasing the lifetime of the diesel bus from 750 000 km to 1 000 000 km, decreases average greenhouse gas emissions per pkm from 81 g/pkm to 80 g/pkm, whereas decreasing lifetime to 500 000 km increases average greenhouse gas emissions per pkm to 83 g/pkm. The average greenhouse gas emissions per pkm similarly has a span of 3 g/pkm between longest and shortest lifetime for all the transit vehicles.

5. Discussion

This chapter briefly repeats the thesis objective and addresses the completion of said objective. Key assumptions and limitations will be touched upon, and an internal and external evaluation will be presented. Based on said evaluations, a suggestion for further work will be given.

The objective of this thesis has been to analyze and assess the environmental impact and performance of several different road vehicles, both private and public. Life cycle inventories for six different model vehicles were compiled, and a life cycle assessment was performed. Life cycle impact results were produced, and climate change potential was assessed in context of passenger transport – the primary function of the vehicles.

5.1 Goal completion

An LCA has been performed on three transit public vehicle technologies and three private personal vehicle technologies. The performed LCA has been done based on modeled vehicle inventories, assembled through data from personal calculations, correspondences with AtB Trondheim, the EcoInvent reports and the NTNU Indecol inventories. The environmental impact associated with vehicle manufacture, operation and disposal has been analyzed for each vehicle, and climate change potential has been benchmarked between the vehicles and in coherence with passenger transport per kilometre.

The operation of the vehicles was found to be by and large the most important factor. Contribution analysis showed that for the majority of the impact categories, operation emissions proved to be a dominating force – accounting for 80% and upwards of total potential for many of the categories. For metal depletion and human toxicity, the material intensity proved to be of a more definite significance, but in general the pattern showed clear results: Lifetime impact of diesel and CNG powered vehicles are largely dominated by the operation emissions. In the context of operation, the CNG bus proved to be slightly more efficient than the diesel powered vehicles, in terms of climate change potential per driven kilometre. Driving pattern, however, appeared to have an even more significant impact. The Diesel bus and coach were modelled to drive the same distance, but with different operation profiles. The coach ended up with almost 16% less lifetime emissions. The CNG bus, in comparison, drove with the same operation profile as the diesel bus, but with different fuel – and contributed 6% less to climate change potentials than the diesel bus. This shows the significance of driving profile. AtB Trondheim have calculated that, on average, the distance between two stops in the Trondheim area is around 200 meters. AtB are currently planning and campaigning for infrastructure changes to make the mean distance between stops 400 meters. A change such as this would mean less stops and accelerations on average, making the intercity driving profile less energy demanding.

5.2 Key assumptions and limitations

When performing life cycle analyses, the available data will not always be satisfactory. Data is often gathered from a variety of sources, and some data will sometimes not be available. These factors lead to assumptions being made, further leading to uncertainty.

The open availability of data has been of some issue in this study. While the reviewed literature refer to an Environmental Impact Assessment on the Volvo 8500 bus released in 2004, said assessment has been later removed from public access. Correspondences with Volvo representatives have not proved to be fruitful in terms of getting access to any impact assessment related to any bus. The Volvo 8500 specific data therefore had to be sourced from an independently written report published by Vestlandsforsking in 2010 (Simonsen, 2012). Using ecoinvent data for parts of manufacture, operation and disposal most likely leads to inaccuracies. Ecoinvent calculates with a more mid European energy mix than Scandinavia, where the buses are operated, which can lead to uncertainties.

When scaling the inventories between vehicles, several processes were scaled linearly by weight. This is an efficient way of scaling, but is not necessarily particularly accurate. For the private vehicle inventories, some shortcomings have already been found and documented in other studies (Sundvor 2012). The share of iron and steel is higher than industry given numbers, and similarly lower for aluminum share.

For the evaluation of lifetime scenarios, an assumption was made that operation and maintenance emissions scaled directly and linearly with vehicle lifetime. One could argue that the effectiveness and of a vehicle atrophies over age, giving a non-linear operation and maintenance profile. The assumption of a linear lifetime is most likely a source of inaccuracy. Furthermore, a full decommission was assumed regardless of vehicle lifetime. This might not be a realistic assumption, as not all vehicles are disposed of at the end of their service life – they can be resold or repurposed.

A study by Ellingsen (2011) shows the intensity of greenhouse gases per ton vehicle to be between 4 and 6 ton CO2-eq per ton vehicle. This is in compliance with the intensity found and presented in chapter 4.1.1 Production phase. The CO2 intensity of the buses, however, is quite low – lower than one would suspect. Simonsens (2012) study lists calculated weight and greenhouse gas emissions – giving an emission intensity consistent with the results found in this study. The discrepancy between private vehicle and transit vehicle greenhouse gas emission intensity is substantial, but during this study no data has been found to explain it, thus far.

5.3 Study implications and suggestions

The LCA and study of the several vehicles have shown the environmental effects of the manufacture, operation and disposal of – primarily – two vehicle technologies: diesel and CNG powered vehicles. The operation phase has been identified as the most vital step in the vehicles lifetime, in terms of environmental impact. Thus, in the event that a policy maker would want to address environmental issues associated with transport, the most natural place to start would be the operation phase. The study shows that for many purposes, the use of public transport is more environmentally friendly than private transport, in the context of emissions per person kilometer travelled.

The fact that the transit vehicles prove to be more environmentally efficient than the cars, on average, will perhaps not come as a big surprise. Environmental activists have for several years campaigned for more people to use public transport, lauding it as a more environmentally friendly form of travel. One must keep in mind, however, the passenger load variances from the average. As shown in Figure 7, variance in the transit vehicle passenger load is more volatile than variance in private vehicle load. In the same way that there will be periods of the day when the transit vehicle drives at full capacity, there will be times when the only passenger is the lone driver. These situations, where the bus operates with the driver alone, are highly intensive in terms of emissions per pkm – compared to a scenario where a private passenger vehicle automobilist drives alone. For low passenger counts, the transit vehicles are drastically less environmentally friendly than private vehicles.

In an optimal –and perhaps unrealistic- scenario, transit vehicles would only be in operation when passenger load is assured to be above the break even loads presented in Figure 7. At other times when the average number of passengers on the bus would be low, people in need of transport would employ private vehicles. This policy would most likely both demand an extremely high amount of monitoring and on the fly decision making however, and would also introduce an element of unacceptable unreliability on the bus routes.

In some ways, a less constrictive version of this policy is already in action: public transport is generally not in operation in the middle of the night; a time when average passenger load would be very low. At peak passenger hours more buses are generally deployed than in hours of less activity. This way of covering bus routes is constantly monitored and researched by the bus companies, to ensure both reliability in service and to avoid unnecessary (near-) empty buses. (Krokstad, 2013).

6. Conclusion

This study has found that for most environmental impact categories of interest, the most important factor is vehicle operation. For metal depletion and human toxicity potential, the material intensity of the vehicles were shown to be of significance, but the contribution analysis showed the operation phase to be the biggest factor in terms of stressor emissions.

The LCA showcases the benefits and shortcomings of CNG buses. The operation of the bus releases approximately 20% less CO_2 at the point of operation. Actual greenhouse gas reduction was showed to only be 7% however, due to increased emissions of methane associated with the production of CNG. The reduction in climate change potential for the CNG bus is accompanied by reduced marine eutrophication potential as well as lowered particulate matter and photochemical oxidant formation – and offset by an increase in fossil depletion potential.

The significance of driving patterns was shown by comparing the emissions from the coach and the intercity buses. The coach, driving the same distance as the diesel bus, was shown to emit approximately 16% less greenhouse gases.

The coach proved to emit the least greenhouse gases in total, due to its environmentally efficient driving pattern. When comparing in the context of emissions per person kilometre driven however, the coach was shown to be less efficient than both the diesel and CNG bus at all passenger loads. This is explained by the lack of standing capacity for the coach. Driving mainly on the highway comes with the limitations of only allowing seated passengers.

In terms of greenhouse gas emissions per passenger kilometre travelled, all three bus technologies were shown to be –on average- more environmentally beneficent than both the hatchback and the SUV, and in most cases the Subcompact. Passenger loads were compared and the break-even point were found. On average the transit vehicles were found to a better choice from an environmental point of view, and always a better choice with 23 passengers or more.

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Appendices

Appendix A. Life Cycle Inventory Input Data

Due to the size of the vehicle inventories, they can be found as digital appendices.

Appendix B: Relevant data

Table of fuel use, used for Chart 1 and Chart 2

Vehicle	Fuel use (diesel eq) [kg/km]	Energy use [Mj/km]	Unit
Diesel Bus	0,3	16,08	Mj/km
CNG bus	0,297	13,662	Mj/km
Coach	0,253	11,638	Mj/km
Hatchback	0,05865	2,4242	Mj/km
SUV	0,0527	2,6979	Mj/km
Sub	0,02805	1,2903	Mj/km

Table of total greenhouse gas emissions, used for Figure 4

Climate Change [ton CO2-eq]	Manufacture	Operation	Maintenance	EOL
SUV	9,69	56,53	56,99	57,14
Hatchback	6,63	42,08	42,40	42,58
Sub	6,10	26,61	26,91	27,08
Diesel Bus	34,21	884,62	899,94	901,33
Coach	41,06	742,61	758,98	760,65
CNG Bus	35,23	824,58	840,60	842,34

Table of production phase climate change potential, used for Chart 3

Weight	Vehicle	Materials	Manufacture	Emission intensity
1,25	Hatchback	5,22	1,41	4,18
1,77	SUV	6,70	1,72	3,78
1,15	Sub	4,80	1,29	4,18
10,9	Diesel Bus	27,20	7,01	2,50
13,13	Coach	32,64	8,42	2,49
11,35	CNG Bus	27,24	7,99	2,40

Table of operation phase climate change, used for Chart 4 and Chart 5

	Hatchback	SUV	Sub	Diesel Bus	Coach	CNG Bus
Fuel Production	5,93	10,77	3,33	137,48	99,38	300,03
Fuel Use	29,52	37,34	17,18	712,93	602,18	489,32
Sum	35,45	48,12	20,52	850,40	701,55	789,35

Table of differing lifetime total greenhouse gas emissions, used for Chart 6

	manufacture	**0**	**250**	**500**	**750**	**1000**	**EOL**
Bus 500k	34,21	34,21	345,57	656,93	656,93	656,93	658,32
Bus 750k	34,21	34,21	345,57	656,93	968,29	968,29	969,68
Bus 1000k	34,21	34,21	345,57	656,93	968,29	1279,65	1281,03
Coach 500k	41,06	41,06	307,83	574,60	574,60	574,60	575,99
Coach 750k	41,06	41,06	307,83	574,60	841,37	841,37	843,04
Coach 1000k	41,06	41,06	307,83	574,60	841,37	1108,14	1109,81
CNG 500k	35,23	35,23	327,43	619,62	619,62	619,62	621,01
CNG 750k	35,23	35,23	327,43	619,62	911,82	911,82	913,21
CNG 1000k	35,23	35,23	327,43	619,62	911,82	1204,02	1205,40

Table of impact potentials for private vehicles, used for

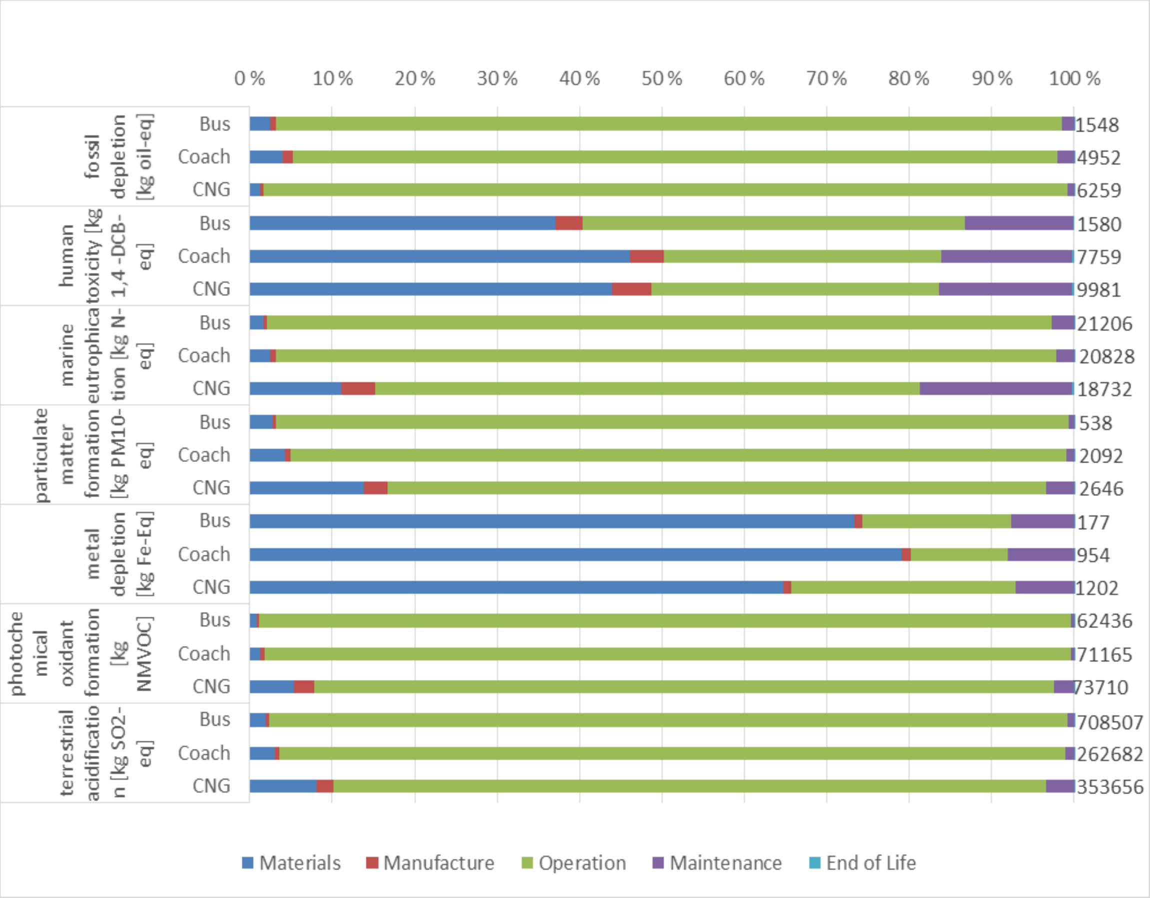

Figure 5

	fossil depletion [kg oil-eq]		
	Bus	Coach	CNG
Materials	8756,34	10507,61	8765,38
Manufacture	2534,30	3041,15	3238,89
Operation	336966,39	243578,56	690839,32
Maintenance	5389,44	5543,84	5651,68
End of Life	9,31	11,22	11,68
Sum	353655,79	262682,39	708506,95
Materials	human toxicity [kg 1,4 -DCB-eq]		
Manufacture	Bus	Coach	CNG
Operation	27371,13	32845,36	27386,72
Maintenance	2434,11	2920,93	3059,19
End of Life	34081,33	23883,98	21726,51
Sum	9679,27	11340,36	10081,89
Materials	144,64	174,24	181,43
Manufacture	73710,48	71164,86	62435,74
Operation	marine eutrophication [kg N-eq]		
Maintenance	Bus	Coach	CNG
End of Life	19,63	23,55	19,65
Sum	5,86	7,03	7,15

Materials	1143,93	902,91	116,74
Manufacture	32,30	20,43	32,72
Operation	0,30	0,37	0,38
Maintenance	1202,02	954,28	176,63
End of Life	particulate matter formation [kg PM10-eq]		
Sum	Bus	Coach	CNG
Materials	74,56	89,48	74,63
Manufacture	10,46	12,55	15,06
Operation	2542,88	1970,09	430,25
Maintenance	17,51	19,52	18,28
End of Life	0,13	0,15	0,16
Sum	2645,54	2091,79	538,39
Materials	metal depletion [kg Fe-Eq]		
Manufacture	Bus	Coach	CNG
Operation	13723,80	16468,56	13726,43
Maintenance	198,46	238,16	207,46
End of Life	3368,28	2434,79	5766,47
Sum	1439,15	1683,60	1502,93
Materials	2,08	2,50	2,61
Manufacture	18731,78	20827,61	21205,90
Operation	photochemical oxidant formation [kg NMVOC]		
Maintenance	Bus	Coach	CNG
End of Life	84,66	101,59	84,75
Sum	28,18	33,82	39,57
Materials	9831,36	7588,26	1417,53
Manufacture	35,93	34,90	37,41
Operation	0,49	0,59	0,62
Maintenance	9980,61	7759,16	1579,87
End of Life	terrestrial acidification [kg SO2-eq]		
Sum	Bus	Coach	CNG
Materials	124,14	148,97	124,29
Manufacture	24,06	28,88	31,65
Operation	6060,72	4718,71	1339,50
Maintenance	50,00	54,95	52,10
End of Life	0,33	0,40	0,42
Sum	6259,26	4951,91	1547,95

Table of impact potentials for private vehicles, used for Figure 6

Impact category	fossil depletion [kg oil-eq]		
	Suv	Hatchback	Sub
Materials	2441,52	1922,99	1769,15
Manufacture	544,91	449,85	413,87
Operation	15057,58	13530,00	7201,45
Maintenance	247,35	174,19	160,25
End of Life	15,09	21,33	21,33
sum	18306,45	16098,37	9566,05
Materials	human toxicity [kg 1,4 -DCB-eq]		
Manufacture	Suv	Hatchback	Sub
Operation	7804,27	5933,76	5459,06
Maintenance	983,73	789,93	726,74
End of Life	1389,33	1218,82	690,82
sum	311,89	219,64	202,07
Materials	408,34	98,36	98,36
Manufacture	10897,56	8260,52	7177,05
Operation	marine eutrophication [kg N-eq]		
Maintenance	Suv	Hatchback	Sub
End of Life	6,58	5,06	4,65
sum	1,90	1,57	1,45
Materials	15,10	13,57	7,22
Manufacture	0,38	0,26	0,24
Operation	0,05	0,04	0,04
Maintenance	24,01	20,50	13,60
End of Life	metal depletion [kg Fe-eq]		
sum	Suv	Hatchback	Sub
Materials	5135,49	4035,28	3712,46
Manufacture	42,31	34,85	32,06
Operation	150,51	135,24	71,99
Maintenance	48,42	34,10	31,37
End of Life	1,65	1,75	1,75
sum	5378,38	4241,23	3849,63
Materials	particulate matter formation [kg PM10-eq]		
Manufacture	Suv	Hatchback	Sub
Operation	25,17	20,10	18,50
Maintenance	0,94	0,78	0,71
End of Life	48,51	42,03	24,59
sum	0,70	0,49	0,45
Materials	0,08	0,06	0,06
Manufacture	75,40	63,47	44,32
Operation	photochemical oxidant formation [kg NMVOC]		
Maintenance	Suv	Hatchback	Sub

End of Life	24,42	19,18	17,64
sum	2,20	1,82	1,68
Materials	140,96	126,66	67,42
Manufacture	1,43	1,00	0,92
Operation	0,27	0,19	0,19
Maintenance	169,28	148,85	87,85
End of Life	terrestrial acidification [kg SO2-eq]		
sum	Suv	Hatchback	Sub
Materials	74,40	60,75	55,89
Manufacture	2,67	2,20	2,03
Operation	113,88	102,33	54,47
Maintenance	2,08	1,46	1,35
End of Life	0,19	0,18	0,18
sum	193,22	166,93	113,91

Table of greenhouse gas emissions by load factor, used for Figure 7

Load Factor	Suv	Hatchback	City Car /Subcompact	Bus	CNG	Coach
1 %	285,7	212,9	135,4	1624,0	1517,7	2028,4
2 %	285,7	212,9	135,4	812,0	758,9	1014,2
3 %	285,7	212,9	135,4	541,3	505,9	676,1
4 %	285,7	212,9	135,4	406,0	379,4	507,1
5 %	285,7	212,9	135,4	324,8	303,5	405,7
6 %	285,7	212,9	135,4	270,7	253,0	338,1
7 %	285,7	212,9	135,4	232,0	216,8	289,8
8 %	285,7	212,9	135,4	203,0	189,7	253,5
9 %	285,7	212,9	135,4	180,4	168,6	225,4
10 %	285,7	212,9	135,4	162,4	151,8	202,8
11 %	285,7	212,9	135,4	147,6	138,0	184,4
12 %	285,7	212,9	135,4	135,3	126,5	169,0
13 %	285,7	212,9	135,4	124,9	116,7	156,0
14 %	285,7	212,9	135,4	116,0	108,4	144,9
15 %	285,7	212,9	135,4	108,3	101,2	135,2
16 %	285,7	212,9	135,4	101,5	94,9	126,8
17 %	285,7	212,9	135,4	95,5	89,3	119,3
18 %	285,7	212,9	135,4	90,2	84,3	112,7
19 %	285,7	212,9	135,4	85,5	79,9	106,8
20 %	285,7	212,9	135,4	81,2	75,9	101,4
21 %	142,9	106,4	67,7	77,3	72,3	96,6
22 %	142,9	106,4	67,7	73,8	69,0	92,2
23 %	142,9	106,4	67,7	70,6	66,0	88,2
24 %	142,9	106,4	67,7	67,7	63,2	84,5
25 %	142,9	106,4	67,7	65,0	60,7	81,1
26 %	142,9	106,4	67,7	62,5	58,4	78,0

27 %	142,9	106,4	67,7	60,1	56,2	75,1
28 %	142,9	106,4	67,7	58,0	54,2	72,4
29 %	142,9	106,4	67,7	56,0	52,3	69,9
30 %	142,9	106,4	67,7	54,1	50,6	67,6
31 %	142,9	106,4	67,7	52,4	49,0	65,4
32 %	142,9	106,4	67,7	50,8	47,4	63,4
33 %	142,9	106,4	67,7	49,2	46,0	61,5
34 %	142,9	106,4	67,7	47,8	44,6	59,7
35 %	142,9	106,4	67,7	46,4	43,4	58,0
36 %	142,9	106,4	67,7	45,1	42,2	56,3
37 %	142,9	106,4	67,7	43,9	41,0	54,8
38 %	142,9	106,4	67,7	42,7	39,9	53,4
39 %	142,9	106,4	67,7	41,6	38,9	52,0
40 %	142,9	106,4	67,7	40,6	37,9	50,7
41 %	95,2	71,0	45,1	39,6	37,0	49,5
42 %	95,2	71,0	45,1	38,7	36,1	48,3
43 %	95,2	71,0	45,1	37,8	35,3	47,2
44 %	95,2	71,0	45,1	36,9	34,5	46,1
45 %	95,2	71,0	45,1	36,1	33,7	45,1
46 %	95,2	71,0	45,1	35,3	33,0	44,1
47 %	95,2	71,0	45,1	34,6	32,3	43,2
48 %	95,2	71,0	45,1	33,8	31,6	42,3
49 %	95,2	71,0	45,1	33,1	31,0	41,4
50 %	95,2	71,0	45,1	32,5	30,4	40,6
51 %	95,2	71,0	45,1	31,8	29,8	39,8
52 %	95,2	71,0	45,1	31,2	29,2	39,0
53 %	95,2	71,0	45,1	30,6	28,6	38,3
54 %	95,2	71,0	45,1	30,1	28,1	37,6
55 %	95,2	71,0	45,1	29,5	27,6	36,9
56 %	95,2	71,0	45,1	29,0	27,1	36,2
57 %	95,2	71,0	45,1	28,5	26,6	35,6
58 %	95,2	71,0	45,1	28,0	26,2	35,0
59 %	95,2	71,0	45,1	27,5	25,7	34,4
60 %	95,2	71,0	45,1	27,1	25,3	33,8
61 %	71,4	53,2	33,9	26,6	24,9	33,3
62 %	71,4	53,2	33,9	26,2	24,5	32,7
63 %	71,4	53,2	33,9	25,8	24,1	32,2
64 %	71,4	53,2	33,9	25,4	23,7	31,7
65 %	71,4	53,2	33,9	25,0	23,3	31,2
66 %	71,4	53,2	33,9	24,6	23,0	30,7
67 %	71,4	53,2	33,9	24,2	22,7	30,3
68 %	71,4	53,2	33,9	23,9	22,3	29,8
69 %	71,4	53,2	33,9	23,5	22,0	29,4
70 %	71,4	53,2	33,9	23,2	21,7	29,0
71 %	71,4	53,2	33,9	22,9	21,4	28,6
72 %	71,4	53,2	33,9	22,6	21,1	28,2

73 %	71,4	53,2	33,9	22,2	20,8	27,8
74 %	71,4	53,2	33,9	21,9	20,5	27,4
75 %	71,4	53,2	33,9	21,7	20,2	27,0
76 %	71,4	53,2	33,9	21,4	20,0	26,7
77 %	71,4	53,2	33,9	21,1	19,7	26,3
78 %	71,4	53,2	33,9	20,8	19,5	26,0
79 %	71,4	53,2	33,9	20,6	19,2	25,7
80 %	71,4	53,2	33,9	20,3	19,0	25,4
81 %	57,1	42,6	27,1	20,0	18,7	25,0
82 %	57,1	42,6	27,1	19,8	18,5	24,7
83 %	57,1	42,6	27,1	19,6	18,3	24,4
84 %	57,1	42,6	27,1	19,3	18,1	24,1
85 %	57,1	42,6	27,1	19,1	17,9	23,9
86 %	57,1	42,6	27,1	18,9	17,6	23,6
87 %	57,1	42,6	27,1	18,7	17,4	23,3
88 %	57,1	42,6	27,1	18,5	17,2	23,0
89 %	57,1	42,6	27,1	18,2	17,1	22,8
90 %	57,1	42,6	27,1	18,0	16,9	22,5
91 %	57,1	42,6	27,1	17,8	16,7	22,3
92 %	57,1	42,6	27,1	17,7	16,5	22,0
93 %	57,1	42,6	27,1	17,5	16,3	21,8
94 %	57,1	42,6	27,1	17,3	16,1	21,6
95 %	57,1	42,6	27,1	17,1	16,0	21,4
96 %	57,1	42,6	27,1	16,9	15,8	21,1
97 %	57,1	42,6	27,1	16,7	15,6	20,9
98 %	57,1	42,6	27,1	16,6	15,5	20,7
99 %	57,1	42,6	27,1	16,4	15,3	20,5
100 %	57,1	42,6	27,1	16,2	15,2	20,3