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Carbon dioxide abatement options for heavy-duty vehicles and future vehicle fleet scenarios for Finland, Sweden and Norway

Thesis submitted for approval of the degree of Master of Science in Technology.

Espoo 26.11.2017
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Abstract of master's thesis

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Abstract

Road transport is responsible for a significant share of the global GHG emissions. In order to address the increasing trend of road vehicle emissions, due to its heavy reliance on oil, Nordic countries have set ambitious goals and policies for the reduction of road transport GHG emissions. Despite the fact that the latest developments in the passenger car segment are leading towards the progressive electrification of the fleet, the decarbonization of heavy-duty vehicle segment presents significant challenges that are yet to be overcome. This study focuses, on the first part, on the regulatory framework of fuel economy standards of road vehicles, highlighting the absence of a European regulation on fuel efficiency for the heavy-duty sector. Energy efficiency technologies can be grouped mainly in vehicle technologies, driveline and powertrain technologies, and alternative fuels. The fuel efficiency of HDVs can be positively improved at different vehicle levels, but the technology benefit and its economic feasibility are heavily dependent on the vehicle type and the operational cycle considered. The electrification pathway has the potential of reducing the carbon emission to a great extent, but the current battery technologies have proven to be not cost efficient for the heavy vehicles, because of the high purchase price and the low range, related to the battery cost and inferior energy density compared to conventional liquid fuels.

A scenario development model has been created in order to estimate and quantify the impact of future developments and emission reduction measures in Finland, Sweden and Norway for the timeframe 2016-2050, with a focus on 2030 results. Two scenarios concerning the powertrain developments of heavy-duty vehicles and buses have been created, a conservative scenario and electric scenario, as well as vehicle efficiency improvements and fuel consumption scenarios. Additional sets of parameters have been estimated as input for the model, such as national transport need and load assumptions. The results highlight the challenges of achieving the national GHG emission reduction targets with the current measures in all three countries. The slow fleet renewal rates and the high forecasted increase of transport need limit the benefits of alternative and more efficient powertrains introduced in the fleet by new vehicles. The heavy-duty transport is expected to maintain its heavy reliance on diesel fuel and hinder the improvements of the light-duty segments. A holistic approach is needed to reduce the GHG emissions from road transport, including more efficient powertrains, higher biofuel shares and progressive electrification.

Keywords road transport, GHG emissions, heavy-duty vehicles, buses, vehicle efficiency, scenario development

Preface

This Master Thesis is the result of a project involving Aalto University and St1 Nordic Oy. The project consisted in the creation of an Excel model for the scenario development of the future road vehicle fleet, fuel consumption and carbon emissions in Finland, Sweden and Norway, and it was accomplished in a team of three students, of which I was part. Due to the complexity of the study, each of us has worked on different aspects of the subject: Eero Kilpeläinen was in charge of the creation of the model structure, Mathias Westerholm has carried out the analysis on light-duty vehicles and fuels, while I investigated the heavy-duty vehicles and buses segments. Three Master Theses have been developed from this six-month project, and, to have a complete overview of the work carried out, it would be necessary to go through all of them, because of their obvious complementarity.

First of all, I would like to thank Mika Aho, Director of Public Affairs at St1 Nordic Oy and my thesis advisor, Professor Martti Larmi and Professor Kari Tammi, my thesis supervisor at Aalto University, without whom this project would not have been possible. A particular thanks to all the colleagues at St1, that provided us guidance and support. Being part, even for just six months, of your company has really helped my professional and human growth. At the same time, I would like to thank Shahid Hussain Siyal, my supervisor at KTH in Stockholm.

Moreover, I am very glad and proud of having had such amazing teammates, and I would like to thank them for the great teamwork and support that showed towards me: I am sure I could not have hoped for better colleagues, and friends. Also, to all the friends I made during these two years in Finland and Sweden: thank you, it has been an incredible adventure.

Last, but not least, I would like to express all my gratitude to my family and my girlfriend, that have supported me with all means during this period. I will never forget, for the rest of my life, what you have done for me.

Matteo Giacosa

Espoo, 26.11.2017

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Abbreviations

AMT	Automated manual transmission
BEV	Battery-electric vehicle
C/LNG	Compressed/liquefied natural gas
CH_4	Methane
CO	Carbon monoxide
CO_2(-eq)	Carbon dioxide (equivalent)
DPF	Diesel particulate filter
EGR	Exhaust gas recirculation
EV	Electric vehicle
FAME	Fatty acid methyl ester
FCV	Fuel cell vehicle
FFV	Flex-fuel vehicle
GCVW	Gross combined vehicle weight
GHG	Greenhouse Gas
GVW	Gross vehicle weight
HBEFA	The Handbook Emission Factors for Road Transport
HC	Hydrocarbons
HDV	Heavy-duty vehicles
HEV	Hybrid electric vehicle
HVO	Hydrotreated vegetable oil
ICE	Internal combustion engine
LCV	Light commercial vehicles
LPG	Liquefied petroleum gas
LRR	Low rolling resistance
N_2O	Nitrogen dioxide
NOx	Nitrogen oxides
OEM	Original Equipment Manufacturer
PC	Passenger cars
PHEV	Plug-in hybrid electric vehicle
PM	Particulate matter
SCR	Selective catalytic reduction
SCR	Selective catalytic reduction
TTW	Tank to wheel
WTT	Well to tank
WTW	Well to wheel

1 Introduction

1.1 Background

The problem of global warming is an important issue that concerns many aspects of our modern and industrialized societies. Greenhouse gas (GHG) emissions from human activities are widely recognized by the scientific community as the main cause of the global warming, and the consequent climate change problems (IPCC, 2014). GHGs include nitrogen dioxide (N2O), methane (CH4), fluorinated gases and carbon dioxide (CO_2), but the latter took up to 76% of the global GHG emissions in 2010, followed by CH4 and N2O, according to the Intergovernmental Panel on Climate Change (IPCC, 2014). Anthropogenic CO_2 emissions from fossil fuels and industrial processes summed up to 65% in 2010 and these are the sectors on which the efforts of the international community have been mostly directed, trying to limit or at least reduce the increase in the global trends. (United Nations Framework Convention on Climate Change, 2014)

From the perspective of the European Union (EU), the total GHG emissions have been decreasing in the last years: between 2010 and 2015 emissions have decreased by 9% (European Environmental Agency, 2016a); this was partly due to the energy efficiency measures, a growing share of renewables in the national energy mixes and the progressive adoption of less carbon-intensive fuels. In most economic sectors emissions decreased (manufacturing, construction, heat production); however, an exception to this decreasing trend is the transport sector: it has been estimated that in the period 1990-2014 the GHG emissions from road transportation have increased by 124 Mtonnes of CO_2-equivalent, with 7 Mtonnes increase just between 2013-2014 (European Environmental Agency, 2016b). In 2014, road transport represented around 19,5% of the total GHG emissions in EU, after the energy supply sector (29,3%); if the emissions coming from the fuel production are considered, this share increases to 22.8% (European Commission, 2014). The International Energy Agency stated that road transport, including passenger and freight, is the primary cause of the carbon emissions in transportation, because of its heavy reliance on oil which, despite many efforts, has not been yet overcome (IEA/OECD, 2015). The decarbonization of road transport presents specific challenges that need to be addressed in the future.

Road freight transport is a key enabler of the economic activity of today’s economies. In the developed countries, while energy use and oil consumption from road passenger vehicles have begun to flatten and decline, fuel consumption of road freight vehicles is increasing, posing a threat to achieving the ambitious GHG emission reduction that EU has set for the future. In fact, EU has always historically been at the forefront of environmental policies even in the sector of road vehicles. Passenger cars and light-duty vehicles are subject to carbon dioxide emission targets. However, fuel efficiency and GHG emissions of HDVs have not been yet addressed with mandatory targets for manufacturers, and this is incompatible with the European target of reducing the GHG total emission of 60% by 2050, compared to 1990 emission levels. In fact, about 25% of the total road GHG emissions in EU is caused by diesel-powered HDVs, and these are outpacing the emissions of passenger cars. HDV share in transport emission is expected to increase to 45% by 2030 under a business-as-usual scenario as stated by (Delgado, et al., 2017).

Within the EU, Nordic countries have always been the most ambitious in GHG emission reduction measures, as demonstrated by the increased adoption of renewable energies in the power sector in the last years. However, the increasing transportation and fossil fuels need affects these countries too, offsetting the efforts of the decarbonization of the power sector.

Finland, Sweden and Norway have then set very ambitious targets on reduction of road transport GHG emissions. Finland aims to reduce road transport emissions by 50% in 2030 compared to 2005 levels (Nylund, et al., 2017), Sweden target is 70% reduction compared to 2010 levels (Nykvist & Suljada, 2017) (Statens Offentliga Utredningar, 2016). Norway has set a reduction of 40% of total GHG emissions by 2030, compared to 1990 levels (Norwegian Ministry of Transport and Communications, 2017). If the reduction is applied directly to road transport the indicative reduction should be of 55%, compared to 2015 levels (Fridstrøm & Østli, 2016). These targets correspond to linear annual reductions of tailpipe emissions between 2016 and 2030 of 5,2%, 7,9% and 5,5% in Finland, Sweden and Norway, respectively. The entity of the reductions can be seen in Figure 1.1. National reduction targets require measures for all road transport segments, promoting alternative powertrains, improvements in vehicle efficiency, and introduction in the fuel mix of less carbon-intensive and sustainable fuels.

1.2 Research problem and objectives

Research is needed for estimating possible future trends and emission reduction options, and measures that can be taken in the road transport sector, for achieving the GHG reduction targets. This means researching and analyzing the technologies that are enabling the decarbonization of the transport sector, quantifying the impact of it in terms of future fuel consumption and GHG emissions. Road transport emissions have since now been addressed with compulsory vehicle emission targets and subsidies promoting more efficient, low emission vehicles and use of biofuels. This trend can be partly seen with the increased adoption of electric vehicles, with Norway leading the way of electrification and Sweden slowly following it, but a holistic perspective is needed to understand the critical challenges of the decarbonization of transport sector. It is then important to understand and quantify how the different characteristics of the vehicle fleet affect the final energy consumption. Transport need, powertrain, efficiency, energy carriers, are some of the most important

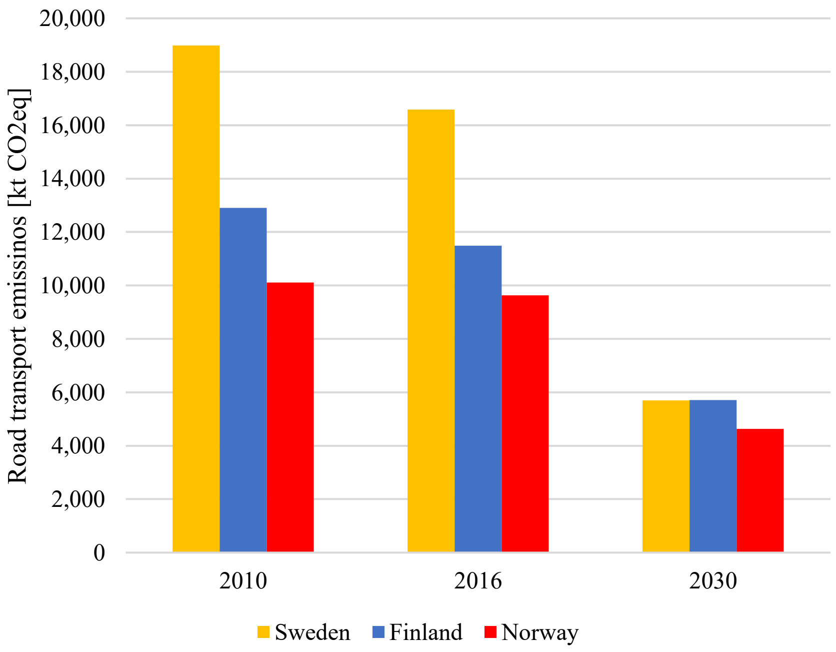


Figure 1.1: National road transport GHG emission reduction targets

features that need to be modeled and related to the final GHG emissions. Moreover, it is important to distinguish between the different segments of vehicles that are composing the road transport sector: to different types of vehicles, corresponds different duty cycles, mileages, and fuel consumption. Future development options are then dependent on the different types of vehicles. The road transport segments and vehicles covered in this work are the heavy-duty vehicles, and in minor part, the buses.

This work aims to focus on these problems in the following way. First, an introduction to the types of vehicles and their characteristics is presented, along with the emission standards that have affected the vehicle developments in the past since now. Then, GHG abatement options are analyzed, focusing on the vehicle, driveline and powertrain technologies, including promising and unconventional technologies that have not reached complete market maturity nowadays, through a review of similar studies in the literature. The last sections concern the creation of a quantitative model able to quantify the aforementioned developments and project into the future the created assumptions used as scenario inputs. The MATERO model has been created with the purpose of evaluating the impact of a change in the current characteristics of the vehicle fleet and quantify the related energy consumption and GHG emission differences caused by that change. Different scenarios about possible developments are created and modeled, establishing different views on how different technologies will develop in the transportation sector and how they will affect the energy markets in the future, basing the assumptions on the previous technological analysis. Results of the comprehensive model are also presented in the last section, along with considerations about the ambitious targets of road transport emission reduction and the feasibility of them related to fleet developments. However, because of the big amount of results that can be obtained and derived from the model, in the results chapter, Swedish case will be examined in more details, along with general consideration on the total energy consumption and emissions in Finland and Norway.

1.3 Scope and methodology

The MATERO model has been created as a part of a joint project to assess the impact on GHG emissions and energy demand of road transport segments under different development scenarios in Finland, Sweden and Norway. In particular, (Kilpeläinen, 2018) focused on the creation of the model structure and mathematical implementation of the modeling work through MS Excel, while (Westerholm, 2017) analyzed the passenger car and light-duty vehicle segments and development scenarios, and fuel consumption. This work focuses on the HDVs and buses segments, as well as efficiency developments. The perspectives of the analysis of the fleet are Finland, Sweden, and Norway, but the European framework will always be used as a benchmark for comparison and general considerations. For the technical development of vehicle efficiencies and non-conventional powertrains, a more general perspective will be considered, provided the fact that vehicle technical improvements affect the whole European market.

As mentioned, road transport includes passenger cars, light commercial vehicles, heavy-duty vehicles and buses. Mopeds and motorcycles are excluded from the analysis, because of the very small impact they have on the GHG emissions from road transport (VTT Technical Research Centre of Finland, 2016). This project leaves out of the scope also the fuel consumption and emissions of the non-road vehicles, such as agricultural machines, snowmobiles, and construction machines that are not allowed to drive on roads. Military vehicles are also excluded, following the IPCC Guidelines (Eggleston, et al., 2006).

The approach of the MATERO model is bottom-up. The model is constructed with a stock-flow-cohort methodology for the estimation of the fleet developments. The national vehicle fleets serve as the starting point of the calculation of the energy consumption. From the total energy consumption associated with each type of powertrain, the total fuel consumption, divided into different energy carriers is calculated. The GHG emissions are then estimated from the carbon intensity of each fuel. Other assumptions, concerning the annual efficiency improvements, transport need and fuels are also estimated as inputs for the model. Since the vehicle fleet used are taken from the national databases of registered vehicles, the modeling work does not take into account the energy consumption and emissions of foreign vehicles, as well as national vehicles operating abroad. Anyway, it can be assumed that the fuel consumption of foreign vehicles is somehow balanced by the consumption of Finnish vehicles driving in other countries. The considered GHG are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF6), according to (IPCC, 2014), but these are always treated as a unique group of emissions. The term “carbon emissions” is also sometimes used as an improper synonym of GHG emissions. Other types of emissions, such as air pollutants (NOx, CO, PM…), are considered as development drivers for the vehicle developments and future regulations, but are not part of the technical analysis and the model results. Moreover, the GHG emission scope covers not only the tailpipe emission (TTW, tank-to-wheel) but also the well-to-tank (WTT) emissions, related to the fuel production. These aspects are covered in (Westerholm, 2017).

The timeframe considered for the future powertrain analysis and scenario development is 2017 to 2050, but the focus will be put on the period until 2030. For the purpose of the model created by (Kilpeläinen, 2018), also historical information between the timeframe of 2012 and 2016 are provided, in order to create a more understandable framework for the scenario creation. Cost analyses are also left out of the scope. However, the results from the modeling work can be used for a further expansion of it, including abatement cost estimations. Moreover, some vehicle developments, especially alternative powertrains, require infrastructure investment to reach market maturity. For the powertrain scenarios, the required infrastructure is not analyzed and left out of the scope of this project.

It is worth noticing that the aim of this study is not creating forecasts, but quantify the impacts of different assumptions through scenario development, since the high uncertainty related to the large number of factors affecting the road transportation.

2 HDV and Buses

2.1 Vehicle classes

Motorized transport can be divided into four main groups: land transport, furtherly divided into road and rail, waterborne transport and air transport. Each of them comprises passenger and freight mode of transport, and the types and driving patterns of the vehicles are changing accordingly to their uses. Road transport is the biggest sector of transportation by the number of vehicles included, and the one that plays the major role in everyday life.

Motorized road vehicles are defined by the United Nations Economic Commission for Europe, Inland Transport Committee, as showed in Table 2.1. These definitions have later been adopted directly by the EU, through the directive 2007/46/EC (United Nations Economic Commission for Europe, 2016) (European Parliament, 2007). The categories presented are the one significant for this work: most detailed categories, that are left out of the scope, are not shown and can be retrieved from the sources.

Table 2.1: Vehicles categories

Category	Definition
L	Motor vehicles with less than four wheels
M	Motor vehicles with at least four wheels designed and used for the carriage of passengers
M1	Vehicles used for the carriage of passengers and comprising no more than eight seats in addition to the driver's seat
M2	Vehicles used for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass[1] not exceeding 5t
M3	Vehicles used for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass exceeding 5t
N	Motor vehicles with at least four wheels and used for the carriage of goods
N1	Vehicles used for the carriage of goods and having a maximum mass not exceeding 3.5t
N2	Vehicles used for the carriage of goods and having a maximum mass exceeding 3.5t but not exceeding 12t
N3	Vehicles used for the carriage of goods and having a maximum mass exceeding 12t
G	Off-road vehicles
O	Trailers and semi-trailers

R, S, T	Agricultural vehicles
Special purpose	Vehicle intended to perform a function which requires special body arrangements and/or equipment

1: when referring to "maximum mass", this means the "gross vehicle weight (GVW)", the maximum laden mass of the vehicle as specified by the manufacturer.

To facilitate the analysis of different powertrains and GHG abatement options, these vehicle definitions can be aggregated considering more intuitive segments.

- Passenger transport:
  - Mopeds and motorcycles: category L;
  - Passenger cars (PC): category M1;
  - Buses: categories M2 and M3;
- Freight transport:
  - Light commercial vehicles (LCV): category N1;
  - Heavy-duty vehicles (HDV): category N1 and N2;

Some vehicles may be regarded as belonging to more than one category according to the different use: this is sometimes the case of N and M vehicles being considered as off-road. Furthermore, HDV segment can include some special purpose vehicles, such as garbage collection trucks or construction vehicles. Other possible division and categorization used in the modeling work are presented in the next chapters.

As previously defined, HDVs are power-driven vehicles, designed and used for the carriage of goods on roads, with a GVW exceeding 3.5t. This segment comprises different types of vehicles, with a broad range of weight classes, in order to satisfy the different need of transport for different situations: from urban delivery to long haul. Moreover, some vehicles are classified as HDV, even if the use is not primarily good transport: for example, this is the case of refuse collection trucks, fire trucks or concrete cement mixers.

2.2 Features

Road transport of goods is performed by a wide range of vehicles that are used in different ways according to the specific need. An optimal vehicle needs to be the right tool for the required task: under or oversizing, or underutilization should be avoided, preventing unnecessary high costs for fuel and maintenance. For this reason, a wide variety of different types of HDV is present in the market. These comprise heavy vans, rigid truck, and tractor units with a GVW of more than 3.5t and are designed to transport goods on roads; however, this definition can be expanded to include some special purpose vehicle, meaning service, urban utility and construction vehicles. Two main types of vehicles are often taken as general examples of an HDV: trucks and tractor units. Trucks can be coupled with trailers or semi-trailers, to increase the load that can be transported; tractor units, also known as road tractors or articulated trucks, are towing units that do not have load capacity themselves; apart from certain occasions, tractor units are designed to be always coupled with a semi-trailer. Trailers and semi-trailers are non-motorized, designed for good transport, and can have different shapes, characteristics and size for the different types of goods that are meant to be transported, or even the different task that must be undertaken (e.g. refrigerated, open body, logging trailers). This is usually the case of tractor units, which can have a broader spectrum of uses thanks to the interchangeability of the semi-trailer. As it can be seen from Figure 2.1, semi-trailer differs from trailer mainly from the fact that they do not have a front axle. The weight of the semi-trailer is then supported, in a large proportion, by to the towing tractor unit or by a dolly, a detachable front axle assembly. If the complete possible combinations are then considered, HDV market becomes more complex, with several thousand shapes and sizes of trucks and vehicles, as well as a variety of powertrain configurations.

The conventional HDV has a diesel engine, and road freight transport is the main user of diesel fuel among all energy sector (IEA/OECD, 2017); because of the typical duty cycles, characterized by constant high speeds, the average efficiency of the engine is higher than diesel passenger cars and buses. Gasoline vehicles play a small role, mainly confined in the lighter segments of the HDVs. It is also possible that some diesel engines have been converted into spark-ignition engine to allow the use of alternative fuels, such as natural gas, both compressed or liquefied.

The commercial services covered by HDVs are many, but some common considerations can be drawn. HDVs used for municipal utility and urban delivery services are generally smaller trucks, typically with GVW up to 12-16 tonnes. Urban environments are characterized by low average speeds with frequent stops, accelerations and decelerations: for this reason, the efficiency of the diesel engine, designed for higher constant speeds, is affected negatively by this type of driving. Long-haul freight transportation is, on the other hand, carried out with the bigger HDVs, often truck with trailers and tractor units with semi-trailers. The gross combined vehicle weight of these vehicles is usually dependent on each country's weight limits, ranging from 40 up to more than 60 tonnes, for example in Finland and Sweden. In this case, the driving pattern is characterized by highway constant speeds, where variations of speeds are usually minimized: the efficiency of the diesel engines benefits from this driving cycle. Regional delivery driving cycle has higher average speeds than urban environments, but frequent decelerations are also present, while construction services are usually carried out by specialized HDVs, whose driving pattern vary a lot depending on the type of activity. (IEA/OECD, 2012)

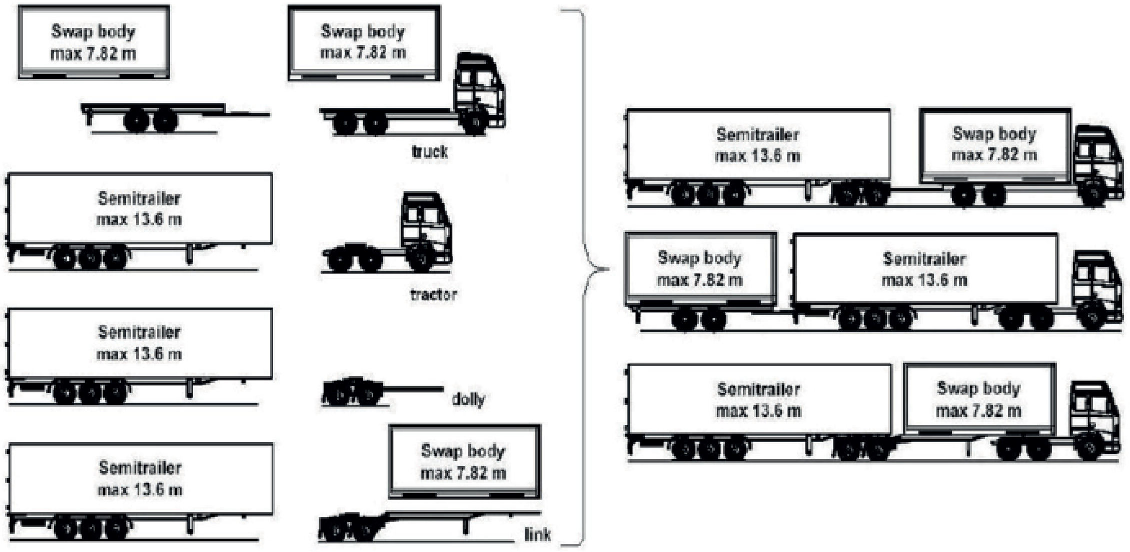


Figure 2.1: Possible combinations for trucks, tractor units and semi-trailer (Bark, et al., 2012)

Buses are vehicles designed for the public transportation of people, and can be divided into two main types: urban buses and coaches. Urban buses have a typical driving cycle with many start and stops, accelerations and very low speeds. Coaches are also buses but designed for longer extra-urban trips, where vehicle speeds are higher and more constant. Diesel powertrain also dominates the buses segment. However, other types of powertrains are seeing a faster development than in the HDV segments: CNG buses are more and more common in cities due to their limited air pollutant emissions and electrified citybus fleets are being planned in the framework of a sustainable urban transportation.

As it can be seen from Figure 2.2, the historical measured fuel consumption of HDVs has not improved in the last 20 years. Even if, in the road vehicle fleet of a county, the number of HDV is smaller than the number of passenger vehicle, the fuel consumption is very high due to the mass of the vehicle: a small improvement in the fuel efficiency of an HDV can have a positive and significant impact on the total energy consumption. One of the main reasons for this stagnation in the efficiency of HDVs might have been the stricter emission standards on exhaust gases adopted during the years, that, calling for increasingly strict limits, have hindered and even worsened the development of the vehicle efficiency (Laurikko, et al., 2013). Next chapter presents an overview of the past and current emission standards.

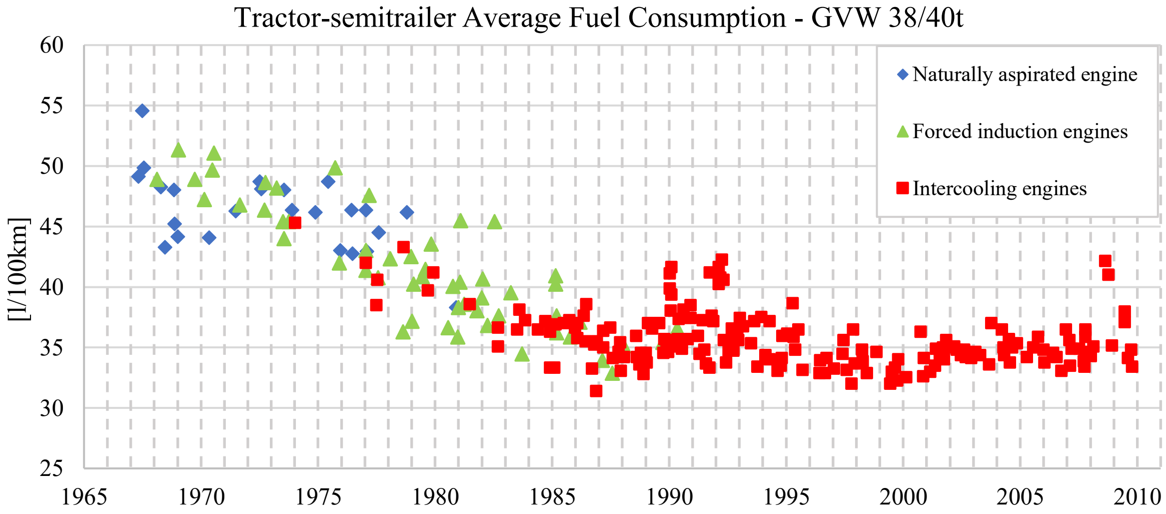


Figure 2.2: Measured fuel consumption of HDV, 1967-2009. Modified from (European Automobile Manufacturers Association, 2010)

3 Emission standards

Since increasing emission standards have influenced the developments and efficiency of HDVs, in this chapter a brief summary of the emission standard is presented, to better understand also what could be the future actions in this sense. Worldwide HDV standards can be divided into two main categories, depending on the type of emission regulated:

- Exhaust emission standards, concerning compounds affecting air pollution standards. These are the most common ones, usually applied to all vehicle segments, and are mostly restricting health hazardous emissions such as CO, HC, NOx, PM.
- GHG emissions or fuel consumption, concerning the CO_2 emissions and the engine efficiency of the vehicle. These standards are currently mostly applied to PC and LCV: currently 80% of global PC sales are covered with fuel economy standards; however, just a few countries, namely Canada, China, Japan and the United States have implemented fuel efficiency regulation also for HDV.

3.1 European HDV exhaust emissions standards

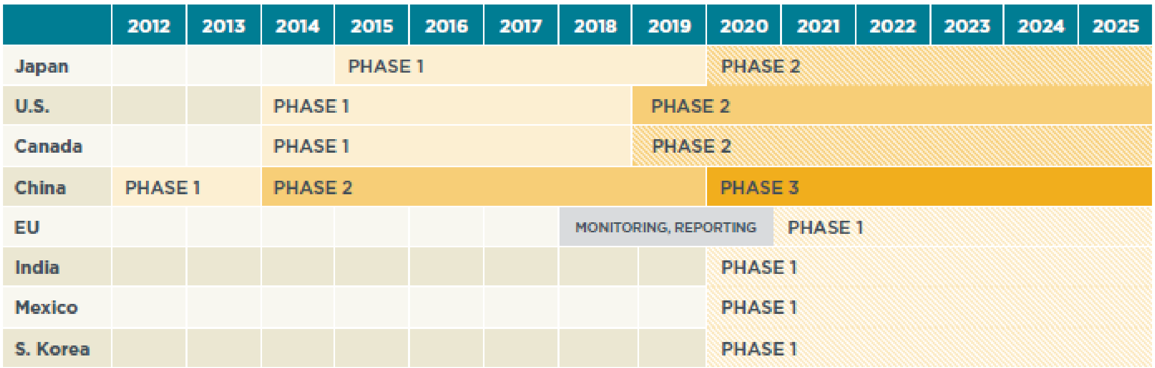
In order to reduce air pollutants from internal combustion engines, EU started to adopt increasingly stringent exhaust emission standards, called Euro classes. Since all the EU member states are subject to this regulation, so are Sweden and Finland, and Norway decided also to implement EU legislation in that matter (Vestreng, 2010). Emission standards for HDVs, including buses, are usually referred to with Roman numbers (Euro I, II…VI), while for PC and LCV with Arabic numbers (Euro 1,2…6). The first standard was introduced for HDV diesel engines with the directive 88/77/EEC in July 1988 for new type-approvals vehicles, and from October 1990 for all newly registered vehicles (European Council, 1987). CO, HC and NO_x were the regulated compounds at that time, while from later standards also PM, PN, NH3 and smoke limits have also been introduced. The Euro standards are divided into two parts referring to two different types of test cycles, stationary and transient. The different emission standards are shown in Table 3.1, along with the reference directive, introduction date (for the new type-approval vehicles), the test requirements and the regulated compounds. For urban buses, the standards were voluntary in the first two stages (I and II), while becoming compulsory from Euro III. Also, from Euro III a new stricter voluntary emission level was introduced, the “enhanced environmentally friendly vehicle” (EEV); compared with latest stages, it is an intermediate step between Euro V and VI. Euro III standard also replaced the Euro I and II ECE R49 test requirement with the European Stationary Cycle (ESC) and the European Load Response (ELR, for the smoke opacity), while introducing the European Transient Cycle (ETC). From Euro VI (January 2013) the tests are defined as the World Harmonized Stationary Cycle (WHSC) and the World Harmonized Transient Cycle (WHTC). More specifically, ESC/ELR and ETC were applied to diesel (compression ignition) engines, while ETC to CNG/LNG and LPG (positive ignition) engines. From Euro VI, WHSC and HHTC are applied to compression ignition engines, while WHTC to positive ignition engines (DieselNet, 2016). Euro VI standards appear to require the most important emission reduction efforts of any previous stage. Euro VI sets particularly strict limits on NOx and HC, and introduce a particle number (PN) and ammonia concentration limit too (Williams & Minjares, 2016) (Chambliss & Bandivadekar, 2015). In transient testing, the requirement on methane (CH_4) are just applied to NG engines, while PN is for diesel engines only. From Euro IV, the stringent limits required the vehicles to install Selective Catalytic Reduction (SCR) systems to abate NOx tailpipe emissions, while Diesel Particulate Filters (DPF) are still not being widely deployed thanks to the common practice of tuning the engines for low PM emissions. The SCR reaction, which requires direct injection of urea in the exhaust gases stream, can produce ammonia, hence the limits on ammonia emissions. Real-world NOx emission expectations have not been usually met in the previous stages, but measurements so far have shown that Euro VI HDV engines are complying with the required real-world performances, even in difficult operating conditions. (European Commission, 2009) (DELPHI, 2016)

Since Euro emission standards for HDV do not include carbon emission standards, the fuel economy may have been negatively influenced by the introduction of exhaust emission abatement technologies, and as shown in Figure 2.2, although some other studies assert the opposite. (Nylund, et al., 2007)

3.2 Worldwide fuel economy standards

Along with air pollutants emission standards, some countries have implemented regulation also for GHG emissions of HDVs, to address the problem of increased fuel consumption caused by aftertreatment systems. GHG emission from vehicles can be reduced by implementing standards on the fuel efficiency, commonly measured in unit of fuel per distance traveled (liters/km, liters/100km), or the carbon efficiency (measured in CO_2/km) of the engine, depending on the issuing country. Fuel consumption is directly proportional to the CO_2 emissions of the vehicle, meaning that the amount of consumed fuel can be directly translated into emitted gCO_2 using a multiplying factor, depending on the type of fuel used (Reinhart, 2015). Finnish transport model LIPASTO, for example, uses a factor of 3.205 gCO_2/g diesel fuel. (VTT Technical Research Centre of Finland, 2016)

EU has developed and introduced a CO_2 emissions reduction program for PC and LCV segments, setting engine carbon efficiency limits by 2021 of 95 gCO_2/km and 147 gCO_2/km, respectively. These targets must be met by each manufacturer, depending on the average of the weight of the newly sold vehicles. For a deeper understanding of the EU regulation in that sense, see (Westerholm, 2017). However, EU has not yet introduced GHG standards for HDV and buses, and CO_2 emissions are currently neither reported nor measured. (European Commission, 2016) Currently, few governments around the world have deliberated efficiency policies for HDV. This list is composed of Japan, U.S., Canada and China, and represents around 50% of the new HDV sales. (Sharpe, et al., 2016). Figure 3.1 summarizes the timeline of the adoption of policies in these countries, as well as the projected



	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Japan				PHASE 1					PHASE 2					
U.S.			PHASE 1					PHASE 2						
Canada			PHASE 1					PHASE 2						
China	PHASE 1		PHASE 2						PHASE 3					
EU							MONITORING, REPORTING			PHASE 1				
India									PHASE 1					
Mexico									PHASE 1					
S. Korea									PHASE 1					

Figure 3.1: Implementation timeline of HDV GHG standards (Sharpe, et al., 2016)

implementation date for other countries. This chapter is going to briefly review the policies undertaken in that sense, as a benchmark for future regulations.

3.2.1 Japan

Japan was the first country in 2005 to implement a regulation on new diesel HDV fuel economy, measured in driven km/liters of fuel. The program was established in November 2005 by the Ministry of Economy, Trade and Industry, but due to giving the priority to manufacturers to meet diesel exhaust emissions standards in 2009, the deadline was set in 2015 for fuel economy targets. These are based on the vehicle GVW, applied to each manufacturer, using a "top runner" approach. The top runner method bases the future targets of new vehicles on the most energy efficient vehicle/product available on the market, taking it as a benchmark for calculating the expected improvements. Manufacturers must meet the mandatory standards by the required year, considering the average fuel economy of newly sold vehicles. Even if the penalties for missing the limits are quite minimal, financial incentives are in place for assuring the effectiveness of the regulations, such as progressive taxes on the vehicle weight and engine displacement (promoting lighter vehicles) and additional tax reduction for exceeding the expected limits. (Langer & Khan, 2013) (Ikegami, 2005)

The 2015 targets are applied to commercial vehicles with GVW > 3,5t, including buses with more than 10-passenger capacity. However, just diesel vehicles are considered: gasoline, LPG, NG vehicles are excluded from the regulation. The expected improvements for new 2015 vehicles on average, compared to 2002 best performance are around 12%, meaning:

- For trucks: from 6,32 km/liter to 7,09 km/liter (assuming around 2623 gCO_2/liter of diesel, from 414,6 gCO_2/km to 369,6 gCO_2/km);
- For buses: from 5,62 km/liter to 6,30 km/liter (from 466,3 gCO_2/km to 416,0 gCO_2/km);

The fuel efficiency of a vehicle is calculated through a computer simulation tool based on the engine dynamometer testing. Two different cycles, urban and interurban are performed for the engine test, combined using weighting factors for reflecting the mix of duty cycles in which a vehicle operates, considering half of the maximum allowed payload. However, since standard values are assigned for the driving resistance and chassis size, improvements coming from transmission efficiency, rolling and air resistance, and light-weighting are considered to a limited extent. It is also not clear how the possible hybridization of a vehicle, like regenerative-braking technology, can be captured, since the hybrid vehicles were excluded when determining the top runner in 2002. It appears that the overall impact of the Japanese regulation is focused on conventional diesel engine improvements. (Muncrief, 2013) (ICCT & DieselNet, 2017)

3.2.2 United States

United States were the second country to develop fuel efficiency standards in 2007, conducted jointly by two different agencies: The National Highway Traffic Safety Administration (NHTSA), under the authority of the Energy Independence and Security Act, and the Environmental Protection Agency (EPA), under the program of Clean Air Act. The NHTSA developed the standard on a fuel consumption basis (gallons of fuel/1000 (short-ton-) miles), while the EPA on a GHG emissions basis (gCO_2/(short-ton-) mile).

The Phase I of the regulation was adopted in 2011 and covered certain types of road HDV of model year 2014 to 2018 with GVW ≥ 3.86t (8500 lbs.):

- Tractor units (combination tractors), excluding the trailer and semi-trailer, divided into nine sub-segments based on weight, cab type and roof height;
- Heavy-duty pickups and trucks, to which a "work factor" is applied in order to consider payload, towing possibility and wheel drive;
- Vocational vehicles/trucks, divided into three sub-segments depending on the weight, consistent with engine classifications;

For pickup and vans, the standards are usually on a mile basis, while for vocational vehicles and tractor units, the payload is taken into consideration using a short-ton-mile basis. The payload considered accounts generally for half of the maximum allowed payload, but it depends on the vehicle category. Moreover, for diesel engines of tractor units and vocational trucks, specific engine-based standards should be met, depending on the brake horsepower-hour CO_2 emissions and fuel consumption (Sharpe, et al., 2016) (ICCT & DieselNet, 2017). The GHG emissions and fuel consumption limits are set as a percentage reduction in model year 2017 compared to a 2010 benchmark; the required reductions are depending on the different vehicles categories, but they range from 6% to 23%. Chassis test is not required, the vehicles are measured over different characteristics, like aerodynamic features and tire rolling resistance. The vehicle testing is then conducted by a simulation software, developed by EPA in 2011, called Greenhouse Gas Emission Model (GEM), inputting the previously measured characteristics, using three different test cycles: The Heavy-Duty Diesel Truck Schedule, and two steady-state cycles for different speeds; the final results are weighted over these three cycles results. Manufacturers can fulfill the required limits on the average of sold vehicles within a class. (DELPHI, 2016) (DieselNet, 2016)

Before the implementation of Phase I, California (U.S.) implemented fuel efficiency measures for trucks and tractors longer than 16.15 meters, expecting the gradually but compulsory adoption of fuel-saving technologies, like low rolling resistance tires and trailer aerodynamics features. The measures were decided by the California Air Resources Board, requiring that the vehicles should comply with the U.S. EPA SmartWay certification, or be retrofitted to meet it; a vehicle not meeting the requirements cannot operate on a Californian highway. The gradual adoption of technology is regulated through a minimum fleet conformance threshold, that is applied to vehicle owners, including those operating outside California. All vehicles, including small fleets, must comply with the regulation by the starting of 2017. On June 2015, a new standard (Phase 2) was proposed by EPA and NHTSA, covering vehicle model years 2018 to 2027, and on August 2016 the final rule was published. The structure is similar to Phase 1, but the trailer category is also included now, based on 10 different trailer types (dry, refrigerated…). Engines are still regulated separately, as in Phase 1. The two standards together, considering the timeframe 2014-2027, would bring a fuel consumption reductions of around 9% to 12% for the engines, about 16% to 20% for pickups and trucks, 20% for vocational vehicles and up to 30% for tractor units, compared to 2010 levels. Phase 2 also introduced new weighting factors for the steady cycle tests, following the trends towards engine downspeeding, and GEM was updated to better estimate real-world emissions of the more efficient technologies. Also, adoption of improved efficiency technology requirements for the HDV fleet are implemented, as in the Californian SmartWay program. However, when Phase 2 was proposed at a federal level, California noted that the standards were not sufficient enough to achieve a significant GHG emissions reduction, in line with the State reduction goals. So, the California Air Resource Board started the development of a California Phase 2 standards program, with more stringent regulations and expecting further reduction compared with the federal Phase 2. End 2017 is the period on which these new standards are expected to be proposed. (Sharpe, et al., 2013) (Santos & Magtoto, 2017)

3.2.3 China

Chinese Ministry of Industry and Information Technology has first announced its plan to limit the fuel consumption of HDV in 2008; after the testing of different types of vehicles to collect data to estimate the fuel consumption level of the fleet between 2010 and 2011, the Stage I (Industry Standard) standards were adopted at the end of 2011, fully implemented for new vehicles in 2012. At the starting of 2012, the Ministry of Industry and Information Technology required all manufacturers to report fuel consumption data and then, Stage II (National Standard), with more stringent limits, was finalized at the end of 2013, and implemented for all new HDV sales in 2015. (Muncrief, 2013) (Langer & Khan, 2013)

The Stage standards are set on a fuel consumption basis (liters/100km), concerning certain types of gasoline and diesel commercial vehicles with GVW > 3.5t: tractor units, trucks, coaches, dumpers and citybuses. The last two categories were excluded from the first Stage because there were too few data to produce a more comprehensive regulation. Alternative fuel vehicles (NG and electricity) are not regulated, along with specialized vocational vehicles. The limits follow a step function, depending on the GVW and the vehicle type. Stage II lowers the limits, compared with the previous Stage, of around 10.5% to 14.5%, requiring improvements for around 50% of the Chinese production of HDVs. (Zheng, 2013) (Delgado, 2016)

All the base models of each category are tested using the chassis dynamometer testing with the United Nation Worldwide Transient Vehicle Cycle (modified for China driving patterns), considering the maximum allowed payload; variant vehicles can either be tested on a chassis dynamometer or through a computer simulation software. Aerodynamic drag and rolling resistance values are also measured through testing. Vehicles not meeting the standards cannot be produced. Moreover, every vehicle must comply with the standard, and there is not the opportunity for an Original Equipment Manufacturer (OEM) to take advantage of producing more efficient vehicles to “subsidy” less efficient ones. However, since the overall efficiency of the vehicle is considered, hybridization and aerodynamic features are viable solutions for an OEM, as well as improvements in combustion engine improvements. Recently, on April 2016, the Chinese government issued the Stage III for public comment, with the intention of fully implement it for all new vehicles in 2021. New Stage aims at reducing fuel consumption by again around 10-15% compared to Stage II. (Reinhart, 2015) (ICCT & DieselNet, 2017)

3.2.4 Canada

In early 2013, Canada adopted the U.S. Phase 1 standards for HDV GHG emissions for newly registered vehicles and engines, starting from 2014. The same timeframe as U.S. is considered (2014-2018) and almost the same vehicles classes, considering some difference in the registration of vehicles. The expected GHG reductions from vehicles are ranging from 6% to 23% for the model year 2017 vehicle compared to a 2010 baseline, depending on the categories. There is one key difference: Canada Phase 1 is only regulating CO_2 emissions and no fuel consumption limits are expected, even if the two values are strictly related.

Moreover, imported engines from U.S. that are certified to meet U.S. standards do not have to demonstrate the compliance with Canada ones (Canada Gazette, 2012). Canada proposed on March 2017 the new phase of GHG standards, closely aligned to U.S. Phase 2. Canada Phase 2 is expected to be finalized by spring 2018. (Sharpe, 2017a) (Environment and Climate Change Canada, 2017)

3.2.5 EU developments

EU has historically been at the forefront of vehicle emission standards, but despite this leadership, EU does not still have a regulation on the carbon emissions of HDVs. In 2006 the European Commission started to investigate about possible policy options to reduce GHG emissions from this segment, and, in 2009, the developments for a certification protocol for HDV CO_2 emissions started. On May 2017, the Technical Committee of Motor Vehicles approved the draft of the type-approval procedure. This is based on vehicle testing combined with a simulation tool, VECTO (Vehicle Energy Consumption Calculation Tool). The results of the vehicle testing serve as input of the software, that calculates, through different cycles, the fuel consumption. Then, the official final CO_2 emission value assigned to the given HDV is estimated from the carbon content of the selected fuel. (European Automobile Manufacturers Association, 2016) (Nikifors & Fontaras, 2016)

VECTO is still in development phase, but it is expected to become available for stakeholders in 2018. It can measure, calculate, report and monitor simulate fuel consumption and related CO_2 emissions for different types of HDV, configuration and mission profiles. Despite many delays, the Commission has proposed that starting from 1st of January 2019 OEMs should have to simulate and report, through VECTO, fuel consumption and CO_2 emission from new model coming in the EU market. Data will be monitored, gathered, and publicly available in 2020; these will serve as benchmark and support for a further regulation on HDV fuel consumption, possibly coming in 2021. (European Commission, 2017) (Muncrief & Rodríguez, 2017)

Table 3.1: EU emission standards for HDV and buses. Modified from (DieselNet, 2016) and (DELPHI, 2016)

	Directive	Class	Date	Test	CO	HC	NOx	PM	PN	NH3	Smoke
					[g/kWh]				[1/kWh]	[ppm]	[1/m]
Stationary cycle	88/77/EEC	I, ≤85 kW	1992	ECE R49	4.50	1.10	8.00	0.612	-	-	-
	91/542/EEC	I, >85 kW			4.50	1.10	8.00	0.36			
	91/542/EEC	II	1996		4.00	1.10	7.00	0.25	-	-	-
	96/1/EEC		1998		4.00	1.10	7.00	0.15			
	1999/96/EC	III, EEV	1999	ESC and ELR	1.50	0.25	2.00	0.02	-	-	0.15
	2001/27/EC	III	2000		1.50	0.66	5.00	0.10			0.80
	2005/55/EC 2005/78/EC 2006/51/EC	IV	2005		1.50	0.46	3.50	0.02	-	-	0.50
	2006/51/EC 2008/74/EC	V	2008		1.50	0.46	2.00	0.02	-	-	0.50
	(Reg.) EC 595/2009	VI	2013	WHSC	1.50	0.13	0.40	0.01	8.0E+11	10	-

	Directive	Class	Date	Test	CO	NMHC	NOx	PM	CH_4	PN	NH3
					[g/kWh]					[1/kWh]	[ppm]
Transient cycle	1999/96/EC	III, EEV	1999	ETC	3.00	0.40	2.00	0.02	0.65	-	-
	2001/27/EC	III	2000		5.45	0.78	5.00	0.16	1.60		
	2005/55/EC 2005/78/EC 2006/51/EC	IV	2005		4.00	0.55	3.50	0.03	1.10	-	-
	2006/51/EC 2008/74/EC	V	2008		4.00	0.55	2.00	0.03	1.10		-
	(Reg.) EC 595/2009	VI	2013	WHTC	4.00	0.16	0.46	0.01	0.50	6.0E+11	10

4 GHG abatement options

As showed in Figure 2.2, the fuel consumption of HDVs has remained relatively flat for more than 15 years, due to more stringent exhaust emission standards and lack of strong policies directed to increased fuel efficiency. Indeed, specific technologies for effectively abating the fuel consumption are not yet being widely deployed. Technologies are directly and indirectly incentivized by GHG standards, which, if well-designed and implemented, can also quicken the research on new technologies and overcome market inefficiencies and barriers, resulting in an increased adoption speed and market penetration. However, also non-technological improvements can achieve important fuel savings.

There are three fundamental ways to improve the efficiency of a vehicle, thus reducing the fuel demand:

- reducing the energy required to move the vehicle;
- reducing the conversion and transmission losses of the fuel energy delivered the vehicle's drive wheels;
- recovering the energy that is lost during non-tractive vehicle operations, such as braking. (Meszler, et al., 2015).

Usually, efficiency technologies are introduced by OEMs when they present a considerable economic advantage for the fleet owner, which is willing to pay for a more expensive, but enhanced, vehicle if the additional costs are quickly recovered by savings in fuel consumption. Fuel cost represents around 30% of the total running costs of an average HDV, and it has been reported that is generally higher than the personnel employment costs of the drivers (European Automobile Manufacturers Association, 2016). It has been evaluated that the payback time of an improving efficiency technology for an HDV has generally to be not more than 2-3 years, to be considered viable by the purchaser; technologies with estimated higher payback time are generally discarded as the time horizon starts to be too long, even if they offer a large potential for cutting fuel consumption. In this case, stronger regulatory approaches are needed to induce the introduction of more expensive options. Moreover, the typical payback period can range from 6 months, for small fleets owners, to 3 years for larger fleets, considering an average lifetime of the vehicle of 8 to 20 years, depending on the vehicle type (Law, et al., 2011) (Schroten, et al., 2012). However, with the recent developments of GHG standards, aiming towards more severe requirements on HDV fuel economy, and EU goal to set the first regulation in that sense by 2021, there is a potential for an accelerated deployment of efficiency technology in the market in the next years.

Low carbon technologies available nowadays for HDVs can be grouped in three main areas, defining the field of action of each potential improvement:

- Vehicle technologies, affecting the vehicle body and aerodynamics, and the rolling resistance;
- Powertrain technologies, including the engine efficiency, alternative powertrains, transmissions and driveline;
- Alternative fuel vehicles, considering natural gas (compressed and liquefied) and biofuels;

There also some technologies and GHG reduction measures that do not find a specific classification in the main aforementioned categories, and involve driver behavior, logistics and in-use fuel economy.

HDVs are subject to different driving cycles and applications, depending on the type and specific function. This means that the benefits of technology options vary greatly among different vehicle classes. The payback period of one specific fuel-efficient technology can be lower than 3 years for a specific application and thus be considered economically feasible by the buyer; however, for a different type of vehicle, it is possible that the same technology does not bring the same benefit because of the different duty cycle. This is, for example, the case of electric hybridization: it brings consistent advantages in an urban environment, due to the frequent "start-and-stop" driving pattern, while fuel efficiency is not greatly affected in highway operation, which is typical driving of long-haul heavy vehicles. (Baker, et al., 2009)

In this chapter, a brief description of the available efficiency technologies is presented, including deployment barriers and benefits expected by each of them. In Figure 4.1, a summary of the different technology applicability and vehicles segments is shown. It is important to highlight that vehicle technologies (included in "core technologies", in the figure), alternative fuels and ICE engine improvements are equally applicable to all types of commercial vehicles, while the option of electrification (hybridization and EV) has a narrower range of applicability, starting to be economically and technically feasible for lighter segments (Breemersch, 2017). It is also important to note that the benefits deriving from the combination of different technologies are not necessarily additive, but it is reported that only combining vehicle, engine and drivetrain technologies, the fuel economy of current HDVs can be improved by around 30% to 50%, excluding alternative fuels. The mentioned potential is heavily dependent on the type of trucks. (IEA/OECD, 2012) (King, May 2011)

It is worth noticing that, as seen in Figure 4.2, technologies other than electrification, can provide consistent benefits on the fuel consumption and GHG emissions, especially for the

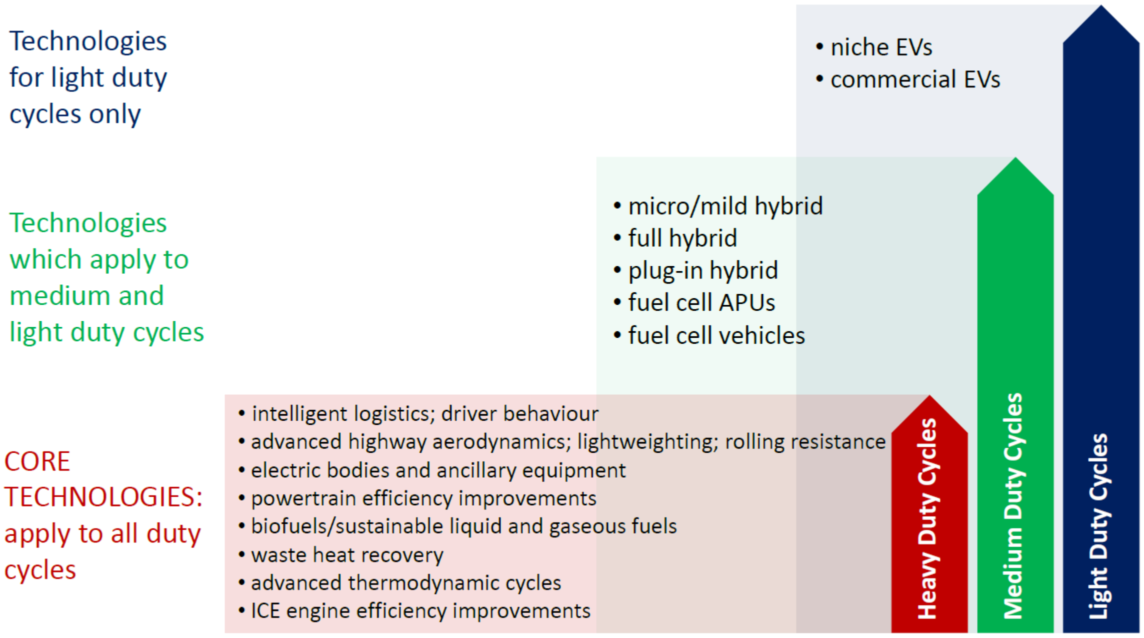


Figure 4.1: Applicability of efficiency technologies (King, May 2011)

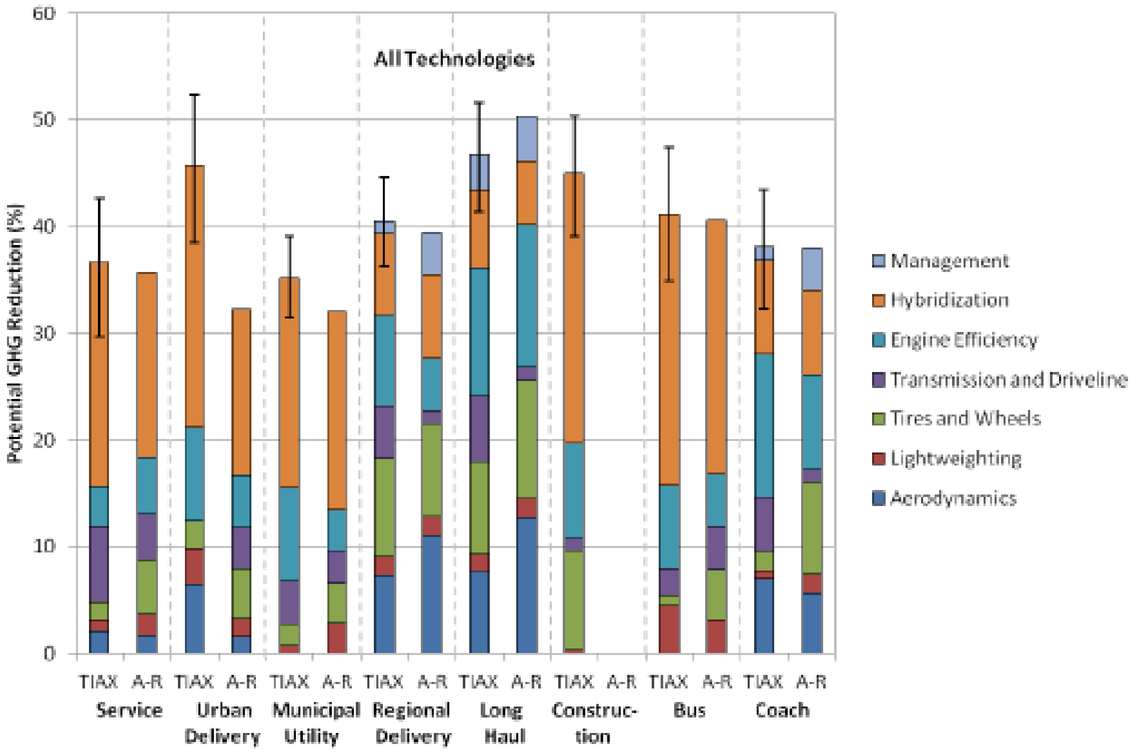


Figure 4.2: Potential GHG reductions from HDV and buses segments by technology, compared TIAX and AEA-Ricardo (A-E) studies. Source: (Law, et al., 2011)

most fuel-intensive class of the HDV segments, the long-haul operations. Since electrification and the challenges related to it are analyzed in (Westerholm, 2017), this analysis will particularly focus on vehicle, driveline and powertrain technologies.

4.1 Energy balance of an HDV

To better understand the proposed technologies for decreasing vehicle GHG emissions, it is important to look at the overall picture of the energy balance in a typical HDV. The flow of energy losses of a typical HDV is shown in Figure 4.3; in this case, a tractor unit with a single semi-trailer attached is considered, with GVW of around 36t, fully loaded, and driving constantly at around 80 km/h per one hour on an ideal highway.

The majority of the losses happen in the engine, because of the conversion losses. Of the total energy inserted in the vehicle as chemical energy of the liquid fuel, just about 42% is converted in mechanical work that moves the system; the rest is lost as heat rejection (thermodynamic losses related to the ICE efficiency), energy escaping from hot exhaust gases, frictions and gas pressure differentials; exhaust gas heat can be partially recovered through turbocharging systems (not shown in figure). Most of the power available at the crankshaft is used to overcome aerodynamic losses and the rolling resistance of the tires; these losses have the same order of magnitude, given the mentioned driving conditions, of about 20% in this example (Delgado & Lutsey, 2015). The auxiliary loads, such as alternators and compressors for pneumatic brakes, and the drivetrain consume both around 3% of the brake power. Aerodynamic losses and rolling resistance represent around 85% of the non-engine losses (Sharpe, et al., 2013).

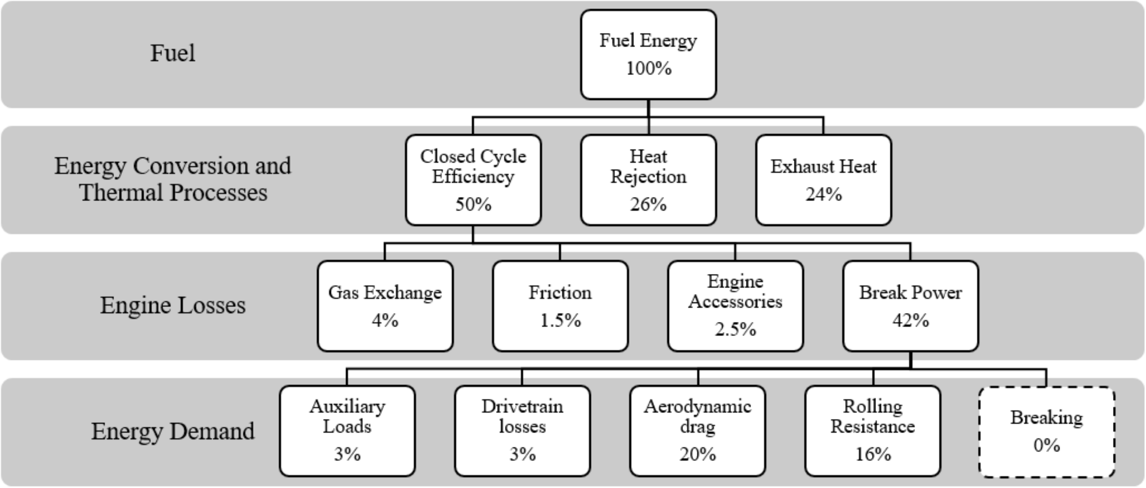


Figure 4.3: Energy balance of a fully loaded tractor unit, on a highway cycle. Modified from (National Academy of Sciences, 2014)

This energy audit balance highlights the possibilities, in terms of energy savings, of a redesign or a particular efficiency technology. The rolling resistance is highly affected by the load carried. When the payload is reduced, the weight on the tires is decreased and so is the rolling resistance, while the aerodynamics losses share increases. Then, for a reduced payload vehicle the aerodynamic losses gain more importance. It has been estimated that a percentage point reduction in aerodynamic drag and rolling resistance brings a half percent and one third percent reduction in fuel consumption, respectively, considering constant highway speed (Davis & Figliozzi, 2013) (Zhao, et al., 2013). A waste heat recovery system would bring significant advantages: if these energy losses can be recovered at a 15% rate, they would cover the energy used by the auxiliaries. (Laurikko, et al., 2013)

The considered HDV is running on a highway at constant speed; this means that no braking phase is expected. In the graph is shown in order to note that if a more transient driving cycle is considered, the braking losses will have a major role in the energy balance. As a general rule, braking and aerodynamic losses follow an opposite trend. It is expected that in an urban environment, where idling and braking phases are very consistent, braking energy consumption can reach a maximum of around 18-20% of total energy input. Meanwhile, since the average speed decreases considerably, aerodynamic losses would decrease to around 5%, since aerodynamic drag is proportional to the square of average speed. The rolling resistance would also be reduced to around 10%. High braking losses mean an increased potential for hybrid systems, which usually include a regenerative braking energy recovery systems, where a battery is recharged through an electric motor used as a generator during braking phase. (Delgado, et al., 2017)

4.2 Vehicle technologies

Vehicle technologies to reduce fuel consumption and increase the efficiency of the HDV focus mostly on reducing the rolling resistance, the aerodynamic drag and the mass of the vehicle. The most common technologies are low rolling resistance tires, aerodynamics streamlined designs and lightweight materials. Low rolling resistance tires and aerodynamics fairings are already available in the market, although the adoption is still limited to some cases. Most of the vehicle technologies do not require specific new vehicle design, allowing their market introduction not only to new models; greater fuel consumption reduction on a vehicle fleet basis can be achieved by applying these technologies directly to older vehicles through retrofitting. Technologies aimed at helping the driver/engine to achieve a more efficient driving pattern (e.g. intelligent vehicle technologies) are also described in this section. (Gao, et al., 2015)

4.2.1 Tire technologies

The rolling resistance is a force in opposite direction of the rolling direction, located at the road level, making the tires less efficient. The dissipation of the energy comes from the inelastic cyclic deformation of the tire, happening during each revolution, and the normal forces at the contact point when rolling on the road. As shown in Figure 4.3, overcoming the rolling resistance takes more than a third of the brake power at highway speeds in a long-haul truck and is a major contributor to the overall fuel use. The rolling resistance is proportional to the vehicle mass and the speed, and is also influenced by the road surface properties: for these reasons, is a complex interaction that involves more than one factor (Leduc, 2009). Since this resistive force is linearly proportional to the weight load on each tire, a constant of proportionality can be defined, the coefficient of rolling resistance C_{rr}, as:

$$C_{rr} = \frac{resistive\ axial\ force}{normal\ force}$$

For each type of tire, a definite C_{rr} can be measured. It is also dependent on the temperature of the tire, the tread wear, the inflation pressure, and the momentary alignment of the tire contact patch compared to the direction of the wheel (slip angle). A truck that is driving in a crosswind situation has generally higher rolling resistance, as well as aerodynamic losses, because of the steering angle and the side pressure. However, since comprehensive data on these mixed interactions are lacking, models and procedures for the estimation of C_{rr} can be quite inaccurate or oversimplified (Sharpe, et al., 2013). All these situational factors need to be considered when comparing in-use vehicle performances (National Academy of Sciences, 2010). Tires values of C_{rr} are dimensionless and range typically from 0,4% to 1% for older and less efficient tires.

Low rolling resistance tires (LRR tires)

The energy losses caused by the rolling resistance occur then both in the tread area and on the sidewalls of the tire; for this reason, it is possible to design tires that have an implicit decreased coefficient of rolling resistance. These improvements can be achieved using different tread materials, such as silica, that are reducing the resistance but maintaining the necessary grip required for the rolling. Also, the tread design can be optimized to reduce the dissipations, along with reinforcements to the side walls to reduce the deformations. In the last years, tire technology has moved towards the direction of reducing the rolling resistance: modern tires have a C_{rr} value of around 0.4-0.5%, but these are not yet widely applied for the lack of regulatory mandates and higher costs for the purchaser. The estimated potential benefits of LRR tires are approximately a 30-35% reduction on the rolling resistance, with can translate into up to 5% fuel savings for long-haul trucks, 3% for coaches and 1% for other applications, if all tires are replaced (Hill, et al., 2011). In general, rolling resistance losses are dominant at low and medium speeds: at higher speeds, the aerodynamic drag starts to be the major loss of energy. Therefore, low rolling resistance tires offer the greatest proportional benefits at low-medium speed ranges (National Academy of Sciences, 2014).

Barriers and disadvantages compared to traditional tires include additional costs and a possible reduced grip which can affect the traction and braking performance of the vehicle. EPA SmartWay program aims to force the introduction of LRR tires, requiring targets values for C_{rr} of trailer tires. European Union also introduced a tire labeling system to display information on the rolling resistance, in order to allow an informed purchasing choice (Delgado, et al., 2017).

Single-wide tires

HDVs, and in particular long-haul vehicles, have typical dual tires on an axle. Additional reductions in rolling resistance can be obtained using single-wide tires, which can be implemented also directly on the LRR tires. These can carry higher loads, the sidewalls are just two (with consequently reduced side flexion compared to four sidewalls), friction with the road and heat dissipation is reduced thanks to the only rim, while the wide base reduces also the rotational inertia. Fuel consumption benefits range according to the application, but estimates give improvements of 10 to 36% on the rolling resistance (Meszler, et al., 2015) and a consequent 5% of fuel economy for long distances vehicles and higher payloads (Reinhart, 2015). The applicability, however, can be quite limited: single-wide tires must be mounted on a special axle end and wheel, and may not be suited for operations that require a wide steering capacity because of the big amount of scrubbing given by the wide contact patch. Urban delivery and construction works may not be suited operations. There can also be national regulations that openly oblige twin wheel on the drive axle for heavier vehicles, for safety reasons; this is the case of United Kingdom, for example (Hill, et al., 2011). There are concerns about the problem that roads, especially the ones with a thin top layer, can be damaged more by the single-wide tires than normal dual tires and uncertainty on the stability during tire failure. Single-wide tires are very sensitive to tire pressure: both over and under inflation cause erosion of the tread and the side walls. A good control of the tire pressure is required to achieve the expected fuel consumption benefits. Supplementary tire pressure monitoring systems are necessary with use of single-wide tires, notably in vehicles with high number of axles. (Leduc, 2009)

Automatic tire pressure adjustment

In general, tire deformation, tread shearing and energy losses are reduced with a higher tire inflation, since the contact patch is smaller; despite this, inflation is limited for by the need of traction and reasonable pavement pressure. In combination with more efficient tires, automatic tire pressure monitoring systems utilize the air compressor on the vehicle to control and adjust the pressure, maintaining it at the correct level for safety and optimized fuel consumption for the specific payload and road conditions. These systems are generally expensive, but if used for vehicles that operate on long distances and different terrains, fuel consumption reductions can be quite reasonable, on the order of 2-4% on average. LRR single-wide tires coupled with automatic tire pressure systems can, in general, be installed to most HDVs, and are proven to be one of the most cost-effective solutions for reducing the fuel consumption. All the benefits combined can consistently reduce the rolling resistance, and decrease the fuel consumption up to 10% for long trucks and tractor units. However, in 2015 just about 11% of tractor units sold in the U.S. were equipped with these technologies. The share decreases to 2% in EU and China, in the same year (Delgado, et al., 2017).

4.2.2 Aerodynamics

Aerodynamic drag is a force that opposes the movement of a body in a fluid, in the case of an HDV of a vehicle that moves through the air. The drag force on a vehicle running on a road can be described mathematically as:

$$F_D = \frac{1}{2}\rho U_\infty^2 A C_D(\psi_\infty)$$

Where F_D is the drag force, ρ is the air density, U_∞ is the relative speed of the vehicle and the air, A is the projected frontal area of the vehicle, ψ_∞ is the yaw angle between the vehicle direction and the air, $C_D(\psi_\infty)$ is the drag coefficient, which is dependent on the yaw angle. It is important to note that:

- Air temperature, barometric pressure and humidity affect the density and thus the drag;
- Wind speed, direction and turbulence are a major contributor to the drag too;
- Since the drag varies with the square of the relative vehicle speed, a doubling on the vehicle speed roughly quadruples the drag;
- The mass of the vehicle does not influence the aerodynamic resistance;
- The physical aerodynamic characteristics of the vehicle are included in the drag coefficient.

Between an urban and highway environment, the drag square-dependency on the speed is what causes a huge disparity in the power consumption of the aerodynamic losses, which are quite minimal at low average speeds. Long-haul HDVs, such as tractor units and trucks with trailer, have big surfaces and run at high average speeds and so are more affected by the aerodynamic drag. The drag coefficient is not only a function of the yaw angle, but also elements of the body of the vehicle have a major influence on it, for example, the cab and trailer design, the trailer configuration, the gap regions and appendages (Patten, et al., 2012). The drag coefficient then sums up the intrinsic aerodynamic performance of the vehicle, and can be improved with consequently direct decrease of aerodynamic drag and fuel consumption. It has been estimated that, at an average speed of 80 km/h, a 20% reduction of the drag coefficient can translate into 10% fuel consumption. With small yaw angles, the majority of the drag is located in the tractor cab (70%), while the rest is due to the body-trailer combination. Despite this, a small increase in the yaw angle can greatly increase the share of the body-trailer part due to the big surface area, quickly exceeding the front tractor. Vehicle design has a large potential for improvement in that sense, allowing also particularly cost-effective possibilities of retrofitting. Beside the fuel consumption improvements, better vehicle aerodynamics increase stability and safety in harsh climate conditions (Patten, et al., 2012). Four major areas of improvements in aerodynamics can be identified: the truck/tractor streamlining, the tractor-trailer gap, the trailer underbody and the trailer tail. Vehicle designers seek to minimize the drag coefficient acting in the mentioned areas and the use of aerodynamic devices has grown steadily in the past years. HDVs manufacturers began to install in new vehicles aerodynamically shaped hoods, bumpers and fuel tank fairings already in the 80s, but many improvements are still possible. Drag coefficients for modern aerodynamically designed trucks with trailer are around 0,6-0,65, while LCVs range from 0,3 to 0,5, measured in the wind tunnel tests; manufacturers usually do not publish C_D values, because a standardized procedure for the testing has not been yet widely adopted (National Academy of Sciences, 2010).

A wide range of aerodynamics fittings is available nowadays. Add-on aerodynamic devices, applied both to the truck/tractor and trailers, are a very cost-effective solution for the reduction of the drag coefficient. Roof fairings with cab extenders help to reduce the air vortices and turbulences that are created in the area between the cab and the frontal part of the trailer, but these are used only infrequently due to small C_D improvements (Law, et al., 2011). Vortex stabilizers, flow tabs and wheel covers have also been developed and tested, but usually present minor improvements. The most common ones are the side skirts and fairings, to improve the underbody dynamics. It has been estimated that side skirts can bring up to 5% fuel consumption improvements for HDVs with high average speeds, making them the most efficient aerodynamic technology. No impacts on safety issues and road pavements are expected. However, average improvements in efficiency are estimated at around 3%. Trailers can also be designed by manufacturers with an improved aerodynamic shape (teardrop shape) or with extensions beyond the trailer length to increase performances and reduce turbulences at the end of the vehicle. Expected benefits can reach up to 10% in terms of fuel consumption, considering high-speed vehicles. It has been also proposed the use of active aerodynamics, which are movable/retractable parts that would activate only when specific speed/wind conditions apply; additional power requirements and maintenance are nonetheless needed for the activation and it is not clear if these are overcome by the benefits. In total, implementing a comprehensive aerodynamic package on an HDV, including skirt, roof and rear fairings, vortex stabilizers and smooth surfaces, can improve the fuel economy by around 10% on long-haul vehicles.

The mentioned aerodynamic improvements can have several barriers that vary with the technology. In general, adds-on increase the vehicle weight, reducing the transportable payload; if these are not placed and installed correctly can also create a fuel penalty instead. Teardrop-shaped trailers, which are generally more expensive, present a decrease in the available volume for the load. The trailer extensions and the side fairings can, depending on the national regulations, make the vehicle exceed the maximum legal length and width, or, if included in the total measures already, result in a loss of load space (Schroten, et al., 2012). In United States, the adoption of aerodynamics measures to reduce fuel consumption has been quite rapid, in particular for the trailer skirts. According to a national survey, 83% of the new trailers deploy side skirts in U.S. (Delgado, et al., 2017). This is due to the recently implemented measures in terms of improving HDV energy efficiency in California under the SmartWay California Air Resource Board program. This specifically requires an aerodynamic HDV improvement, to reduce fuel consumption of around 5%, target mostly efficiently met with the side fairings, creating a widespread market for them. Unfortunately, in 2015 in the EU, only about 10% of the new trailers had side skirts (Delgado, et al., 2017). This is due to the European regulations on the maximum measures of vehicles, which create a barrier for the installation of fairings. Currently, the maximum length of a tractor-trailer combination in the EU is 16,5m, even though recent developments expect that in 2017 an allowance for longer measures for the aerodynamic redesign and adds-on of HDVs would be put into force. Moreover, there is a lack of knowledge and comparative studies on the aerodynamic performances of European HDVs.

4.2.3 Lightweighting

The GHG emissions and the relative fuel consumption of an HDV are directly dependent on the weight of the vehicle. From a physics perspective, the power needed to accelerate and maintaining the vehicle speed, overcoming the rolling resistance, is approximately proportional to the load on each axle. The relationship is linear, in the form of:

$$gCO2/km = a \cdot vehicle\ weight + k$$

Where a is the gradient of the line (measured in $\frac{g\,CO_2}{km \cdot tonne}$) and k is the constant (Hill, et al., 2015). From a high number of observations and testing, it is possible to calculate the two unknown parameters for each time of HDV and duty cycle, to estimate the benefits in terms of fuel savings coming from a reduction of the vehicle weight. For a detailed explanation of the relationship between fuel consumption and weight, see (Westerholm, 2017) and (Kilpeläinen, 2018).

It is possible to use lightweight materials to replace heavy steel parts of the vehicle and obtain a weight reduction without decreasing the transportation possibilities of the HDV. Manufacturers nowadays are commercializing and developing alternative materials, such as aluminum and composites, to reduce the curb weight (weight of vehicle with an empty payload) of the box/trailer of a truck. Costumers have the option of choosing additional lightweight features and packages. Aluminum alloys are already being used in the cab structure and wheels, but can also be adopted for certain powertrain parts and suspensions. Reducing curb weight in weight-restricted application, where the amount of allowed payload is limited by regulations (and based on the GVW), gives the operator the opportunity to increase the transportable load and decreases the fuel use per transportation work. In the last years, there has been an increased but necessary deployment of weight-adding equipment on the vehicle, such as emission control systems, aerodynamic devices, and waste heat recovery systems. The expected benefits can be reduced by the weight increase. Aluminum structures can offset this weight increase (Delgado & Lutsey, 2015) (Hill, et al., 2015). Lightweight materials are applicable to almost all HDV vehicles types, but have higher proportional benefits in bigger and heavier vehicles under frequent stop-and-start cycles, such as construction and utility trucks, where the rolling resistance has a major impact in the energy losses (Meszler, et al., 2015). The actual benefits in terms of fuel consumption vary greatly depending on the vehicle and application, since different weight-fuel consumption linear relationships can be drawn. However, the European Aluminum Association states a 4,2% benefit in vehicle efficiency per tonne of weight saved in weight-limited applications and a 1,7% in volume-limited applications. Also, according to literature, aluminum alloys could save on average around 1% of fuel per tonne of reduced weight (Hill, et al., 2011).

Reasonable reductions of 600-700 kg are possible on an average truck, but the number can reach 2000 kg if also an additional trailer is considered. Under the perspective of a longer timeframe, (Hill, et al., 2015) are expecting the possibility of reducing the curb weight of around 16% by 2030 and 30% by 2050. Drawbacks of lightweight materials are the increased costs, given by the materials itself or by the need of application-specific designs. Aluminum, compared to steel, has a more energy-intensive manufacturing process. Carbon composites are also a possibility, but the material is not as cost-effective as aluminum composites, since prices are very high. (IEA/OECD, 2017) (Sharpe, 2017b)

4.2.4 Driver assistance and intelligent vehicle technologies

Important sources of energy losses in a vehicle are dependent on the driver behavior, meaning that the way an HDV is driven through the road can greatly influence its efficiency and fuel consumption. For this reason, driver training, routes and driving optimization devices, as well as continuous onboard feedback devices that report the fuel consumption performance of the driver, are usually measures expected to be among the most cost-effective ones, with the fastest payback periods, due to the generally low costs and their wide range of applicability among all HDVs. Under a wide perspective, the bigger potential for cutting CO_2 emissions lies within the long-haul segment, but also in an urban environment, these technologies have proven their effectiveness (IEA/OECD, 2017).

Technical efforts are directed towards ensuring that the engine is used at its most efficient point. Intelligent vehicle technologies, or intelligent vehicle systems, are commonly applied for crash avoidance and mitigation, using road-optimized positioning systems to obtain detailed real-time information on the vehicle position, road and traffic situation, as well as the speed and position of the vehicles nearby. Moreover, recently their use has been extended to accordingly modify or provide feedback at the driver on the optimal vehicle speed, route or, in case of hybrid vehicles, power split ratio to increase fuel economy. However, the fuel consumption benefits may not be measured during test condition, due to the specific real-world driving conditions they are deployed. The most common technologies are predictive/adaptive cruise control, speed control systems, and platooning. The expected benefits range from 1% to 20%, depending on the route type, application, familiarity with the driver skills. (Hill, et al., 2011) (Meszler, et al., 2015)

Driver training

Driver training is the base condition for almost any fuel consumption improvements. It is aimed at improving the understanding of safe and fuel-efficient driving. The initial investment is low (big freight fleets are already providing general training for new drivers) and not only GHG emissions can be reduced, but also air pollutants and operational costs. Improved driving skills include minimal speed fluctuation, use of engine braking, optimization of gear selection and timing, trip planning and optimal use of onboard equipment (including cruise control systems, active aerodynamics, tire pressure sensors, fuel economy displays…). Specific driver training can be more effective for high load operations and long haul, since more energy requirements are involved in accelerating, braking and gear shifts. However, also in urban drive cycles benefits can be consistent due to the high number of start and stops and consequent frequent accelerations and braking. The smooth changes in speed and gears could also potentially increase the travel time. Benefits estimates reach up to 10%, but training effectiveness can also fall off time after the first training sessions because of the restoration, in the driver behavior, of non-efficient driving styles. However, nowadays assistance technologies are being introduced, helping the driver maintain a good conduct in term of efficiency. (Skinner, et al., 2010) (Breemersch, 2017)

Driver support systems

Driver support systems encompass different types of technologies, mostly sharing the feature of monitoring and indicating to the driver real-time fuel economy and supporting eco-driving. Green zone indicators are display signals, on tachometer or on a separate meter, that show the driver the optimum range of engine speed for a better fuel efficiency. Speed control systems generally encourage the shift of gears and speed when the engine is above optimum point but below engine rated speed. Top gears are encouraged during long cruises. The rate of acceleration is limited and the driver is then encouraged to upshift. Acceleration control systems can be also deployed in this case, to prevent the full use of the available power reserve when the vehicle is lightly loaded and control the optimal speed as a function of the vehicle mass. Buses manufacturers already offer these systems for lightly loading runs. All types of HDVs can adopt these support systems, and benefits vary greatly according to the driver driving style, road conditions and duty cycles. Combined benefits in terms of

CO_2 emissions can reach up to 10%, with an average of around 5%. Barriers to the applicability include more sources of distraction to the driver, understanding of the system operations and the fact that test cycles do not detect the benefits. Speed and acceleration control systems can cause safety concerns since overtaking and sudden acceleration for safety reason must be detected and allowed. Speed control systems can be part of the adaptive cruise control systems, and can be directly activated by them. (Zhao, et al., 2013) (Sharpe, et al., 2013)

Predictive/adaptive cruise control

Predictive cruise control takes advantage of the already developed onboard GPS technology to determine the exact position of the vehicle and elaborate which driving conditions should be considered for the next 1-2 kilometres, for which the ideal speed and gear are determined. The system can provide the driver the suggestions with real-time monitors, or act itself on the vehicle systems without human intervention. If the considered HDV is almost at end of a steep climb, the systems seek to maintain a higher gear. If a steep climb is immediately followed by a descent, less fuel is injected before reaching the end of the ascent, using the mass to "push" the vehicle over the top. Fuel savings occur for the diminished need to accelerate and time in low gears. Laser/radar sensors mounted on the front of the vehicle detect other vehicles ahead and modify the speed of the HDV accordingly, preventing crashes and optimizing the driving within the desired separation distance. Moreover, the change in the vehicle is speed is also optimized, meaning that the accelerations and decelerations are small and smooth, minimizing the fluctuations of accelerator pedal pressure and sudden braking compared to manual driving. Thanks to the predictive speed controller and predictive gear, fuel consumption and CO_2 emissions can be reduced by up to 5%, especially on routes with many variations of heights. These technologies are already quite deployed in US and UE, with around 45% of the new tractor units sold in 2015 having them equipped. Most benefits are for the long haul, but any truck can be equipped without limiting usage. (Rodriguez, et al., 2017) (Hill, et al., 2011)

Vehicle platooning

Platooning is the practice of trucks driving closely following each other, forming a “road train” of single vehicles. Vehicles drive close at constant speed, reducing air drag (and thereby fuel consumption) and increasing road safety. The vehicles are able to form the platoon thanks to smart vehicle-to-vehicle communication devices and driver support systems: in this way, if the first vehicle of the line reduces its speed by braking, the following ones will act accordingly without any reaction time given by the driver; the same thing happens with accelerations. Having long HDVs running close to each other increases the capacity of the roads for all vehicles too. Platooning is just possible on highways, and at high speeds, when the aerodynamic drag is one of the major losses of energy in the balance. This technology is then more applicable to long-haul freight vehicles (long trucks and tractor units). Fuel consumption benefits range from 5% to 15% at high speeds. The expected benefit decreases with the increase of the gap distance between two vehicles: it has been estimated that with 20 meters gap the improvements correspond to the mentioned 5%, while the 15% happens with a 4 meters gap. Road conditions, congestions profiles and vehicle mission types also influence the improvements (IEA/OECD, 2017). Current barriers lay within the field of autonomous vehicle controls, and it is currently prohibited in some countries, contravening specific road regulations for HDVs. Safety concerns also arise due to the possibility of copycat driving fore vehicles supposed to be outside the line, such as passenger cars. Other problems involve driver perceptions (both vehicles in the platoon itself and external) and attitudes: the driver of the HDV has increased possibilities of distractions while not driving, posing questions for a sudden and unexpected human intervention, while external drivers could feel intimidated by the line of trucks, and having overtaking issues. Moreover, there is an increased responsibility on the driver of the first vehicle. Nevertheless, demonstration programs started in Japan and are also underway in the United States and Europe, and adoption of automation devices will promote its technical feasibility.

The mentioned driver assistance and intelligent vehicle systems are part of the broader process of automation happening in the vehicle sector. Self-driving cars are being tested and it is likely that in the medium term are going to be available on the market. Autonomous trucks are the next steps in the vehicle automation. The highway driving cycle, made of constant speeds and limited braking and curves, can be particularly suited for autonomous long-haul vehicles. Potential benefits of autonomous vehicles in term of efficiency encompass all the above-mentioned technologies, while adding a more efficient utilization of the fleet, minimizing human errors and daytime driving, reducing congestions. Fully automated HDVs are already in use in the mining industry, for example. Difficult dilemmas are posed about, liability, software certifications and safety. (IEA/OECD, 2017) (National Academies of Sciences, Engineering and Medicine, 2017)

4.3 Driveline and powertrain technologies

This field of increased efficiency measures encompasses a broad range of technologies, from automated transmission to electric vehicles. Driveline (including transmission) and powertrain technologies focus on increasing thermal efficiency, engine energy and parasitic losses reduction. Increased efficiency of transmission and driveline mostly reduces frictional losses happening during the transmission of energy, connecting the engine torque to the wheel propulsion, using smart lubrification systems. Some of the driveline technologies are directed towards improved and integrated transmissions-engine operations, enabling the engine to operate for a longer time at high-efficiency conditions. The simplest approach is the matching of the gearing system to the specific application, selecting the optimal top gear and rear axle ratio for the typical cruise speed. For smaller HDVs, more ratios can generally bring a better match between road speed and engine speed.

Engine and powertrain design has many ways to reduce fuel consumption, and some these solutions are already applied to the light-duty segment, for example turbocharging, variable flow pumps, turbocharging and hybridization (IEA/OECD, 2012). Optimized diesel fuel combustion also offers valuable improvements, with high-pressure injection systems and increased compression ratios. Engine efficiency typically improves on a yearly basis incrementally. The recovery of the high enthalpy in the exhaust gases, through bottoming cycles and turbocompounding, is also a high-potential development, especially for vehicles with high annual mileage (Rodriguez, et al., 2017). Waste heat recovery systems are not yet deployed in the HDV segment, but OEMs are actively developing concepts to be implemented in the next years (Breemersch & Akkermans, 2015) (Reinhart, 2015). Hybridization can bring valuable benefits to the fuel consumption, especially for transient operations like urban driving cycle with frequent start and stop activity; these benefits, however, can be quite varied also considering the level of hybridization, ranging from mild to full hybrids. Technical uncertainties about battery life, range and costs are still critical for some applications. (Hill, et al., 2011)

Most of the mentioned technologies, and the ones that are going to be reviewed in this chapter, cannot be retrofitted to existing vehicles in the fleet, due to their complexity and the substantial changes that are involved in the vehicle engine architecture. Costs constitute a significant barrier, even if in latest years there have been considerable advances. In spite of the fact that these technologies are going to be introduced in the new vehicles with an improved design in the next years, limiting their adoption share in the vehicle fleet, fuel consumption benefits are on average very high, especially for alternative powertrains.

4.3.1 Driveline technologies

Losses at driveline level are reduced mitigating the frictions in the transmission, shaft, differential and axles. In-gear efficiency, low-friction lubricants and more efficient systems can reduce mechanical and parasitic losses and provide 2-5% fuel consumption reductions (Delgado & Lutsey, 2015). Vehicle auxiliaries (water and oil pump, fuel injection system, HVAC systems…) are typically gear- or belt-driven, and even if not activated, these systems can lead to parasitic losses increasing with the engine speed. Completely decoupling these systems from the driveline when are not use, through a system of clutches, can improve the overall efficiency of the driveline.

Automated manual transmission (AMT)

AMT technology is essentially a more efficient standard manual transmission, on which additional sensors and actuators are installed, allowing the transmission control module to perform the shifting activity instead of the driver. The transmission is mechanically similar to a standard manual transmission, and for this fact is more efficient than the automatic one, combining the comfort of not having the clutch pedal and manual shifting.

Fuel savings come from the possibility of downspeeding/downsizing the engine (see next chapter), reducing fuel frictions and pumping losses, and the fact that the shift performances (both smoothness and timing) of the actuators match the one of a skilled driver, providing more optimized engine operation compared to an average driver, keeping the engine operation point in its high-efficiency region. With AMT, there is also greater potential for a deep integration of engine and transmission control systems, including microprocessor technology to continuously monitor vehicle speed, acceleration, torque demand and weight and in combination with the engine matching the driving condition with the best operational point. (Hill, et al., 2011) An improvement to the AMT is the dual-clutch transmission, where two separate clutches, one for odd and one for even gears are included, enabling shifts without interruptions, increased smoothness and increased possibilities for downsizing. Benefits replacing the standard manual transmission with AMT can reach up to 10%, and even higher values are reported in applications where frequent gear changes are needed. On average, reported values range from 4 to 6%. Optimized gearing shifts increase the lifetime of the transmission. However, driver training would decrease the effectiveness of ATM, since the driver is already skilled for efficient gear shifting (Law, et al., 2011). Barriers to AMTs are the additional costs and complexity of the system, with additional components that can fail, and the problem of some systems not able to deliver a smooth shift, compared to an automated transmission. Moreover, the best drivers can beat the effectiveness of an AMT. AMTs are applicable to almost any HDV, but highest benefits are delivered over an urban driving cycle. AMTs have gradually gained market share in the last years. In Europe, AMTs are already widely adopted in the HDV market, going from a low 5% in the early 2000s to about 50-70% of new trucks and tractor units respectively, being mounted with it (Rodriguez, et al., 2017). Improved automation and integration developed in parallel with ATMs, allows the engine to activate at the right time, when nor acceleration neither braking power are needed, the freewheel function.

Eco-roll freewheel function

Eco-roll freewheel function, also known as neutral coasting, automatically disengages the driveline from the engine, putting the transmission into neutral, when the vehicle is not required to maintain the vehicle speed. During this operation, the engine is put into idle mode. The driveline and normal operation of the transmission-engine systems are re-engaged when brake or accelerator command is activated by the driver, or when also engine brake is applied. A monitor display signal to the driver the indication of the state of the driveline too. Unnecessary braking losses are minimized, using the large mass of the HDV as a kinetic energy storage system in combination with predictive/adaptive cruise control systems. Predictive cruise control, as mentioned, would reduce the speed during uphill operation, switching to freewheel once reached the downhill driving. Achieved benefits in that way are dependent on the terrain conditions, but manufacturers claim 1-2% CO_2 reductions (Baker, et al., 2009), more relevant for high-mileage highway driving. However, some safety issues can arise from the freewheel, because the driver has not the control over the vehicle during neutral transmission, thus a failsafe mode is required.

The analyzed technologies present opportunities for a deeper integration of the driveline-engine systems, but also underline the fact that the challenge of reducing fuel consumption and GHG emission should be tackled on a whole-vehicle approach, supporting systems communications through the work of the driver. With an idealized engine-transmission integration, the engine operations would be always at the peak efficiency point, achieving fuel reductions up to 5%. (Delgado & Lutsey, 2015)

4.3.2 Powertrain technologies

HDVs are mostly powered by diesel engines, which use high gas temperatures generated by the high compression ratio of the combustion chamber as the ignition. Due to these high compression ratios, the diesel engine is more efficient than the gasoline engine, which requires spark plugs to start the combustion process. However, there are still margins of efficiency improvements in the design of the diesel engine. As well as for driveline technologies, also powertrain technologies focus on the reduction of parasitic losses, caused by water and oil pumps, and air compressors. Increased thermal efficiency solutions are turbocompounding, bottoming cycles, and waste heat recovery systems. Electrical hybridization presents considerable advantages, but alternative types of powertrains, such as fuel cells and fully electric vehicles are still under development phase.

Improved diesel engine

More efficient design of the diesel engine can still achieve major improvements in reducing the fuel consumption and emissions. The combustion process of the fuel generates most of the losses in the engine, reflected in the high temperature of the exhaust gases. Mainly friction losses, piston-to-cylinder interfaces, valve trains and oil churning in bearings affect the engine efficiency. Friction reduction measures would reduce the dissipated energy in the cooling system, increasing the brake power. Low viscosity lubricant, low friction coatings, piston ring and bearing design represent emerging technologies that would increase the efficiency guaranteeing optimal lubrication and durability of the engine. These solutions can reduce fuel consumption up to 2% in long-haul applications.

Optimization of the combustion can also be achieved with high-pressure systems and improved injection (high-pressure injection, better fuel atomization and distribution in the cylinder chamber, timing optimization), higher compression ratios, better design of the combustion chamber, improved insulation systems and coolant. (Hausberger, et al., 2012)

Variable valve actuation, also known as variable valve timing or discrete variable lift, is a technology that has been applied in light-duty applications, and has the potential for being deployed also in the HDV segment. Intake and exhaust valve trains have a major impact on the performance of the engine in term of fuel use through the timing and duration of the lift profile. Valve trains are operated by the camshafts, and a strictly mechanical system operates in the same way at all engine speed and load, resulting in non-optimal operations. The mechanisms that allow the valve to change their behavior are numerous (multiple sets of lobes on the camshaft, eccentric cam drive, multi-air technology…), but usually three parameters are changed: valve timing, duration and lift, allowing the engine control unit to operate the valve trains at the best point for the engine conditions, decreasing fuel consumption and emissions. Nonconventional combustion modes are also facilitated by variable valve timing. Fuel benefits are in the range of 1-2% for bigger HDVs. However, large diesel engines have narrow speed range, higher air flow requirements and complex exhaust gas systems that limit the possibilities of variable valve actuation (Hill, et al., 2011). Advanced engine controls and integration of the engine elements with other vehicle systems, like gas recirculation and after-treatment are part of the design improvements that increase the efficiency of the vehicle on an annual basis; diesel engine efficiency can be improved up to 10-13% on the overall. (IEA/OECD, 2017) (Baker, et al., 2009)

Downsizing and downspeeding

Reducing the power requirements of the vehicle implementing more efficient vehicle technologies may shift the operational points of the engine towards lower efficiency regions. The engine can then be replaced with a downsized one, with lower displacement, peak power and torque, and operating at higher loads, where usually is located the high-efficiency region. Another approach involves adopting a more efficient engine, utilizing the technologies described above, that gives the same torque and power output even having a lower displacement. Downsizing is facilitated by dual-clutch transmission, which reduces the torque losses during the shifts. Moreover, a better performance of the aftertreatment system is expected, since downsized engines have a faster increase of their exhaust temperatures. The benefits depend greatly on the level of downsizing, but average values consider 1 to 5% decrease in fuel consumption. for certain application, however, the torque requirements are quite high, and the drivability of the vehicle might be compromised by a possible downsizing. To maintain the torque, an increased compression ratio or air manifold pressure are required, affecting negatively NOx emissions. (National Academy of Sciences, 2010)

Downspeeding is involved in all technologies that cause to operate the engine at lower speed, significantly decreasing the friction and pumping losses, reducing fuel consumption by reducing the friction in the vehicle, especially for low ranges of speeds. Frictional losses in the engine increase with the square of engine speed, thus a reducing a half of the rotational speed translates in just a quarter of the friction loads. Numerically lower rear axle ratios are used to decrease the engine speed at cruising speed. More frequent transmission shifting is required, increasing the transient events of the engine, a problem that can be addressed with a dual-clutch automated transmission system. Turbocharging, by increasing the power density of the engine, allows lower speeds with the same torque output, facilitating the downsizing/downspeeding of the engine. (Meszler, et al., 2015)

Downspeeded engines have lower peak power, and fleet owners are typically reluctant for this, because of acceleration problems and lower torque. As with downsizing, the torque is reduced, as so displacement or manifold pressure should be increased, possibly offsetting the fuel-savings benefits. Air handling should also be optimized with the turbocharging system. Variable valve actuation can restore the decreased torque adjusting the valve timing.

Diesel-electric hybridization can supplement the needed torque too, but with higher costs. The electric motor can assist the engine when propulsion boosts are needed (hill climbing). Moreover, downspeeded and downsized engines suffer from higher stresses for the torque requirements, and need efficient lubrication oil systems. Downspeeding engines, on the overall, can achieve a fuel consumption reduction of 1 to 5%, depending on the level of downspeeding. (Delgado & Lutsey, 2015)

Engine and vehicle accessories

The operation of the engine and vehicle is dependent on many accessories and supporting systems. Water and oil pumps, air compressor, cooling fan, alternator, power steering, air conditioning and alternator represent additional parasitic/auxiliary loads to the engine, since these are generally belt or gear-driven, taking power directly from the engine, impacting fuel economy performance and increasing with the engine speed. Auxiliary loads can take up to 9% of the brake power of an HDV. Reducing the amount of the energy required by those systems would lower fuel consumption. Technologies to handle the auxiliary loads include clutches, variable flow pumps, and variable speed electric motors. Decoupling these accessories from the engine, when their functioning is not needed, can be done using different clutches on the shafts, as previously explained. The demand for additional loads coming from the accessories can be optimized according to the engine operating conditions and using the inertia of the vehicle, for example operating these devices when the vehicle is in braking phase. Air compressors, maintaining the pressure for the air brake system and the suspensions, are idling 95% of the time, producing parasitic losses. Using a clutched air compressor, on-demand coupling is possible, trying to maximize the time the compressor is engaged when the vehicle is decelerating or running downhill. The coupling can be carried on with an electromagnetic or pneumatic clutch, passive bimetallic or electronically controlled viscous systems. Cooling and air conditioning fans are also driven with the engine through a fixed transmission ratio, and, similarly to the air compressors, can be used just during on-demand operation, decoupling with a thermally passive control, or actively with pneumatic or electromagnetic clutches. Moreover, adoption of variable speed fans permits an adjustable power consumption, optimized according to the demand, during the vehicle operation. Many types and configuration of variable speed fans are possible, although electric drives architectures for the cooling fans present technical challenges caused by the instantaneous high-power requirements. The air conditioning system can, however, be converted into battery and all-electric system. The power steering unit can also be converted into an electrically powered hydraulic steering, reducing particularly the losses during highway driving. (Rodriguez, et al., 2017)

Oil and water pump can be mounted with electric variable displacement and variable flow pumps, respectively. Demand for pressure of the engine fluids and discharge flows varies greatly with engine operation; on-demand operation using clutch systems are again a feasible option. Oil pumps have usually fixed displacement and are oversized to handle the hardest engine operating conditions. The active control on the displacement modifies the flow rate, matching the engine need for oil flow and pressure, even at low ranges of 1-2 bars. Mechanical and electric variable flow pumps are also available for the coolant water flows, which vary pump speed, according to the engine speed and load conditions. Pure electric drives present the same problems as for the cooling fans. (Delgado, et al., 2017)

Electrically driven devices can sensibly reduce the power demand, resulting in greater CO_2 savings than the mechanical counterpart, allowing on-demand operation and variable speeds, but present technical and market barriers because of their failure possibilities and uncertainty on the durability. Higher costs are also involved, but on hybrid vehicles, with the introduction of a battery and electric motor to support the engine, the electrification of engine accessories seems more feasible due to the high current requirements, which cannot be met with a normal 24-volt battery. (IEA/OECD, 2017)

The achievable fuel savings vary with the effective use of the ancillary systems by the vehicle, its operation and duty cycle. Reported values range from 0,5% up to 8%, with a full integration of all the mentioned systems. Due to the higher costs of these technologies, their applicability in terms of cost-effectiveness is limited to the bigger HDVs and the long-haul sector, although the hybridization of the vehicles is more directed towards the lighter segments of the HDVs. The described on-demand couplings should be controlled by the engine control unit, and it is notable that a complex integration with all vehicle accessories is needed to achieve significant savings. (Meszler, et al., 2015) (Skinner, et al., 2010)

HDVs that are destined to the transport of some typologies of goods and are equipped with a special trailer/body, such as temperature-controlled bodies, consume a consistent amount of energy that is generally provided by the diesel engine. The replacement with an alternative source can bring consistent advantages, but the applicability and benefits vary depending on the power system being replaced. A battery can be used to power the trailer in hybrid vehicle applications. For refrigerated trailers, nitrogen can be an option, although there are safety concerns. Reported fuel savings range from 10 to 20% with an average of 15%, depending on the application. (Hill, et al., 2011)

Turbocharging and turbocompounding

Turbocharging is a technology that recovers kinetic energy that would be otherwise lost and wasted in the exhaust gases. A turbine, which is driven by the exhaust flow pressure is mechanically connected to a compressor positioned on the intake air stream, which compresses it, entering the intake manifold at increased pressure. The compressor then is improving the engine volumetric efficiency increasing the charge density of the air flow, permitting more power per cycle. The power density of the engine is improved, along with the efficiency of the EGR (exhaust gas recirculation) system. Running at lower speeds while providing the same power output reduces the friction losses. The engine can also be downsized, being lighter and smaller with the same power output as a non-turbocharged one, with consequently fuel consumption benefit (Sharpe, et al., 2013). Turbocharging has been widely adopted both in U.S. and Europe, becoming a standard technology for HDVs. The tightened NOx emission standards in U.S. in 2004 has led to the adoption of EGR systems, increasing market penetration of turbocharging in tractor units and trucks to 100%. On the other hand, in Europe, the use of SCR systems that require lower EGR rates has resulted in a slower penetration of turbocharger systems. Main concepts for turbocharging are variable geometry turbines, multi-stage turbocharging and asymmetric twin-scroll housings. The turbines of the turbochargers are usually variable geometry turbines, allowing the adjustment of the exhaust gas speed and pressure at the inlet of the turbine according to the vehicle speed and load. Having an improved turbine/compressor contribute to diminish fuel consumption: axial compressors and radial compressor with high-pressure ratio are emerging as viable technologies. However, because of the need of the EGR system to have a negative pressure difference between the intake and the exhaust manifold, the turbocharger efficiency could be intentionally reduced. This problem can be addressed with the twin-scroll turbochargers, which has one scroll optimizing the EGR and the other one the intake air boosting. Multi-stage turbocharging combines different turbochargers in series adding degrees of freedom and optimizing the operation (Rodriguez, et al., 2017). Turbocharging only can reduce the fuel consumption by 2 to 5%, depending on the efficiency of the system used. Turbocompounding and VVA technology can be easily combined with turbocharging, with additional fuel consumption benefits along with a more flexible operations engine, opening possibilities for dual-fuel concepts (see following chapter). A downsized turbocharged engine with VVA has the potential to offer up to 10% fuel consumption reduction. (Law, et al., 2011) (Delgado, et al., 2017)

Turbocompounding is a similar technology that aims to recover energy from the exhaust gases by means of a turbine. It can be electrically or mechanically. Instead of being coupled with a compressor in the intake manifold, the turbine placed on the exhaust flow transmits the recovered energy directly to the crankshaft in the form of mechanical energy (mechanical turbocompounding), or power an electric generator (electrical turbocompounding). Turbocompounding is usually adopted as an addition to turbocharging, and is placed downstream of it. The electric turbocompounding provides to the vehicle a broader range of options to use the recovered energy. Recovered electricity can be stored in a battery and used to directly power electrical accessories, assist the powertrain or, using an electric compressor, improve the boost responses in transient operation. Mechanical turbocompounding provides higher brake power and torque, allowing possibilities for downsizing. On the other side, it can lead to power losses because of the fixed ratio between the turbine speed and the engine. This problem can be addressed using fluid coupling and a specific gear set. The aftertreatment system can be negatively impacted since backpressure is increased with a decrease in the exhaust temperature (Delgado, et al., 2017). Benefits for turbocompounding, both mechanical and electrical vary from around 2% and 5%. High-speed constant operations are the most suited one for turbocompounding, while the technology is not expected to be cost-effective in transient operations, even if regenerative braking increases the possibilities for the electrical turbocompounding. (Delgado, et al., 2017) (Hill, et al., 2011)

The electrical turbocompounding is of particular interest in hybrid powertrains, since it can assist the engine through an electric motor or directly charge the battery of hybrid system. It is particularly fitted for hybrid long-haul HDVs, where the regenerative braking possibilities are quite limited. In this case, the claimed fuel consumption benefits reach up to 8-10%. The complexity and the increased costs of adding an electric storage, along with the high voltage system and the generator have halted the market adoption of the electric turbocompounding. According to (Rodriguez, et al., 2017), only mechanical turbocompounding systems have been offered in the market, with only a minimal share of new vehicles adopting it, mostly in U.S. (IEA/OECD, 2012) (Delgado & Lutsey, 2015)

Waste heat recovery and bottoming cycles

Another option for increasing the efficiency of the engine by decreasing the exhaust losses are the waste heat recovery systems. In general, waste heat recovery systems are applied to industrial processes where a big amount of energy is lost as heat in the exhaust streams. Thermal energy is recovered using a coolant flow and converted in usable mechanical or electric energy. This technology has not been commercialized yet either in light-duty or heavy-duty segments, but it has proven to be a possible viable technology in the future to increase the brake thermal efficiency up to 50%.

Tested waste heat recovery technologies in HDVs are the bottoming cycles, in particular the organic Rankine cycle. This is a thermodynamic cycle that generates electricity from the waste heat; the high-temperature exhaust is used in a boiler unit to evaporate a working fluid at high pressures, which is then expanded in a turbine creating mechanical or electrical power. The expanded working fluid is then condensed and pumped in the evaporator for another cycle. The working fluid is an organic, high-molecular mass fluid which boiling point occurs at lower temperatures than water. In this way, heat can be recovered even from

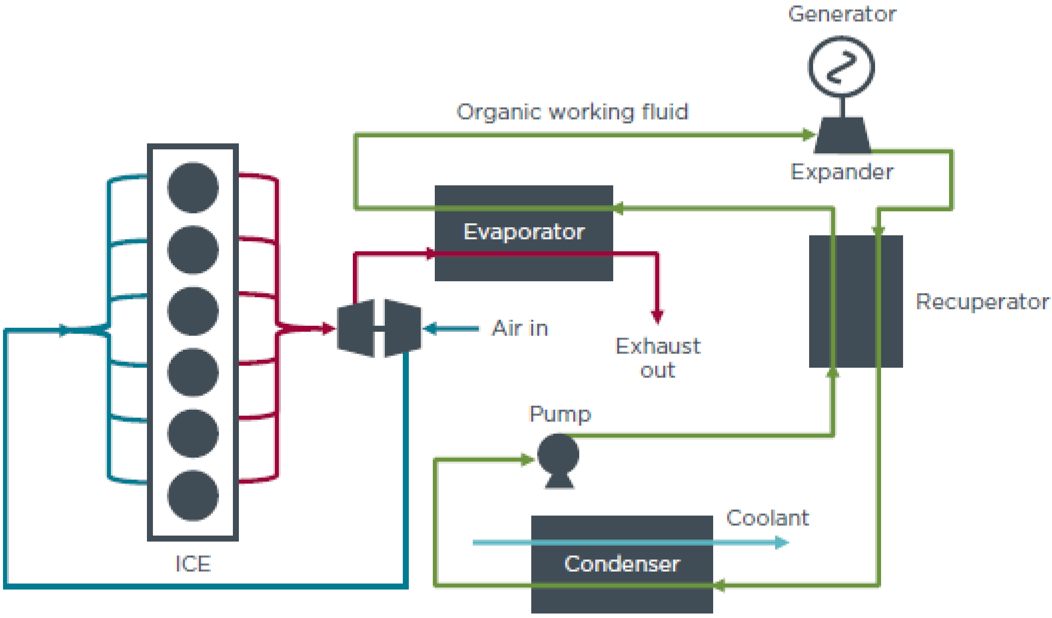


Figure 4.4: Organic Rankine cycle waste heat recovery system. Source: (Rodriguez, et al., 2017)

low-temperature sources. The electricity recovered by the turbine through a generator can be used to power auxiliaries and assist the engine, as described in the electrical turbocompounding. The turbine can also feed the mechanical power to the crankshaft, by means of a gearbox. In vehicles with EGR systems, organic Rankine cycles offer the advantage of eliminating the EGR cooler. In general, the organic Rankine cycles has proven to be more efficient than the turbocompounding at the best-operating conditions. The two systems cannot coexist in the same engine since they are using the same source of energy (Reinhart, 2015). Although bottoming cycles are not yet commercialized, tests on long-haul HDVs have shown fuel consumption savings of between 2 and 10%, depending on the cycle and components efficiency (IEA/OECD, 2012) (Hill, et al., 2011). A typical cycle includes an evaporator, an expander (turbine), a condenser and a feed pump to drive the fluid (Figure 4.4). The complexity of the system, applied in a vehicle, translate into high costs, additional space requirements and weight, as well as problems in the applicability for transient operations vehicles. The application would be then limited just to the long-haul segment, thanks to the high waste heat availability. Moreover, aftertreatment device operations, like catalytic converters, can be negatively affected by the lower temperature of the exhaust gases. Safety issues linked with the choice of the organic fluid need also to be considered. (IEA/OECD, 2012)

4.3.3 Hybridization and electrification

Electricity and electric vehicles are often regarded as the future of road transportation, at least in the long term. The main potential for the electrification of is considered to be in the light-duty segment, due to their speed profile characterized by variations, accelerations and braking, as well as start/stop urban driving cycle, as shown in Figure 4.5. Big developments are undergoing especially in passenger cars, in the market adoption of HEVs (hybrid-electric vehicles), PHEVs (plug-in electric vehicles) and BEV (battery-electric vehicles). For commercial vehicles, developments towards electric vehicles are only happening in the light-duty segment and buses. The use of electricity as energy source eliminates local and air pollutants emissions, since no combustion of liquid fuel is required. The electricity is stored in a battery and converted into mechanical energy by an electric motor, which powers the driveline and so the wheels. On a tailpipe basis (TTW, tank to wheel), emissions (both air

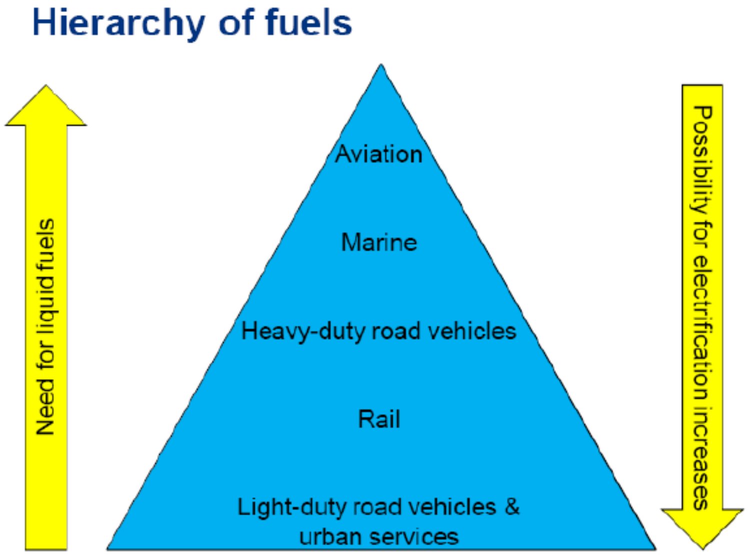


Figure 4.5: Hierarchy of fuels (VTT Technical Research Centre of Finland, 2016)

pollutants and GHGs) are eliminated when the electric motor is used. Emissions are then just caused by the way the electricity is produced (well to tank emissions, WTT), either with low-carbon technologies or fossil sources. Carbon neutral transportation, using electric vehicles, can only be achieved if the electricity is produced 100% from carbon-free technologies, such as hydropower, wind or nuclear power, ideally renewable sources. Current electricity mix in EU is not 100% renewables, even if local differences exist, like Nordic countries. Even if depending on the period, a country like Norway usually produces 95% of its electricity from hydropower (IEA/OECD, 2017). The batteries used for electric HDVs use lithium-ion chemistry, as for Light-duty vehicles. (VTT Technical Research Centre of Finland, 2016)

HEVs have two different power sources: a conventional ICE and one or more electric motors. Various designs of hybrids are possible, with different degrees of hybridization depending on the power requirements covered by the electric power source. Vehicle cost and weight increase accordingly, as well as the fuel consumption benefits. Micro-hybrids have a small electric motor that is just providing start/stop function, with no tractive power, and prevents idling periods of the ICE. Mild hybrids have larger motor and battery pack, which allow to provide supplementary tractive power and regenerative braking capabilities. Full hybrids have a very high level of integration of the hybrids components into the vehicle, allowing the electric motor to directly power the vehicle for an extended period of time, but requiring at the same time a large battery pack. (Baker, et al., 2009)

There are three different powertrain architectures that define how the two powertrains are coupled and act on the driveline: series hybrid, parallel hybrid and power-split configuration. It is important to notice that these architectures can either be implied into full or mild hybrid vehicles.

Series hybrid

Series configuration is the simplest hybrid architecture. In the series architecture, the ICE is connected only to an electric generator and powers it, producing the electricity that is then fed into a battery or to the electric motor (Figure 4.6). The motion generated by the electric motor is transmitted to the wheels through the driveline. The battery is recharged when depleted directly by the engine. Series HEVs are also known as range-extended electric

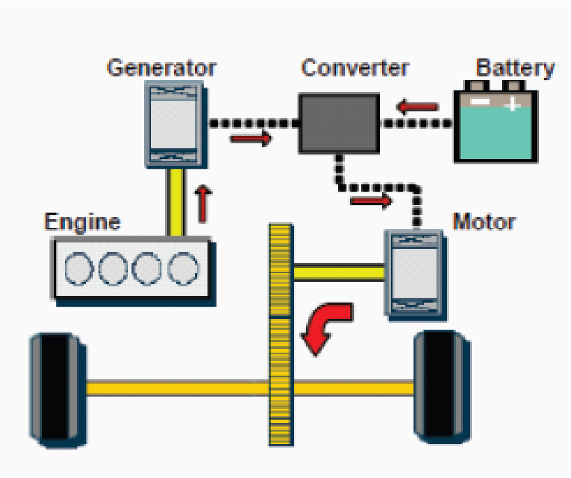


Figure 4.6: Series HEV architecture. Source: (National Academy of Sciences, 2010)

vehicles. The ICE has no mechanical connection with the driving wheels, and run independently from the load required by the vehicle, having the battery as the "load-matching unit". In this way, the engine can run in an optimal operative range avoiding idling periods, achieving better efficiency and thereby reducing fuel consumption. Also, the towing capacity is hugely increased at low speed. As a consequence of having the whole power demand of the vehicle completely satisfied by the electric powertrain, a large and expensive energy storage system pack is required, along with the electric generator and motor: mass and volume are added. However, the ICE is typically smaller than in the other configuration since the power demand it has to meet is limited. The mechanical transmission is also eliminated, somewhat balancing the increase of weight and volume from the electric system. The mechanical energy of the ICE is converted first is electricity, which is then again converted into mechanical traction. The conversion losses are thus doubled, and this makes this configuration not attractive for high-speed trucks. This configuration is used especially in citybuses, due to the high amount of engine idling and the start and stop duty cycles, and some construction HDVs, like mining vehicles. (Qin, 2016)

Parallel hybrid

In parallel HEVs, both the electric motor, powered by the battery and the ICE have a mechanical connection with the driveline. The wheels are powered in parallel by the two energy converters. A dedicated generator is not needed: the electric motor recharges the battery pack when needed, acting as an electric generator (Figure 4.7). Parallel hybrids are furtherly classified according to the different positions that the electric machine can have. To each of these positions, a different role is played by the electric motor. For HDVs, it has been evaluated that the best option is having the electric drive before the transmission, allowing the electric mode launching from standstill (Rodriguez, et al., 2017). The operating strategy of the two parallel powertrains is determined according to the load and the speed of the vehicle by the engine control unit, aiming to achieve the best operating points. In an HDV, the vehicle should be run in electric-only mode at lower speeds, reducing the idling time of the ICE, while at higher speeds, when the engine operates at high efficiency, the battery should be recharged and the vehicle operated using the conventional powertrain. The electric machine is then used for assisting the engine during startup and boost moments. The battery is also recharged during the braking phase. The power need from both powertrains is reduced, thus both the ICE and electric machine can be downsized if compared to the

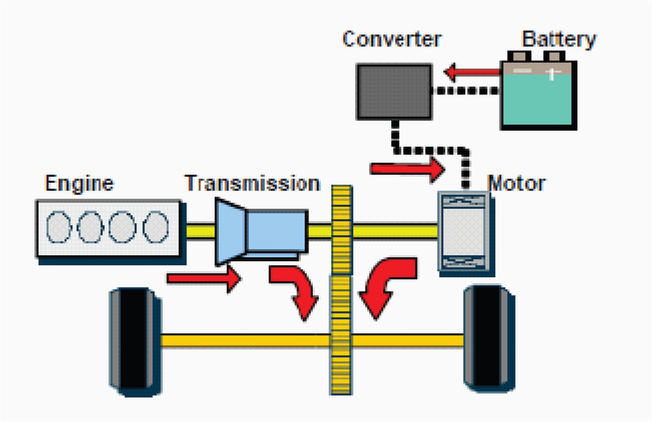


Figure 4.7: Parallel HEV architecture. Source: (National Academy of Sciences, 2010)

series hybrid. However, the ICE is no more completely decoupled from the vehicle load and speed, and, even if some degrees of freedom are achievable, is no more possible to run always the engine at the best operating range. It is possible also to furtherly downsize the ICE while increasing the size of the electrical system, even if it is not practical for long-haul and high-power demanding operations. The parallel hybrid is used mostly on hybrid PC and commercial vehicles.

Power-split hybrid

Power-split architecture is also known as series-parallel, since it combines the two concepts together. As showed in Figure 4.8, the mechanical power produced by the ICE is divided into two paths by a planetary/epicyclical gear. One is coupled directly with the driveline, providing the power to the wheels. The other one is coupled with an electric generator, which produces electricity: this can feed a battery pack, or it is converted into mechanical energy again by an electric motor, coupled with an electric transmission with the wheels. Moreover, the electric motor can work as a generator for the regenerative system and use the recovered energy from decelerations and braking to produce electricity, storing it in the battery (German, 2015). The system is extremely efficient because the power split configuration combines the advantages of a series and a parallel hybrid: the system can either operate as a series or parallel, according to the situation, trying to achieve the optimal efficiency. The level of flexibility reached is very high. Using the epicyclical gear, the ICE can be completely decoupled from the load and being adjusted independently, recharging the battery and working as a series. If needed, the ICE can be mechanically coupled directly with the driveline, using the electric powertrain as an assisting system for certain operations. During the vehicle start, at low speeds, or when the battery is charged, the ICE is turned off because the motor is more efficient, while during normal operations, the power is split either in electric or mechanical and the motor assists the propelling of the truck. The engine is turned on when the battery has reached the minimum allowed state of charge. The versatility of the powertrain is hugely increased, but on the other hand, a great complexity is added. The applicability of the series-hybrid architecture is constrained by the addition in volume and weight of the two electrical machines, the complex gearbox and the battery pack, as well as the complicated powertrain calibration and the control algorithm. The power split configuration is mainly used in PC HEV. (Zhao, et al., 2013)

Even if all three main types of hybrid configurations have been deployed in different vehicles, the parallel hybrid one is the most suitable for the HDVs, because of the vehicle's

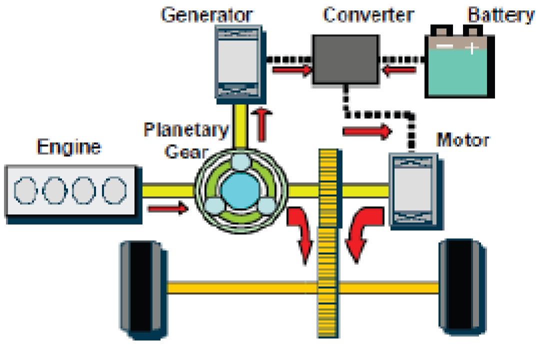


Figure 4.8: Power-split HEV architecture. Source: (National Academy of Sciences, 2010)

power and torque requirements. From a literature review based on simulations and testing of different vehicles and test cycles, a full hybrid HDV in long-haul operations (rigid trucks and tractor units) can save between 6 to 10% of fuel. However, for lighter HDVs in urban operations fuel consumption benefits appears to be more consistent. Values range from 15 up to around 40%, in more optimistic studies. (Rodriguez, et al., 2017) (Hill, et al., 2011) (Lajunen, 2014) (IEA/OECD, 2012)

In commercial vehicles, the use of HEV is in general still very limited, because the fuel consumption benefits do not offset the increase in cost, weight and complexity of powertrain brought by the hybrid configuration, even if both benefits and drawbacks vary widely with HDV type and mission profile. Challenges remain mostly in the areas of the battery, for the costs and additional weight. Current hybrid solutions for HDVs exceed the three-year payback time for being considered by a fleet owner. It has been evaluated that the achievable payback time for a HEV bus can be around 4 years and for a long-haul truck around 6 years (IEA/OECD, 2012). Instead, in PC segment hybrids have reached economic maturity and are currently present in measurable and consistent shares in the market (Westerholm, 2017). Some efforts have been made in proposing hybridization solutions for trucks, but these have been usually short-lived (Rodriguez, et al., 2017). (California Air Resources Board, 2015)

PHEV and BEV

PHEV vehicles are considered as an intermediate step between HEV and fully-electric vehicles. Plug-in hybrids have the possibility of recharge the battery pack using an external source of energy, the electric grid. For this reason, a dedicated charging station, is needed for recharging the battery. The HEV architectures previously described are also applied to the PHEVs. Since the battery is no more charged only through the ICE and the regenerative braking system, a bigger focus is on the electric mode with the aim of increasing the time spent relying only on the motor. The electric machine is generally of bigger size than in a HEV. The vehicle is generally recharged during the night-time, when electricity prices and demand are low. The ICE can be switched according to the state of charge, working as a series hybrid. The aim of a PHEV is to maximize the time spent using the electric power source, minimizing fuel consumption and taking advantage of the high powertrain-to-wheel conversion efficiency of the electric system, reaching around 85%. However, the battery storing capacity and the availability of charging stations may limit the use of the electric mode. A PHEV PC is estimated to bring fuel consumption reductions of up to 70%, but a more realistic 40-50% is expected in real-world driving conditions. For PHEV HDVs, tested vehicles report a reduction of around 30 to 60%. However, the testing and commercialization has just concerned a very small niche of vehicles, mostly utility, work and delivery vehicles. The benefits offered in fuel consumption are negatively balanced by the problems in range, cost and added mass of the electric system, which reduces the payload possibilities of freight HDVs. However, the previously mentioned intelligent vehicle technologies would have an important contribution to minimize the fuel consumption of a PHEV vehicle. In fact, a better use of the two powertrains can be managed knowing the type of road ahead, the expected load, speed, acceleration, and distance. Currently, in the HDV market, developments for PHEV are undergoing in the lighter models, especially in the utility HDVs, like construction and refuse trucks, for their short daily routes and the start and stop driving, although many projects are still in the pilot/demonstration phase. It might be convenient for a utility truck to use the electric power source, reducing noise, emissions and eliminating diesel engine idling. However, the battery pack, in that case, needs a considerable size. (California Air Resources Board, 2015)

BEVs are just driven by an electric motor, powered by an externally recharged battery pack. The ICE is eliminated, and the vehicle has no other power source other than the electric powertrain. In this way, no tailpipe emissions are emitted, and WTW emissions are just depending on the electricity mix of the recharging grid. BEVs in the HDVs segment are still at pilot stage, with California being at the forefront of the developments. The targeted vehicle types to be electrified are trucks in urban operations. However, the battery pack needs to be of very large size to assure a reasonable range and fulfill the power requirements of a heavy vehicle. This fact raises the problem of a big increase in vehicle cost, along with problems in the volume and mass of the battery, and the need for a daily vehicle charge. Road noise is minimized, but this can bring some safety issues with vulnerable road users. These problems can be addressed partially with the concept of supplying the electricity to the vehicle while it is in motion, through electric road systems (overhead catenary lines, inductive charging). Pilot demonstrations are undergoing in Sweden and Germany. However, these types of systems require high investments costs. (IEA/OECD, 2017)

As mentioned, since the main additional cost for PHEV and BEV is the battery cost, PHEVs have much lower costs than BEV. Currently, battery pack costs for vehicle road applications are around 200€/kWh, a price that has to fall within the range of around 100€/kWh in 2025 to have an electric vehicle that competes with the same price range of conventional vehicles. Reports estimate that there is a big potential for bringing down the costs, with a high-volume manufacturing (economy of scale). Payback time of an electric HDV compared to a conventional one depends on technology choice and the annual mileage. For a better understanding of the battery packs, the potential improvements and prices, see (Westerholm, 2017). Moreover, the prospect for the growth of the electric vehicle market is also linked to the availability of charging stations and infrastructure, especially for vehicles used in urban environments.

Buses and in particular, urban buses, present differences in terms of driving cycles and utilization, as well as costs that allows an increased potential for the electrification of the powertrains, towards fully electric buses. The start and stop duty cycle particularly suits the hybridization (both HEV and PHEV), and the high mileages and utilization are favoring the electric motor. Moreover, the fact that public transportation companies are heavily supported economically by public funds can compensate the initially higher investment costs. It has been demonstrated by (Pihlatie, et al., 2014) that a fully electric citybus can have a lower total cost of ownership than a conventional diesel bus, due the significant reduction in operating costs thanks to the high efficiency of the electric powertrains. A short-range BEV bus fleet with shared opportunity charging infrastructure is the most economical solution. Hybrids and BEV buses are expected to increase the shares in the new registrations also pushed by local plans for sustainable cities and transportation (Pedersen & Skytte, 2016) (Laurikko, et al., 2015). However, when long-haul public transportation is concerned (coaches) the diesel powertrain can be still considered as the dominant powertrains in the next future, due to the high battery requirements, as with the heaviest vehicles of the HDV segment. (Nylund & Koponen, 2012)

Fuel cell vehicles can be considered as a particular type of vehicle electrification: a fuel cell vehicle is equipped with an electric motor, powered by the electricity stored as hydrogen in the fuel tank. The hydrogen is converted into electricity through an onboard fuel cell. Since hydrogen is stored in a pressurized tank (35 to 70 MPa), the hydrogen has a much higher energy density than the batteries. The range per unit of volume compared to the battery technology is much higher, even if still around four times lower than the diesel powertrain. The technology is, however, not yet economically mature, as costs of the powertrain systems can even double the diesel ones, and the refueling infrastructure in Europe is almost non-existent (Skinner, et al., 2010). FCVs produce, as the BEVs, no tailpipe emissions, with the WTW emissions depending only on the production of hydrogen, which nowadays is produced almost entirely from natural gas. FCV urban buses have already been successfully tested in Europe, and FC small trucks are planned to be under development. (IEA/OECD, 2015) (IEA/OECD, 2017)

4.3.4 Natural gas and biofuels

Numerous alternative fuels have nowadays the potential to be used as a substitution to the diesel powertrain for the transportation system (Figure 4.9), reducing harmful and GHG emissions. The most important ones are natural gas, in the forms of CNG or LNG, and biofuels. CNG and LNG are two different forms natural gas is stored in the fuel tanks, and the engine used to burn natural gas is in both cases the positive ignition system. To make it suitable to be transported as an automotive fuel, natural gas is compressed to a pressure around 200 to 300 bars (CNG) or liquefied through cooling up to -162 °C (LNG). The volumetric energy density is in these ways hugely increased and the fuel can be used as proper alternative fuel. Both are stored in onboard cylinders: in the case of CNG, these cylinders need to be pressurized, while LNG requires isolated cryogenic cylinders to avoid the boiling. In the engine, both types of natural gas are delivered in gaseous state. However, even if the energy density is increased, the both CNG and LNG are still less dense forms of energy than petroleum-based liquid fuels such as diesel and gasoline by a factor of around 0,2 and 0,6, respectively. This means that natural gas-based vehicles need to have larger fuel tanks to store the same energy as diesel and gasoline. Since LNG is more energy dense than CNG, it allows driving for higher distances without refueling, making it more suitable for long-haul operations. Moreover, because of the risk of boil-off, which happens in around 5 days after the tank is left unventilated, LNG needs to be adopted for HDVs that drive regularly and for long distances. On the other hand, smaller HDVs and buses, with lower annual mileages and less regular operations tend to adopt CNG instead of LNG. CNG cars and light-duty vehicle are already deployed in some European countries, where the gas network is already widely present on the territory. CNG urban buses and refuse trucks are also present to a sensible amount in Sweden (IEA/OECD, 2017). Natural gas vehicles compared to diesel produce less local pollutants, and for this, public policies have supported natural gas for public and freight transportation to improve the local air quality. Natural gas combustion does not almost produce PM and NOx levels are very low too, in a range of 3 and 10 times less on a g/km basis, respectively (Posada, 2009) (National Academy of Sciences, 2010). However, in terms of GHG abatement, natural gas does not provide

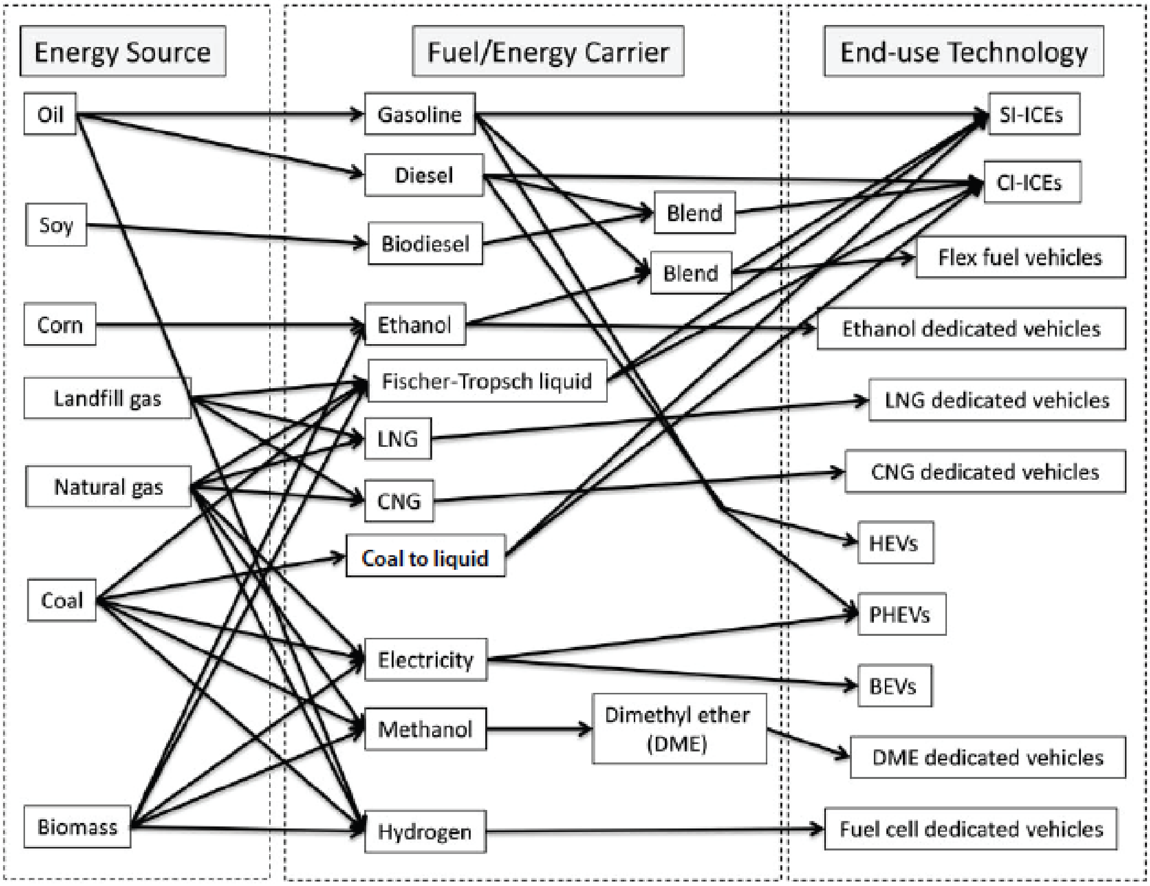


Figure 4.9: Vehicle fuel pathways. (National Academy of Sciences, 2014)

significant benefits. The lower carbon content of natural gas is balanced by the lower calorific values compared to diesel, as well as the issue related to methane high global warming potential, lower efficiency of the spark-ignition engine and methane leakage issues. All these factors are reflected in the conflict of literature sources that evaluate the potential of GHG emission reduction of natural gas, discussed in (IEA/OECD, 2017). The development of the national gas grid and the availability of refueling stations are key factors for the adoption of natural gas vehicles, as well as the cost difference with diesel fuel. The generally increased cost of a natural gas vehicle compared to a diesel one lies in the storage tanks. Natural gas price is generally lower than diesel, and in cases where the differential is very high and the investment cost of the infrastructure are not passed on to the end users, CNG and LNG can offer reasonable payback periods, ranging even from 2 to 4 years. The adoption of natural gas HDVs and buses is then very related to stricter emission standards of the diesel engine, especially for PM. (VTT Technical Research Centre of Finland, 2016)

The limited potential for natural gas to abate GHG emission can be addressed using biofuels, in this case biogas. In, general, there are many biofuel options that can used to substitute the fossil counterpart. Figure 4.10 shows the main options for the substitution of fossil diesel. Biofuels can be blended with fossil fuels or directly used as a replacement for diesel. Drop-in biofuels are by definition "functionally equivalent to petroleum fuels and fully compatible with existing petroleum infrastructure" (Karatzos, et al., 2014), meaning that can either be used in blending or pure, without major modification for the ICE powertrain. Conventional biofuels, instead, can be accurately defined from their peculiar

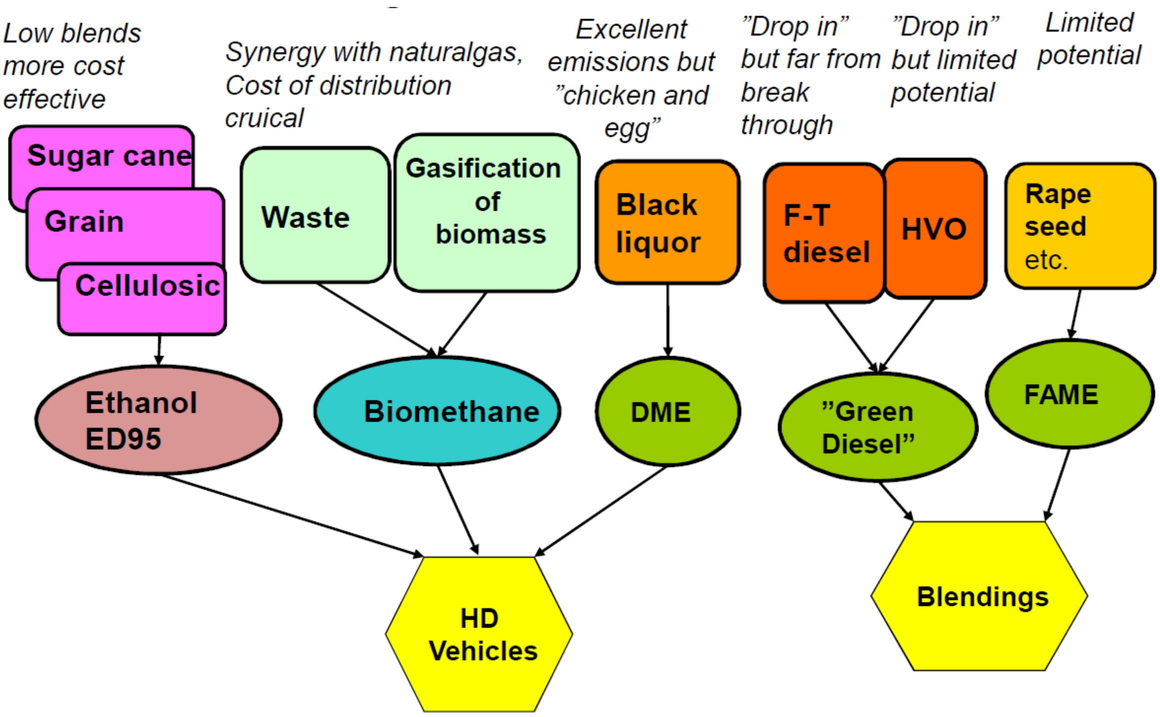


Figure 4.10: Biofuels substituting fossil diesel. (Hådell, 2012)

chemical composition alone types of biofuels, and cannot be used in pure form in the existing conventional powertrains and petroleum infrastructure. Hydrotreated vegetable oil (HVO) and fatty acid methyl ester (FAME) are examples of drop-in and conventional biofuels, respectively (Karatzos, et al., 2014). Biodiesel fuels, such as FAME, are subject to blending walls, due to vehicle compatibility issues, although there are some vehicles with modifications in the engine that allow the pure use. The blending wall for FAME in diesel fuel in Europe is 7 vol%. HVO share in the diesel fuel depends on each country bio share mandate, as HVO can completely substitute fossil diesel. Finland and Sweden are the countries in Europe with the highest share of HVO in the fossil diesel (Westerholm, 2017) (European Commission, 2013). Biomethane is physically and chemically similar to natural gas, and is used in natural gas HDVs and buses. ED95 consists of 95% in volume of bio-based ethanol with additives and lubricants that improve the ignition properties. In fact, ED95 is currently used in HDVs and buses with a specific compression ignition engine, designed exclusively for this type of fuel. The vehicle availability is very limited, since in Europe just one manufacturer is currently producing ED95 vehicles. In Sweden, there have been demonstrations of buses running on ED95 engines, but the market is still very limited (VTT Technical Research Centre of Finland, 2016). (Skinner, et al., 2010)

The potential of GHG abatement from biofuels is very dependent on the feedstock used for the production, as well as the method used for calculating it. Debates are ongoing about the negative effects of the land use change of biological feedstock, addressed in the EU Fuel Quality Directive (European Commission, 2015). For many biofuels, there is the concern about the sustainability and the availability of certain feedstocks, as well as the competition with food crops. For this work, it has been assumed that that biofuels offer 70% reduction in GHG emissions compared to the corresponding fossil energy carrier. Data about the use and share of biofuels in the fuel consumption of Finland, Sweden and Norway can be found in (Westerholm, 2017). Nowadays, the use of biofuels is currently driven by blending mandates and subsidization, since production costs are still high and do not deliver the competitiveness necessary for the market uptake. However, since on one side an increased use of bio share in the fuel mix of the European countries is expected, the use of dedicated powertrains for conventional biofuel is unlikely because of the costs. The use of biogas is directly related to the adoption of gas vehicles. In general, the implementation of ambitious national plans for transport sector decarbonization has since now provided the incentives for the adoption of compatible vehicles (Karatzos, et al., 2014) (Romejko & Nakano, 2017). Drop-in biofuels and low-blends are, in low-carbon scenarios, the only viable alternative to the very expensive electrification pathway for long distance transport modes.

4.4 Compounded improvements for 2030

Based on the mentioned efficiency improvements, (Hill, et al., 2011), (Law, et al., 2011), (Schroten, et al., 2012), and (Breemersch & Akkermans, 2015) estimate the possible and potential improvements in vehicle efficiencies that are likely to happen if certain conditions are fulfilled for 2030. The fuel efficiency technologies considered in these studies have also been used in the previous chapter for the technology analysis, as these studies have served as sources for the presented expected percentage benefit. (Hill, et al., 2011) develop three scenarios, business-as-usual (BAU), cost-effective and challenging, presented in an increasing order for the expected improvements of fuel consumption for the different HDV and buses classes presented in the study. The penetration of the efficient technologies in the BAU scenario is set at slow rate, especially for the alternative powertrains. In the cost-effective scenario, only the technologies that have a payback time of around 2-3 years are adopted, while, in the challenging scenario, all the technologies that are likely to become commercialized by 2030 are considered. It is important to notice that the applicability of a technology is considered in relation to the mission profile of the HDV and buses categories. The considered vehicle segments are Service, Urban Delivery, Municipal Utility, Regional Delivery, Long Haul, Construction, Bus, and Coach. (Law, et al., 2011) analyze the assumptions, data and results of the previous study, relating them to the US situation, and propose different vision and method for calculating the compounded improvements for the future, using the same vehicle categories as the analyzed study. Conclusions on GHG reduction potential of HDVs in EU are drawn, keeping the previous study as a benchmark. However, for the compounded efficiency benefits, the study considers the total potential, as if all the applicable technologies in a segment are adopted, along with a more likely scenario, in which only the technologies with equal or less than 3-year payback are considered. The calculated results are similar to (Hill, et al., 2011) findings, although the second study approach uses technology packages adoption, not considering the penetration rate of single individual technologies. (Breemersch & Akkermans, 2015) reviews previous studies on the subject, and integrate the results of them with a survey to develop a comprehensive approach to CO_2 emission reduction from HDVs. Instead of the two other studies, just two vehicle segments are considered, doing just one duty cycle: Long Haul and Regional Delivery. The compounded improvements in vehicle efficiencies for the mentioned studies are shown in Table 4.1. It must be noticed that (Hill, et al., 2011) and (Law, et al., 2011) present the compounded benefits including the benefits of electrification and alternative fuel vehicles. The potential of these have been excluded in the values presented in the table, because these are considered in the next scenario analysis as different powertrains already, and the efficiency improvements are considered implicitly in the powertrain scenarios for the future. The values presented refer just to the vehicle, driveline and powertrain technologies excluding the contribution from the powertrain hybridization, electrification and alternative fuels. This has been possible using the calculation assumptions presented in the studies. For the (Hill, et al., 2011) study it has been possible to not consider the mentioned benefits using the presented formula, assuming that the percent fuel consumption reduction (%FCR) presented for individual technologies are not additive:

$$\%FCR_{tot} = 100 \cdot \{1 - \left[1 - \left(\frac{\%FCR_{tech1}}{100}\right)\right] \cdot \left[1 - \left(\frac{\%FCR_{tech2}}{100}\right)\right] \dots \left[1 - \left(\frac{\%FCR_{techN}}{100}\right)\right]\}$$

Where tot refers to combined options and $techN$ the considered N-technology (National Academy of Sciences, 2014). By reversing the formula, it is possible to calculate just the compounded benefits of the considered technologies.

Table 4.1: Expected compounded efficiencies by 2030 for different vehicle segments

		Hill, et al., 2011			Law , wt al., 2011		Breemersch & Akkermans, 2017
		BAU	CE	Progr.	Potential	3-years PB	
HDV	Service	5%	7%	12%	37%	9%	-
	Urban delivery	5%	7%	13%	46%	17%	-
	Municipal utility	2%	5%	15%	35%	15%	-
	Regional delivery	8%	9%	12%	41%	27%	13%
	Long Haul	9%	13%	19%	47%	34%	12%
	Construction	6%	9%	13%	45%	29%	-
Buses	CityBus	7%	12%	23%	41%	21%	-
	Coach	6%	10%	16%	38%	24%	-

5 The quantitative model for vehicle fleet and GHG emission development

The MATERO model that has been created for this project, works as the quantitative background for the estimation of GHG emissions, energy demand and fuel consumption for road transport in Finland, Sweden and Norway. The road transport considered is limited to passenger cars, light commercial vehicles, heavy-duty vehicles and buses. The model approach is mainly bottom-up, in which the energy demand of the vehicle fleet is calculated from the mileage and specific energy consumption of vehicle segments and sub-segments modeled in the fleet. As described in (Westerholm, 2017), a top-down approach has been used to verify the results of the bottom-up model: for example, the model uses fuels sold to the road transport sector to estimate emissions for 2012-2016. The road vehicle fleet is divided into 21 sub-segments and 13 powertrains. The considered powertrains are Gasoline, Diesel, BEV, Gasoline and Diesel PHEV, Gasoline and Diesel HEV, Flex-fuel vehicle, CNG, LNG, Fuel cell vehicle, ED95 and Other, which include all the other types of powertrains. Then, for the years 2017-2050, the vehicle fleet, divided into segments and sub-segments, is combined with the annual average mileage, the energy consumption, to get the total energy demand for different powertrains. The energy consumption is calculated based on eight energy carriers: Gasoline, Diesel, Electricity, E85, CNG, LNG, Hydrogen and ED95, assigned to each powertrain accordingly. The total fuel consumption is obtained

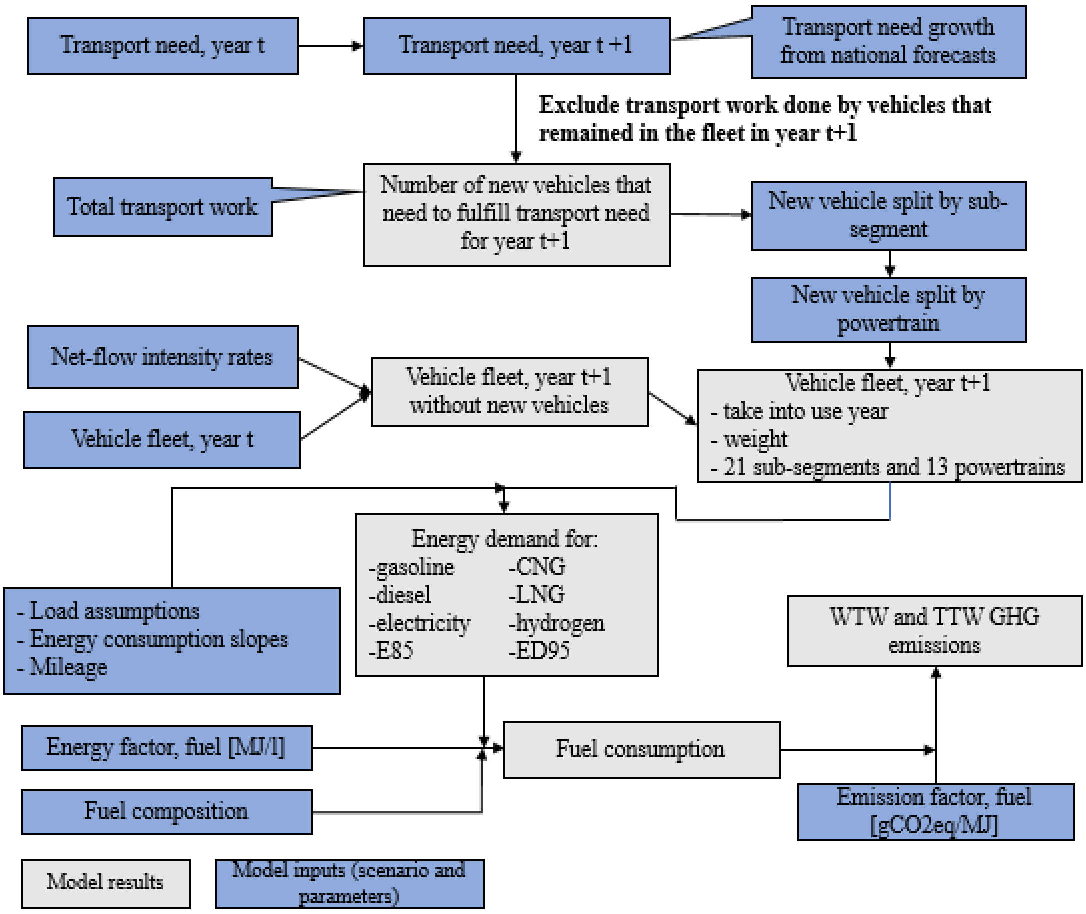


Figure 5.1: Schematic structure of the model fleet, energy and emission calculations.

through the energy factor of each energy carrier, and the final GHG emissions from the emission factors. The considered GHG emissions are both WTW and TTW, consistent with (IPCC, 2014). Figure 5.1 summarizes the conceptual structure of the model. The model type is also known as stock-flow-cohort, and is described in detail in (Kilpeläinen, 2018). The assumptions for the energy calculations and the emission factors are presented in (Westerholm, 2017).

5.1 HDV and Bus fleets

Due to the many different types of specialized vehicles in the HDV segment, with different operation cycles, it can be misleading to group them into a category whose aim is to represent the "average vehicle". HDVs that are part of the same weight group, can have a different annual mileage and driving pattern, with consequently different energy consumption and GHG emissions. However, for the aim of this project and for a correct functioning of the stock-flow-cohort model, it has been necessary to make some general consideration on the HDV and Buses segments, and create different sub-segments representing the stock of vehicles, ideally operating on the road in the same way.

Of a particular importance of the HDV segment, are the vehicles that are designed for transportation work, which can be considered as the HDV main reason of existence. Moreover, due to the high annual mileages and loads, reflecting the central role played by them in an advanced economy, transportation HDVs are the vehicles that consume the majority of the road fuel used in the transportation sector (mainly diesel). These vehicles are usually trucks and tractor units, with trailers and semi-trailers possibly attached to increase the transportable load. The remaining vehicles are mainly special purpose utility HDVs, like fire trucks, refuse trucks or heavy road construction machinery.

The following classification of HDVs has been created for all three countries, independently of the specific fleet vehicles:

- Truck with trailer: this category groups the freight transportation trucks that are able to carry a trailer to increase the transportable load;
- Tractor unit with semi-trailer: in this sub-segment are grouped the tractor units, which are vehicles specifically designed for towing a semi-trailer;
- Other: all the HDVs that cannot be defined as the previous two sub-segments.

It is important to notice that the first two categories are also including truck and tractor units able to tow more than one trailer or semi-trailer. On the other side, the last category, along with including special utility vehicles, comprises also small trucks and freight vehicles not able to attach a trailer, along with utility vehicles.

The GVW of an HDV is an important factor that describes the size of a vehicle, thus giving information about the operation of the vehicle and possibilities of powertrain and efficiency development, as described in chapter 5.6. For example, if an HDV is classified as a truck with a GVW of 20 tonnes and three axles, there is a good probability that it might be used to tow an additional trailer, or a semi-trailer (using a dolly support). To furtherly divide these three sub-segments and better represent the differences of size in the HDV segment, the following weight classes have been considered in each of the mentioned sub-segments: less or equal to 12 tonnes, 12 to 40 tonnes, 40 to 60 tonnes and more than 60 tonnes. The considered weight refers to the gross combined vehicle weight (GCVW) for the Truck with trailers and the tractor units, meaning that the possible additional weight of the trailer/semi-trailers is included. For the Other sub-segment, just the GVW is considered. Assumptions on the towing capacities are needed for segmenting the truck/tractor units based on the gross combined vehicle weight. Since each country has different limits on the maximum weight of different types of vehicles, different assumptions are formulated for each country.

For the Buses segmentation, a different approach has been adopted. A first line of ideal separation can be drawn on the passenger capacity, following the European Directive 2001/85/EC (European Council, 2011):

- The buses with a capacity not exceeding 22 passengers in addition to the driver can be considered as a unique sub-segment, called Minibuses;
- The vehicles exceeding 22 passengers in addition to the driver are furtherly divided into two sub-segments:
    - Citybuses, predominantly used in urban traffic;
    - Coaches: non-urban long-distance traffic.

The segmentation into Citybuses and Coaches is made because Citybuses tend to have better possibilities of utilizing alternative powertrains, due to the frequent start and stop driving pattern. The differentiation between a Citybus and a Coach is, however, not very clear, at least from the perspective of this work, and some assumptions are needed to facilitate the segmentation. According to EU directive 2001/85/EC vehicles with a capacity exceeding 22 passengers are divided into three segments:

- Class I, constructed with areas for standing passengers, to allow frequent passenger movement;
- Class II, constructed principally for the carriage of seated passengers, and designed to allow the carriage of standing passengers in the gangway and/or in an area which does not exceed the space provided for two double seats;
- Class III vehicles constructed exclusively for the carriage of seated passengers;

Minibuses are in a similar way segmented into class A and B, where Class A are designed for carrying standing passengers and Class B vehicles are not designed for carrying passengers. This segmentation helps to differentiate between a Citybus and a Coach, as Class I buses often are Citybuses and Class III buses often Coaches. It is worth noting that this is an estimate and a required assumption for the modeling work. Class II buses do not have a specific and clear connotation, and have been modeled case to case, according to the different information provided by each country, and external reports, as presented in the next chapters.

5.1.1 Finland

Data on all the registered vehicles are publicly available from the Finnish Transport Safety Agency (TRAFI), and the database can be retrieved at (Finnish Transport Safety Agency (Trafi), 2017). The database presents all the registered vehicles according to a set of parameters, including date of registration, passengers, mass in running order, powertrain and GVW. The division between Trucks and Others is done using the information about the vehicle group and body type, provided in the database. Since no information is provided on the gross combined vehicle weight and the possibility to attach a trailer, assumptions on whether a certain type of vehicle could carry a trailer are needed. Since the vehicles are modeled according to the GCVW, the maximum possible weight of a truck and tractor unit with trailer/semi-trailers has been estimated according to the national regulations for the maximum permitted weight (Finnish Transport and Logistics, 2017) (Finnish Ministry of

Transport and Communications, 2013). The maximum allowed length of a heavy-vehicle combination in Finland is 25,25m, while the maximum allowed weight for heavy vehicle combinations in Finland has been increased in October 2013 up to 76t. The additional weight that a towing truck can transport with a combination of trailers is dependent on its number of axles and the GVW of the towing truck. Based on the mentioned sources, each truck and tractor unit has been assigned to a modeled weight sub-segment, with an average value of GCVW, according to the Table 5.1 below. For the buses, the passenger capacity and the buss class are known parameters. Class I buses have been assigned to the Citybus sub-segment, while class II and III vehicles are assigned to the Coach sub-segment, since no additional information can be extracted to clearly define the driving pattern.

Table 5.1: Assumptions for GCVW for trucks and tractor units in Finland.

The Min. and Max. reported GVW refer to the range of database reported weigh in which a vehicle happen to be collocated for the further segmentation.

	Truck			Tractor unit	
	2 axels	3 axels	4+ axels	-	
Min. reported GVW	3,5	20	27	3,5	20
Max. reported GVW	19	26	42	19	40
Assigned weight seg.	40-60	≥60	≥60	40-60	40-60
Assigned GCVW	43	61	61	43	50

5.1.2 Sweden

In Sweden, some data about registered vehicles can be obtained from public statistics (Transport Analysis, 2017) (Statistika centralbyrån, 2017). Additional data have been purchased from the statistics office to increase the level of detail of some vehicle segment. The split between Truck and Other sub-segment is done by combining the information about the vehicle group and body type. Moreover, information about the possibility to attach a certain load to the vehicle is also known, present through a parameter called “attachability criteria”, which specify also the maximum towing weight. In this way, the Truck and Tractor unit sub-segment can be assigned to the modeled GCVW category without assuming an average GCVW, with a higher level of confidence. In Sweden, the maximum allowed weight for HDVs has been recently increased from 60 up to 64 tonnes for a higher number of HDV classes. The maximum length is the same as in Finland, 25,25 meters (Transport Styrelsen, 2016). For the buses, the number of passengers and the bus class is known. Class I buses have been assigned to the Citybus sub-segment, while Class II and III to the Coach sub-segment.

5.1.3 Norway

In Norway, registered vehicles information can be retrieved from the statistics office (Statistics Norway, 2017). Additional information for a higher level of detail has been purchased from (Opplysningsrådet for Veitrafikken AS, 2017). The division between Truck and Other is accomplished combining information on the own statistic segments and information on the body type. Since no information is provided on the GCVW and the possibility to attach a trailer, assumptions on whether a certain type of vehicle could carry a trailer are needed. The same approach of the Finnish case has been adopted, where the GCVW is estimated from the national regulation and the available information. The maximum allowed weight and length in Norway are 50 tonnes and 19, respectively, even if in special cases a maximum of 60 tonnes and total length of 25,25 meters are also allowed (IRU, 2015) (The Directorate of Public Roads Norway, 2015). Based on the mentioned sources, each truck and tractor unit has been assigned to a modeled weight sub-segment, according to the Table 5.2 below.

Table 5.2: Assumptions for GVCW for trucks and tractor units in Norway
The Min. and Max. reported GVW refer to the range of database reported weigh in which a vehicle happen to be collocated for the further segmentation.

	Truck			Tractor unit	
	2 axels	3 axels	4+ axels	-	
Min. reported GVW	12	20	27	3,5	21
Max. reported GVW	19	26	50	20	40
Assigned weight seg.	12-40	40-60	40-60	40-60	40-60
Assigned GCVW	39	48	50	37	44

For the buses, the number of passengers is a known parameter, as well as additional information on the bus type, from which the final bus sub-segment can be assumed.

In Figure 5.2 the total fleets in 2016, segmented according to the presented assumptions, are presented. Some general considerations can be deduced from the vehicle fleets. The modeled weight classes are considering the maximum loading possibilities of each HDV, based on the available data, including additional trailers and semi-trailers. The model weight sub-segments are the starting point of the load assumptions, which are presented in chapter 5.3. The weight classes 0-12t for Truck with trailer and Tractor unit with semi-trailer do not present any vehicle in any country. This is because the HDVs that have the possibility of attaching a trailer/semi-trailer are assumed to have a higher GCVW than 12 tonnes, depending on the country regulations. The smaller delivery trucks that, based on the available data, do not have the possibility of attaching a payload are categorized in the Other sub-segment. In Finland, since higher loadings are permitted, also the 12-40t weight sub-segment for the towing HDVs does not present any vehicle, since most of the vehicles are divided between the other two weight sub-segments. The Other sub-segment is mainly composed of smaller HDVs, delivery trucks and utility vehicles which do not have the possibility to have a trailer attached. Even if the Other sub-segment appears to have the highest number of vehicles, the transport work done by the other two sub-segments is much higher, with a huge impact on the CO_2 emissions. The country with the highest number of HDVs is Finland (more than 90 000 units), followed by Sweden (81 423 units) and Norway (slightly more than 70 296 units). The ranking is inverted when looking at the Bus segment: Norway ends up to with the most vehicles (16 330 units), followed with Sweden (13 880 units) and Finland (nearly 12 000 units).

Considering as an example just the Swedish vehicle fleet, more detailed consideration can be drawn. From Figure 5.3 it is notable that in the past years the average weight of the HDV fleet has been slightly but constantly increasing. This trend can be noticed also from the age structure of the HDVs, presented in Figure 5.4: the old vehicles in the fleet tends to be lighter vehicles, especially Other HDV (≥40 tonnes) and Truck with trailers, 12-40t. However, in the last ten years, an increased amount of bigger trucks and the introduction of tractor units have taken place, leading to a heavier fleet. In Finland and Norway, similar

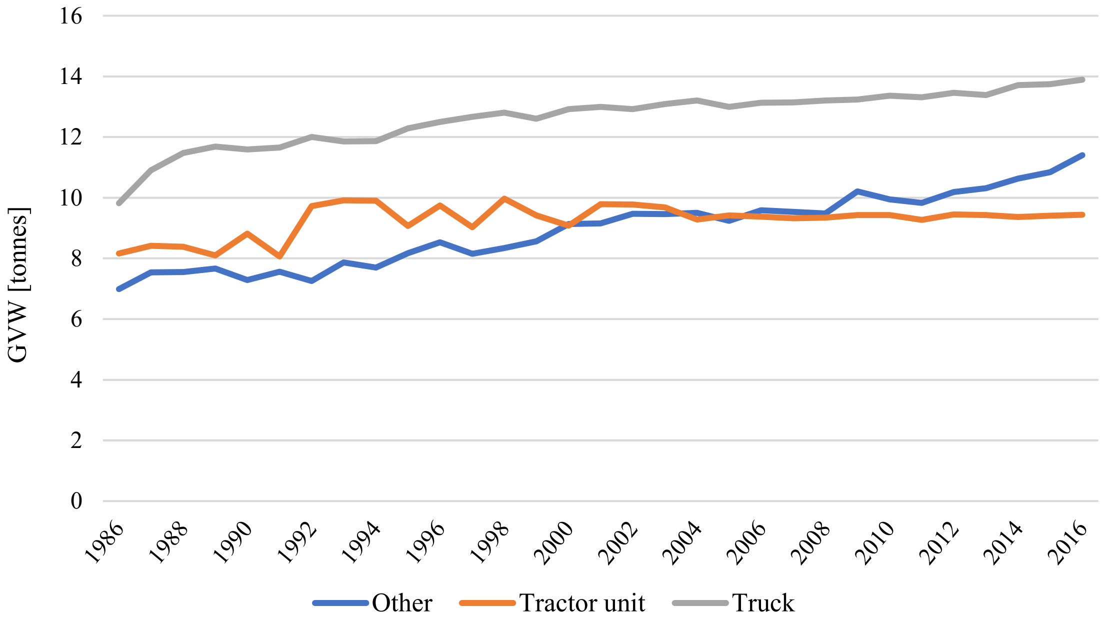


Figure 5.2: HDV average reported GVW, Sweden, historical fleet 1986-2016

tendencies can also be observed, with no remarkable differences. These reflect the increased possibilities, in the Nordics, of transporting bigger and heavier payloads, which leads to more efficient transportation and logistics services, since the fuel consumption and relative emissions per tonnes of transported goods are in this way decreased. It can also be observed that, after 10-12 years, just 50% of the new vehicle registrations are still present in the fleet. Also in Norway, half of the HDV vehicles are remaining after around 11-13 years. In Finland, the situation is slightly different, with 50% of the vehicles still registered in the fleet after around 20 years. On average, vehicles are older in Finland than in the other two countries. This trend can also be applied to the PC fleet, with the Swedish market being the more dynamic one in terms of fleet renovation. A faster fleet renovation increases the speed

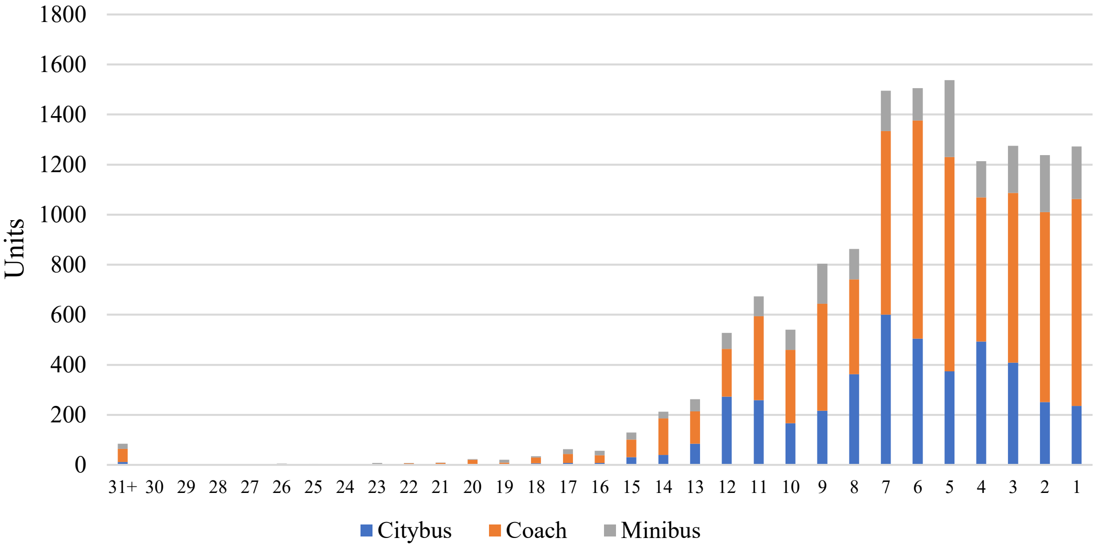


Figure 5.3: Bus fleet in 2016 in Sweden, by age and sub-segment

of adoption of new powertrains and fuel efficiency measures, thus improving the rate of reduction of fuel consumption and GHG measures.

In Figure 5.5 the age structure of the buses in Sweden is presented. The Bus segment has a very different age structure than the HDV: after 15 years, the bus fleet is almost completely deregistered or scrapped. The volatility on the new registrations is also much higher. The Coaches are the most numerous sub-segment. This may be due to the fact that all Class II buses are modeled as Coaches, possibly overestimating their number. However, there is not enough information for a more detailed segmentation, and so this assumption has been adopted. The vehicle fleets are also presented completely in Appendix 1, divided by vehicle segment and powertrain, along with the scenarios.

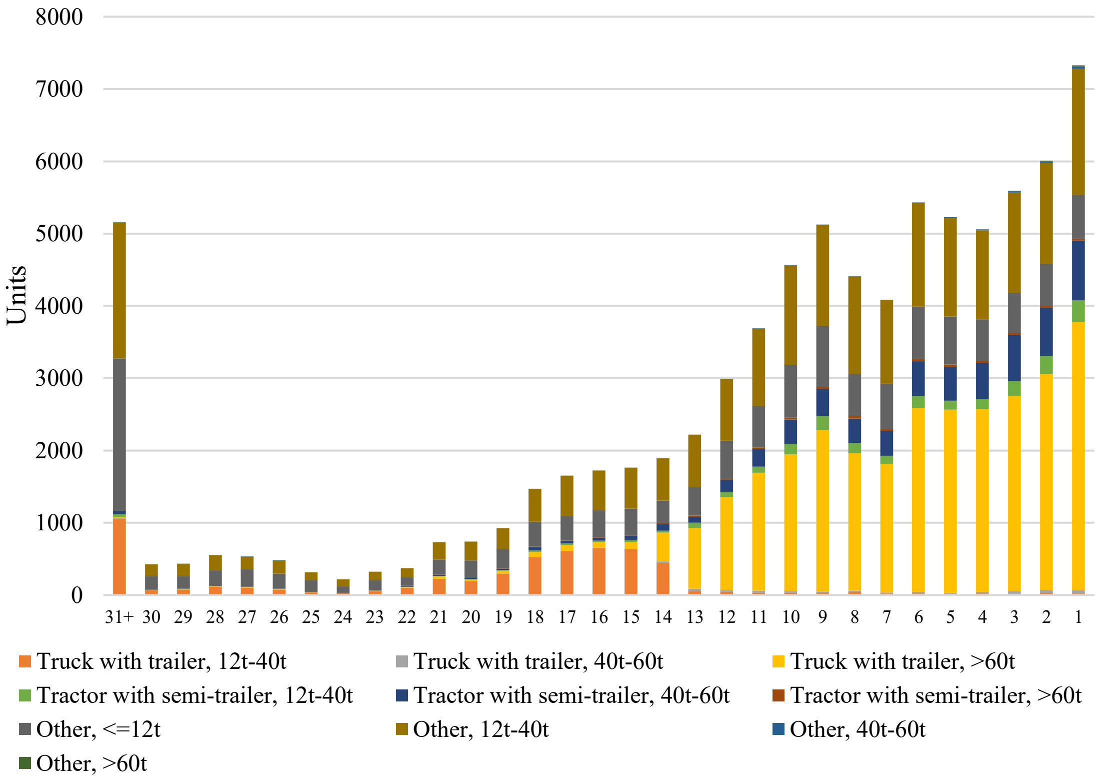


Figure 5.4: HDV fleet in 2016 in Sweden, by age and GCVW

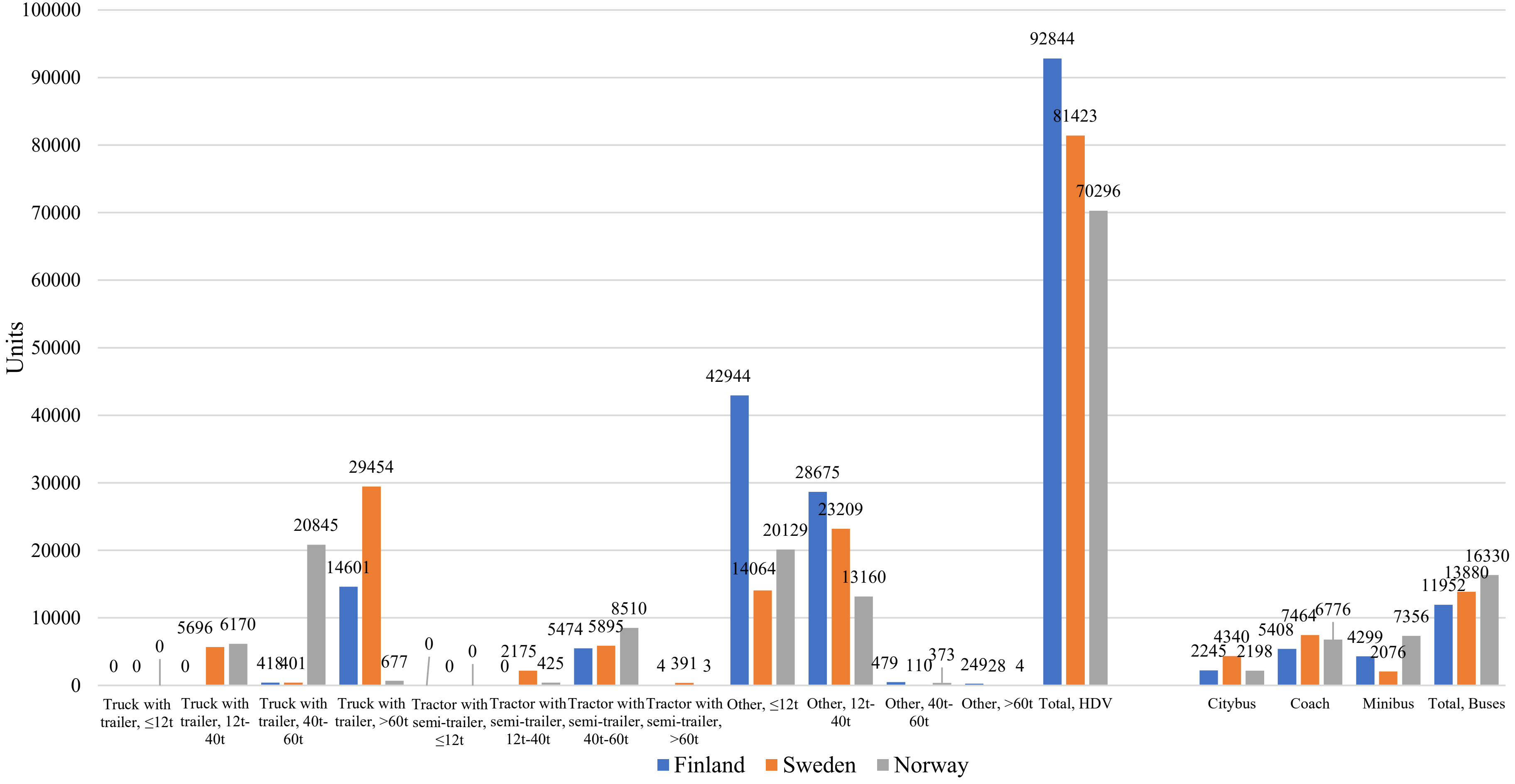


Figure 5.5: Segmented HDV and Bus fleets in 2016 in Finland, Sweden and Norway

5.2 Mileage and transport work

The mileage and transport work are central parameters for the estimation of the future fleet of a country, as well as the emissions. For HDVs and buses, the transported load has a major impact in determining the carbon emissions of the vehicle, since the fuel consumption is directly proportional to the vehicle weight. In Finland, Sweden and Norway, total driven mileage and average annual mileage have been estimated from odometer reading. These are collected during vehicle inspections, and the vehicles must be inspected periodically. The periodicity of the vehicle inspections depends on the vehicle segment and national regulations: in Sweden and Finland commercial vehicles are required to be inspected every year, in Norway utility vehicles are required to be inspected in the second year, and, after that, every year. Taxis, buses and HDVs are part of these more strictly regulated categories. The estimated share of vehicles that are covered by annual inspections is 59% in Finland, 65% in Sweden and 75% in Norway (Westerholm, 2017).

In Sweden, the average mileage is obtained through the 2012-2016 vehicle fleet from SCB, since the odometer readings are a reported parameter. The average annual mileage is calculated for each sub-segment, vehicle age and powertrain. In Finland, data about average mileage of vehicles can be obtained from Statistics Finland (Tilastokeskus, 2017), even if the level of detail is not completely homogeneous with the requirements of the model. In this case, the age distribution has been adjusted using the Swedish data. For Norway, average mileage data have been extracted from Statistics Norway (Statistics Norway, 2017); however, this resulted in a lower mileage if compared to the other two countries. For this reason, average mileage of HDV has also been extracted from (Fridstrøm & Østli, 2016), which presents higher annual mileages for trucks with trailers. The two set of data have been combined using the same age structure of Statistics Norway applied to the annual mileage for 1 years old vehicles taken from (Fridstrøm & Østli, 2016). The reporting of average mileage by vehicle segment does not always follow the segmentation used in the model. In this case, the average mileage is taken from a similar group of vehicles. As previously mentioned, the HDV segment is dominated by the diesel powertrain, in all three countries. There is not available data about the annual average mileage of powertrains different by the diesel one. However, in the powertrain scenarios alternative powertrains that are no almost non-existent will be introduced in the fleet. For these alternative powertrains, it has been assumed that the average annual mileage will be the same as the diesel ones. It has been assumed that, if new alternative powertrains will be introduced in the market, these vehicles are required to drive as much as the diesel counterparts, for being an economically viable option and not dramatically increase the costs per kilometre. The buses mileages are an estimation, since it is difficult to differentiate between Coaches and Citybuses. However, in Sweden data can be directly extracted from the SCB vehicle fleet. For Finland and Norway, estimations are needed because the reported sub-segments are different from the one used in the model. Figure 5.6 presents, as an example, the calculated final values for the annual mileage of the Bus and HDV categories, by age of the vehicle and combined sub-segments. In the modeling work, the total mileage obtained from the HDV and Bus segments has been matched with the reported one by each country statistic office, using multiplying factors. For further details on the calculation and assumptions of average annual mileages of PC and LCV, see (Westerholm, 2017) and (Kilpeläinen, 2018).

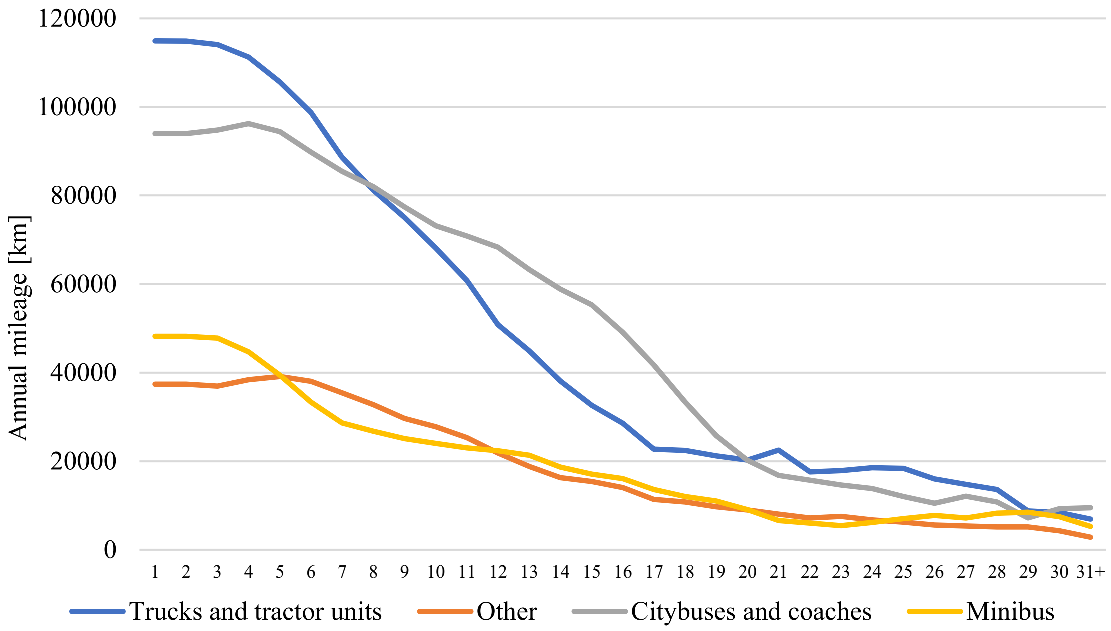


Figure 5.6: Annual mileage by vehicle age in Finland for HDV and buses

For HDVs and buses, the annual mileage is not the most critical parameter to describe the transport work that the vehicles are doing in the road transport sector of a country. HDVs and buses are vehicles designed especially for transporting goods and people, and their activity as transport work is then better described using the tonne-kilometres and the passenger-kilometre. The tonne-kilometre is defined as the transport of one tonne of goods, including packaging and tare weights, over a distance of one kilometre; similarly, the passenger-kilometre is the unit of transport work of one passenger over one kilometre. The total tonne-kilometres and passengers-kilometres of a country are usually reported by national statistics offices, and are a measure of the condition of the economic growth in the transportation sector. National forecasts on the future trends of national transport need have been developed by Finland, Sweden and Norway, and these have been used in the model to forecast the new stock of vehicles incoming in the fleet in future years (Kilpeläinen, 2018), combining the annual average mileage with the transported quantity of goods and people by each HDV and buses estimated through the weight calculation, presented in chapter 5.3.

The Finnish transport agency (Liikennevirasto), in 2014 published a national forecast on transport need development for 2030 and 2050 (Ristikartano, et al., 2014). The forecast has been developed focusing on 2030, but extended until 2050. The road freight transport has been evaluated as dependent on the industry transport intensities and structural changes in the manufacturing sector. In the past, the increase closely followed the GDP growth. However, in developed economies, this matched growth cannot keep continuing. As a result of this assumption, the road traffic volumes will be subject to a ceiling, slowing the growth of forecasted transport need compared to GDP. Road freight traffic is anyway expected to increase, also impacted by the change in the average weight of individual vehicle loads (Finnish Transport and Logistics, 2017). The historical data presented in the forecast have been compared with the ones reported by Statistics Finland (Tilastokeskus, 2017), observing that the values are comparable. Liikennevirasto forecasts the transport need growth as a growth percentage for 2030 and 2050 compared to 2012 values, 16% and 34%, respectively, for the freight transport work. Linear interpolation is calculated for the remaining years between the forecasted values. For the road passenger transport, represented by the segment buses and hugely influenced by the population growth and split in mode of transport, the same methodology has been adopted. The growth rates for passenger transport in 2030 and 2050 compared to 2012 are 10% and 15%, respectively.

In Sweden, the national forecasts for transport need are published periodically by the Swedish Transport Administration (Trafiverket). Separated forecasts are developed for freight transport and transport of people. The referred documents for this work are (Trafikverket, 2016) and (Trafikverket, 2016b). The forecasted increase in road good transport, for 2040 is 66% compared to 2012. This growth percentage rate has been applied to the historical data reported by the Swedish agency Transport Analysis (Transportarbete 2000-2015). Linear interpolation method has been used for the years between the forecasted values. Since the forecast does not include year 2050 in the analysis, for the remaining 10 years a growth factor of 14,7% has been applied for year 2050 compared to year 2040, which is coherent with the growth of the previous decades. For the road transport of people, the forecast is calculated as an annual percental growth between two periods, 2014-2040 and 2040-2060, of 0,7% and 0,6%, respectively. Historical data have also been extracted from Transport Analysis, and the annual growth rates have been applied to them.

In Norway, the agency that develops national transport need forecasts is the Institute of Transport Economics (TØI). The latest freight transport and travel demand projections have been developed in 2017 (Hovi, et al., 2017) (Madslien, et al., 2017). The forecasts refer to growth annual rates between different considered periods: 2016-2022, 2022-2030, 2030-2040, 2040-2050, which measure 2%, 2,1%, 1,9%, 2,1%, respectively. This growth rates have been applied to the historical figures reported by Statistics Norway and TØI (Statistics Norway, 2017) (Farstad, 2016). For passenger road transport, a similar method has been applied: the same time periods are considered, with annual growth rates of -0,1%, 0,4%, 0,6% and 0,5%, for 2016-2022, 2022-2030, 2030-2040, 2040-2050, respectively.

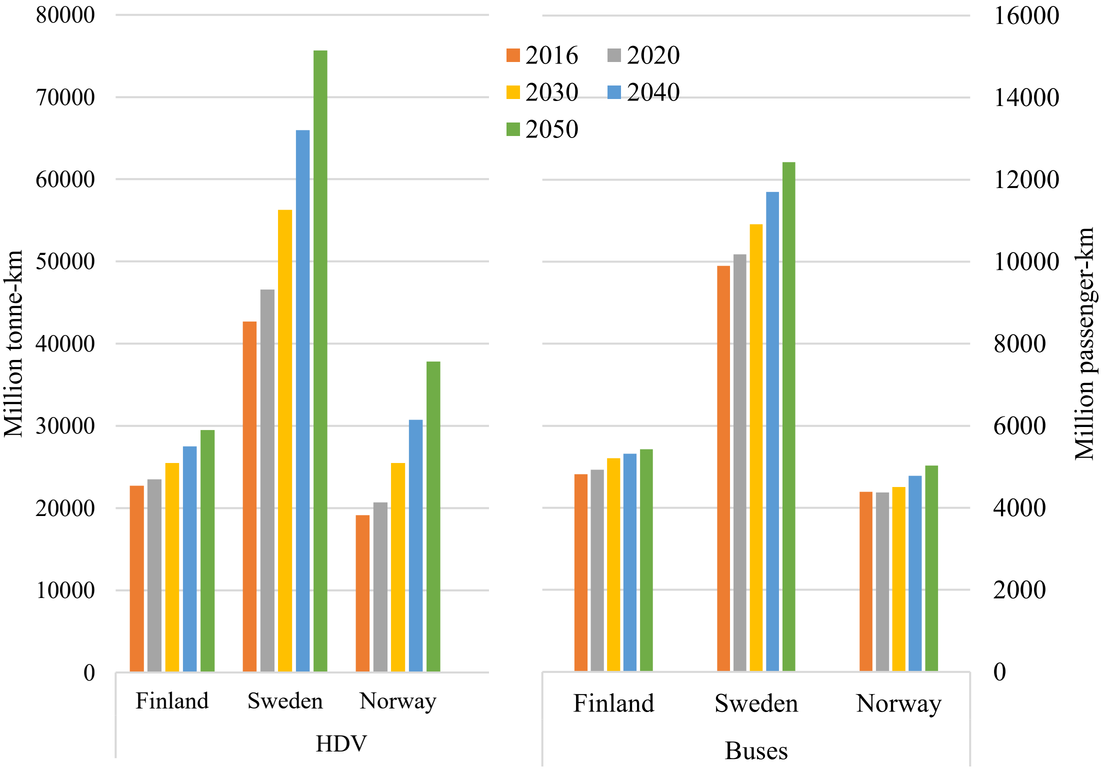


Figure 5.7: Transport need growth in Finland, Sweden and Norway

In Figure 5.7 the different adopted transport need growths are presented. As a result of the previous calculations, in between 2016 and 2030 the transport work for HDV increases in Finland by 12%, 32% in Sweden and 33% in Norway. Between 2016 and 2050, the growth rates are 30%, 77% and 98%, respectively. The country with the highest transport work nowadays, both for goods and people, is Sweden, followed by Finland and Norway. However, the forecasted growth rates are very different to each other. If the period 2016-2050 is considered, Norway presents the biggest growth in HDV transport work, almost doubling the 2016 value. Sweden has also a high forecast, while Finland HDV transport work is only predicted to grow by 30%. In the people transport sector, instead, the situation is slightly different. Between 2016 and 2050 the highest increase happens in Sweden, with 26% growth in the total passenger-km. Norway and Finland presents similar values of 15% and 13%, respectively. Since the increase in transport need is used to model the vehicles incoming in the fleet, the growth rates are crucial parameters that have a direct impact on the final results. It is important to notice that LCVs are modeled using the total mileage as transport need. This choice has been decided on the fact that the freight transportation work of the LCV segment is negligible when compared to the transportation work accomplished by the HDVs. An LCV is considered to be the same as a PC with an increased transported weight (Fridstrøm & Østli, 2016). (Kilpeläinen, 2018)

5.3 Load assumptions

The energy consumption of a vehicle has been modeled in MATERO as a linear function of the vehicle weight, called energy consumption slope. The mass for each vehicle sub-segments is then needed, to estimate the actual weight of the vehicle while running on the road, and with it, calculate the energy consumption. For estimating the actual vehicle weight, a separate set of assumptions and calculation has been developed, and is presented in this chapter. For the PC, LCV, and Bus segments, the weight of the transported passenger has been taken into consideration. The considered passenger average weight is 75 kg, to which is added an additional weight representing the "luggage" of 20kg per passenger. Moreover, to consider the freight transportation work LCV also accomplish, an additional 200kg weight per vehicle is considered: LCVs for freight transport are almost just used for urban delivery tasks, with low actual weight and high share of empty running (Fridstrøm & Østli, 2016). The average number of passengers for Citybuses, Coaches and Minibuses is estimated from publications of the national statistics and research centers, (Finland: (VTT Technical Research Centre of Finland, 2016), Sweden: (Trafik Analys, 2017b), Norway: (Statistics Norway, 2016)). However, a discrepancy in reported data for all three countries has been found: the reported transport work of buses in passenger-km is lower than the calculated one through the average annual mileage of single vehicles and the reported average number of passenger per vehicle, even with the same source of data. For this reason, the average numbers have been manually adjusted to match the reported 2016 bus transport work (total passenger-km). For LCV, an average of 1,25 passengers/vehicle has been assumed, while for PC different values per sub-segments are adopted. The assumptions are shown in Table 5.3. The mass in running order of each of the aforementioned vehicle segments by age of vehicle is directly extracted from the fleet databases. The actual vehicle weight on average in traffic for PC, LCV and buses is eventually calculated adding to the mass in running order the average number of passenger, decreased by one unit because the driver is considered, multiplied by the passenger average weight plus the luggage weight. The additional load for LCV is eventually added.

Table 5.3: Assumption on average passengers by sub-segment and weight

	FIN	SWE	NOR
	Average passengers/vehicle		
Citybus	10,8	12,0	11,3
Coach	6,5	9,5	7,3
Minibus	5,0	7,3	5,3
PC 0-1000kg	1,2		
PC 1000-1400kg	1,2		
PC 1400-1800kg	1,4		
PC 1800-2500kg	1,6		
PC 2500kg+	2,0		
LCV	1,3		
Average pass.weight [kg]	75,0		
Luggage weight [kg]	20,0		
Additional LCV load [kg]	200,0		

For the HDV, the calculation and assumption set is more complex, since different factors need to be taken into consideration when calculating the effective running load of freight vehicles. First, the mass in running order (MRO_v) of the HDV sub-segments is extracted from the databases, divided by age. From the Finnish database, it is also possible to obtain the empty weight of trailers and semi-trailers: an average value has been estimated for all three countries of 7 tonnes for a smaller trailer (assigned to the weight categories of 12-60tonnes) and 10 tonnes for a bigger one (more than 60 tonnes); a similar method has been adopted for the semi-trailers, whose weights are 6tonnes and 9tonnes, for the weight categories of 12-60 tonnes and more than 60tonnes, respectively. Towing HDVs (trucks and tractor units) are not transporting all the time an additional trailer: usually, even if, according to the GVW and the axle number, it would be possible for an HDV to carry additional weight, smaller trucks are hardly running with a trailer. Data about the share of driving mileage a sub-segment is driving with a trailer can be estimated through national surveys for logistics companies about the goods transport by road. The data have been extracted from (Official Statistics of Finland, 2017) for Finland and (Trafik Analys, 2017) for Sweden. Norway data have been estimated through the Finnish and Swedish one, considering the stricter regulations on HDV weight. The assumed shares of driving with trailer, are shown in Table 5.4. The presented shares are multiplied by the relative trailer weight to obtained a weighted average weight of a trailer that includes the vehicles running without it (MRO_t). The gross vehicle weight (GVW) and gross combined vehicle weight (GCVW) of an HDV, including possible trailers, is also extracted from the databases, as it has been previously presented in chapter 5.1.

The load factor (LF), for each sub-segment, is needed to estimate the transported quantity of goods. The load factor is the measure of the amount of loading capacity of the HDV used in average on the road, based on weight. Moreover, for the road freight transportation another parameter can be defined, the empty running (ER). This is a parameter that considers the whole road freight transport of a country, meaning the share of total mileage that is done with an empty vehicle. It can be calculated from (Eurostat, 2017), dividing the total annual empty kilometres of road freight transport vehicle movements by the total kilometres. Sweden is the country with the lowest share of empty running in 2016, scoring 17%, while Finland and Norway present higher values, 23% and

Table 5.4: Share of driving with trailer/semi-trailer by sub-segment, on the total annual mileage

	Finland	Sweden	Norway
Truck with trailer, <=12t	0%	0%	0%
Truck with trailer, 12t-40t	0%	0%	3%
Truck with trailer, 40t-60t	3%	44%	76%
Truck with trailer, >60t	75%	91%	-
Tractor with semi-trailer, <=12t	100%	100%	100%
Tractor with semi-trailer, 12t-40t	100%	100%	100%
Tractor with semi-trailer, 40t-60t	100%	100%	100%
Tractor with semi-trailer, >60t	100%	100%	100%
Other, <=12t	0%	0%	0%
Other, 12t-40t	0%	0%	0%
Other, 40t-60t	0%	0%	0%
Other, >60t	0%	0%	0%

24 % respectively (Official Statistics of Finland, 2017). The weighted average of the carried load in traffic of an HDV ($Load_{avg}$) can be then calculated as follows:

$$Load_{avg} = ((GCVW - MRO_v - MRO_t) \cdot LF) \cdot (1 - ER)$$

The weighted average of a vehicle weight in traffic (VW_{avg}) is then:

$$VW_{avg} = load_{avg} + MRO_t + MRO_v$$

The VW_{avg} is used to calculate the fuel consumption through the energy consumption slopes. It is important to notice that, especially for HDV, an alternative powertrain other than diesel can affect the transportable load because of the additional mass and volume required by the different powertrain system. For this reason, as introduced by (Fridstrøm & Østli, 2016), a relative payload factor should be accounted, as a reduction factor of the transportable load. The considered payload reduction factors compared to conventional diesel powertrain are summarized in Table 5.5. The relative payload factors presented by (Fridstrøm & Østli, 2016) have not been analyzed and discussed, but it is worth noticing that assuming no weight reduction for a FCV vehicle compared to a conventional diesel one is an optimistic assumption, also because, in the same table, a payload reduction factor for BEV of 75% is estimated. In the calculation, the VW_{avg} is multiplied by the presented factor to get the final transported load if a powertrain different than the diesel one is considered. For each vehicle of the fleet, by age, powertrain and sub-segment the load calculation is accomplished. In this way, the total HDV transport work is calculated combining the total transported load with the total HDV mileage previously calculated.

The load factor depends on the mission of the vehicle, and it can vary greatly from vehicle to vehicle. According to (Hill, et al., 2011), the payload factor for freight HDVs increases with the size of the vehicle, meaning that a bigger truck/tractor unit, especially used for long-haul transportation, has a higher utilization of the loading capacity. Reported sample values from (Hill, et al., 2011) range from 50% load factor for urban delivery HDVs to 75% for heavier HDVs. It is reasonable to derive that, for a more efficient transport system and decreased freight traffic volumes, the payload factor tends to increase, since truck fleet owners want to minimize the costs per km by utilizing at

Table 5.5: Relative payload factors by powertrain, compared to diesel powertrain. Modified from (Fridstrøm & Østli, 2016)

Relative payload factors	
Gasoline	100%
Battery electric vehicle	75%
Hybrid electric vehicle, Gasoline	95%
Hybrid electric vehicle, Diesel	95%
Plug-in hybrid electric vehicle, Diesel	90%
Plug-in hybrid electric vehicle, Gasoline	90%
Fuel cell vehicle	100%
Compressed natural gas	82%
Liquefied natural gas	90%
Flexi-fuel vehicle	100%
ED95	95%
Other	67%

most the capacity of their vehicles. However, according to (European Environmental Agency, 2017), load factors for laden trips are generally under 50%, and are slightly declining in European countries. The tendency for a more efficient goods transportation is nowadays balanced by the opposite change in the delivery services, which are increasingly proposing fast delivery services in exchange of a premium: it is then not convenient for logistic companies to increase the load factor of the laden vehicles if a fast delivery can be achieved (Adra, et al., 2010). For the purpose of this work, the load factor has been estimated in the following way. First, the total 2016 HDV mileage obtained through the model has been compared with the reported one by each country statistic office. The load factors have been estimated by matching the reported HDV transportation works in 2016 by each country with the modeled ones. The following values have been obtained, presented in Table 5.6. In Table 5.7 the total weighted average of the transported load and the vehicle weight by sub-segment and country are also presented. It is important

Table 5.6: Calculated load factors for HDV

	Finland	Sweden	Norway
Truck with trailer, <=12t	35%	45%	40%
Truck with trailer, 12t-40t	35%	35%	56%
Truck with trailer, 40t-60t	49%	46%	57%
Truck with trailer, >60t	40%	43%	57%
Tractor with semi-trailer, <=12t	35%	35%	40%
Tractor with semi-trailer, 12t-40t	40%	45%	51%
Tractor with semi-trailer, 40t-60t	40%	45%	57%
Tractor with semi-trailer, >60t	40%	45%	57%
Other, <=12t	35%	35%	40%
Other, 12t-40t	35%	35%	40%
Other, 40t-60t	35%	35%	40%
Other, >60t	35%	35%	40%

to notice that the estimated tonnes are a weighted average of all vehicle situations, including empty running, load factors and, for heavier vehicles, the share of running without an additional trailer attached. The created model allows the possibility to change each of the presented parameters for the future. Even if the historical trends are showing an increase in the average GVW of the HDVs (Figure 5.3), further assumptions have not been formulated for the mass in running order, the gross vehicle weight and the gross combined vehicle weight of the future sub-segments of the HDVs. However, since Norway is the only considered country in which the maximum allowed weight does not exceed 50 tonnes, it is possible that in the next future this weight limit can be increased to have a homogenous regulation between the Nordic countries.

Table 5.7: Total weighted average of load (first column) and total weighted average of vehicle weight (second column), in traffic by country.

	Finland		Sweden		Norway	
			[tonnes]			
Truck with trailer, 12t-40t	2,7	15,2	4,2	15,8	3,5	12,6
Truck with trailer, 40t-60t	3,0	14,2	8,6	23,2	11,2	31,0
Truck with trailer, >60t	10,9	32,2	13,8	36,6	20,5	58,1
Tractor with semi-trailer, 12t-40t	1,3	19,8	9,0	23,0	8,8	23,2
Tractor with semi-trailer, 40t-60t	10,0	25,1	11,3	27,0	12,4	28,5
Tractor with semi-trailer, >60t	15,0	40,2	15,1	38,6	17,9	37,0
Other, <=12t	0,5	3,9	0,8	5,9	0,8	5,2
Other, 12t-40t	2,7	15,2	3,0	15,7	4,4	18,4
Other, 40t-60t	4,5	33,8	5,7	30,2	6,9	26,8
Other, >60t	0,8	72,0	1,2	67,0	12,3	47,5

5.4 Energy consumption of HDV and buses

The energy consumption of the different HDV and buses sub-segments is calculated through The Handbook Emission Factors for Road Transport (HBEFA), which provides emission factors for different vehicle categories (PC, LDV, HGV, urban buses and coaches), each divided into different categories, depending on vehicle type and weight, for a wide variety of traffic situations. HBEFA has been developed by the Environmental Protection Agencies of Germany, Switzerland and Austria. In the meantime, further countries (Sweden, Norway, France), as well as the JRC (European Research Center of the European Commission), joined with their support in the HBEFA project (INFRAS, 2017). The HBEFA emission factors are used to calculate the energy consumption of the different powertrains, vehicles and segments for different years, in HBEFA identified according to the reference Euro Class. Moreover, in each weight segment, the emission factors are also presented for different loading conditions of the vehicle, at 0, 50 and 100% of the load capabilities, depending on the vehicle class considered. From a huge amount of data, that are discrete points describing the emissions on a gram per kilometre basis for a specific weight and vehicle type, a linear slope trend has been extracted for each sub-segment using linear regression. In this way, it is possible to calculate the emissions for all weights. HBEFA provides data on a country level, but unfortunately, Finland is not part of the HBEFA project. For the missing values of Finland HDVs and buses, the extracted slopes of Sweden have been used instead. It is important to note that the data provided by HBEFA are in the form of emissions per kilometre driven by the vehicle, already in a simulated real-world driving condition. The carbon emissions on an energy basis (gCO_2/MJ) have been used to convert the gCO_2/km into MJ/km. In Figure 5.8 the different energy consumption slopes for HDV and buses are shown. The graph is reporting the Swedish case, as an example. The Norwegian data do not present remarkable differences. The energy consumption slopes for different powertrains have also been calculated on assumptions. For example, the energy consumption of a powertrain whose number is not statistically relevant in the HBEFA database has been derived using the energy consumption of a similar vehicle segment. Moreover, since in the HDV and buses vehicle fleet presents mostly conventional diesel powertrain, for different powertrains a relative energy factor has been assumed, based on (Fridstrøm & Østli, 2016). These are explained in (Westerholm, 2017) and presented in Appendix 4. For further information on the energy consumption slopes, the fuel calculation and emission factors, as well as the passenger car and light-commercial vehicle fleets, see (Westerholm, 2017) and (Kilpeläinen, 2018).

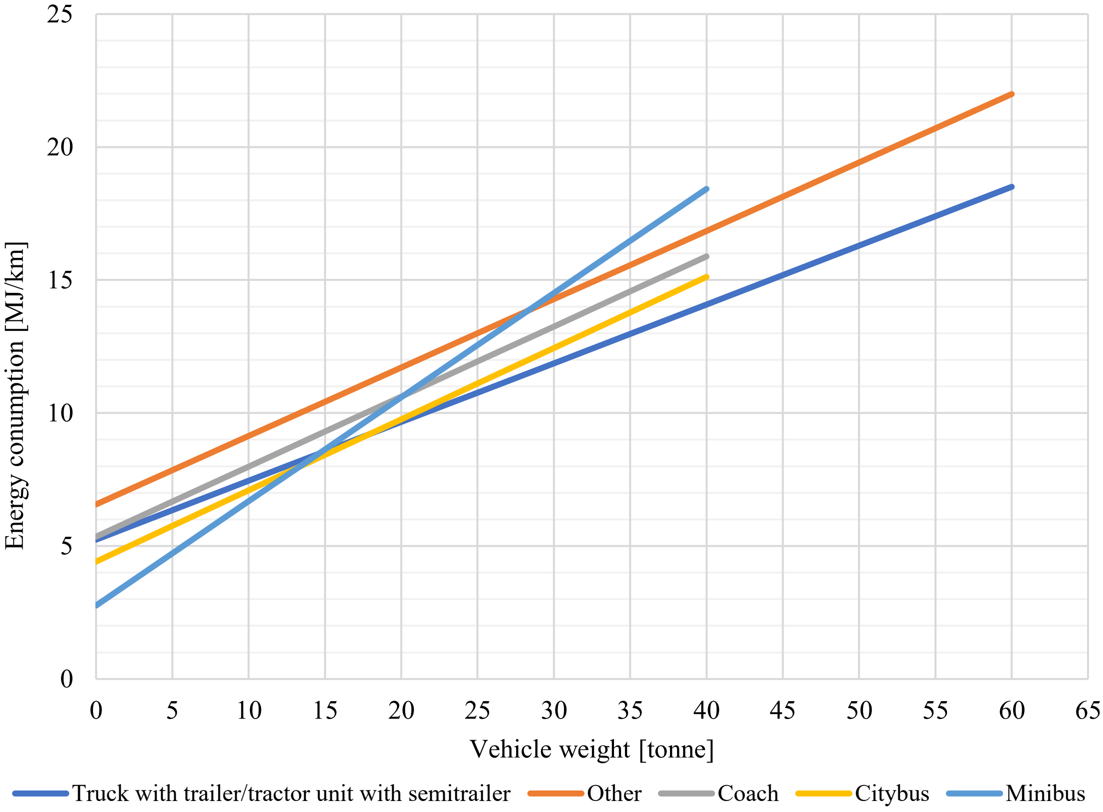


Figure 5.8: Energy consumption slopes in Sweden, for the diesel powertrain vehicles

5.5 Efficiency improvements

Every year, the average efficiency of the vehicle fleet slowly improves, as a tendency of the manufacturers to offer every year improved engines and vehicle models to reduce fuel consumption. Future vehicle efficiency improvements scenarios have been created to consider the trends. A study by Roland Berger (Slot, et al., 2016) on fuel and vehicle developments for 2030 expects that, for meeting the emission targets on PC and LCV in 2021, the annual improvement in powertrain efficiency should be in the order of approximately 4,6% until 2021, but before that year the improvements will continue at a slower pace of 0,9% annually. For LCVs, buses and HDVs, the study also expects around 1,6%, 1,2% and 1,1% annual improvements, respectively. It is noticeable that the efficiency improvements considered in the study are compounded growth rate, independently on the segment powertrain changes and the different sub-segments and types of vehicle in each segment. Also (Fridstrøm & Østli, 2016) for the BIG Norwegian model estimate the annual change in specific fuel consumption for the years 2015-2075 for ICE vehicles, in the order of -0,25% for PC, -0,37% for LCVs and -0,13% for HDVs.

For this work, the scenarios have been created based on the analyzed scenarios in chapter 4.4. As it can be noticed, however, the vehicle segments considered by (Hill, et al., 2011) and (Law, et al., 2011) are different to the ones considered for this work, also because the technology adoption considered in the studies depends on the particular category, which is characterized by a specific duty-cycle. For this reason, a different aggregation of the expected improvements is needed. For the efficiency improvements, the Truck with trailer and the Tractor unit with semi-trailer sub-segment weights are not considered, since even if the weight may be different, the same improvements can be expected in the future, as they are assumed to be following the same duty cycle independently from the weight. The allocation of the 2030 improvements following the previous studies category is shown in Table 5.8. Citybus and Coaches are considered as the same categories that are modeled. Truck with trailer and Tractor unit with semi-trailer have been considered as unique categories, both assigned to Long haul. The Other sub-segment has been divided in just three weight sub-segments, as presented. The allocation for Other and Minibus is more complicated since in our model every HDV that cannot tow an additional weight has been allocated to Other sub-segment. Minibuses are also not considered in the efficiency improvements. From the considered studies, no information can be deducted in that sense. It has been assumed that the modeled Other sub-segments present a mix of the duty cycles/categories in the study, depending on the weight. For this reason, a simple average of the showed duty cycle has been considered, because of the lack of information. Using the values in (Hill, et al., 2011), two scenarios for 2030 have

Table 5.8: Assumptions for the scenarios improvements of the modeled sub-segments

Modelled	Duty cycles
Truck with trailer	Long Haul
Tractor with semi-trailer	Long Haul
Other, <=12t	Service, urban delivery, construction, municipal utility
Other, 12t-40t	Regional delivery, construction
Other, 40t+	Long haul, construction
Citybus	CityBus
Coach	Coach
Minibus	Service, urban delivery, construction, municipal utility

been created: a “Conservative”, using the estimated efficiency improvements delineated in the business-as-usual scenario, and a “Progressive”, using the values of the cost-effective scenario. The estimated improvements refer to 2030, while in the model the efficiency improvements are inputted on an annual basis. Annual improvements have than been calculated to reach the 2030 value, assuming a linear trend until 2030. After 2030, the annual the annual efficiency improvements are decreasing every year with a factor of 0,975 until 2050. This decreasing factor represents the trend of increasingly difficult and cost-ineffective efficiency improvement in conventional vehicles for the future. All the calculated values are presented in Table 5.9. The “annual” column refers to the annual efficiency improvement set until 2030, in which column the compounded value starting from 2017 is showed, as well as in the 2050 the compounded value for that year is presented, considering the annual reduction mentioned above. PC and LCV potential efficiency improvements are not analyzed specifically in this work. The abovementioned Roland Berger study estimate the efficiency improvements of PC in the order of 4,6% annually until 2021. This very high value relates to the CO_2 efficiency of the new vehicles, and thus considers the abatements coming from electric vehicles, which are for example in the case of BEV, 0 gCO_2/km. In fact, apart from improving the efficiency of conventional vehicles, vehicle manufacturers can sell vehicles with low CO_2 emissions, such as electric vehicles, to improve their average CO_2 emissions of sold vehicles, and meet the very restrictive targets for vehicle efficiencies for 2021. These are explained in detail in (Westerholm, 2017). For this reason, Sweden model has been used to create the annual improvements for 2021. From 2009 the reported CO_2 efficiency of the new vehicles sold in Sweden has improved annually on average of around 4%. Part of these improvements are due to the electric vehicles (HEV, PHEV and BEV). In our scenarios, the indicative Swedish target is around 102 gCO_2/km, which is reached using the assumptions of the PC electric scenario and an annual efficiency improvement of 2,8%. The value has been considered too high also in relation to the mentioned studies. For this reason, the indicative value of 1,4% is set for both PC and LCV segments, between 2016 and 2021. After this, the annual efficiency improvement is 1,0% in 2022 and decreasing every year with a factor of 0,95 until 2050. Just one scenario has been created in this case, because stronger efficiency improvements of the new vehicles are likely to come from electrification.

Table 5.9: Scenarios for efficiency improvements

	CONSERVATIVE			PROGRESSIVE		
	Annual	2030	2050	Annual	2030	2050
PC	1,4%	17%	20,2%	1,4%	17%	20,2%
LCV	1,4%	17%	20,2%	1,4%	17%	20,2%
Truck with trailer	0,7%	9%	19,7%	1,1%	13%	27,4%
Tractor with semi-trailer	0,7%	9%	19,7%	1,1%	13%	27,4%
Other, <=12t	0,4%	5%	11,9%	0,6%	8%	16,8%
Other, 12t-40t	0,5%	7%	14,8%	0,7%	9%	19,2%
Other, 40t+	0,6%	7%	16,1%	0,9%	11%	23,6%
Citybus	0,6%	7%	15,8%	1,0%	12%	24,5%
Coach	0,4%	6%	12,4%	0,8%	10%	20,9%
Minibus	0,4%	5%	11,9%	0,6%	8%	16,8%

5.6 Powertrain developments in Finland, Sweden and Norway

The vehicles incoming to the fleet are estimated through the transport need forecast of each country: the missing transport work of the vehicles leaving the fleet at the end of the modeled year added to the annual transport need growth gives the total transport work that needs to be covered by the new vehicles of the next modeled year. From this, the number of new vehicles is calculated based on the single vehicle sub-segment transport work. Once the number of new vehicles of a segment is calculated, the amount is divided according to the considered powertrains depending on the development scenario. The Bass diffusion model of innovations (Bass, 1969) is used to model future market shares of different powertrains. The model utilizes a fixed market potential, or saturation level, to generate unconditional predictions, as a function of time. The Bass model thus is used to estimate the speed of diffusion of an innovation, starting from historical figures: pricing, customer preferences and choice sets have not been included in this study. The Bass diffusion has already been used in modeling the adoption rate of new vehicle powertrains in the fleet, as shown by (Jochem, et al., 2017) and (Al-Alawi & Bradley, 2013). For additional details about the modeling of new vehicles and Bass diffusion, see (Kilpeläinen, 2018) and (Westerholm, 2017).

Two scenarios have been developed for HDVs and buses, a conservative scenario, presenting slow rates of adoption of alternative powertrains, and an electric scenario, presenting developments in the adoption of electric powertrains (HEV, PHEV, BEV). However, there is a high degree of uncertainty about the future developments of vehicle powertrains. Unexpected trends may be caused by technological developments, subsidies and emission reduction targets: for these reasons, the developed scenarios need to intended not as a forecast, but as a description of the consequences in terms of fuel consumption and GHG emissions, given certain assumptions on possible developments.

5.6.1 Conservative scenario

The conservative scenario presents, as defining assumption, a slow and very limited development in the alternative powertrains adoption of HDVs and buses. As described in chapter 3, technical developments for reducing the exhaust emissions and air pollutants in the road traffic sector have been particularly pushed as a response to the adoption by the EU countries of gradually stricter regulations, introducing emission requirements for new vehicles and models. For HDVs, diesel particulate filters and selective catalytic reduction systems have become standard technologies to reduce the high NOx and PM emissions produced by the diesel powertrains. However, as shown by historical figures of the last 5 years (2012-2016, Appendix 1), in the HDV segment stricter regulations of exhaust emissions have not turned in an adoption of alternative powertrains: hybrid, electric and natural gas powertrain shares in new registrations have remained very limited if compared with the diesel ones, mainly used in special applications and developed just for some niche segments. This fact shows that, for HDV fleet owners, DPF and SCR are still a more cost-effective solution than the adoption of more expensive powertrains, whose fuel consumption benefits do not offset the increased purchase costs in a short amount of time. Since HDV powertrain electrification has not been considered by fleet owners as a cost- effective way of reducing fuel consumption, few pilot applications have been developed nowadays for heavier tractor units and trucks. For the future up to 2050, lighter HDVs up to 12 tonnes, especially urban trucks without trailer, modeled as Other sub-segment, are expected to adopt a small share of electric-hybrid diesel powertrain for increased efficiency, as well as natural gas (CNG), as measures to address stricter emission controls in urban environments in the future, aside from DPF and SCR systems.

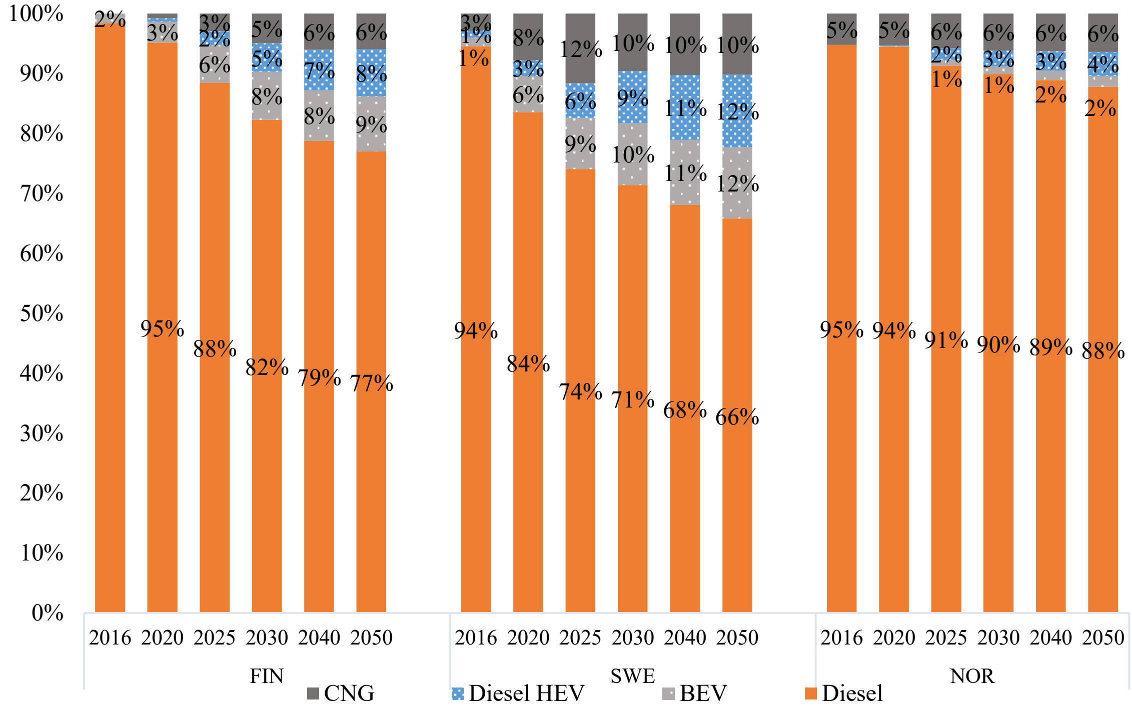


Figure 5.9: New buses registrations powertrain split in the conservative scenario

In fact, as previously analyzed in chapter 4.3, the hybrid powertrains provide higher fuel consumption benefits in an urban environment, and are more likely to be adopted in the delivery truck segment. However, the diesel powertrain is expected to maintain shares of around 93-95% of the total new registrations of HDVs, in all three countries, up to 2050.

For buses, the future powertrain situation, even in the conservative scenario, is expected to show more developments than in the HDV segment, as presented in Figure 5.9. This is because, from historical data, adoption of alternative powertrain can already be noticed, being driven by stricter emission regulations. In the past years, there has been a trend towards the use of alternative powertrains especially for citybuses in bigger urban environments. Urban transportation companies have shown the will of electrifying the urban bus fleet, pushed also by the improved public image (HSL, 2017). The same trend has been seen applied to natural gas buses: Sweden and Norway present already a relatively consistent share of CNG buses, increasing in the last years (NGV Journal, 2011). For these reasons, as modeled using the Bass diffusion, the shares of CNG buses are expected to increase. However, there is an important difference in the allocation of the new powertrains: the change in the total Bus fleet is mainly due to the Citybus and Minibus sub-segments, while the Coach sub-segments, designed mainly for highway driving, keeps being dominated by the diesel powertrain. Norwegian BEV buses developments are particularly limited because of the low number of Citybuses in the Norwegian fleet.

5.6.2 Electric scenario

The electric scenario assumes that in the future battery technology reaches the cost-competitiveness needed for being considered as an economically viable option compared to ICE vehicles, at least for certain vehicle segments. For further details on the improvements in costs and technologies of lithium-ion batteries, see (Westerholm, 2017). The very aggressive Norwegian electric scenario developed by (Fridstrøm & Østli, 2016) has been used as a benchmark for the Norway electric scenario of this work, as well as for the Swedish and Finnish ones. Electrification of the fleet is quicker in Norway, followed in order by Sweden, and Finland. These situations have been assumed following the current markets for electric vehicles, already in quick expansion for Norway, but not for Finland. Sweden lies between the two extreme country situations, presenting a moderate introduction of electric powertrains. In the electric scenario, HDVs in the lighter sub-segments are expected to see an increased share of hybrid-diesel electric powertrains. In fact, as analyzed in chapter 4.3, HEV powertrain offers moderate fuel consumption benefits for a relatively limited cost, in particular in urban duty cycles. The lighter Truck with trailers, Tractor units with semi-trailers and, above all, the Other sub-segment, are the sub-segments driving the electrification of the HDV fleet. BEV vehicles are also being introduced in the fleet for urban delivery trucks (Other <12 tonnes), while also in Truck with trailers and Tractor unit with semi-trailers sub-segments, HEV powertrains are expected to increase. BEV HDVs still take a very limited share of the new vehicle registrations because of the high-power requirements and technological challenges related to it. Natural gas HDVs are also being replaced by more efficient diesel HEV.

Buses are expected to have an even quicker and higher rate of electrification in the future. The electrification of urban buses is a trend that urban transportation companies are already achieving, as explained in the previous chapter. Moreover, also the Minibuses, operating mostly in urban environments, are expected to be heavily electrified. CNG buses are expected to be replaced by BEV and diesel HEV vehicles. Electrification of the urban buses fleets is also made possible by the fact that companies are heavily financed by the national countries, creating ambitious plans for sustainable city transportation. A feature of the electric scenario is the introduction of fuel cell vehicles. It has been assumed that, in a hypothetic electric scenario, the fuel cells vehicles in the HDV and buses segments starts to be adopted from the year 2025, as also assumed by (Fridstrøm & Østli, 2016) and (IEA/OECD, 2017). Assumed new registrations in the electric scenarios are shown in Figure 5.10 and Figure 5.11.

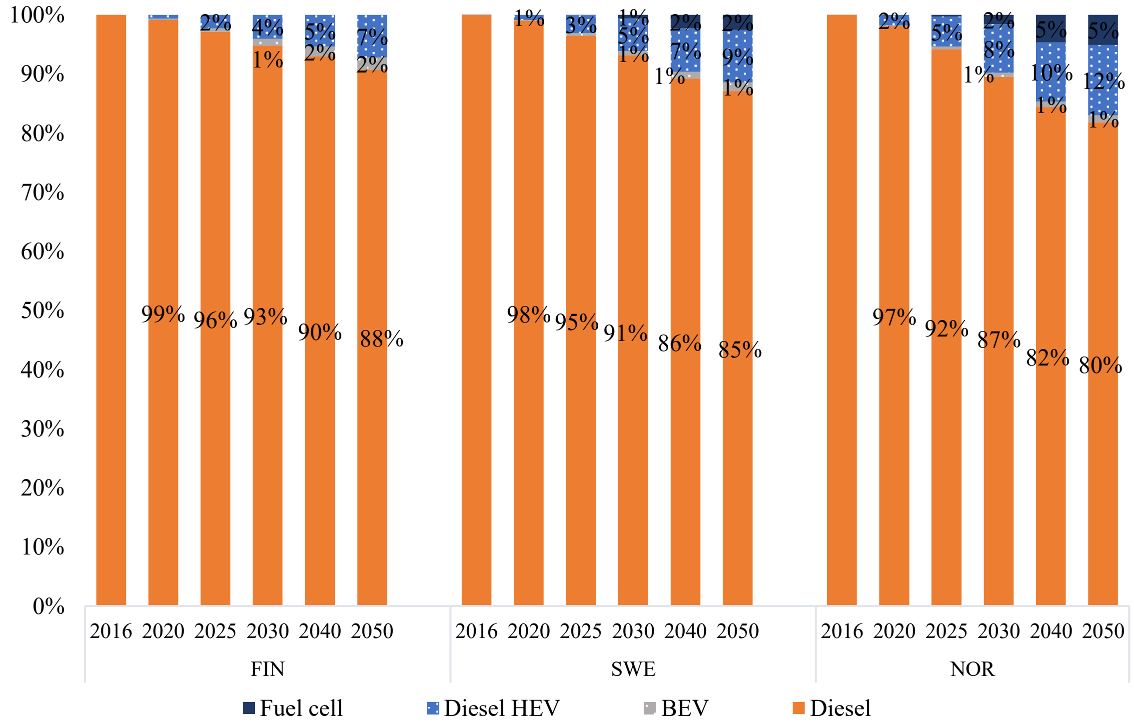


Figure 5.10: New HDV registrations powertrain split in the electric scenario

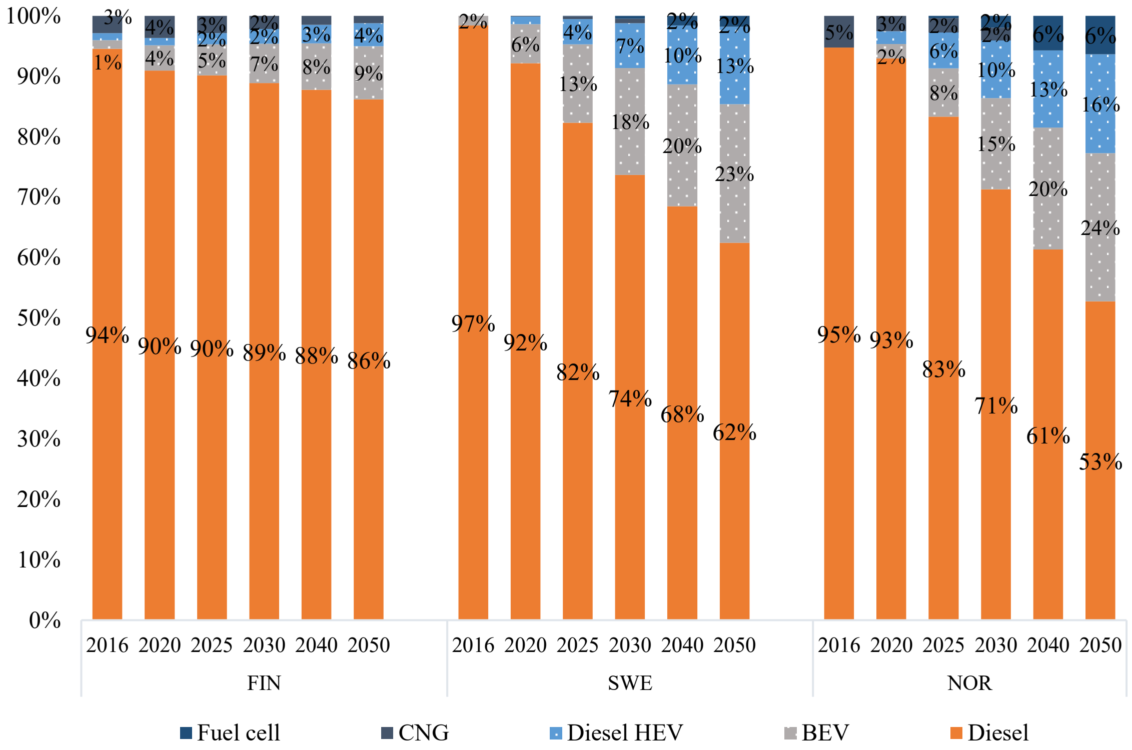


Figure 5.11: New buses registration powertrain split in the electric scenario

6 Results and considerations

The results presented in this chapter are elaborated from the scenarios of the MATERO model. It is worth noticing that, being this work based on a model created with (Westerholm, 2017) and (Kilpeläinen, 2018) for the countries of Finland, Sweden and Norway, not all the defining assumption and results are shown. Some of the presented graphs and future expectations are based on assumptions not showed in this work. The presented results will be focusing on the fleet developments and GHG emissions of the HDV and buses. Passenger car and LCV segment developments are included in the estimation of the total GHG emissions Focus will be in Sweden cases. Finnish case is analyzed in more details in (Westerholm, 2017). The conservative scenario and electric scenario results presented in this chapter refer, if not specified, to the base scenario for the fuels, and to the conservative scenario for the vehicle efficiencies. The details about the fuel scenarios are presented in (Westerholm, 2017). Following the model structure, from the energy consumption by powertrain and vehicle segment, the fuel consumption is calculated, and the carbon emissions are also derived from the fuel consumption. Different energy by powertrains can be covered with different types of fuel, and these can either be fossil or bio-based. The methodology is described in (Westerholm, 2017). The biofuels are assumed to provide 70% reduction in GHG emissions compared to the corresponding fossil fuel, on a WTW basis, while on a TTW basis the GHG emissions are of biofuels are calculated as zero. Three fuel scenarios have been created for each country, a base, a low and high, referring to the share of biofuel considered in the fuel mix. If not specified, the presented results refer to the base fuel scenario. Additional results can be found in the Appendix 1, Appendix 2 and Appendix 3.

6.1 Vehicle fleet developments

Figure 6.1 presents the HDV fleet in the electric scenario for the three modeled countries. The buses in the electric scenario are also presented in Figure 6.2. The

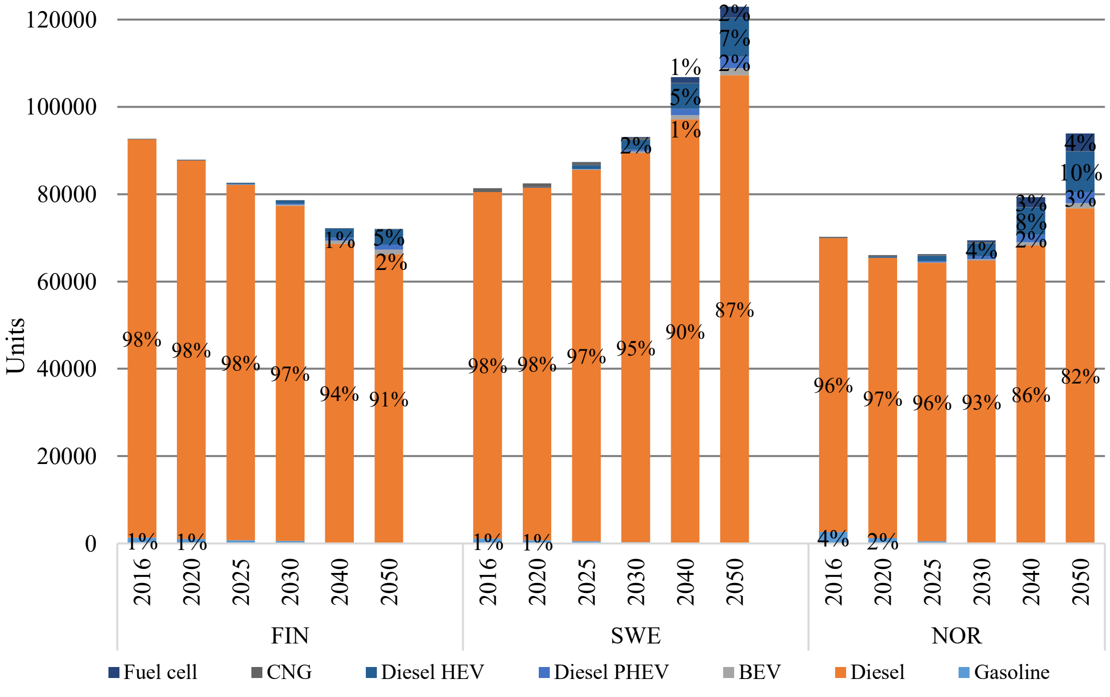


Figure 6.1: Electric scenario HDV fleet in Finland, Sweden and Norway

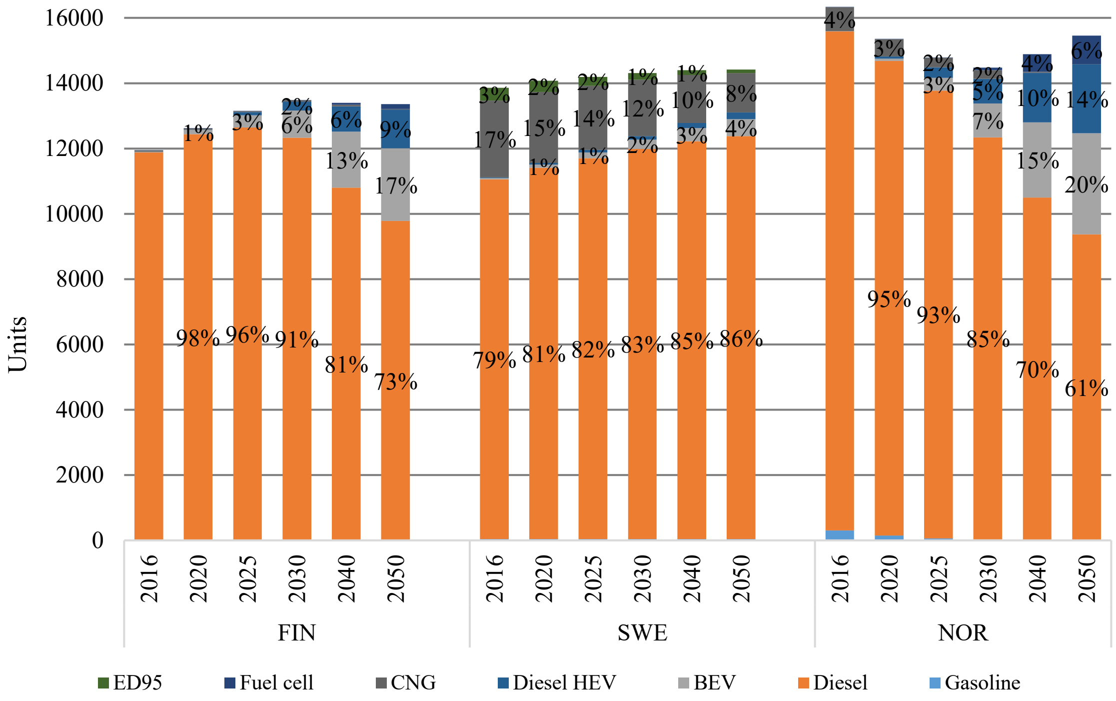


Figure 6.2: Electric scenario Bus fleet in Finland, Sweden and Norway

conservative scenario is not presented, since the powertrain developments in the conservative scenario are very minimal, and the diesel powertrain share amounts up to almost 95% in all three countries, with minor shares of CNG and Diesel HEV, especially in Norway. The vehicle fleets are anyway presented in the Appendix 1 for both conservative and electric scenarios. In the electric scenario, for HDVs, the diesel powertrain is still the dominant one, with shares of around 91%, 87% and 82% in Finland, Sweden and Norway, respectively. Finland is the country in which the developments towards electrification are slower, with 5% diesel HEV in 2050. In Sweden diesel HEVs reach around 7% and PHEVs and Fuel Cells around 2% both, while in Norway, the same powertrains amount to 10%, 2,7% and 4,3%, respectively. The fleet shares are related to the powertrain splits of new vehicles in the electric scenario, presented in Figure 5.10. The future vehicle fleet estimation is the starting point of the final GHG calculation and abatements, and is dependent on the transport need. New vehicles are calculated from the annual transport need increase and are a result of the stock-flow cohort methodology. Both the conservative and the electric scenario presents around the same number of new vehicles per year, since the transport need and weight assumptions are not changing from one scenario to another. Minor differences in the number of new HDVs sold from the conservative and electric scenario are caused by the fact that the load that can be transported by some alternative powertrains, especially the electrified, is lower than the conventional diesel one because of the mass and volume occupied by the battery. In the electric scenario, since there are more electrified vehicles, new vehicles are slightly higher because the same transport need is undertaken by more vehicles. The transportable load reduction factors for alternative powertrains are shown in Table 5.5.

For the buses, the situation is more dynamic for all three countries, and the adoption of alternative powertrains is faster. The share of BEV in 2050 in Finland is 17%, 3,6% in Sweden and 20% in Norway. Similarly, the share of HEVs is 9% in Finland, 1,5% in Sweden and 14% in Norway. CNG vehicles are slowly replaced by electric powertrains, and fuel cell vehicles are also slowly being introduced in the fleet.

The main factor that influences the development of the fleet is the transport need, which is also the main reason of the differences in the registrations of new vehicles between the three countries. As explained in chapter 5.2, the transport need for the HDV segment is measured in tonne-kilometre, and the forecast formulated by each country is leading to different estimations for the future. Total transport need increase is 12% in Finland, 32% in Sweden and 32% in Norway between 2016 and 2030. The corresponding vehicle fleets are decreasing by 15% in Finland, 1% in Norway and increasing by 15% in Sweden. Compared to 2050, the number of vehicles in Finland decreases by 22%, while in Sweden and Norway increases by 52% and 34%, respectively. These apparently contrasting developments are explained by the assumption on transported load and the mileage of the new vehicles, along with the type of new vehicles registered. According to (Tilastokeskus, 2015), the number of small HDV in Finland in decreasing, and it will continue to decrease in the future. For this reason, the share of transport work in tonne-kilometre covered by the lighter sub-segments of the HDVs, represented in this work by Other <12t, is more and more decreasing. This means that, in the future, it is expected that in Finland more transport work will be overtaken by the heavier sub-segments of the HDV fleet: Truck with trailer and Tractor unit with semi-trailer. Since the latter sub-segments have higher mileage and can transport more load, less vehicles are needed to cover the annual lost transport work by the vehicles leaving the fleet and the annual increase. Moreover, since in 2013 Finnish government increased the maximum weight limits of HDVs up to 76 tonnes, the new vehicles of the heaviest sub-segments are modeled using 76 tonnes as benchmark (see chapter 5.3), and heavier vehicles are modeled in the future. The estimated developments of the HDV fleet sub-segments in Finland are shown in Figure 6.3. In Sweden, instead, since there is no information on the future developments of the different sub-segments, the shares are set to the values of 2012-2016 also for the future. In Norway, as in Finland, (Fridstrøm & Østli, 2016) estimate that in the future more and more heavier vehicles will be adopted, to make the transportation system more efficient. This assumption is also adopted in this work, and for this reason, at least until around 2030, the HDV vehicle fleet in Norway is decreasing. However, the forecasted transport need is increasing to a so fast pace that the increasing

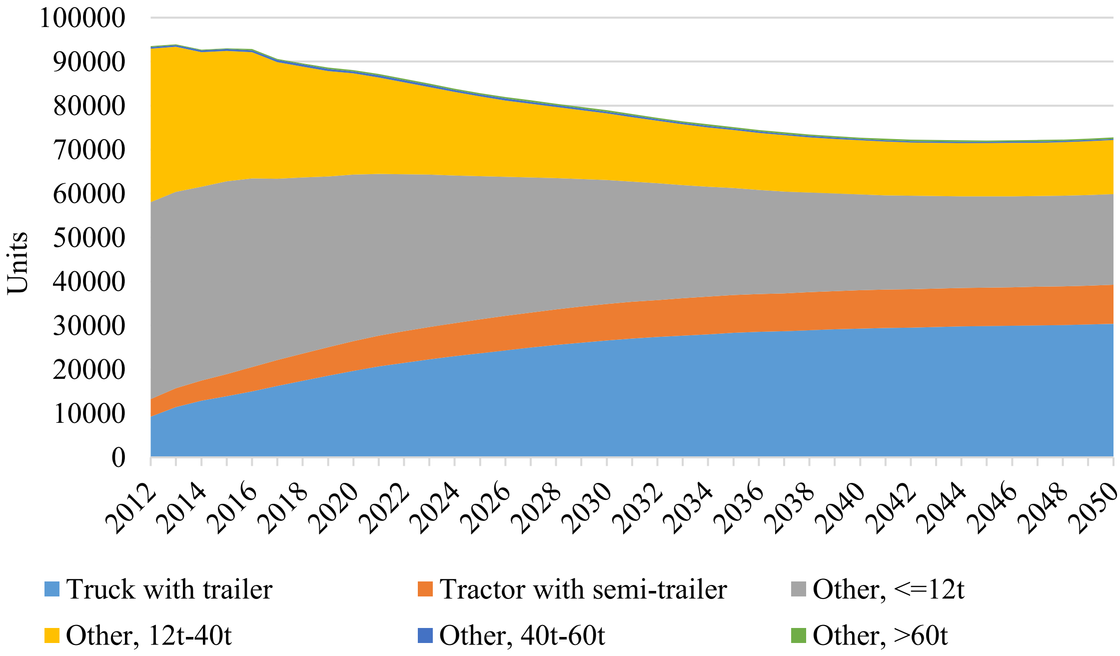


Figure 6.3: Finnish HDV fleet by sub-segment 2012-2050

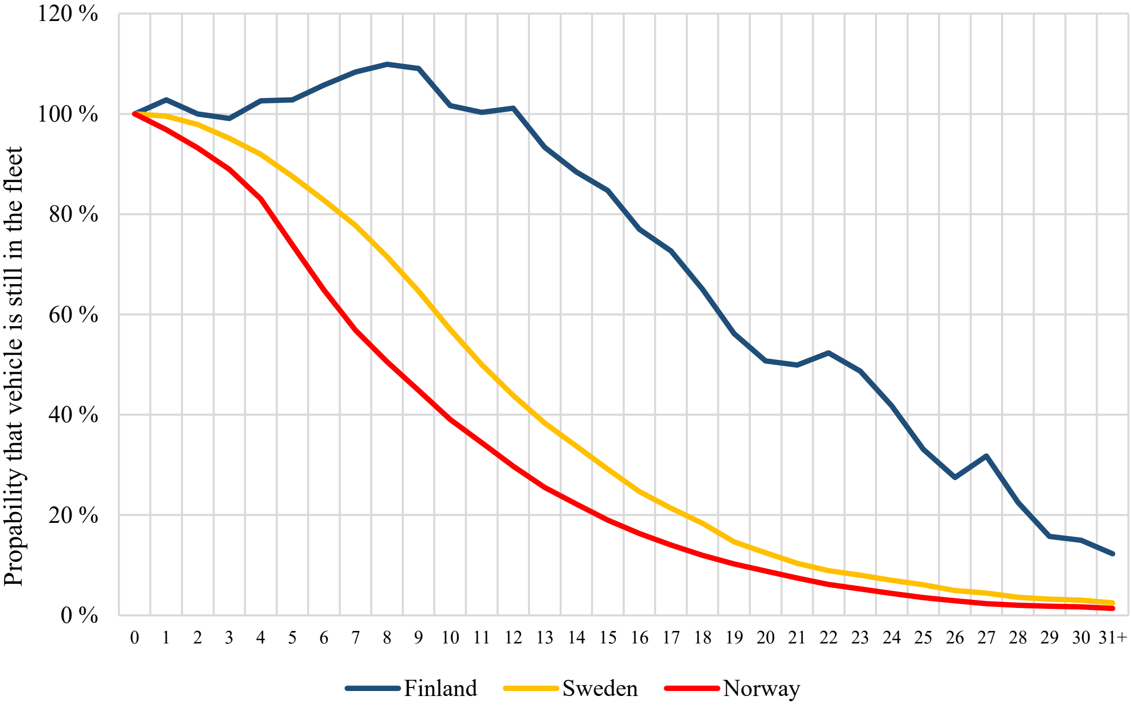


Figure 6.4: Survival curves of Truck with trailer segment in Finland, Sweden and Norway

size trend of the HDV is not enough to fully accomplish that much transport work, and the vehicle fleet eventually increases.

The vehicles leaving the fleet, and the vehicles older than 1 year old entering the fleet are modeled using the net-flow intensity rates. For a detailed explanation about the methods and the modeling meaning of them, see (Kilpeläinen, 2018) and (Fridstrøm & Østli, 2016). Some consideration on the different characteristics of the HDV in the three selected countries can be drawn from the net-flow intensity rates. As an example, in Figure 6.4 the survival rates of the Truck with trailer sub-segments are presented. The survival rates are calculated form the net-flow intensity rates, and represent the possibility that a certain type of vehicle will be present in the fleet after a given time. The differences between countries are evident. Finnish HDVs are older on average than the Swedish and the Norwegian ones, which are usually replaced at a faster pace. In fact, just after slightly less than 8 years, 50% of the Norwegian trucks with trailers have left the fleet, while the same share is reached in Sweden at 11 years, in Finland around 20 years. The Finnish fleet has then more inertia than the other two fleets. A high inertia of the fleet refers to the slow renewal of the vehicle fleet. Faster fleet renovation brings a higher number of new vehicles being registered every year, that are in general more fuel-efficient and can have a different powertrain. As a result of this, in Finland the vehicles are in general older, and the change in the powertrains and efficiency of the vehicles is slowed down: even if the share of the alternative powertrains in the new registrations is high and the efficiency of new vehicle is improving, the results of this changes can be noticed later in Finland than in Norway and Sweden, since in these countries the vehicle fleets are renovating to a faster pace. Even if the new vehicles are, in terms of emissions and efficiency, greatly improved, if the fleet has a slow renewal rate, the improvements will just be noticed after many years. On the other hand, in a more dynamic fleet, which a faster renewal, the positive improvements are noticed and benefitted earlier.

6.2 Energy consumption and GHG emissions of HDV

The fleet developments and the transport work carried out by the HDV result in the energy consumption of the vehicle fleet. As explained in (Westerholm, 2017), electric vehicles have more efficient powertrains, and in the model the energy consumption of an electric powertrain is set to be 26% of a conventional gasoline engine. In a BEV, where the electric powertrain is the only one, the energy consumption of the vehicle is then reduced by 74%, if compared to the gasoline counterpart. By following these assumption, the electric scenario is more efficient. However, the number of electric HDVs (HEV, PHEV and BEV) in the electric scenario does not reach high values, and the energy consumption of diesel powertrains remain still the most dominant one in all three countries. The total HDV energy consumption in Sweden by powertrain in the conservative and electric scenarios is presented in Figure 6.5. In the conservative scenario, diesel energy consumption in 2030 amount up to 98%, with 2% share of CNG and LNG. In the electric scenario, diesel HEVs energy consumption increase their share to 3%, increasing in 2050 up to 7%. Diesel vehicles, including diesel HEVs, are carrying on up to 98% of the transport work in both scenarios, and this is evident from the energy consumption, as the transport work is directly related to the energy consumption. In total, in the Swedish conservative scenario, the HDV energy consumption increases by 20% between 2016 and 2030, and, if compared with 2050, the increase rises to 43%. In the electric scenario, the energy consumption increases by 19% in 2030 and 39% in 2050. Similarly, in Norway, the HDV energy consumption increases by 22% in the conservative scenario in 2030, and by 58% in 2050; in the electric scenario, it increases by 20% in 2030 and by 53% by 2050. In Finland, however, the total HDV energy consumption is slightly decreasing: in the conservative scenario, the decrease is 4% in 2030 and 3% in 2050, while in the electric scenario, these values are both 5%. The decrease in Finland, can be explained by the low increase in the forecasted transport need combined with a more efficient fleet of heavier and bigger vehicles. The number of HDV vehicles is

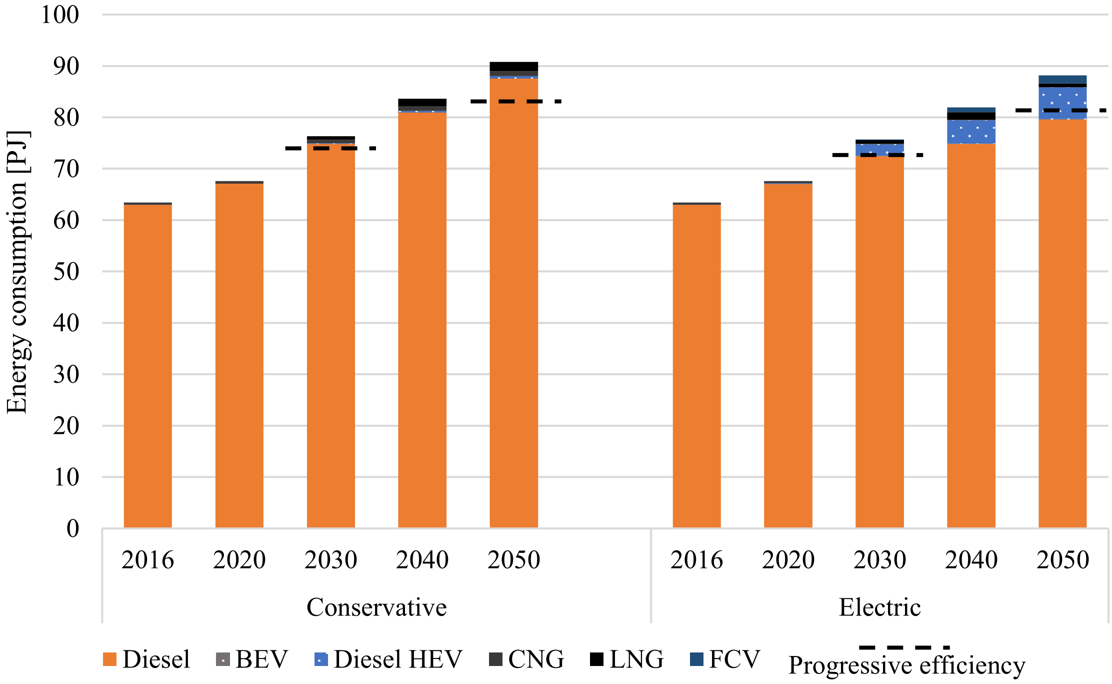


Figure 6.5: Energy consumption of HDV by powertrain in Sweden.
The dashed lines represent the energy consumption for that year if the progressive efficiency scenario is considered.

decreasing, as seen in the previous chapter, by 15% in 2030, but the energy consumption should be related to the transport work, rather than the number of vehicles. A more efficient transport system is composed by less vehicles that are carrying on the same transport work. In Sweden and Norway, the efficiency of the transport system does not increase to the level of offsetting the high estimation of the transport need. Even if in Norway, heavier vehicles are introduced in the fleet, the maximum allowed weight is still 50 tonnes, which is considerably lower than the 76 tonnes in Finland and 64 tonnes in Sweden. The estimation of the future transport need is even the highest (see chapter 5.2). For this reason, the increase in the energy consumption is even higher in Norway. The efficiency improvements have a noticeable impact in the energy consumption. As mentioned, the improvements of the vehicle efficiency are calculated and introduced in the new registered vehicle of each year. For this reason, the inertia of the fleet has a major impact, slowing down the effects on the whole vehicle fleet. The results presented above refer to the conservative efficiency scenario, presented in chapter 5.5. If the progressive efficiency scenario is considered, the energy consumption of the fleet is expected to decrease in comparison with the conservative ones. In Figure 6.5, the dashed lines represent the HDV total energy consumption in the selected years and powertrain scenarios, if the progressive efficiency scenario is considered. In 2030, the energy consumption is decreased by around 3% and by around 8% in 2050, in both the conservative and electric powertrain scenarios. It is worth noticing that the magnitude of the decrease in energy consumption brought by the efficiency improvements is increasing considering a longer period, since more efficient vehicles are added to the fleet and the older inefficient ones are being replaced.

From the energy consumption, the TTW and WTW carbon emissions are calculated using the carbon intensity of each fuel considered in the fuel scenario. In the considered base fuel scenario, the share of biofuels is set to be 30% in 2030 in Finland and Norway, and 57% in Sweden, on a physical energy share, from the shares in 2016 of around 5% in Finland, 22% in Sweden and 10% in Norway. The development of the WTW emissions from HDV in the electric scenario is presented in Figure 6.6. In Finland, the HDV WTW emissions are decreasing by 29% between 2016 and 2030, in Sweden by 31% and in Norway by 5%. However, considering the correspondent values in 2050, in Finland and Sweden the decrease stops at 29% and 30%, respectively and in Norway the emissions

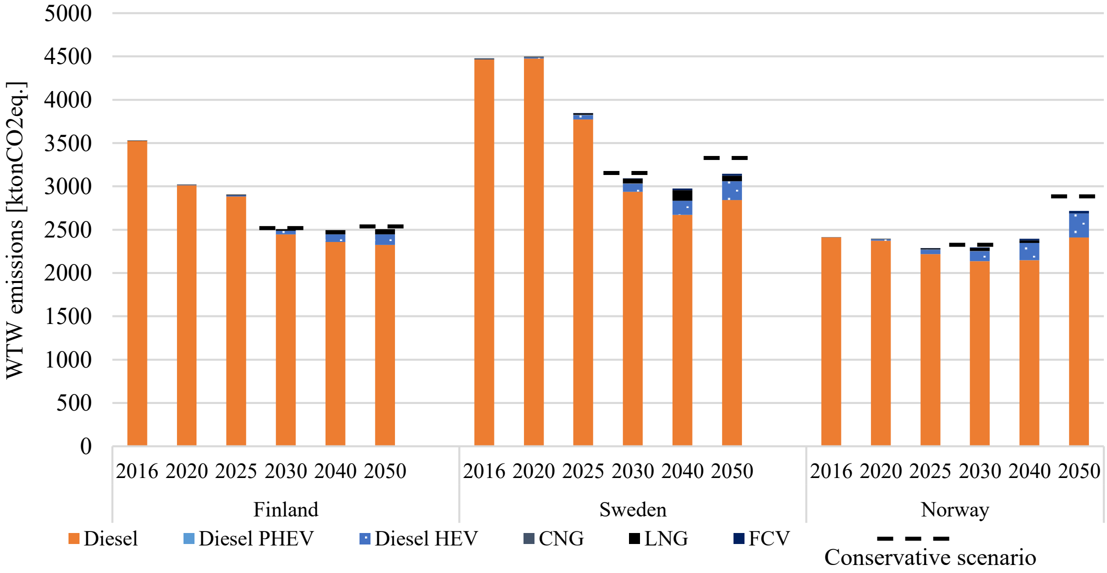


Figure 6.6: HDV WTW emissions in the electric scenarios.
The dashed lines represent the HDV WTW emissions for that year for the conservative powertrain.

are even expected to increase by 12%. The reason for these differences has to be found in the diesel fuel composition assumptions for 2030 and 2050. The main biofuel options in for substituting fossil diesel fuel are hydrotreated vegetable oil (HVO) and fatty acid methyl ester (FAME). In the base scenario in Sweden, the volumetric share of HVO in diesel fuel reach 73%, while FAME 7% (the maximum allowed in the fuel standards). In Finland, the shares of HVO and FAME reach 34% and 7% and in Norway 33% and 7%, respectively. This means that the bio shares of diesel fuel are greatly increased in all three countries from the current situation, and then the WTW emissions are expected to decrease. The biggest increase is assumed in Sweden, and, for this reason, even if the energy consumption of HDV increases by 19% in 2030, the WTW emissions decrease by 31%. In the base fuel scenario, after 2030, the shares of the different components are set constant as in 2030. Because of this, after 2050, in Finland and Sweden the WTW emissions are not keeping the decreasing trend and flattens, in Norway, an increase compared to 2016 can be noticed due to the high increase in the transport work of HDVs.

The WTW emissions of the electric powertrain scenario do not differ much from the WTW emissions in the conservative powertrain scenario, keeping constant the other scenario inputs. The dashed lines in Figure 6.6 represents the total HDV emissions of the conservative scenario. The biggest difference is in Norway, where the share of electric vehicles is higher than in Finland and Norway. However, the expected emission reduction due to the alternative HDV powertrains is around 6,5% in Norway and 5% in Sweden, passing from 2910 to 2717 ktonCO$_2$-eq., and from 3307 to 3146 ktonCO$_2$-eq., respectively.

6.3 Total road transport developments

In this chapter, an overview of the vehicle fleet developments, fuel and energy consumption, and carbon emission is presented for Sweden case. Passenger cars and LCV will also be included in the analysis to assess the whole road transport sector.

In Sweden, in 2016, passenger cars are the biggest segment, with 88% of the vehicle fleet, 82% of the total driven mileage and 65% of the total WTW emissions. Light commercial vehicles make up to 10% of the total vehicle fleet, 11% of the total mileage and 10% of the total WTW emissions. HDVs represents 1,5% of the total vehicle fleet, 6% of the total mileage and 21% of the total WTW emissions. Similarly, buses account for 0,3% of the vehicle fleet, 1% of the mileage and 3% of the total WTW emissions. It is worth noticing the large share of the HDV WTW emission, compared to the small number of vehicles if the total road fleet is considered.

The passenger cars are divided in this work into five different sub-segments based on their weights. Considered weight sub-segments are vehicles up to 1 tonne, 1 to 1,4 tonnes, 1,4 to 1,8 tonnes, 1,8 to 2,5 tonnes and more than 2,5 tonnes. PC are considerably lighter than HDVs and buses, and the related specific energy consumption and emissions are roughly six times less than the average HDV. The transportation work of passenger cars is the annual mileage, and the emissions are directly related to it. The average annual mileage is also lower for PC than HDVs. However, despite the lower mileage and lower fuel consumption, because of their big number, passenger cars segment is currently responsible for most of the driven mileage on road, as well as fuel consumption and emissions in the road transport sector. Passenger cars are indeed the biggest road transport segment for number of vehicles in all three countries: in Finland, PC accounts for 86% of the fleet in 2016 and 82% in Norway, for number of vehicles. The share of total driven mileage is 81% in Finland and 78% in Norway, and the share in total WTW emissions is 60% in Finland and 58% in Norway. LCVs are considered in this work and one unique segment, without further weight or type segmentation. Light commercial vehicles do not present big differences in the annual activity and energy consumption, as the main task and operation cycle is the urban delivery. LCVs usually account for the second biggest share in the vehicle fleet for number of vehicles, but on fuel consumption and emissions are overtaken by HDV transport, since the average annual mileages are lower and the transported load negligible if compared with HDVs. For these reasons, the critical parameter that has been used to represent the transport work of LCV is the annual mileage. There is a noticeable difference in the annual driven mileage by a diesel PC and gasoline PC. On average, in the annual values used in the model, the mileages of diesel passenger cars are around 20% higher than BEVs, PHEVs and HEVs.

Compared to the HDVs, which are dominated by the diesel powertrains, PC and LCV segments have adopted a wide range of different powertrains. Conventional gasoline vehicles take the majority most of the PC fleet in 2016 in Finland and Sweden, with share of 72% and 61%, respectively. In Norway, however, gasoline PCs account for just 45% of the fleet, while the conventional diesel share is 47% in Norway, 27% in Finland and 33% in Sweden. In the last years, pushed by the targets on reported CO_2/km emissions for year 2021 (95 CO_2/km, on the weighted average of new vehicles) and the more and more strict air pollutant regulations in Europe, the vehicle manufacturers have started a trend towards the electrification of new vehicle models, and this has particularly taken place in the Norwegian market. PC new registrations in Norway in 2016 show the increase of BEV up to 16% (already 4% of the total fleet), 13% of gasoline PHEV, 11% of gasoline HEV and 1% of diesel PHEV. In Finland, it is notable 4% of gasoline HEV in new PC registrations and in Sweden 1% of BEV, 2% of gasoline PHEV and 4% of gasoline HEV. The powertrain scenario for PC and LCV are described in detail in (Westerholm, 2017). PC and LCV follow roughly the same powertrain development trend, with minor difference in the adoption of electric powertrains and phasing out of diesel. The electric scenario expects a phasing out of diesel powertrains, that are being replaced by electric ones. By the year 2030, the shares in new registrations of BEV in Finland, Sweden and Norway accounts for 30%, 36% and 43%, respectively. Conventional gasoline vehicles are also replaced by gasoline PHEV and gasoline HEV, but at a slower rate than conventional diesel. Gasoline HEV and PHEV new registration shares in 2030 account for 43% in Finland, 46% in Sweden and 48% in Norway. The forecasted transport need is significantly increasing in Norway and Sweden, and, at a slower rate in Finland too, according to the national forecasts. Between 2016 and 2030, transport need for PC is expected and modeled to increase by 10% in Finland, 13% in Sweden and 15% in Norway. Moreover, due to the phasing out of diesel vehicles, which have a higher mileage, more vehicles need to be registered in the fleet to cover that missing mileage. Because of the increasing forecasted total mileage, new powertrain split and the phasing out pf diesel vehicles, the number of passenger cars in the vehicle fleet is growing by 5 % in Finland, 11 % in Sweden and 25 % in Norway between 2016 and 2030.

Because of the new powertrains and the improved energy efficiency of the new vehicles assumed in the analyzed scenarios, the energy consumption per kilometre (MJ/km) of all vehicle segments is increasing. The new registered vehicles in the electric scenario are, between 2016 and 2030 more efficient by 45% for PC, 36% for LCVs, 10% for the HDVs, and 15% for buses.

The fuel scenarios have a large impact on the road transport WTW emission of a country. The fuel scenarios are described in detail in (Westerholm, 2017). In Sweden, the share the physical energy share of biofuels is above 20 % in 2016, considering the whole fuel mix. The renewable share of diesel is roughly 31 %, and 3,3 % for gasoline. For the base scenario, the biofuel physical energy share for 2030 is set to be 57%, with the volumetric share of ethanol in gasoline assumed to be 14 %, and the volumetric share of FAME and HVO in diesel to be 7 % and 73 %, as previously mentioned.

As a result of the mentioned assumptions and scenarios, the energy consumptions and GHG emissions in the electric scenario in Sweden are presented in Figure 6.7. Before looking at the total values, the different vehicle segment shares present results worth noticing. Due to the fast electrification of passenger cars and light commercial vehicles, meaning the adoption of a more energy efficient powertrain than the conventional ICE ones, the share of consumed energy by the PC decreases consistently, and the HDV share increases consequently. The energy consumption of PC decreases from 63% of the total in 2016 to 56% in 2030 and to less than a half, 48% in 2050. Therefore, the energy consumption share of HDVs increases from 22% in 2016 to 29% in 2030 and to 38% in 2050. In the other two countries, the same trend can be observed. In the Finnish electric scenario, the PC energy consumption share decreases from 60% in 2016 to 57% in 2030, while HDV the energy consumption share of HDV is increasing from 25 % in 2016, to 27 % in 2030 and 34 % in 2050. For Norway, the share of energy consumption by HDV increases from 20 % in 2016 to 27% in 2030 and 36 % in 2050, while the PC share decreases from 57% in 2016 to 51% in 2030 and 46% in 2050. Buses and LCV energy consumptions are roughly keeping the same share in all three countries, without important changes. The very slow electrification of the HDV segment, combined with the big forecasted increase in the transport need and the big reliance on diesel powertrains for the years to come, are expected to shift the energy consumption from the PC segment towards the heavy-duty segment. Since the diesel powertrains will remain the most dominant one in the HDV segment, the need of liquid diesel fuel will likely remain at very high levels in the future, even if a possible phasing out of the diesel powertrain in the PC segment is expected. This trend can be noticed also from Figure 6.8, where the total energy consumption by energy carrier is presented for all three selected countries. It was noted in the previous chapter that, apart from a small decrease of the HDV energy consumption in Finland, in Sweden and Norway the energy consumed by the HDV segment is significantly increasing, in both electric and conservative scenario, due to the high forecasted increase of transport need. However, if the whole vehicle fleet is considered, the situation is very different. Even if the high increase in transport need is also expected for the passenger car and LCV segments, the energy consumption in the electric scenarios is decreasing in all three countries. In Sweden, the total energy consumption is decreasing

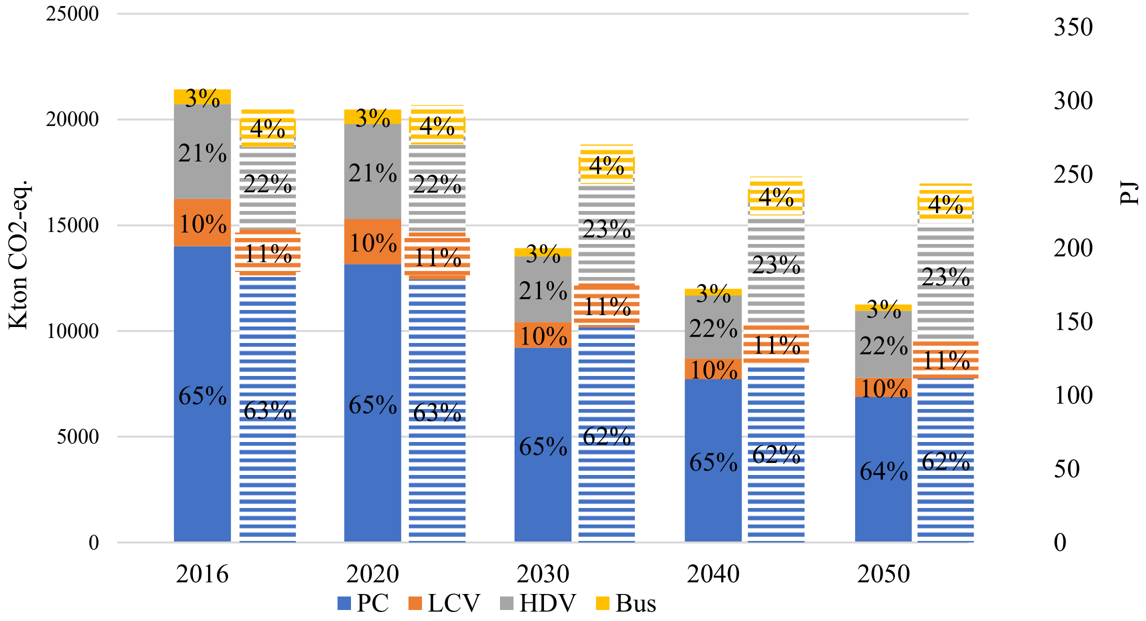


Figure 6.7: Total road transport GHG emissions and energy consumption by vehicle segment. Striped columns represent the energy consumption. Shares of the total are also presented.

by 9% between 2016 and 2030, and by 18% by 2050. In Norway, the reduction by 2030 is 12% and 16% in 2050 and in Finland 12% by 2030 and 31% in 2050. This is caused by the decrease in the energy consumption of passenger cars and LCVs, mainly caused in turn by the electrification. In fact, as the diesel energy consumed by PC is constantly decreasing, the diesel energy consumption of HDV is increasing. Moreover, PC gasoline energy consumption is expected to decrease at a slower rate than PC diesel, because the main electric hybrid powertrains (HEV and PHEVs), having a high share in the new registrations, are expected to be gasoline HEVs and PHEVs. Even with an aggressive electrification of the passenger car and light-duty vehicle fleets, liquid diesel consumption will remain still high. Figure 6.9 presents the liquid diesel fuel consumption in Sweden, divided by the vehicle segments. Diesel consumption is including fossil diesel, HVO and FAME components. It is notable the decreasing trend of the passenger car and LCV segments, while the HDV fuel consumption is constantly increasing. Compared to 2016, the volume of diesel fuel consumed by PC decreases by 23% in 2030 and by 61% in 2050. This decrease is balanced, but not completely, by the HDV consumption going from 1787 million liters in 2016 to 1942 million liters in 2030, an increase of around 9%. In 2050 the HDV diesel fuel consumption increases by 12%, compared to 2016. Similarly, in Norway HDV diesel consumption increases by 4% in 2030 and by 11% in 2050. In Finland, however, because of the lower increase of transport work and more efficient good transportation due to the bigger size of the heavy vehicles, the HDV diesel consumption decreases by 9% in 2030 and 19% in 2050. In total, diesel consumption decreases in Sweden by 9%, 18% in Finland and 26% in Norway.

The GHG emissions are calculated based on the fuel scenarios, where different shares of biofuels are assumed. The national reduction targets introduced in Figure 1.1, are compared with the calculated total TTW GHG emissions in Figure 6.10. Road transport emission reduction targets for 2030 are for Finland 50% compared to 2005, 70% compared to 2010 for Sweden and 55% compared to 2015 for Norway. The modeled GHG emissions are decreasing in all three countries. In Finland, the reduction in 2030 compared to 2016 is around 36%, in Sweden 47% and in Norway 40%. However, as it can be seen from the figure, the national targets are not met with the considered assumptions: electric powertrain scenario, base fuel scenario and conservative efficiency

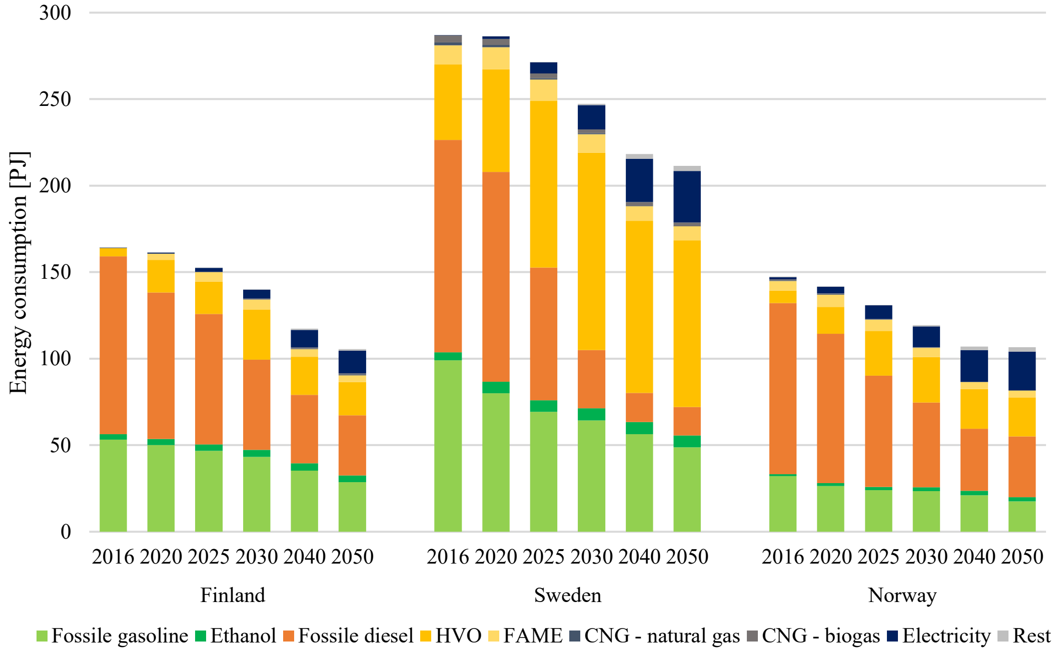


Figure 6.8: Total road transport total energy consumption in the electric scenario by energy carrier

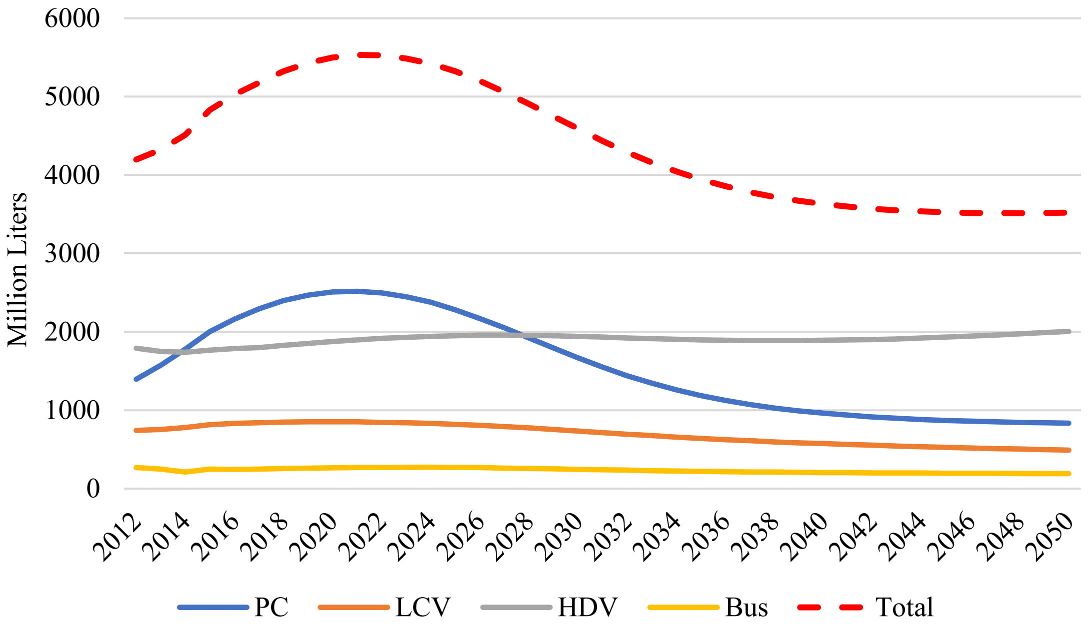


Figure 6.9: Liquid diesel consumption in the electric scenario in Sweden by vehicle segment. Diesel refers to the sum of fossil diesel fuel, HVO and FAME.

scenario. The main cause of this is the big expected increase in the transport need for all vehicle segments, that balances the increasing uptake of electrified vehicles in the market and the increased share of biofuels in the future. Additional measures and more aggressive scenarios need to be assumed to meet the expected targets. In Finland, the 2030 target would be met with 40% physical bioenergy share in the fuel mix, corresponding to the high biofuel scenario, and an improvement on the new vehicle efficiency that is 1,5 times higher than the conservative vehicle efficiency scenario. The target would be also met with a volumetric share of biodiesel of 68%, meaning a total physical bioenergy share of 45%. In Sweden, because of the ambitious target, the target would not be met even with a 100% biodiesel share, meaning 67% total bio share. Just an increased uptake of electric vehicle, including also in the HDV fleet, would make the target achievable. In Norway, that target can be reached with a high fuel scenario (total fuel bio share set to 40%), and an improvement in the new vehicle efficiency 3 times higher than the assumed conservative efficiency scenario. alternatively, the target can also be met with a 51% physical bioenergy share (71% of biodiesel).

A large set of different scenarios and assumptions have been created for the model. The variability and the different estimation methods for the created assumption challenge the understanding of the impact of some specific input parameters. Some considerations can be drawn anyway. It is clear, to this extent, that the forecasted transport need, as an input parameter of the model, plays an important role in the future emissions and fuel consumption, especially for the HDV segment. However, the uncertainty concerning the national transport need forecast is very high, considering that the estimations depend on long-term projections of population growth and developments of the economic activity and its structure. The load factors are also estimated for different HDV sub-segments, as presented in Chapter 5.3, and, as it was noted for the Finnish case, it can greatly influence the energy and fuel consumption, and consequent emissions of the HDV segment. For these reasons, the relation of the transport need growth on the TTW emission and fuel consumption has been tested for the Swedish case, to estimate its impact. Also, the load

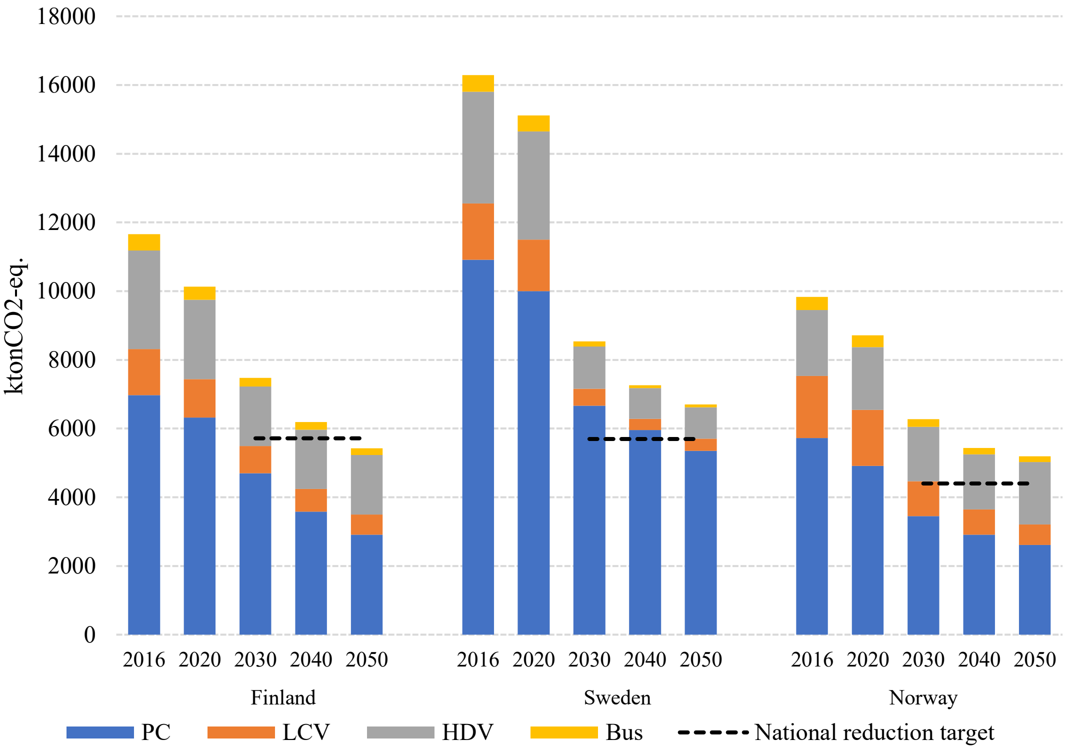


Figure 6.10: Total road transport TTW emission by segment in the electric scenario. Comparison with national reduction targets

assumptions of only HDVs have been varied, to quantify the impact on the diesel consumption. The results are presented in Table 6.1. The analyzed results refer to the electric powertrain scenario in Sweden, with the base fuel scenario and conservative vehicle efficiency improvements. If the forecasted transport need does not change from year 2016 (0% input), the total TTW emissions are clearly decreased in respect to the base scenario, by 13%. Similarly, increasing the forecasted transport need by 100% of the base assumption, results in 15% higher TTW emissions. Considering just the HDV TTW emissions, the variation, thus the sensitivity to this parameter is much higher than considering the whole vehicle fleet. In fact, setting the transport need increase to 0%, brings a reduction of the HDV TTW emission of 24%. The increase by 100% of the base case increases the HDV emissions by 31%. Similar dynamics can be observed in the diesel consumption of the fleet and the specific for HDVs. In fact, to a constant transport need the HDV diesel consumption decreases by 24%, and the increase by 100% of the base case increases the HDV diesel consumption by 31%. However, the change in the load assumption presents some critical considerations. It is worth noticing that the load factor assumptions have a major impact on the HDV emissions and fuel consumption. Changing the load assumption only affects the number of new registered vehicles, related activity, fuel consumption and GHG emissions of the HDV segment. Decreasing the load factors, while keeping the annual mileages and the transport need growth as the base case, means that more vehicles are needed to transport a unit of load, and this is translated to an increase of new vehicles being registered in the fleet. In this way, the emissions and fuel consumption per unit of transport work are increased, reducing the efficiency of the national freight transportation logistic system. If related to national regulations, the decrease in HDV load factors would signify that the maximum allowed weight of road vehicles is decreased. It can also represent the shift in the logistic systems towards fast delivery services, at the expenses of transport efficiency. From the results, the model appears to be very sensible to the change in load factors: a decrease of 50% in the assumed load factors for all the different segments of the HDV results into 62% increase compared to the base case of the HDV TTW emissions, and an increase of 66% of the HDV diesel consumption. On the other hand, an increase of the assumed load factors would prove to be an effective measure for GHG abatement, even compared with the whole vehicle fleet. A smaller increase of 25% of the assumed load factors would result into 7% decrease of the total GHG emissions and a reduction of the total diesel consumption of 6%, a 12% decrease if just the diesel consumption of HDV is considered. Current trends in Nordic countries are suggesting that the maximum allowed weight and size of HDV vehicles are expected to be increased by government regulation, but, on the other hand, fast delivery services, pushed by the digitalization of the market, are starting to play a negative role in the efficiency of the transport system. If HDV vehicles are used more efficiently, resulting in higher loads or larger vehicles, significant decline in GHG emissions could be achieved.

Table 6.1: Impact of transport need and load factors in the Swedish electric scenario in 2030, on TTW emissions and diesel consumption

Transport need	Total TTW emissions [ktonCO_2-eq.]		HDV TTW emissons [ktonCO_2-eq.]		Total diesel cons. [million liters]		HDV diesel cons [million liters]	
0%	7432	87%	932	76%	3842	84%	1473	76%
50%	7963	93%	1070	87%	4198	91%	1692	87%
Base	**8536**	**100%**	**1227**	**100%**	**4591**	**100%**	**1942**	**100%**
150%	9152	107%	1405	114%	5028	110%	2225	115%
200%	9817	115%	1607	131%	5511	120%	2548	131%
HDV load factors	Total TTW emissions [ktonCO_2-eq.]		HDV TTW emissons [ktonCO_2-eq.]		Total diesel cons. [million liters]		HDV diesel cons [million liters]	
50%	9817	115%	1986	162%	5929	129%	3216	166%
75%	9152	107%	1477	120%	5031	110%	2357	121%
Base	**8536**	**100%**	**1227**	**100%**	**4591**	**100%**	**1942**	**100%**
125%	7963	93%	1081	88%	4334	94%	1701	88%
150%	7432	87%	987	80%	4169	91%	1547	80%

7 Conclusions

This work analyzes the abatement options for CO_2 emissions of the heavy-duty vehicles, through vehicle efficiency improvement measures and powertrain developments of the HDV fleet in Finland, Sweden and Norway. Moreover, the total road transport energy and fuel consumption, and GHG emissions are estimated in the same countries. During the past years, the European Union has introduced stricter exhaust gas emission standards for road vehicles, improving importantly the limits of air pollutants emitted by heavy-duty vehicles. Recently, CO_2 emission standards for new passenger cars and light-commercial vehicles have also been introduced by the European Union, in order to improve the efficiency of the vehicle fleet and address the problem of GHG emissions from road transport. However, unlike other countries, EU has not yet introduced CO_2 emission standards for HDV; moreover, in the last 15 years, due to the mentioned air pollutants emissions standards, the energy efficiency of the HDV segment has not improved, and the focus of vehicle manufacturers has been concentrated on PM and NOx emission. The challenge of creating a comprehensive carbon efficiency policy for the HDV segment is highlighted by the fact that this segment is characterized by a wide variety of different types of vehicles, with a wide range of different operations and related duty cycles optimized for the specific task of the vehicle. For this reason, a regulation that can be applied to a broader level is difficult to formulate. However, the energy efficiency of HDVs can be positively improved at different vehicle levels, especially for some vehicle types. Carbon efficiency technologies and improvements can have different field of action for the potential development: the vehicle body, the aerodynamics and the tires, the combustion engine, the transmission and the driveline, as well as alternative powertrains and fuels. Vehicle technologies, such as low rolling resistance tires and lightweighting are effective measures especially in the long-haul HDV segment. Vehicle electrification/hybridization is estimated to provide the most benefits for smaller urban HDVs, such as urban delivery trucks and citybuses. The electric powertrain is more efficient than the ICE engine, and do not produce any tailpipe emissions: the carbon emissions are only dependent on the carbon intensity of the electricity mix of a country. However, the biggest barriers for the adoption an electrified HDV are still to be overcame. These includes the high purchase price and the low range, related to the battery cost and inferior energy density compared to conventional liquid fuels. Due to the higher mileages and power requirements of big HDVs, the battery and electrical system would have a considerable size in terms of mass and volume, increasing the purchase price of the vehicle to the extent it is not yet considered an economically feasible solution, even for HDVs operating in an urban environment. Fully-electric citybuses, however, have proven to be a feasible option for a sustainable transport system, pushed by the willingness of local government to tackle air pollution in urban environments. Nonetheless, hybrid electric vehicles, both PHEVs and HEVs, offer a consistent improvement in vehicle efficiency if adopted by HDV operating on a specific duty cycle of frequent accelerations, decelerations and braking activity. For electric trucks to be competitive, requires that the savings coming from the reduced fuel consumption have to overcome, in a relatively short timeframe, the significantly higher purchase price.

To assess the future developments in terms of GHG emissions and fuel consumption of the road vehicle fleet, a quantitative model was created to quantify the impact of different development scenarios for Finland, Sweden and Norway, until 2050. Different scenarios, able to accommodate different sets of input parameters, have been created: considered input scenarios include powertrains, vehicle efficiency improvements, transport need growth and fuel bioenergy share. Other parameters have been estimated since are necessary for the energy and emission calculations, but no scenarios have been developed for them: for example, the annual mileages of the vehicle segments, the specific energy consumption and the transported loads. Currently, the HDV segment is dominated by the diesel powertrain, due to the higher efficiency of the diesel engine. It is unlikely that, in the next future, the diesel powertrain will be replaced by a less carbon-intensive option. However, for this study, two powertrain scenarios have been created for all three countries. The conservative scenario represents the continuation of the current trend of vehicle powertrains, and the electric scenario, where a slow adoption of alternative electric powertrain is expected at least in the smaller segments of the HDVs and the citybuses. Even assuming a fast adoption of alternative powertrain or a fast increase of the fuel efficiency of new vehicles, the effects of this changes are noted at a slow pace, if the whole vehicle fleet is considered. This is caused by the high inertia of the vehicle fleet: the renewal of the vehicles is slow, and improved vehicles are joining the fleet in a small number if related to the whole vehicle fleet. The results of increased efficiency vehicles on the energy consumption and GHG emissions can only be noticed in the long term, on the contrary of the use of biofuels, which has a sudden and direct impact on the emissions.

Nordic countries have set very ambitious targets for the reduction of national emissions of GHG, especially for a very carbon-intensive sector like road transport. These challenging goals seem to be in contrast with the national estimation of the transport need growth, in particular for Sweden and Norway. In fact, even if the passenger car, light commercial vehicle segments and citybuses would be quickly electrified, the mentioned inertia of the fleet and the huge reliance of fossil diesel of the HDV segment would keep the emissions at high levels, not sufficient to achieved the reduction goals, even in the long term. The transport work overtaken by the HDV is estimated to increase in the future, and its share of the total energy consumption is expected to overtake the passenger car one, currently the highest one. An effective measure to reduce the fuel consumption and emissions of the HDVs, and consequently the whole road transport sector, would be a more efficient transport logistic system, allowing bigger and heavier vehicles, and incentivizing the increase of the load factors of the commercial vehicles. Moreover, without a comprehensive and binding public regulation on the carbon emissions of HDVs, it is unlikely that vehicle manufacturers would adopt game-changing measures for improving the efficiency of HDVs. To achieve significant reductions in carbon emissions from the road transport sector, a broad effort is required, involving all sector of possible improvements, from high shares of biofuels to powertrain development, as well as an improved overall efficiency of the transportation system. Further and more detailed analyses are needed to evaluate the different options in terms of abatement costs, including also infrastructure considerations, the impact of electric vehicles on the electricity grid and the availability and sustainability criteria of biofuels.

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9 Appendix

Appendix 1. Vehicle fleets

Electric scenario PC vehicle fleet in Finland, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	1 879 949	701 708	844	2 196	245	18 824	426	3 582	1 820	0	2	0	20
2020	1 784 004	747 082	16 739	20 105	299	65 162	503	3 591	2 374	0	2	0	16
2025	1 585 368	669 505	115 237	85 728	341	205 811	540	3 237	2 966	0	2	0	10
2030	1 345 377	510 727	300 967	184 458	285	385 426	427	2 181	3 374	0	2	0	5
2035	1 098 525	351 996	500 805	283 959	173	547 156	248	1 068	3 541	0	1	0	2
2040	852 965	232 618	689 050	369 709	89	669 091	126	526	3 571	0	0	0	1
2045	654 012	153 455	847 282	434 769	46	747 550	65	245	3 576	0	0	0	0
2050	506 146	100 958	976 966	482 416	19	796 954	25	91	3 588	0	0	0	0

Electric scenario LCV fleet in Finland, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	8 725	293 537	170	0	0	0	0	5	245	0	0	0	11
2020	6 314	303 374	496	102	0	307	0	5	400	0	0	0	12
2025	3 363	305 319	2 700	730	0	2 191	0	4	1 458	0	0	0	11
2030	1 781	297 096	11 301	1 964	0	5 892	0	3	4 382	0	0	0	8
2035	906	278 583	26 605	3 338	0	10 014	0	2	8 049	0	0	0	5
2040	435	257 514	43 901	4 609	0	13 827	0	1	11 676	0	0	0	3
2045	207	239 403	59 840	5 570	0	16 711	0	1	14 631	0	0	0	2
2050	84	227 251	72 038	6 210	0	18 630	0	0	16 650	0	0	0	1

Electric scenario HDV fleet in Finland, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	1 315	91 282	1	0	0	3	2	66	81	1	0	0	93
2020	1 034	86 706	11	0	12	3	53	61	100	2	0	0	81
2025	771	81 368	72	0	72	2	281	47	101	34	0	0	61
2030	558	76 807	228	0	225	1	801	33	81	148	0	0	43
2035	349	71 966	445	0	442	1	1 482	21	59	310	0	0	27
2040	191	68 463	681	0	672	0	2 173	12	41	470	0	0	16
2045	97	66 647	910	0	902	0	2 859	5	28	600	0	0	9
2050	40	66 140	1 136	0	1 140	0	3 562	2	20	696	0	0	3

Electric scenario Bus fleet in Finland, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	16	11 865	13	0	0	0	0	0	40	0	2	0	16
2020	10	12 423	127	0	0	0	17	0	35	0	2	0	15
2025	5	12 635	380	0	0	0	94	0	29	0	2	0	12
2030	2	12 323	836	0	0	0	279	0	37	0	9	0	8
2035	1	11 585	1 317	0	0	0	535	0	44	0	31	0	4
2040	0	10 802	1 710	0	0	0	778	0	43	0	66	0	2
2045	0	10 247	2 005	0	0	0	993	0	32	0	108	0	1
2050	0	9 777	2 232	0	0	0	1 183	0	18	0	146	0	0

Conservative scenario PC vehicle fleet in Finland, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	1 879 949	701 708	844	2 196	245	18 824	426	3 582	1 820	0	2	0	20
2020	1 778 340	763 412	6 224	17 665	299	57 589	503	3 591	5 970	0	2	0	16
2025	1 638 352	741 435	52 810	56 936	341	145 847	540	3 237	22 274	0	2	0	10
2030	1 552 518	648 448	141 132	109 927	285	242 974	427	2 181	52 134	0	2	0	5
2035	1 490 530	531 025	228 390	162 104	173	322 980	248	1 068	85 489	0	1	0	2
2040	1 447 007	421 125	304 566	205 699	89	380 617	126	526	116 772	0	0	0	1
2045	1 437 853	329 440	360 227	238 542	46	420 518	65	245	143 027	0	0	0	0
2050	1 448 071	258 235	396 971	263 030	19	452 355	25	91	163 587	0	0	0	0

Conservative scenario LCV fleet in Finland, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	8 725	293 537	170	0	0	0	0	5	245	0	0	0	11
2020	6 660	303 736	332	0	0	19	0	5	364	0	0	0	12
2025	4 348	308 594	975	0	0	689	0	4	1 424	0	0	0	11
2030	3 345	310 047	1 919	0	0	3 014	0	3	4 356	0	0	0	8
2035	2 916	307 455	2 881	0	0	6 330	0	2	8 037	0	0	0	5
2040	2 718	303 977	3 724	0	0	9 754	0	1	11 677	0	0	0	3
2045	2 659	301 677	4 338	0	0	12 677	0	1	14 633	0	0	0	2
2050	2 659	301 423	4 743	0	0	14 747	0	0	16 645	0	0	0	1

Conservative scenario HDV fleet in Finland, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	1 315	91 282	1	0	0	3	2	66	81	1	0	0	93
2020	1 103	86 617	2	0	0	3	25	61	167	2	0	0	81
2025	942	81 194	10	0	0	2	127	47	384	34	0	0	61
2030	780	76 837	40	0	0	1	362	33	688	148	0	0	43
2035	569	72 459	92	0	0	1	667	21	984	310	0	0	27
2040	350	69 513	159	0	0	0	974	12	1 249	470	0	0	16
2045	200	68 311	233	0	0	0	1 254	5	1 474	600	0	0	9
2050	100	68 488	316	0	0	0	1 518	2	1 670	696	0	0	3

Conservative scenario Bus fleet in Finland, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	16	11 865	13	0	0	0	0	0	40	0	2	0	16
2020	10	12 477	74	0	0	0	7	0	44	0	2	0	15
2025	5	12 808	199	0	0	0	49	0	83	0	2	0	12
2030	2	12 720	406	0	0	0	164	0	195	0	1	0	8
2035	1	12 240	593	0	0	0	340	0	346	0	1	0	4
2040	0	11 685	730	0	0	0	514	0	484	0	0	0	2
2045	0	11 334	826	0	0	0	661	0	582	0	0	0	1
2050	0	11 066	892	0	0	0	778	0	638	0	0	0	0

Electric scenario PC vehicle fleet in Sweden, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	2 888 035	1 529 782	7 532	16 355	2 477	54 075	1 050	224 808	43 692	0	0	0	46
2020	2 570 511	1 864 006	62 736	96 163	5 781	158 950	3 189	191 186	51 778	0	0	0	35
2025	2 159 264	1 639 583	369 295	332 224	7 571	432 648	6 847	114 595	55 218	0	0	0	22
2030	1 765 255	1 040 644	923 701	651 973	7 167	789 957	9 989	46 443	54 895	0	0	0	12
2035	1 393 787	543 616	1 490 813	937 214	5 563	1 107 693	12 154	18 312	54 424	0	0	0	5
2040	1 064 567	291 399	1 941 258	1 127 972	4 071	1 313 843	13 291	9 204	55 131	0	0	0	3
2045	841 617	184 821	2 249 651	1 229 508	3 077	1 407 495	13 874	3 922	55 735	0	0	0	1
2050	692 564	127 757	2 492 884	1 287 173	2 212	1 438 005	14 362	1 778	56 299	0	0	0	1

Electric scenario LCV fleet in Sweden, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	52 441	471 375	1 552	0	0	56	0	1 700	7 578	0	0	1	9
2020	34 677	543 815	8 300	381	0	811	763	1 361	8 456	0	0	2	7
2025	18 743	580 375	34 958	2 253	0	4 537	4 505	745	6 698	0	31	2	4
2030	9 579	569 294	85 827	6 253	0	12 520	12 506	314	3 884	0	967	1	2
2035	4 440	534 382	145 545	11 565	0	22 699	22 693	144	1 862	0	4 037	1	1
2040	1 939	497 330	197 748	18 336	0	33 120	33 117	83	842	0	9 083	0	0
2045	871	460 320	238 466	26 179	0	43 121	43 120	37	415	0	14 146	0	0
2050	381	424 352	274 067	35 190	0	53 426	53 426	14	206	0	18 042	0	0

Electric scenario HDV fleet in Sweden, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	1 074	79 434	0	0	0	0	23	0	821	0	0	57	14
2020	770	80 730	18	0	4	0	147	0	805	3	0	45	9
2025	481	85 092	129	0	103	0	826	0	673	98	5	27	5
2030	301	89 133	360	0	413	0	2 274	0	505	412	139	15	3
2035	194	92 719	659	0	927	0	4 075	0	324	804	569	8	1
2040	110	97 001	976	0	1 501	0	5 737	0	193	1 108	1 269	5	1
2045	55	101 834	1 294	0	2 065	0	7 290	0	108	1 126	1 980	3	0
2050	22	107 242	1 627	0	2 639	0	8 847	0	57	791	2 542	1	0

Electric scenario Bus fleet in Sweden, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	36	11 017	38	0	0	0	27	0	2 346	0	0	390	26
2020	41	12 185	397	0	0	0	157	0	1 467	0	0	151	7
2025	23	12 583	1 124	0	0	0	516	0	457	0	1	19	0
2030	6	11 916	2 078	0	0	0	1 040	0	107	0	41	2	0
2035	1	11 105	2 817	0	0	0	1 513	0	32	0	158	0	0
2040	0	10 545	3 334	0	0	0	1 891	0	9	0	332	0	0
2045	0	10 061	3 741	0	0	0	2 245	0	1	0	476	0	0
2050	0	9 617	4 152	0	0	0	2 624	0	0	0	557	0	0

Conservative scenario PC vehicle fleet in Sweden, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	2 888 035	1 529 782	7 532	16 355	2 477	54 075	1 050	224 808	43 692	0	0	0	46
2020	2 579 338	1 852 894	46 748	81 303	5 844	191 259	3 194	190 180	53 085	0	0	0	35
2025	2 352 879	1 724 744	173 733	229 938	7 852	484 502	6 940	113 581	59 385	0	0	0	22
2030	2 241 571	1 306 646	386 152	423 404	7 655	859 854	10 097	45 538	61 586	0	0	0	12
2035	2 076 146	957 539	606 260	642 107	6 213	1 203 493	12 161	17 728	62 656	0	0	0	5
2040	1 880 549	789 536	782 910	824 035	4 873	1 450 276	13 269	8 895	64 207	0	0	0	3
2045	1 702 469	714 724	903 630	960 522	4 036	1 602 073	13 863	3 704	65 171	0	0	0	1
2050	1 560 054	667 125	993 545	1 068 687	3 350	1 709 300	14 362	1 598	65 972	0	0	0	1

Conservative scenario LCV fleet in Sweden, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	52 441	471 375	1 552	0	0	56	0	1 700	7 578	0	0	1	9
2020	35 894	543 251	5 180	0	0	1 126	1 077	1 362	11 047	0	0	5	7
2025	20 662	585 450	16 157	0	0	4 138	4 106	745	19 343	0	0	9	4
2030	10 891	597 932	33 133	0	0	8 559	8 544	314	27 959	0	0	12	2
2035	5 171	600 277	50 359	0	0	12 979	12 973	144	34 678	0	0	13	1
2040	2 247	603 919	63 682	0	0	17 224	17 221	83	38 768	0	0	14	0
2045	1 016	604 608	72 670	0	0	21 265	21 263	37	40 848	0	0	15	0
2050	470	604 786	79 698	0	0	25 514	25 514	14	42 281	0	0	15	0

Conservative scenario HDV fleet in Sweden, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	1 074	79 434	0	0	0	0	23	0	821	0	0	57	14
2020	832	80 481	0	0	0	0	59	0	1 062	3	0	104	8
2025	577	84 867	12	0	0	0	233	0	1 495	98	0	156	4
2030	383	89 953	46	0	0	0	595	0	1 976	412	0	193	2
2035	265	95 442	104	0	0	0	1 043	0	2 426	804	0	220	1
2040	170	101 937	175	0	0	0	1 471	0	2 855	1 107	0	246	0
2045	109	108 836	256	0	0	0	1 866	0	3 234	1 313	0	270	0
2050	71	115 955	345	0	0	0	2 262	0	3 590	1 461	0	292	0

Conservative scenario Bus fleet in Sweden, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	36	11 017	38	0	0	0	27	0	2 346	0	0	390	26
2020	41	12 004	342	0	0	0	140	0	1 715	0	0	151	7
2025	24	12 082	799	0	0	0	428	0	1 347	0	0	19	0
2030	6	11 548	1 235	0	0	0	861	0	1 487	0	0	2	0
2035	1	11 267	1 474	0	0	0	1 267	0	1 561	0	0	0	0
2040	0	11 281	1 626	0	0	0	1 556	0	1 599	0	0	0	0
2045	0	11 354	1 750	0	0	0	1 733	0	1 648	0	0	0	0
2050	0	11 459	1 881	0	0	0	1 887	0	1 692	0	0	0	0

Electric scenario PC vehicle fleet in Norway, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	1 198 158	1 254 476	97 359	30 488	2 310	55 609	735	0	116	0	116	0	16
2020	970 619	1 318 781	209 932	129 084	6 566	153 782	841	0	564	0	199	0	10
2025	867 018	1 175 698	376 760	291 076	9 627	325 026	988	0	1 462	0	243	0	5
2030	890 514	864 263	550 644	494 138	12 459	508 988	925	0	2 322	0	287	0	2
2035	961 222	576 956	684 354	681 863	10 717	654 605	738	0	2 967	0	219	0	1
2040	1 066 112	368 155	792 112	825 435	6 352	747 902	676	0	3 252	0	120	0	0
2045	1 167 166	230 805	885 933	943 515	3 901	796 768	656	0	3 352	0	78	0	0
2050	1 253 361	147 607	969 079	1 046 886	2 054	820 889	638	0	3 426	0	36	0	0

Electric scenario LCV fleet in Norway, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	31 766	460 640	2 566	55	2	0	0	0	394	0	0	0	3
2020	17 397	496 922	8 668	43	2	557	557	0	1 138	0	0	0	2
2025	8 265	511 961	27 199	25	1	3 446	3 446	0	3 424	0	0	0	1
2030	3 746	503 718	55 939	11	1	9 666	9 666	0	7 010	0	0	0	0
2035	1 431	486 043	84 575	5	0	17 369	17 369	0	10 596	0	0	0	0
2040	555	470 039	106 316	3	0	24 139	24 139	0	13 261	0	0	0	0
2045	236	458 217	121 520	1	0	29 550	29 550	0	14 891	0	0	0	0
2050	94	450 020	133 386	0	0	34 159	34 159	0	15 871	0	0	0	0

Electric scenario HDV fleet in Norway, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	2 675	67 296	2	0	0	0	0	0	253	0	0	0	70
2020	1 215	64 204	3	0	0	0	40	0	635	2	0	0	43
2025	502	64 327	27	0	0	0	321	0	1 119	85	0	0	21
2030	219	66 728	78	0	0	0	986	0	1 474	345	0	0	9
2035	95	70 104	136	0	0	0	1 741	0	1 754	640	0	0	4
2040	35	74 525	188	0	0	0	2 326	0	1 994	856	0	0	2
2045	13	80 415	244	0	0	0	2 802	0	2 233	1 028	0	0	1
2050	5	87 190	307	0	0	0	3 240	0	2 473	1 181	0	0	0

Electric scenario Bus fleet in Norway, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	309	15 272	10	0	0	0	0	0	733	0	5	0	1
2020	146	14 556	7	0	0	0	1	0	641	0	3	0	1
2025	60	14 053	42	0	0	0	69	0	564	0	0	0	0
2030	25	13 357	144	0	0	0	307	0	648	0	0	0	0
2035	10	12 929	275	0	0	0	711	0	736	0	0	0	0
2040	4	12 638	381	0	0	0	1 095	0	799	0	0	0	0
2045	1	12 567	453	0	0	0	1 347	0	842	0	0	0	0
2050	1	12 569	523	0	0	0	1 523	0	874	0	0	0	0

Conservative scenario PC vehicle fleet in Norway, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	1 198 158	1 254 476	97 359	30 488	2 310	55 609	735	0	116	0	116	0	16
2020	970 619	1 318 781	209 932	129 084	6 566	153 782	841	0	564	0	199	0	10
2025	867 018	1 175 698	376 760	291 076	9 627	325 026	988	0	1 462	0	243	0	5
2030	890 514	864 263	550 644	494 138	12 459	508 988	925	0	2 322	0	287	0	2
2035	961 222	576 956	684 354	681 863	10 717	654 605	738	0	2 967	0	219	0	1
2040	1 066 112	368 155	792 112	825 435	6 352	747 902	676	0	3 252	0	120	0	0
2045	1 167 166	230 805	885 933	943 515	3 901	796 768	656	0	3 352	0	78	0	0
2050	1 253 361	147 607	969 079	1 046 886	2 054	820 889	638	0	3 426	0	36	0	0

Conservative scenario LCV fleet in Norway, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	31 766	460 640	2 566	55	2	0	0	0	394	0	0	0	3
2020	17 397	496 922	8 668	43	2	557	557	0	1 138	0	0	0	2
2025	8 265	511 961	27 199	25	1	3 446	3 446	0	3 424	0	0	0	1
2030	3 746	503 718	55 939	11	1	9 666	9 666	0	7 010	0	0	0	0
2035	1 431	486 043	84 575	5	0	17 369	17 369	0	10 596	0	0	0	0
2040	555	470 039	106 316	3	0	24 139	24 139	0	13 261	0	0	0	0
2045	236	458 217	121 520	1	0	29 550	29 550	0	14 891	0	0	0	0
2050	94	450 020	133 386	0	0	34 159	34 159	0	15 871	0	0	0	0

Conservative scenario HDV fleet in Norway, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	2 675	67 296	2	0	0	0	0	0	253	0	0	0	70
2020	1 215	64 204	3	0	0	0	40	0	635	2	0	0	43
2025	502	64 327	27	0	0	0	321	0	1 119	85	0	0	21
2030	219	66 728	78	0	0	0	986	0	1 474	345	0	0	9
2035	95	70 104	136	0	0	0	1 741	0	1 754	640	0	0	4
2040	35	74 525	188	0	0	0	2 326	0	1 994	856	0	0	2
2045	13	80 415	244	0	0	0	2 802	0	2 233	1 028	0	0	1
2050	5	87 190	307	0	0	0	3 240	0	2 473	1 181	0	0	0

Conservative scenario Bus fleet in Norway, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	309	15 272	10	0	0	0	0	0	733	0	5	0	1
2020	146	14 556	7	0	0	0	1	0	641	0	3	0	1
2025	60	14 053	42	0	0	0	69	0	564	0	0	0	0
2030	25	13 357	144	0	0	0	307	0	648	0	0	0	0
2035	10	12 929	275	0	0	0	711	0	736	0	0	0	0
2040	4	12 638	381	0	0	0	1 095	0	799	0	0	0	0
2045	1	12 567	453	0	0	0	1 347	0	842	0	0	0	0
2050	1	12 569	523	0	0	0	1 523	0	874	0	0	0	0

Appendix 2. Energy consumptions

Energy consumption (PJ) by energy carrier in Finnish electric scenario

	2016	2020	2025	2030	2040	2050
Fossil gasoline	53,14	50,06	46,83	43,19	35,23	28,64
Ethanol	3,30	3,51	3,65	4,12	4,26	3,95
Fossil diesel	102,63	84,78	75,47	52,17	39,61	34,71
HVO	4,82	18,83	18,51	28,99	22,01	19,29
FAME	0,00	3,49	5,58	5,73	4,35	3,81
CNG - natural gas	0,08	0,09	0,13	0,23	0,43	0,51
CNG - biogas	0,09	0,10	0,15	0,27	0,49	0,59
Electricity	0,04	0,42	2,18	5,14	10,25	13,20
Rest	0,00	0,01	0,06	0,24	0,65	0,82

Energy consumption (PJ) by energy carrier in Finnish conservative scenario

	2016	2020	2025	2030	2040	2050
Fossil gasoline	53,14	50,13	47,69	46,60	45,85	46,43
Ethanol	3,30	3,52	3,72	4,44	5,55	6,40
Fossil diesel	102,63	85,47	78,40	56,90	47,04	41,95
HVO	4,82	18,98	19,23	31,62	26,14	23,31
FAME	0,00	3,52	5,80	6,25	5,16	4,60
CNG - natural gas	0,08	0,18	0,60	1,38	2,80	3,59
CNG - biogas	0,09	0,21	0,70	1,59	3,25	4,16
Electricity	0,04	0,17	0,96	2,14	3,84	4,49
Rest	0,00	0,01	0,06	0,24	0,60	0,72

Energy consumption (PJ) by energy carrier in Swedish electric scenario

	2016	2020	2025	2030	2040	2050
Fossil gasoline	99,11	80,04	69,35	64,30	56,42	48,84
Ethanol	4,62	6,56	6,66	7,04	6,94	6,77
Fossil diesel	122,78	121,29	76,72	33,64	16,92	16,38
HVO	43,50	59,44	96,31	114,13	99,46	96,33
FAME	11,13	12,73	12,32	10,62	8,40	8,13
CNG - natural gas	1,62	1,23	0,75	0,49	0,21	0,12
CNG - biogas	4,09	3,60	2,71	2,29	2,17	2,20
Electricity	0,24	1,50	6,47	13,99	24,92	29,75
Rest	0,00	0,01	0,19	0,87	2,84	2,98

Energy consumption (PJ) by energy carrier in Swedish conservative scenario

	2016	2020	2025	2030	2040	2050
Fossil gasoline	99,11	84,34	83,35	89,96	96,15	93,91
Ethanol	4,62	6,82	7,77	9,52	11,83	13,07
Fossil diesel	122,78	120,83	78,14	36,34	20,61	20,68
HVO	43,50	59,22	98,08	123,30	121,16	121,61
FAME	11,13	12,69	12,55	11,48	10,23	10,27
CNG - natural gas	1,62	1,36	1,16	1,03	0,57	0,33
CNG - biogas	4,09	3,99	4,21	4,83	5,73	6,21
Electricity	0,16	0,86	2,67	5,26	9,18	10,89
Rest	0,00	0,01	0,18	0,70	1,53	1,76

Energy consumption (PJ) by energy carrier in Norwegian electric scenario

	2016	2020	2025	2030	2040	2050
Fossil gasoline	32,20	26,35	24,03	23,47	21,05	17,54
Ethanol	1,12	1,70	1,85	2,23	2,56	2,43
Fossil diesel	98,91	86,43	64,37	49,02	35,94	35,18
HVO	7,19	15,36	25,91	26,25	22,87	22,40
FAME	5,46	7,11	6,35	5,31	4,16	4,07
CNG - natural gas	0,44	0,32	0,19	0,14	0,02	0,00
CNG - biogas	0,44	0,37	0,27	0,27	0,09	0,08
Electricity	1,43	3,89	7,86	12,05	18,28	22,38
Rest	0,29	0,02	0,17	0,72	2,01	2,62

Energy consumption (PJ) by energy carrier in Norwegian conservative scenario

	2016	2020	2025	2030	2040	2050
Fossil gasoline	32,20	30,52	34,33	41,24	53,32	59,17
Ethanol	1,12	1,97	2,64	3,92	6,49	8,20
Fossil diesel	98,91	87,95	67,93	54,33	42,33	41,98
HVO	7,19	15,63	27,34	29,09	26,95	26,73
FAME	5,46	7,24	6,70	5,88	4,89	4,85
CNG - natural gas	0,44	0,42	0,44	0,47	0,34	0,05
CNG - biogas	0,44	0,48	0,63	0,88	1,34	1,77
Electricity	1,31	2,64	4,43	6,17	8,37	9,67
Rest	0,29	0,01	0,10	0,38	0,78	0,95

Appendix 3. GHG emissions

TTW GHG emissions (ktonCO_2eq.) by vehicle segment in the Finnish electric scenario

	2016	2020	2030	2040	2050
PC	6 971	6 315	4 695	3 576	2 906
LCV	1 341	1 123	797	669	589
HDV	2 874	2 312	1 726	1 720	1 730
Bus	467	381	258	221	201

TTW GHG emissions (ktonCO_2eq.) by vehicle segment in the Finnish electric scenario

	2016	2020	2030	2040	2050
PC	6 971	6 329	5 005	4 390	4 130
LCV	1 341	1 124	825	776	748
HDV	2 874	2 312	1 733	1 735	1 752
Bus	467	384	275	253	243

TTW GHG emissions (ktonCO_2eq.) by vehicle segment in the Swedish electric scenario

	2016	2020	2030	2040	2050
PC	10 916	10 001	6 660	5 951	5 354
LCV	1 633	1 499	498	331	349
HDV	3 256	3 144	1 227	895	914
Bus	487	468	150	87	82

TTW GHG emissions (ktonCO_2eq.) by vehicle segment in the Swedish conservative scenario

	2016	2020	2030	2040	2050
PC	10 916	10 077	7 664	7 541	7 298
LCV	1 633	1 503	517	332	335
HDV	3 256	3 143	1 237	917	998
Bus	487	464	158	99	96

TTW GHG emissions (ktonCO_2eq.) by vehicle segment in the Norwegian electric scenario

	2016	2020	2030	2040	2050
PC	5 719	4 914	3 450	2 912	2 610
LCV	1 807	1 626	1 015	732	600
HDV	1 920	1 830	1 585	1 605	1 818
Bus	381	341	224	181	166

TTW GHG emissions (ktonCO_2eq.) by vehicle segment in the Norwegian conservative scenario

	2016	2020	2030	2040	2050
PC	5 719	5 053	4 192	4 333	4 532
LCV	1 807	1 648	1 150	979	930
HDV	1 920	1 830	1 606	1 693	1 957
Bus	381	342	251	225	217

Appendix 4. Relative energy factors

Relative energy factor for different powertrains. Source (Fridstrøm & Østli, 2016)

Powertrains	Factor (MJ/MJ)
FCV % of BEV	250,0 %
Flexifuel % of gasoline	100,0 %
ED95 % of diesel	100,0 %
Electricity % of diesel	30,0 %
CNG % of diesel	115,0 %
LNG % of diesel	115,0 %
Gasoline % of diesel	115,0 %
Gasoline HEV % of gasoline	85,0 %
Diesel HEV % of diesel	85,0 %
Gasoline PHEV % of Gasoline / BEV	105,0 %
Diesel PHEV % of Diesel / BEV	105,0 %