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Rapport
BYG•DTU R-022
2001
ISSN 1601-2917
ISBN 87-7877-077-7

September 2001

Technology Analysis of Public Transport Modes

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Final report for an Industrial PhD Fellowship carried out in co-operation between the Department of Energy Planning at RAMBØLL, and the Energy Planning Group at the Department of Civil Engineering, Technical University of Denmark.

The Industrial PhD Fellowship (EF number 747) was partly funded by the Danish Agency for Trade and Industry under the Ministry of Business and Industry and administered by the Committee on Industrial PhD Fellowship under the Danish Academy of Technical Sciences.

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List of symbols and acronyms

CH_4: methane.
CH_2: compressed hydrogen.
CI: compression ignition.
CNG: compressed natural gas.
CO: carbon mono-oxide.
EL: electricity.
ES: electricity storage.
FC: fuel converter.
GHG: greenhouse gases.
ha: hectare.
HC: hydrocarbons.
H_2: hydrogen.
ICE: internal combustion engine.
km: kilometre.
kW: kilowatts.
l: litre.
LiIon: Lithium ion batteries.
LiPo: Lithium polymer batteries.
LRV: light rail vehicle.
m: meter.
MeOH: methanol.
MJ: mega joule equal to 10^6 joule.
NG: natural gas.
NiMH: Nickel metalhydride batteries.
NMHC: non-methane hydrocarbons.
NO_X: nitrogen oxides mainly NO and NO_2.
OEM: original equipment manufacturer.
PbAcid: Lead acid batteries.
PEM: proton exchange membrane.
PM: particulate matter, small solid components in the air.
ppm: parts per million.
RME: rape methyl ester.
SI: spark ignition.
SOC: state of charge.
SOFC: solid oxide fuel cell.
TC: transport concept.
USABC: United States Advanced Battery Consortium.

Acknowledgments

Many thanks to my supervisors Chief Consultant Bjarne Juul Cristensen and Chief Consultant Elsebeth Hansen from the Department of Energy Planning at RAMBØLL, Senior Researcher Kaj Jørgensen from the System Analysis Department at RISØ, Professor Niels I. Meyer and Associate Professor Jørgen S. Nørgaard from the Energy Planning Group at the Department of Civil Engineering at the Technical University of Denmark.

Thanks for information and help received from Senior Consultant Flemming Bak at the Technological Institute of Denmark and Lars Overgaard from SCANIA, Research and development, Buses and Coaches.

Thanks to the contact person representing the Committee on Industrial PhD Fellowship, Executive Director of International Operations, Henning H. Terkelsen from COWI.

Finally many thanks to my wife Inge for keeping the home and our kids in a reasonable state during the last intensive months of the PhD study.

Peter Meibom
September 2001

1. Summary

This report describes the results of a three year PhD study analysing the technological possibilities for reducing the future energy consumption and emission of greenhouse gases (GHG) of urban public transport modes. The study was carried out in a co-operation between the Department of Energy Planning at RAMBØLL and the Energy Planning group at the Department of Civil Engineering, Technical University of Denmark.

The study should not be interpreted as making predictions about **how** the development of urban public transport modes will be in the future. Instead it should be seen as a study that analyses and compares some of the possible technological developments of public transport modes, that can happen if reductions in the energy consumption and emission of GHG achieve high priority by the sellers and buyers of urban public transport modes.

1.1 Methodology

This study analyses the energy consumption and emission of GHG[1] connected with the extraction, production and distribution of vehicle fuels, and the energy consumption and emission of GHG from the operation of urban public transport modes.

Figure 1-1 illustrates the phases involved in a life cycle study of transport modes. As can be seen, the life cycle energy consumption and GHG emissions connected with the use of a given vehicle using a given fuel depends on the following:

1. The raw materials and processes involved in the production, storage and distribution of the vehicle fuel. The path from the extraction or production of the feedstock to the distribution of fuel to the vehicle at the required pressure and temperature is called the fuel cycle.
2. The materials and production processes used in the construction of the vehicle and vehicle infrastructure.
3. The energy consumption and GHG emissions of the vehicle driving in a given driving cycle.
4. The energy consumption and GHG emissions connected with the maintenance of vehicles and vehicle infrastructure.
5. The energy consumption and GHG emissions connected with the disposal of vehicles and vehicle infrastructure.

The issues mentioned in the points 2, 4 and 5 in the above list are not analysed in this project. According to different life cycle studies of cars [Nielsen & Gudmundsson 1999; Grell 1997; Weiss et al. 2000] and other transport modes [Kalenoja 1996] the fuel cycle phase and vehicle operation phase included in this study constitute around 80-95 % of the life cycle energy consumption and life cycle GHG emissions, and approximately 90-100 % of the life cycle local emissions. Therefore the main part of the life cycle energy consumption and GHG emissions of transport modes are included in this work.

[1] The following three greenhouse gases are analysed: CO_2, CH_4 and N_2O.

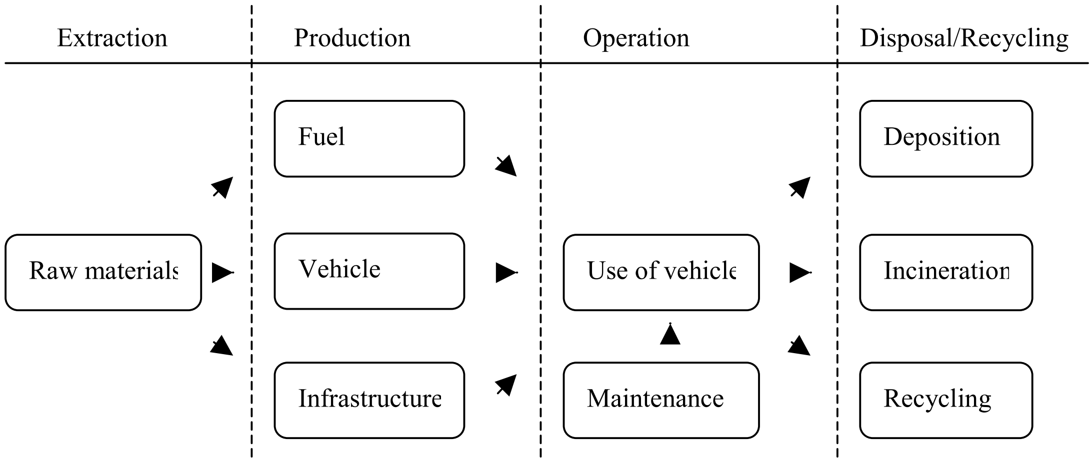

Figure 1-1 The phases involved in a life cycle analysis of a transport mode.

The main focus of the study is a technology assessment of hardware[2] technologies of importance for the energy consumption and GHG emissions of public transport modes. Other characteristics of importance for the performance and market success of the technologies are also taken into account most notably the issues of cost and emission of air pollutants[3].

The energy consumption and GHG emissions of a vehicle driving in a given driving cycle depend on the efficiency of the propulsion system (also called the tank-to-wheel efficiency) and the size of the vehicle loads. Therefore the hardware technologies of importance for the energy consumption and GHG emissions can be divided into three classes:

- Fuel cycle technologies.
- Propulsion system technologies.
- Vehicle load reduction technologies.

The technologies included in the fuel cycles are analysed in a more aggregated manner than the propulsion system technologies. Because each fuel cycle includes many technologies, it is chosen to look at the resulting performance of the whole fuel cycle without giving data about the individual technologies. The same goes for the vehicle load reduction technologies, where the possible reduction in vehicle load parameters is analysed without going into details about individual technologies. In contrast to this, the technologies included in the propulsion systems are treated individually, and the resulting performance of a propulsion system emerges by combining a given selection of propulsion subsystem technologies.

A large number of technologies have a potential for improving the propulsion system efficiency and reducing the vehicle loads. Therefore the technologies have been bundled into appropriate technology bundles[4]. This is done according to the model of the energy

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[2] Hardware technologies are technologies related to the hardware existing in the public transport sector, i.e. vehicles, vehicle infrastructure and fuel infrastructure. Software technologies are technologies related to the planning and organisation of the public transport modes.

[3] The emissions of NO_X, CO, HC and particles are analysed.

[4] The term bundling is adopted from the FANTASIE project [Davison et al. 1997].

consumption in a vehicle presented in chapter five, such that each subsystem in the propulsion system and each vehicle load parameter constitute a technology bundle.

The methodology used to analyse a given technology bundle is a literature review where literature about a given subject is collected, analysed and synthesised. The literature collected is mostly research publications (proceedings, articles and reports) produced by researchers from universities and other publicly funded research institutions. The quite expensive technology studies and market forecasts from industry consultants and the like are not used, but informations from the homepages of different companies are included. The languages of the literature have been restricted to English and the Nordic languages (Danish, Swedish and Norwegian).

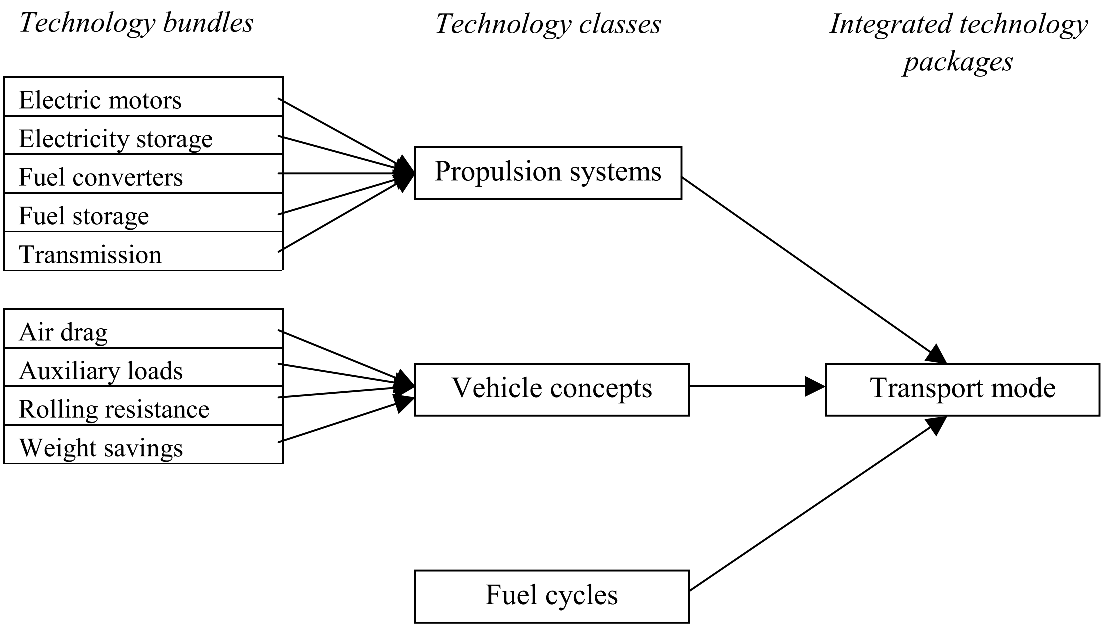


Figure 1-2 Construction of transport modes by combining the results of the analyses of fuel cycles, propulsion systems and vehicle concepts.

The results from the technology analysis of fuel cycles, propulsion subsystems and vehicle loads are used to construct integrated technology packages at the vehicle level, i.e. a light weight, series hybrid bus with a compression ignition diesel engine (see Figure 1-2). For each technology group the most promising short and long term technologies are selected, and these technologies are used to design short term and long term versions of different types of public transport vehicles.

A vehicle design model has been developed that can calculate the required sizes of the different propulsion subsystems in the vehicle, the mass of the propulsion subsystems, the curb mass of the vehicle, and the cost of the propulsion subsystem.

Finally the fuel cost, energy consumption, GHG emissions and emission of air pollutants of the designed vehicles driving in specified driving cycles are calculated, and the performance of different vehicle designs are compared.

1.2 Scope

The possibilities for improvements are analysed within two time frames, a short term (year 2005) and a long term (year 2020). Different vehicle types are analysed:

- Urban transit buses of different sizes (7.2 m, 9 m, 12 m, 18 m and 24 m).
- An local train of the same type as the newest generation of S-trains operating in Greater Copenhagen at present.
- A light rail vehicle or tram where a well-described light rail vehicle platform from Siemens named Combino has been used as the starting point for the modelling.

The following propulsion systems are analysed:

Time frame	Propulsion system
Short term (2005)	Conventional system with compression ignition (CI) internal combustion engine (ICE) using rape methyl ester (RME) Conventional system with spark ignition (SI) ICE using compressed natural gas
Both short and long term	Electric system with contact line (light rail vehicles and trains) Electric system with batteries (buses) Series hybrid electric system with CI ICE using diesel Conventional system with CI ICE using diesel
Long term (2020)	Series hybrid electric system with fuel cells using gasoline, hydrogen or methanol

The following fuel cycles are analysed:

Time frame	Propulsion system
Short term (2005)	RME produced from rape Compressed natural gas (CNG) produced from natural gas
Both short and long term	Electricity (EL) produced from wind power Electricity produced from natural gas Diesel produced from petroleum
Long term (2020)	Hydrogen (H_2) produced at decentralised refilling stations from electricity produced from wind power Hydrogen produced at decentralised refilling stations from natural gas Methanol (MeOH) produced from wood or grass Methanol produced from natural gas extracted at remote places Gasoline produced from petroleum

Technological possibilities for reduction of the vehicle loads are analysed within the following areas:

- Weight savings by improved vehicle design and the use of lighter materials.

- Reduction of accessory loads, i.e. energy consumption of heating and cooling equipment, power steering, ventilation, lights, computers and communication equipment.
- Reduction of the rolling resistance by use of better tires.
- Reduction of air resistance by optimised vehicle design.

1.3 Limitations

Apart from the exclusion of some of the life cycle phases from the analysis, the main limitations connected with this study are the following:

- Only technologies related to the energy consumption, emission of GHG and emission of air pollutants connected with the use of vehicles and production of vehicle fuels are investigated in this project. Technologies related to increasing the utilisation of a given transport mode by being able to adjust the capacity of the offered transport services more precisely to the actual travel demands[5], are not included in this project. Nor is technologies related to the planning and organisation of public transport modes.
- New technologies have been evaluated under the assumption that they will gain large enough shares of the market either in the short or the long term to be able to go down the learning curve and improve their performance to levels which apply to large scale production of the technologies. This assumption means that the important issue of how the new technologies can make a successful market entry is not treated in this work. Especially for fuel cells using compressed hydrogen, the establishment of a hydrogen refuelling infrastructure constitutes a substantial barrier, although it is lower for a fleet of vehicles like public transport modes than for individual owned cars.
- As the number of fuel cycles, propulsion system technologies, vehicle load reduction technologies and vehicle types that could be relevant to include in this study are very large, it was not possible to include all potentially interesting fuel cycles, propulsion system technologies, vehicle load reduction technologies and vehicle types in the work. It is hoped that the technologies considered most interesting today has been included in the project.

Finally it should be mentioned that the evaluation of the possible future performance of new technologies is connected with considerable uncertainty. Sensitivity analysis of the results has been carried out to illustrate this.

1.4 Results

The main results are the following:

- In the long term (2020) the combination of reduced vehicle loads, an improved transmission system and an improved diesel engine can reduce the energy consump-

[5] Like for example demand-responsive transport modes.

tion and emission of GHG of conventional 12 m buses driving in Line5_mod with approximately 50% relatively to a conventional diesel bus today.

- A shift from a conventional propulsion system using a diesel engine to a series hybrid propulsion system using a diesel engine enables a further 50% reduction of the energy consumption and emission of GHG, such that the energy consumption and emission of GHG of 12 m series hybrid diesel buses in 2020 driving in Line5_mod are approximately 25% of the values for a conventional diesel bus today. The retail price difference between conventional diesel buses and comparable series hybrid diesel buses will in the long term be very small (below 5000 $).
- Already in the short term (2005) an approximately 50% reduction of the energy consumption and emission of GHG can be achieved by the use of series hybrid diesel buses relatively to a conventional diesel bus today.
- In the long term, an electric 12 m bus using Lithium Polymer batteries can be designed with the ability to operate 16 hours in Line5_mod between recharges while keeping the curb mass at approximately 8.5 tons. Using electricity produced from renewable energy sources like wind power such a bus will have zero or near-zero greenhouse gas emission and the energy consumption will be approximately 13% relatively to a conventional diesel bus today. Using electricity produced by natural gas combined cycle power plants without district heating the greenhouse gas emission connected with the use of the electric bus will be approximately 17% relatively to a conventional diesel bus today, and the energy consumption will be 23% relatively to a conventional diesel bus today. The emission of air pollutants on the street-level from the bus will be zero. The retail price including the battery replacement costs will be approximately 120000 $ higher for the electric bus compared to a comparable conventional diesel bus.
- Series hybrid fuel cell buses will be an interesting option in the long term, the main reason being that they have zero or near-zero street-level emission of air pollutants, while having the potential to become significantly cheaper than the electric buses and achieve a retail price comparable with conventional diesel buses[6]. Zero or very low GHG emissions can be achieved with the use of hydrogen produced via electrolysis using electricity from renewable energy sources or with the use of methanol produced from biomass[7]. Looking at the fuel cell buses using fossil fuels the bus using compressed hydrogen produced from natural gas comes out best with the energy consumption and emission of GHG being respectively 22% and 7% higher for the fuel cell bus using methanol from natural gas, and respectively 3% and 16% higher for the fuel cell bus using gasoline. The energy consumption and GHG emissions of the fuel cell bus using compressed hydrogen from natural gas are respectively 28% and 24% of the values for a conventional diesel bus today.
- The energy consumption and GHG emission reduction potentials of local trains and light rail vehicles in the short and long term are significantly smaller than those found for buses. This is explained with the already high efficiency of the electric with contact line propulsion system, and with the smaller weight reductions assumed for local trains and light rail vehicles compared to buses. The energy consumption

[6] This conclusion depends heavily on the assumption that fuel cells will be durable enough to last the lifetime of a bus (around 60000 operating hours), and that their price come down to approximately 75 $/kW for the fuel cell and 20 $/kW for the reformer.

[7] The GHG emissions connected with the use of a 12 m fuel cell bus using methanol produced from wood are approximately 5% of the GHG emissions of a conventional 12 m diesel bus today.

and emission of GHG of local trains and light rail vehicles can be reduced by approximately 37% from now to 2020 assuming that the electricity is produced by natural gas combined cycle power plants.

- In the long term, using fuel cells in the local trains and light rail vehicles instead of getting power from a contact line will increase the energy consumption between 40%-190% depending on the fuel cell type and fuel cycle, and increase the GHG emissions by 110%-150% for fuel cell local trains and light rail vehicles using fossil fuels. The use of fuel cells in these vehicle types in 2020 will increase the curb mass of the vehicles by approximately 15%.
- In the short term the energy consumption and GHG emissions per seatkm of a 12 m series hybrid diesel bus driving in Line5_mod are only 19% smaller than the energy consumption per seatkm of a 7.2 m series hybrid diesel bus driving in Line5_mod. The same result applies in the long term for 7.2 m and 12 m fuel cell buses using compressed hydrogen. Therefore reductions in the energy consumption and GHG emissions can be achieved on routes with low passenger loads by using smaller sizes of buses.
- Even very large buses (18 m and 24 m) can not compete with light rail vehicles and local trains, when it comes to the energy consumption and GHG emissions per seatkm. In the driving cycle LineLRV the energy consumption per seatkm of the light rail vehicle is considerably smaller (40-50 % depending on the size of the bus) both in the short and long term than the energy consumption per seatkm of the 12 m, 18 m and 24 m buses[8]. This effect is even more pronounced for the local train with an energy consumption per seatkm being around 65-75 % smaller than 12, 18 and 24 m buses, all vehicles driving in LineA. Looking at the emission of GHG in 2005, the results are even more in favour of the light rail vehicle and local train, because they are assumed to be powered by natural gas power plants, and natural gas emits less GHG than diesel relative to the energy content of the fuels.

[8] In the short term the buses evaluated are series hybrid diesel buses and in the long term fuel cell buses using compressed hydrogen.

2. Introduction

This report describes the results of a three year Industrial PhD Fellowship carried out in a co-operation between the Department of Energy Planning at RAMBØLL and the Energy Planning group at the Department of Civil Engineering, Technical University of Denmark. The Industrial PhD Fellowship (EF number 747) was partly funded by the Danish Agency for Trade and Industry under the Ministry of Business and Industry and administered by the Committee on Industrial PhD Fellowship under the Danish Academy of Technical Sciences.

2.1 Motivation for the study

There were several reasons for starting this PhD project. The Energy Planning Group at the Department of Civil Engineering (formerly Department of Buildings and Energy) felt a need for more research in the area of energy, environment and transport, especially because the transport sector is the sector in Denmark (and in most of the developed countries) with the fastest growth in the emission of CO_2 [Energistyrelsen 2000 A; Metz et al. 2000]. For the same reason the Department of Energy Planning at RAMBØLL evaluated the area of energy, environment and transport to be an interesting future business area. Therefore there was a desire to strengthen this area in the Department of Energy Planning at RAMBØLL.

The choice of public transport modes was motivated by the relatively modest amount of research being done in other transport modes than cars with regard to energy consumption and GHG emissions. Among the many existing transport modes apart from cars, urban public transport modes were chosen because the conditions for market introduction of new propulsion systems like fuel cells are especially favourable in this market segment. This is firstly because the reduction in local air pollutants offered by the new propulsion systems is especially attractive in urban areas, so the willingness to pay for these reductions is bigger for urban transport modes than for other modes. Secondly, because the operating patterns (driving cycles) of urban transport modes are especially suitable for the new propulsion systems, meaning that the performance improvements achieved by introducing new propulsion systems in different vehicles will be larger in urban driving cycles than in highway driving cycles. Thirdly, because the urban public transport modes consist of fleets of vehicles, normally being refuelled at one or a few refuelling sites, which reduces the costs connected with introducing fuels requiring a new refuelling infrastructure.

Finally, there was an intention to add knowledge about the environmental profile of urban transport modes to the ongoing discussion about the suitability of road-bound versus rail-bound transport modes.

2.2 Purpose of the project

The purpose of the project is to analyse the technological possibilities for reduction of the energy consumption and emission of GHG of urban public transport modes in the short (2005) and long term (2020).

2.3 Overview over the report

The summary of the project is presented in chapter one, and the introduction is given in chapter two. Chapter three presents some basic concepts used to classify innovations and technologies in the transport sector. General theories about the development of technologies are presented in chapter four. The models developed in this project are presented in chapter five. First, a model for the calculation of a vehicle driving in a specified driving cycle is presented. Then a model that (based on different performance criteria) for a vehicle determines the curb mass, mass of the propulsion system, price of the propulsion system and size of the different propulsion subsystems is presented.

Chapter six presents the technology analysis method used in the project. Chapter seven, eight and nine contain respectively the technology analysis of fuel cycles, propulsion systems and vehicle loads. In chapter ten the results of the model calculations using data from the technology analysis are presented. Chapter eleven discusses the results achieved. The references are given in chapter twelve. An analysis of the connection between weight reductions and security of vehicles is presented in appendix A. Finally appendix B has a short discussion of the difference between using marginal versus average considerations when determining technology values.

3. Classification of transport technologies

In this chapter a framework for the classification of innovations in the transport sector is presented, and a number of important concepts are defined such as transport modes, transport concepts, vehicle concepts, propulsion systems and fuel cycles. It is discussed which criteria a **public** transport mode has to fulfil.

3.1 Introduction

Innovations in the transport sector can be very different with regard to their application area. One innovation can be a software tool aimed at optimising the bus services in a given area, another can be an improved diesel engine reducing emissions, and a third can be a entirely new transport concept combining the properties of individual and public passenger transport.

Because of the large differences among innovations it is useful to introduce a classification framework, which enables the division of innovations into groups. The classification framework presented in this chapter is taken from [Zwaneveld et al. 1998] and makes a grouping of innovations according to the technology level of the innovations, i.e. classification according to the application areas of the innovations.

3.2 Areas of innovation in the public transport sector

Innovations in the public transport sector can be related to the hardware existing in the sector or the organisation/planning in the sector. The hardware in the public transport sector can be divided into the following groups:

- **Vehicles**, which can be subdivided into propulsion systems, vehicle control systems and overall vehicle designs.
- **Vehicle infrastructure** including agrees/egress systems (bus stops, stations), tickets systems and information systems.
- **Fuel infrastructure**: i.e. the technologies used to produce, store, distribute and refuel the vehicles.

The planning/organisation innovations are ideas, methods and tools for supporting decisions taken on the following levels:

- **Strategic level** where the decisions concerned with the general aims and service characteristics of the public transport service are made. The general aims are a mixture of business targets like profitability and market share, and transport policy targets like accessibility/mobility standards and environmental standards. The general service characteristics are the geographical area of supply of the transport service, the positioning of the transport service in relation to substitutes and complements (intermodality), and the main socio-economic target groups for the transport service.

- **Tactical level** where decisions about the detailed service characteristics of the transport service are made. This involves issues concerned with the production of the transport service, i.e. the choice of vehicles, planning of routes and timetables, and issues concerned with the selling of the transport service, i.e. image, fare structure and fare level, and provision of additional services like news and catering.
- **Operational level** is decisions that are concerned with the translation of the tactical aspects into day-to-day services. This involves management of sales staff, drivers, vehicles and infrastructure to ensure realisation of the services according to the tactical planning.

3.3 Fuel cycles, propulsion systems, vehicle concepts and transport concepts

A classification framework that encompasses the division of technologies into hardware and organisation/planning related is given by the concepts: transport mode, transport concept, vehicle concept, propulsion system and fuel cycle. As can be seen from Figure 3-1 a transport mode consists of a combination of a fuel cycle, a propulsion system, a vehicle concept and a transport concept. This approach is an enlargement of the methodology used in [Zwaneveld et al. 1998]. The enlargement consists of the formulation and addition of the concept fuel cycle into the definition of a transport mode.

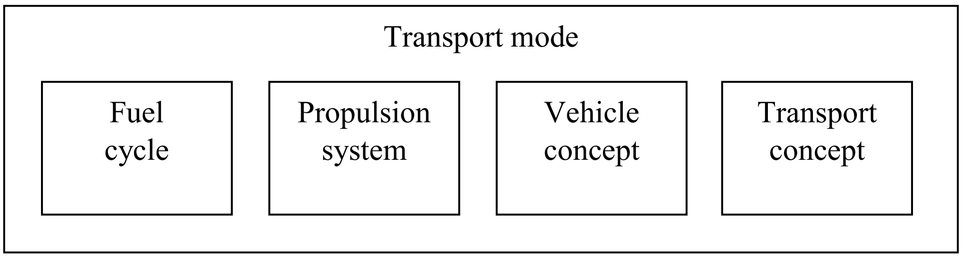


Figure 3-1 A transport mode consists of a fuel cycle, a propulsion system, a vehicle concept and a transport concept.

The above mentioned four terms are defined as follows:

- **Fuel cycle:** *the fuel infrastructure i.e. the technological system used to produce, store, distribute and refuel the vehicles.*
- **Propulsion system:** *the technology used for the movement of the vehicle including the onboard energy storage system.*
- **Vehicle concept:** *the vehicle with corresponding vehicle infrastructure that is used for the movement of goods or persons.*
- **Transport concept:** *the organisational form of possible use/operation of vehicles and associated infrastructure.* Thus, a transport concept more or less involves the functional aspects of using a vehicle concept and a propulsion system.
- **Transport mode:** *a combination of a fuel cycle, propulsion system, vehicle concept and transport concept.* A transport mode can be thought of as a supplier of mobility, in that it offers a possibility to travel.

The fuel cycle, propulsion system and vehicle concept encompasses the hardware related innovations, where as planning/organisation innovations relates to the transport concept.

It is found useful to make a distinction between the propulsion system and the vehicle concept, because a lot of innovation is taking place with regard to more efficient and environmentally friendly propulsion systems, without affecting the basic vehicle design in terms of passenger capacity, space, etc.

As shown in chapter 5 innovations that improve the onboard energy consumption of vehicles can be divided into innovations that increase the efficiency of the propulsion system, and innovations that reduce the vehicle loads. The first type of innovations naturally belongs to the concept propulsion system, and the latter belongs to the vehicle concept, because the reduction of the vehicle loads involves the overall design of the vehicle[9]. Also as pointed out in chapter 5 it is important to analyse the whole fuel cycle from well to wheels, which explains why the fuel cycle has been introduced as a separate concept.

The definition of a transport mode includes organisational, operational and technological aspects. The definition gives rise to a lot of transport modes in that only one of the four terms going into the definition needs to be changed to generate a new transport mode.

Table 3-1 lists the characteristic features of the fuel cycle, propulsion system, vehicle concept and transport concept, and Table 3-2 contains examples.

Fuel cycle	**Propulsion system**	**Vehicle concept**	**Transport concept**
Primary energy source	Fuel	Capacity	Supplier, User, Owner
Fuel	Specific performance	Curb weight	Network
Fuel cycle efficiency	Specific emissions	Range	Lines (Routes)
Fuel cycle emissions	Energy efficiency	Energy consumption	Stops
		Emissions	Timetable
Transport mode			

Table 3-1 Characteristic features of the propulsion system, vehicle concept and transport concept.

Fuel cycle	**Propulsion system**	**Vehicle concept**	**Transport concept**
Diesel, hydrogen produced from electricity from wind turbines	Conventional with CI ICE, series hybrid with fuel cell	Small car, 12 meter bus, train, light rail	individual, taxi, ride-sharing, collective, demand-responsive
Transport mode			

Table 3-2 Examples of fuel cycles, propulsion systems, vehicle concepts, transport concepts and transport modes.

Both the fuel cycle, propulsion system, vehicle concept and transport concept have importance for the energy consumption of the transport mode. The fuel cycle, propulsion system and vehicle concept determines the primary energy consumption of the vehicle per driven kilometre, whereas it is the overall working of the transport mode including the transport concept that determines the degree of utilisation of the mode[10].

[9] This is correct for curb weight reductions and reductions in the air resistance, but reductions in the rolling resistance by change of tires do not involve the overall design of the vehicle.

[10] i.e. the number of passengers relative to the passenger capacity

3.4 Delimitation of the innovations analysed in this study

This study concentrates on analysing the hardware innovations, i.e. the technical possibilities for reducing the life cycle energy consumption of the vehicles. The possibilities for reducing the energy consumption by innovative means of adjusting the capacity of the offered transport services to the actual travel demands (i.e. the innovations belonging to the transport concept) are not analysed in this study.

3.5 Definition of a public transport mode

A public transport mode can be defined as a **planned** transport service offering transport in the same vehicle to persons belonging to **different** households [Meulengracht 1984]. The definition characterise a public transport mode by two aspects:

1. The transport service must be planned in advance, i.e. spontaneously organised transport of persons belonging to different households (like the sharing of a taxi) will not be designated as public transport.
2. The use of the transport service must involve a co-ordination of the trips done by persons belonging to different households. This means that the co-ordination of the transport undertaken in a family in the form of trips involving several family members in a vehicle is not seen as public transport. The same goes for taxi that are not considered a public transport mode in that the transport service offered is normally directed towards one person at the time or towards groups of interrelated persons.

The definition does not provide a totally clear-cut division between public and non-public transport modes. For example a car sharing scheme has as a consequence that some kind of co-ordination of the trips undertaken by persons belonging to different households takes place, through the sharing of the same vehicle fleet. Therefore it is a matter of taste if car sharing schemes should be designated as public transport modes or not. However this project focuses on the traditional public transport modes that involves transport of persons from different households in the same vehicle at the same time.

According to the definition it is the transport concept, that determines if a transport mode is public or not. The chosen propulsion system and the vehicle concept do not enter into the definition.

The definition is based on the organisational and user aspects of the transport mode. Other definitions of public transport modes exist based on the service characteristics of the transport mode. For example in [Alexandersen 1995] a public transport mode is defined as a transport mode, where the traveller can not determine who his fellow travellers should be, and where it is not possible for the traveller to determine the precise start destination and the precise end destination of the journey.

3.6 Transport concepts

According to the definition a transport concept involves the functional aspects of using a vehicle with associated infrastructure. The important parameters when classifying the transport concepts are concerned with the flexibility of the transport modes, the service offered with regard to covering of transport demands, and owner, user and driver aspects:

Flexibility

- **Choice of departure time:** the choice of departure time can be free as in the case of individual transport. It can be demand-driven but more or less limited, or it can be fixed as in the case of timetables.
- **Route choice:** The choice of route can be free (individual transport), it can be demand-driven but within limitations, or it can be fixed, i.e. line-based transport.
- **Access to vehicle on route:** There can be free access to vehicle on route, i.e. the vehicle will stop according to user choice. More limited access but still demand-driven, or fixed access in the form of stops.

Owner, user and driver aspects

- **Owner of vehicle:** user or non-user.
- **Driver of vehicle:** user or non-user.
- **Rights of usage of vehicle:** the rights can be private, belonging to a limited group as in the case of car-sharing, or be public.

Service characteristics

- Different transport modes offer different coverage of the users transport demands. Full coverage of a given transport demand from the start destination to the end destination is termed door-to-door transport. Partly coverage of the transport demand is termed door-to-stop, stop-to-door or stop-to-stop. In these cases other forms of transport must be employed to cover the whole transport demand, e.g. walking to get to a bus stop.

By considering the difference in the functional aspects between transport modes, eight different transport concepts are arrived at [Zwaneveld et al. 1998]. In Table 3-3 the passenger transport concepts is described. The transport concepts used in public transport modes are the demand responsive, continuous collective and collective transport concepts.

Name	Description of transport concept (TC)	Examples
Individual (TC1)	Individual transport with a high degree of flexibility regarding departure time, route and stops. User, owner and driver are often identical and closely related private individuals.	Individual usage/operation of bicycle, car
Taxi (TC2)	Similar to TC1 except for user, driver and owner aspects	-taxi
Demand responsive (TC3)	Semi-individual transport. Transport supply may be restricted as regards departure time, travel route, or access stops in-between. However there is some degree of flexibility in at least one of the above items (e.g. on-request off-line stops of a bus service, taxi pick-up/drop-off schemes at designated stops or areas). Pure door-to-door service (like in TC1 and TC2) is not offered.	-tele bus
Ride sharing (TC4)	A TC where the driver (owner) agrees to make his/her vehicle available to alien passengers with similar travel demands. There is very likely a certain trade-off between the driver's and passengers needs in terms of route and/or time. Can take place in a (formally or informally) organised way or in an ad-hoc spontaneous form.	-car pooling (organised) -hitch hiking (spontaneous)
Rent a vehicle (TC5)	Made available on request, a vehicle is picked-up and returned by the driver at designated locations. The vehicle can then be used in an equally unrestricted manner as in TC1. The user group may be restricted to members of an association (car-sharing schemes) whereby joint ownership and other arrangements may be in place.	-classical vehicle rental -Praxitele -car sharing
Continuous collective (TC6)	The TC is related to TC7 except (within operating hours) no major restrictions exist as to the departure times. This is secured by a permanent (high frequency) service or an on-demand service, which is available to the user almost instantly.	-collective concepts circulating at high frequency -park shuttle -cable liner
Collective (TC7)	The TC is designed to transport passengers at a large scale and in large numbers. Departure time, route and access are all fixed and only stops-to-stop travel is covered.	-ordinary collective transport
Integrated /Combined (TC8)	Integrated TC is an combination of the individual TC and one or more other TCs (which is predominantly a collective TC). Thereby a multi-modal transport chain is formed. The main feature is the integration/combination of more than one mode with a smooth interchange. Such a combination may capitalise on the specific advantages of each single modes and use certain synergy effects (e.g. train and car)	-park and ride

Table 3-3 Description of passenger transport concepts. Table taken from [Zwaneveld 1998, table 5.1].

3.7 Vehicle concepts

A vehicle concept consists of the vehicle with corresponding infrastructure. The vehicle concepts are classified according to the following parameters:

- **Capacity per unit:** this is an important parameter when calculating the total capacity of a transport mode and also holds information about the size of a unit. Two measures of the capacity are relevant, one being the number of seats (the seat capacity), and the other being the maximum number of passengers in the vehicle (i.e. the number of seats plus the maximum number of standing passengers). All though some vehicle concepts are designed with few seats to leave more space for standing passengers, this work uses the seat capacity as the basic measure of the capacity of a unit. For some vehicle concepts (notably buses and the rail-bound vehicles) the capacity can vary a lot within one vehicle concept class. This reflects that the vehicles are produced with different seat configurations and in different lengths, and for local train and metro that the capacity per unit varies with the number of cars in the train configuration.

- **Control:** the control of the vehicle can be entirely manual (man), manual and supported with automatic security and guidance systems (sup), or entirely automatic i.e. no human driver on the vehicle (aut).
- **Infrastructure:** the infrastructure is classified into two main groups; road and rail. There exists vehicle infrastructure with both road and rail infrastructure properties, e.g. roads with vehicle guidance systems.
- **Interaction with other traffic:** the vehicle concept can have its own track entirely separated from other traffic, be separated from other traffic on part of the routes but interact with other traffic on other parts, or share the vehicle infrastructure with other vehicle concepts. The interaction with other traffic has importance for the driving cycle of the vehicle and the regularity of the mode.
- **Energy supply:** The energy storage can be on-board as in the case of vehicles with fuel tanks and internal combustion engines or off-board as in the case of vehicles getting power from contact lines.

	Seat capacity per unit [seats]	Control	Infrastructure	Interaction with other traffic	Energy storage
Bicycle	1	man	road	yes	on-board (human)
Moped/Scooter	2	man	road	yes	on-board
Car	2-8	man	road	yes	on-board
Bus	8-60	man	road	normally	on-board
Light tyre/guided bus	30-60	sup	road with guidance	partly	off board and on board
Local train & metro	50-650	sup/aut	rail	no	off-board
Light rail	30-100	sup	rail	partly	off-board
People mover	2-40	aut	rail	no	off-board

Table 3-4 Classification of vehicle concepts relevant for urban passenger transport.

Table 3-4 lists the vehicle concepts relevant for urban passenger transport. The vehicle concepts can be further subdivided into classes according to the sizes of the vehicles. Buses for urban passenger transport can be subdivided into five classes [Jørgensen 2000]:

- **Mini buses** are passenger vans with a total passenger capacity of 8-15 passengers and a gross vehicle weight rating[11] below 5 tons.

[11] The gross vehicle weight rating is the maximum permissible weight of the vehicle including passengers.

- **Midi buses** are downscaled versions of the standard bus with a total passenger capacity of 30-50 and a gross vehicle weight rating of 8-12 tons.
- **Standard buses** are 10-12 meter long with a total passenger capacity of 70-80 and a gross vehicle weight rating of 16-17 tons.
- **Articulated buses** are 16-18 meter long with a total passenger capacity of 130-140 and a gross vehicle weight rating of 23-23 tons.
- **Double-decker buses** are 12 meter long with two decks and a total passenger capacity of 114 (76 seats).

3.8 Propulsion systems

Even though propulsion systems used in public transport modes exist in a lot of different configurations, the propulsion systems can be perceived as consisting of a relatively limited number of subsystems[12]. By considering the existing combinations of the subsystems a classification with five main groups is arrived at (see Table 3-5).

Propulsion system type	Pantographs or the like	Fuel converter & fuel storage	Electricity storage system	Electric motor/ Generator
Conventional		x	(x)[13]	
Electric			x	x
Electric with contact line	x			x
Hybrid electric		x	x	x
Hybrid electric with contact line	x	x	x	x

Table 3-5 Classification of different propulsion system types according to the combination of subsystems included in the propulsion systems.

The propulsion system classes can be subdivided further according to the design and operating strategy of the propulsion system, and according to the type of fuel converter and electricity storage system used in the propulsion system. The design of hybrid electric propulsion systems is treated in more detail in section 5.4.1. The fuel converters can be classified as shown in Table 3-6, where the combustion engines are classified according to different general design principles. A finer classification of the combustion engines can be done [Zwaneveld et al. 1998], but the level of detail reflected in Table 3-6 has been considered appropriate in this study.

[12] see section 5.4 for a further description of the subsystems.

[13] Only a very small one in the form of the starter battery.

Combustion engines				Fuel cells
Internal combustion[14]			External combustion[15]	
Cyclic combustion[16]		Continuous combustion		
Spark ignition engine[17]	Compression ignition engine[18]	Gas turbine	Stirling engine	Fuel cell

Table 3-6 Classification of fuel converters (adapted from Zwaneveld et al. 1998).

3.9 Fuel cycles

The fuel cycles are classified according to the primary energy source used to produce the fuel and according to the fuel itself. Biomass and wind are per definition taken as primary energy sources, and biomass is subdivided into different types of biomass according to the plant species used. Fuels consisting of the same chemical constituents but in different physical states are treated separately, e.g. liquid hydrogen is considered a different fuel than gaseous hydrogen.

[14] In internal combustion the combustion takes place inside the cylinder and the combustion gas itself is used as the working medium.

[15] External combustion is a process of continuous, external combustion in which the heat generated acts on a separate working medium that performs work as it expands.

[16] All reciprocating-piston engines use cyclic combustion where the different combustion phases (compression, ignition, expansion) happens in the same place (the cylinder) but in separate time intervals succeeding each other. In continuous combustion the combustion phases are separated in space and happen continuously, e.g. in a gas turbine the gas is continuously combusted in a combustion chamber and the hot exhaust gas expands through a turbine thereby generating a torque.

[17] Spark ignition indicates that an electric spark initiates the combustion. It is the main characteristic of the Otto engine being used in nearly all gasoline cars.

[18] In compression ignition engines the heat of the compressed air into which the fuel is injected initiates the combustion. The Diesel engine, which is the dominant engine type in trucks and buses, uses this principle.

4. Technology development

The purpose of this chapter is twofold. Firstly, the chapter provides some general insight into the questions about how technologies develop, and what the interactions are between the development of the technology and other technologies, markets and government. Secondly the actors influencing the development of advanced transport technologies are identified, and the relative importance of the different actors is discussed.

4.1 General findings about the development of technology

Much research has been made about the development of technologies [Utterback 1994 and references herein; Henderson 1997]. In this paragraph some of the main findings will be mentioned, and their relevance for this study discussed.

4.1.1 The technological lifecycle

The lifecycle of a technology is often described with an S-curve (see Figure 4-1). In the start up or fluid phase the performance of the technology improves slowly. The performance criteria and design of the technology is not firmly established, and there is a competition going on between different ideas and designs. A lot of product innovations take place, i.e. innovations regarding the design of the product and the components of the product in the case of assembled products. No firm customer expectations have been established.

Then the companies adopt a dominant design and the performance criteria of the technology are established. The innovation shift from product to process innovation, and there is intensive competition to improve the performance of the technology. The adoption of the dominant design facilitates a shift to incremental product development and aggressive investment in process technology. However, the adoption of the dominant design simultaneously limits the ultimate performance of the technology.

At last the technology approaches its performance limits and the progress rate of the technology slows down. The returns to investment in the technology eventually fall dramatically, setting the stage for a move to another generation of technology and a repetition of the cycle.

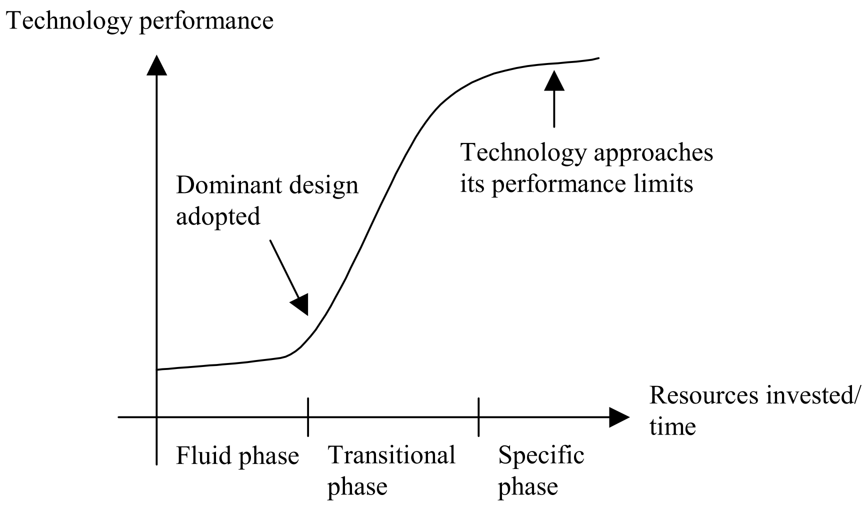


Figure 4-1 The S-curve describing the development of a technology. The performance of the technology is often measured with a parameter expressing the ratio between cost and technical performance, e.g. sale price versus rated power for a power generating technology, but also pure technical parameters are used like the number of transistors per square centimetre for micro chips.

This simple picture of the technological lifecycle is helpful when conducting historical studies of the development of a technology. The picture can be modified to take into account the reaction of the old mature technology, when a new competitive technology is introduced. A number of studies have shown that the introduction of a new technology on the market leads to a burst of improvement in the established technology [Utterback 1994]. This is the outcome of the established players on the market fighting back with renewed product innovation, when they are losing market shares to an invading product. Often the new product has so much more potential for better performance that it is usually just a matter of time before that potential is realised and the new product surpasses the old.

Utterback gives a number of examples, e.g. the displacement of gas lamps with electric lamps of the Edison design. An interesting current example is the ongoing efforts to improve the Otto and Diesel engines to cars under the threat of the emerging fuel cell technology.

The existence of a dominant design for a technology influences the evolution of complementary technologies. Customer expectations and capabilities will to some extent be determined by the performance of the dominant design, meaning that new technologies apart from offering better performance in some areas also need to offer comparable performance in the remaining areas to be successful.

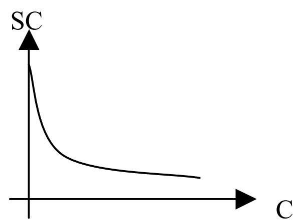
In some cases the dominant design evolves into a whole system of interconnected technologies and institutions that effectively works as a (large) barrier for the introduction of new technologies. This is called technological lock-in, and the conventional car with associated fuelling and maintenance infrastructure is often quoted as an example [Boysen et al. 1997].

4.1.2 Technology learning

Empirical evidence shows that the decline in unit cost of a technology is closely related to its cumulative production and use. Knowledge and experience accumulated from manufacturing, installing and using a technology help to improve its performance and reduce cost [Tseng et al. 1999]. The processes of learning by doing and learning by using are called technology learning. The learning takes time because the experiences gained with producing and using the technology need to be absorbed and analysed in the companies before being of use in the production of new versions of the technology.

The results of technology learning is often modelled as a mathematical relation between manufacturing cost (unit cost) and the cumulative production of the type [Tseng et al. 1999]:

$$SC(C) = a \cdot C^{-b}$$



Learning curve

Where

SC is the unit cost, C is the cumulative production, b is the learning index, and a is the unit cost of the first unit.

Such functions are called learning curves and the processes of technology learning are visually presented as “going down the learning curve”.

The concept of technology learning can partly explain the occurrence of technological lock-in. The dominant technology already on the market has undergone the technology learning process and has low unit cost and is sold in large numbers. The new technology on the other hand is too expensive to gain a share of the market, and can therefore not get started with the technology learning process, and can therefore not get the price down. It is a kind of an evil circle.

If the technology do not manage to enter the market, the investments, research and developments efforts put into the technology will eventually decline, leading to an even slower progress rate of the technology.

4.1.3 Entities influencing the development of technologies

It is in general very hard to predict the development in performance of a technology. Even in the case of a technology already on the market where there exists a seemingly straightforward way of predicting the technical performance, the forecast attempts can be persistently wrong. Henderson illustrated this in a study on the development of optical lithography [Henderson 1997] where the improvement in the performance was consistently underestimated. The reason is that the determination of the technical performance of a technology rest on a series of assumptions about the probable evolution of user needs and capabilities and the potential of component and complementary technologies

[Henderson 1997]. Therefore to make a good forecast you need not only to know the technology in detail but also the development in component and base technologies, and also the development of user capabilities and needs that can influence the required performance of your technology[19].

When it comes to estimating the development of technologies that are still in the fluid phase, it gets even harder. As shown by the technology learning approach (see section 4.1.2) the market success of technologies that has not yet reached industrial mass production numbers also has a significant influence on the progress rate of the technology, especially with regard to cost reductions. So an important part of the evaluation of the development of a technology is to analyse the possibilities for market success of the technology. This can be done by analysing the barriers and drivers existing for the market introduction and success of the technology. The analysis of barriers and drivers needs to be done on the actor (stakeholder) level, because some characteristics of a technology can constitute a barrier for one actor and a driver for another. For example the use of electricity in electric vehicles can be a driver for the introduction of electric vehicles for the government, in that it reduces the oil dependence of a country, but a barrier for the existing gasoline and diesel distributors in that a major introduction of electric vehicles will reduce their share of the market.

The political priorities of society can have a crucial influence on the development of a technology. With regard to transport technologies political bodies on local, regional, national and international levels can influence the choice between and development of technologies. Technologies that are perceived as beneficial for society can be stimulated in a number of ways, and likewise technologies that in some respects are considered harmful can be met with demands (e.g. emissions limits), that forces the technologies to develop or loose market shares.

Often the different signals and messages coming from political bodies on different levels are internally contradicting, which reflects that the priorities of different political bodies are not the same. Even the signals coming from one political body can be and often are contradictory over time. There is nothing strange in the different signals and messages coming from political bodies in that it just reflects the different priorities existing in society, but it can create confusion among the actors about the future market possibilities for the technology.

The interactions between the technology and different entities in the surroundings are illustrated in Figure 4-2.

[19] This last point refers to technologies where the relieving of some of the technical demands can open up possibilities for much better performance. An example is given by the electric car that would stand a much greater chance of commercialisation, if the requirement on driving range was relieved, e.g. if an evolution in user needs created a market for clean, short-range urban vehicles.

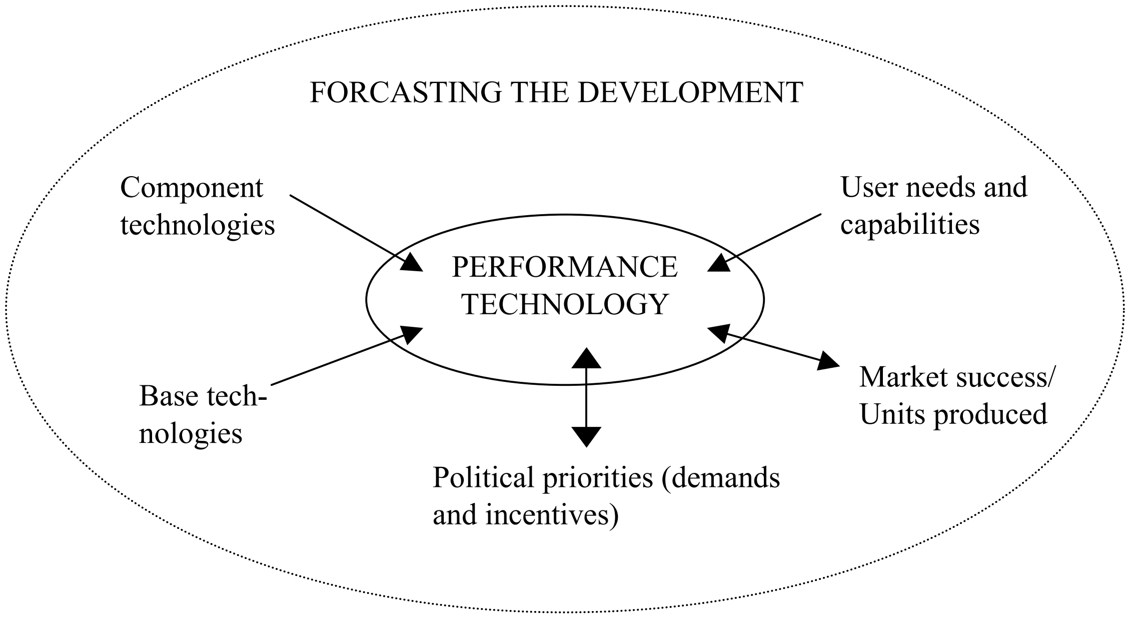


Figure 4-2 Forecasting of the development of a technology also involves forecasting the market success of the technology, the evolution in user needs and capabilities, the development of component and base technologies and the evolution in the priorities of political bodies.

4.1.4 Determination of the technical performance of technologies

But how are the results found in the literature on the technical performance of technologies determined? In general the performance results come from measurements. The status of the measurements depends on the maturity of the technology. For mature technologies already on the market the measurements of the performance will typically be under real life conditions, i.e. the results must be considered a reliable picture of the present performance of the technology. For new technologies still in the laboratory or only introduced in a few prototypes care has to be taken to distinguish between results coming from measurements in the laboratory and results from more realistic measurement conditions.

The laboratory measurements will often overestimate the performance of the technology in real life conditions. Firstly because the laboratory values often are for the basic technology without the additional equipment necessary for thermal and electric control and management which will increase the weight/volume/cost of the technology, and secondly because real life conditions typically are far more severe than laboratory conditions. Finally the effect that researchers like all other people have a motivation to present their results in the best possible light to get success and funding can not be ignored.

It is logical that it is the present performance values of a technology that are used as the starting point for the forecast of the performance into the future. But as illustrated by Henderson this can lead to an underestimation of the future performance, because it is nearly impossible to have an overview over all the developments in component and base technologies that can lead to an large improvement in the technology in the future.

4.2 Actors influencing the development and market success of public transport technologies

When evaluating the barriers and drivers existing for the market introduction of a new technology, it is important to relate the characteristics of the technology to the different actors influenced by the technology. Figure 4-3 gives an overview of the different actors potentially involved in the production and use of public transport modes grouped into four markets namely the fuel market, public transport service market, vehicle market and vehicle infrastructure market.

There are three actors on the fuel market, namely the fuel manufacturer and fuel distributor that produce, store, distribute and sell the fuel, and the vehicle operator that buys and store the fuel. Governmental institutions influence the market conditions in the fuel market through fuel taxes and fuel rebates, and through the standards and regulations governing the production, handling and storing of the fuels.

Different public institutions influence the public transport market. Political councils determine the subsidies put into the markets, and the ways the public transport markets are organised. Often also the general service characteristics of the market (fare level, mobility and accessibility standards) are determined by public institutions. Regulatory authorities control the operation of the public transport market in different ways. The transport planner and vehicle operator can be part of the same organisation. These actors can be either private or public companies according to the organisation of the transport market. The transport planner plans the detailed service characteristics of the public transport service, i.e. fares, routes and time-tables. The vehicle operator maintains and operates the vehicles.

The vehicle market consists of the vehicle buyers and the vehicle manufacturers that develop, produce and sell the vehicles. It is common in public transport that the vehicle operators buy and own their vehicles, but leasing of vehicles also take place in the rail sector. Governmental institutions can influence the development of the vehicle market through environmental and safety standards for the vehicles, by supporting research and development of specific technologies and through economic incentives to certain transport modes.

Finally the vehicle infrastructure market consist of three actors: the manufacturer of the vehicle infrastructure, the actor responsible for the maintenance and overall operation of the infrastructure, and the vehicle operator using the infrastructure. For rail bound modes there are a very close connection between the vehicle market and the vehicle infrastructure market, because the vehicle manufacturers often also are vehicle infrastructure manufacturers, i.e. for new railway tracks the company delivering the vehicles will often also be the company building the infrastructure.

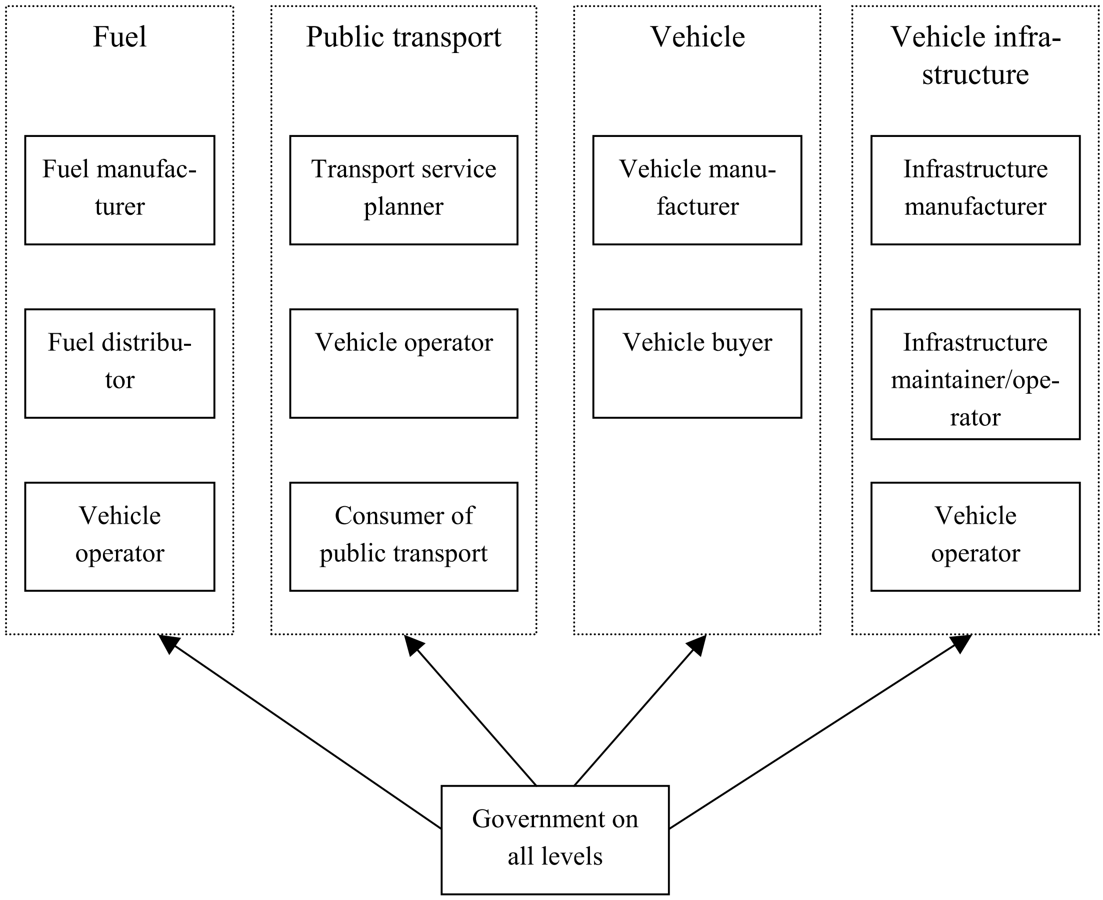


Figure 4-3 Overview of the actors involved in the production and operation of public transport modes. The actors have been grouped into four markets according to what "product" they work with, namely the fuel market, public transport service market, vehicle market and vehicle infrastructure market. Governmental institutions on both the local, regional, national and international level interact with and influence the markets.

When analysing the importance of each actor with regard to the production and market introduction of transport innovations, a basic distinction can be drawn between those actors that actually make and sell the innovations, and those actors that influence the design, development and market success of the innovations through their demands and wishes to the innovations.

The first group of actors consists of:

- The vehicle manufacturers and their subcontractors (i.e. the manufacturers of vehicle parts) that develop propulsion systems and vehicles.
- The fuel manufacturers in collaboration with the fuel distributors and the vehicle manufacturers that develop fuels.
- The vehicle infrastructure manufacturers that develop vehicle infrastructure in close collaboration with the vehicle manufacturers.

The second group of actors consists of:

- The buyers of vehicles and fuels, i.e. the vehicle operators, and the buyers of vehicle infrastructure which most often is one or a group of public institutions.

- The other actors in the public transport market influencing the needs and wishes of the vehicle operators, i.e. the buyers of public transport services and the transport service planners.
- Political councils influencing the development of technologies through various initiatives like regulations, support programs and vehicle infrastructure projects.
- Regulatory authorities formulating standards for vehicles and fuels.

When it comes to making and developing the innovations the actors in the first group are the primary entrepreneurs. The actors belonging to the second group can through their demands and wishes significantly influence the research and development work undertaken by the primary entrepreneurs. One example of this is the development of hybrid and electric cars that has taken place as a result of legislation in California demanding that a certain fraction of cars sold in California in 2003 must be zero emission vehicles (the so-called ZEV mandate issued by California's Air Resource Board).

When it comes to bringing the innovations to the market and making them a market success, it is more complicated to determine who are the primary entrepreneurs. The actors in the first group are still very important, because they determine the compromises that very often need to be done between performance and price of an innovation, and they determine the production and marketing strategy. On the other hand public institutions especially political councils can significantly influence the market conditions faced by an innovation.

5. Energy consumption of transport modes

In this chapter the energy consumption of transport modes is described and modelled. First an overview over the models involved in the calculation of the energy consumption of public transport modes is given. Than a model for the energy consumption and GHG emissions of a vehicle driving in a given driving cycle is derived. Finally a model for the design of the propulsion system in a given vehicle is presented. The models provide a background for the analysis of the technological possibilities for reducing the energy losses presented in chapter 7-10.

5.1 Models involved in calculating the energy consumption of public transport modes

The most common indicator for the energy consumption of public transport modes is MJ per person kilometre (pkm), i.e. the average energy consumption for transporting one person one kilometre. This indicator is suitable, because it depends both on the specific energy consumption of the mode, i.e. the vehicle concept, propulsion system and driving cycle, and the number of passengers using the vehicle, i.e. passenger capacity and degree of utilisation.

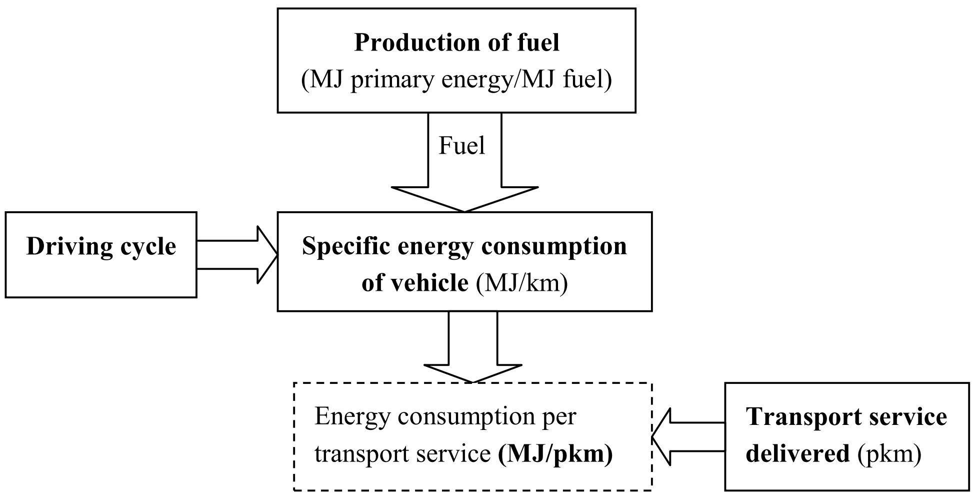


Figure 5-1 The models involved in the calculation of the energy consumption of a transport mode.

However when comparing different transport modes, the indicator must be used with caution, and supplemented with considerations about the service level provided and transport demand covered by the different transport modes. This is because the correct efficiency parameter is the energy consumption (or emission) per transport service delivered. If the transport services of two transport modes are very different, and they are covering different transport demands, a simple direct comparison can give a wrong impression. The transport service of a transport mode depends on a number of parameters, e.g. frequency, travel time, security and interior space per passenger.

The infrastructures of the transport modes are also important to consider when comparing different vehicle concepts. Especially if the transport mode has its own track or is sharing infrastructure with other transport modes. All other things being equal driving in a separate track gives a more smooth driving cycle, than sharing the infrastructure with other vehicles, leading to lower energy consumption and emissions. For example, when evaluating a future public transport solution by comparing a bus and a train solution to a transport demand, it is relevant also to include a bus solution with its own lane in the comparison.

Figure 5-1 shows an overview over the models involved in calculating the energy consumption of public transport modes.

The models are the following:

1) **Model of the driving cycle:** A driving cycle is an example of the way a vehicle drives in a specific traffic situation. The driving cycle consists of a set of time versus speed co-ordinates for the vehicle. Usually the time versus speed co-ordinates is measured by driving a vehicle in real traffic. The purpose of this model is to construct a driving cycle that provides a good approximation to the way the vehicle is used. The driving cycle depends on the transport concept, the vehicle concept and the surrounding transport system. Important parameters in the model are the number of stops per unit distance and the average speed in the driving cycle. The driving cycles used in this project are presented in section 5.9.
2) **Model of the supply of fuel:** When comparing the energy consumption of transport modes using different fuels, it is important to calculate the primary energy consumption connected with the fuel consumption. To do this the primary energy used to produce the fuel and deliver the fuel to the refuelling site must be calculated. This is done with models that take the extraction, conversion, distribution and storage of the fuels into consideration. The total of these steps is defined here as the "fuel cycle" or "well-to-tank". In chapter 7 the results from such models for the fuels relevant for this project are summarised.
3) **Model of the specific energy consumption of the vehicle:** This model calculates the fuel consumption of a vehicle driving in a specified driving cycle. Models of this kind can have different level of detail, but they basically calculates the tractive power needed at the driving wheels to propel the vehicle forward, and the efficiency of the conversion of fuel to mechanical power at the wheels ("tank-to-wheels" efficiency). A model of this kind will be presented in this chapter.
4) **Model of the transport service delivered:** The purpose of the model is to estimate the load factor of the transport mode defined as the average number of passengers per trip using the transport mode. It is necessary to analyse the passenger load in both peak and off-peak hours. The passenger capacity of the transport mode is of importance in peak hours. A higher load factor can be obtained, if the passenger capacity of the transport mode is flexible. The passenger load depends on the service the transport mode offers in competition with other relevant transport modes, and on the overall traffic situation. This makes the passenger load very hard to model. Therefore such a model has not been developed in this project.

5.1.1 Life cycle analysis of transport modes

A life cycle analysis (LCA) of a transport mode includes an analysis of the environmental loads involved in the construction, maintenance, operation and removal of the vehicles and infrastructure used in the transport mode (see Figure 5-2). In theory an LCA must include all processes, that can be associated with the transport mode, e.g. the energy consumption and emissions associated with the extraction of the steel going into the vehicles, have to be included in the LCA. In practice it is not possible to include all processes, so only a subset are analysed. The challenge of the researcher is to include the most important processes, such that the LCA gives a sufficiently accurate picture of the environmental loads associated with the product or system under consideration. The LCA can be simplified by only including few environmental loads in the analysis, e.g. the energy consumption and emission of GHG.

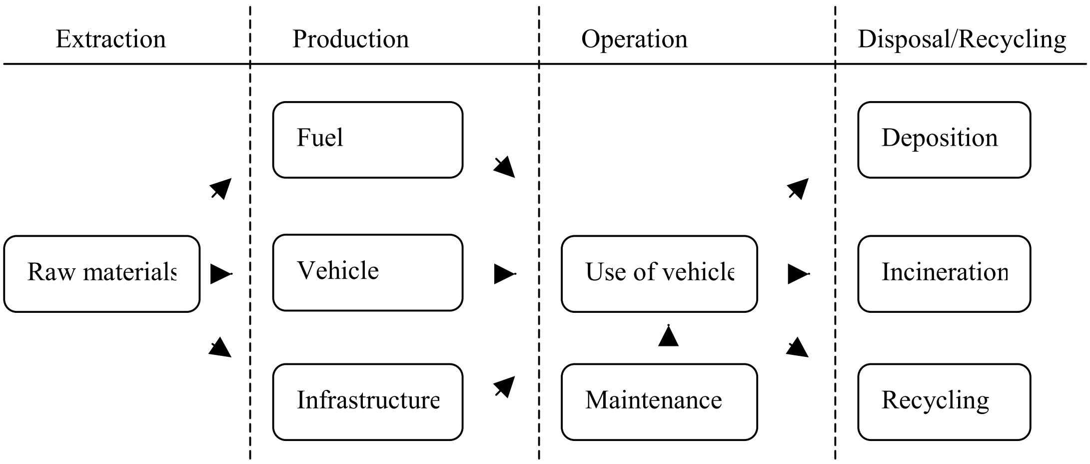


Figure 5-2 The phases and processes involved in a life cycle analysis of a transport mode.

Several LCA's of passenger transport with cars have been carried out [Nielsen & Gudmundsson 1999; Grell 1997 and references herein] and fewer covering other transport modes [Kalenoja 1996]. The main results are:

- **Energy consumption:** For all transport modes approximately 80-95 % of the life cycle energy consumption is associated with the operation of the vehicles (use of vehicle and fuel cycle), (see Figure 5-3).
- **Greenhouse gas emissions:** the results are similar to the results for the energy consumption.
- **Local emissions:** Approximately 90-100 % of the life cycle local emissions is associated with the operation of the vehicles for all transport modes [Kalenoja 1996].

Doing a full LCA would imply the addition of additional models to the above models, namely models of the construction, maintenance and removal of vehicles and vehicle infrastructure.

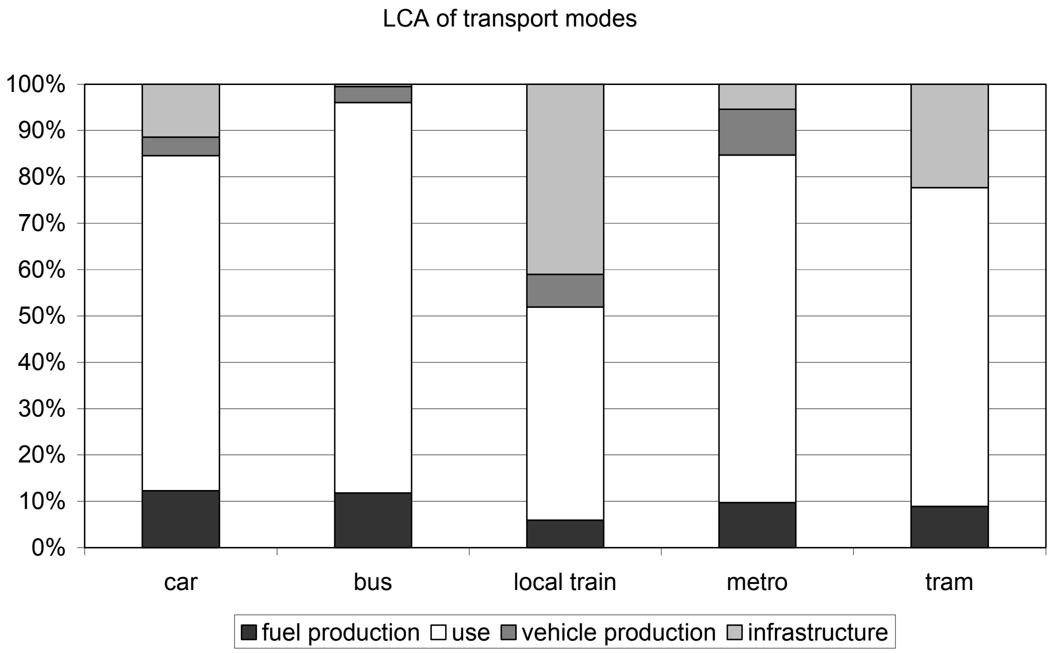


Figure 5-3 The relative distribution of the total energy consumption of different transport modes on the production of the fuel, the use of the vehicle, the construction and maintenance of the vehicle, the construction and maintenance of the corresponding infrastructure. Results from a Finnish LCA-study using data from the Finnish transport and energy system [Kalenoja 1996]. For all modes, except the local train, the fuel production and use of the vehicles constitutes the main part of the total energy consumption (78-96 % of total). No data for the vehicle production phase for the tram was given in [Kalenoja 1996]. The energy consumption connected with the construction and maintenance of vehicle infrastructure per person kilometre for the metro is only 9% of the same figure for the local train, although the vehicle infrastructures of these two modes resembles each other. This underline the large uncertainties connected to the results obtained from LCA-studies of transport modes.

We have chosen to leave out the construction, maintenance and disposal phases of vehicles and transport infrastructure from the analysis done in this project. The energy consumption and emissions connected with the construction and maintenance of the vehicle infrastructure are probably relatively larger for rail bound public transport modes compared to road bound public transport modes as indicated in Figure 5-3. This is because the road bound public transport modes share the vehicle infrastructure with the cars and trucks, and normally constitute a small number of the total number of vehicles using the roads and therefore is only allocated a small share of the energy and emissions used to the construction and maintenance of the roads. Rail bound modes like metro and local train on the other hand often has a dedicated infrastructure of which they are the only users. The omission of the vehicle infrastructure construction and maintenance phases from the analysis, therefore will put the rail bound modes in a better light when compared with road bound modes.

When the traditional choice of materials (mainly steel) in vehicles is substituted with lighter materials like aluminium and composites, the weight savings will reduce the energy consumption connected with the use of the vehicles. On the other hand the new materials may be more energy consuming to produce, as is in fact the case for aluminium compared to steel. The omission of the vehicle production phase from the analysis means that this trade-off can not be analysed, which will put the aluminium intensive vehicles in a slightly better light compared to steel intensive vehicles.

5.2 Model of the energy consumption in vehicles

Figure 5-4 shows a simple model of the energy flows in vehicles. In analogy with a stationary energy system, the energy flows with associated energy losses can be divided into two parts. One is the **propulsion system** or onboard supply system where the conversion of the fuel into useful energy normally in the form of mechanical and electrical energy and the distribution of energy into the end use system is taking place. The other is the end use system consisting of the **vehicle loads.** They determine how much mechanical energy that is needed to overcome the tractive forces and how much energy is used in accessories. The accessory load consist of different kinds of energy consuming equipment not directly involved in the propulsion of a vehicle like compressors, pumps and fans used to heat, cool and ventilate the passenger compartment, lights, audio equipment, power steering and power braking. In a conventional vehicle the accessories are either directly powered by the engine through mechanical belt drives, or powered with electricity produced by an alternator driven by the engine.

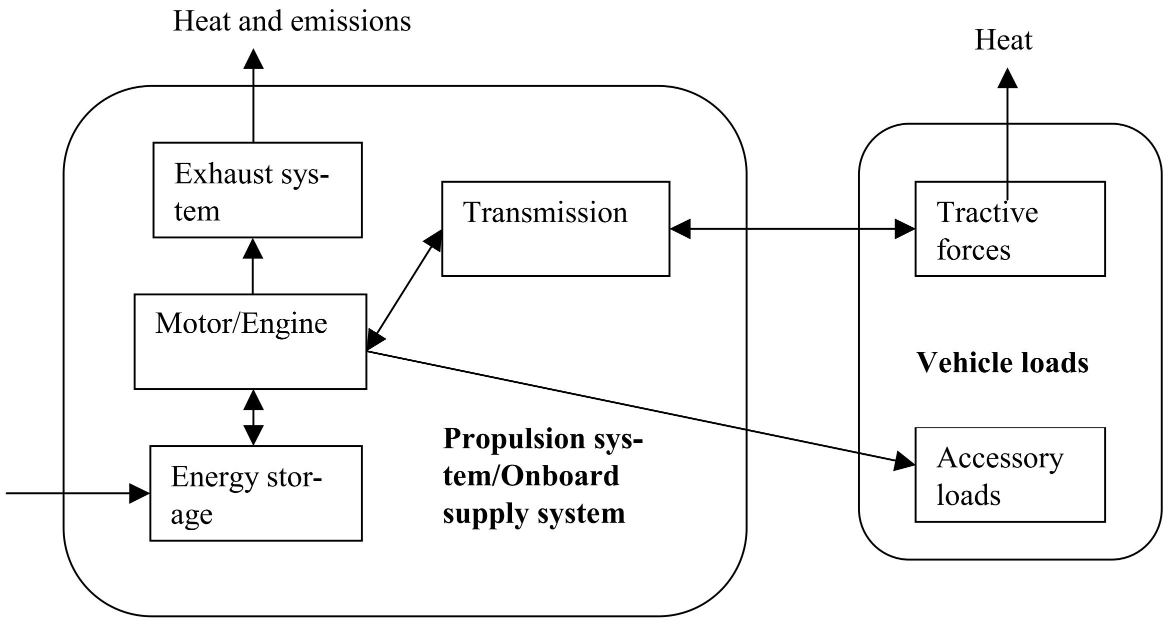


Figure 5-4 Model of the energy flows in vehicles.

In Figure 5-4 the arrows indicate the energy flows in the vehicle. The possibility of energy flowing from the tractive forces and back into the propulsion system has been indicated. This is the case of **regenerative braking**, where the kinetic and/or potential energies of the vehicle are regenerated during braking. Normally this is done by using an electric motor in generator mode to brake the vehicle.

The calculation of the energy consumption of a vehicle in a specified driving cycle consists in calculating the size of the vehicle loads and the efficiency of the propulsion system for each time step in the driving cycle. The efficiency of the propulsion system is determined by the efficiencies of the subsystems that make up the propulsion system. They are dependent on the operating conditions expressed in terms of torque and speed for mechanical subsystems and voltage and current levels for electrical subsystems.

The more advanced the propulsion system is, the more advanced the algorithm for the calculation of the energy consumption becomes. Thus, the algorithms for hybrid vehicles are considerably more complicated, than the algorithm for a conventional ICE vehicle.

5.3 Tractive forces

The forces acting on a vehicle parallel with its direction of travel are known as tractive forces. They determine the force required between the drive wheels of the vehicle and the ground:

$$F_W(t) = F_{ACC}(t) + F_{AIR}(t) + F_{ROL}(t) + F_{GRA}(t) \qquad (5\text{-}1)$$

$F_W(t)$: force required at the ground [N].
$F_{ACC}(t)$: the longitudinal acceleration force [N].
$F_{AIR}(t)$: the longitudinal component of the air drag [N].
$F_{ROL}(t)$: the rolling resistance opposing the movement of the vehicle [N].
$F_{GRA}(t)$: the gravitational force acting on vehicles driving on inclined surfaces [N]. It is given by the projection of the gravitational force onto the inclined surface.

The tractive forces can be grouped into four categories as done in equation 5-1 [Lukaszewicz 1995; An & Ross 1993]. Whereas the longitudinal acceleration force and gravitational force are easy to calculate from first principles, the physical phenomena that cause air drag and rolling resistance are complex. These phenomena will only be briefly described in this study, but there exist simple approximate expressions for the air drag and rolling resistance.

5.3.1 The acceleration force (inertia resistance)

The force required to accelerate a vehicle is given by:

$$F_{ACC}(t) = Ma(t) \qquad (5\text{-}2)$$

M: total mass of the vehicle [kg], $M = M_C + M_P$.
M_C: curb mass of the vehicle [kg].
M_P: mass of the payload, i.e. passengers and luggage [kg].
$a(t)$: the longitudinal acceleration of the vehicle [ms^{-2}]

Considering the torque from the engine/motor system to provide the required torque at the ground, additional torque is needed to overcome rotational inertia and frictional losses in the transmission system. The frictional losses are included in the calculation of the propulsion system efficiency. The inertia in rotational and reciprocating motor, engine and transmission components play a role, when the vehicle is accelerating or decelerating. It is customary to include the force required to overcome rotational inertia in the tractive loads. In a propulsion system with a mechanical transmission, the rotational accelerations of the different components in the transmission system are proportional to the longitudinal acceleration $a(t)$[20]. Therefore the effect of rotational inertia is included in the expression for the tractive loads in an approximate way by adding an extra mass to $F_{ACC}(t)$ [Gillespie 1992]:

$$F_{ACC}(t) + F_{ROT}(t) \approx (M_C + M_P + M_R)a(t) = (M_C m_{EFF} + M_P)a(t) \quad (5\text{-}3)$$
$$m_{EFF} = \frac{M_C + M_R}{M_C}$$

M_R: equivalent mass of the rotating components [kg].
m_{EFF}: the effective mass constant, which includes the effect of rotating and reciprocating parts.
$F_{ROT}(t)$: the rotational inertia force [N].

5.3.2 The gravitational force

The gravitational force is given by:

$$F_{GRA}(t) = Mg\sin(tg^{-1}(\theta(t))) \quad (5\text{-}4)$$

g: constant of gravity [ms^{-2}].
$\theta(t)$: the grade[21] of the surface upon which the vehicle is travelling.

5.3.3 Rolling resistance

The rolling resistance is caused by energy dissipation in the wheels and suspension system of the vehicle and in the ground as a consequence of the interaction between the wheels and the ground when the vehicle is moving. For road bound vehicles the interaction is between the tyres and the road surface, and for rail bound between the wheels and the rail. Rolling resistance can be divided into [Lukaszewicz 1995; Gillespie 1992]:

Resistance caused by deformation of the wheel/tyre is energy losses due to the deformation of the wheel/tyre in the contact area, so called hysteresis. For tyres the resistance decreases with increasing pressure. The resistance is very low for steel rail wheels because of their high elasticity module causing small deformations. The resistance is pro-

[20] The proportionality factor between the rotational acceleration of a transmission or engine component, $\alpha_T(t)$, and the longitudinal acceleration, $a(t)$ is given by: $\alpha_T(t) = N_T a(t)/r$, where N_T is the total transmission ratio between the component and the wheels, and r is the radius of the wheels.

[21] The grade of a surface is the change in the height above sea level of the surface per distance.

portional to the axle load, and increases with advancing speed because the dynamic motions due to track and road irregularities increases with advancing speed.

Resistance caused by deformation of the track/road surface is partly energy losses due to the elastic deformation of the track/road surface in the contact area, so called hysteresis. Partly plastic deformations of the road surface in case of soft surfaces like sand, or for rail bound vehicles deflection of the tracks and substructure with associated energy dissipation. This resistance is proportional to axle load and depends on the hardness of the road surface.

Resistance caused by frictional losses in the contact patch is energy dissipation because of the driving wheels/tyres slipping and sliding relative to the track/road surface. For rail wheels there are also frictional losses between the flange of the wheel and the rail. Apart from the friction between the flange of the wheel and the rail the friction in the contact patch depends on the axle load.

A special case of this resistance is *curve resistance* in that the frictional losses increase in curves due to additional friction. Normally this phenomenon is only taken into account for rail bound vehicles, but it is also important for road bound vehicles [Gillespie 1992].

Bearing resistance caused by the frictional losses in wheel-bearings. It is typically only of importance for the start up of the vehicles especially in cold weather, where the viscosity of the lubricants is low, until they get heated up by the rotation of the axle.

Resistance caused by the suspension of the vehicle is energy dissipated in the suspension system of the vehicle. As dynamic motions due to track and road irregularities increase with advancing speed the losses in the suspension system also increases.

Resistance caused by brake drag is frictional losses due to the brake shoes touching the brake disc or brake drum. This resistance should not ordinarily be present with properly maintained brakes.

Air drag on the inside and outside of the tire. Even though this term could just as well be attributed to the air resistance, it is sometimes included in the rolling resistance.

The total rolling resistance is the sum of the contributions from all of the above mentioned mechanisms. Most of the contributions are proportional to the axle load, and the total rolling resistance is normally expressed as being proportional to the total mass of the vehicle [Gillespie 1992; Jørgensen & Sorenson 1997], even though part of the bearing resistance is independent of vehicle load [Lukaszewicz 1995]. Some of the contributions are dependent on speed. This is sometimes taken into account by making the rolling resistance linear dependent on vehicle speed [NREL 2000; Lukaszewicz 1995] or higher order polynomias. Often the rolling resistance is modelled as independent of speed [Gillespie 1992; An & Ross 1993; Jørgensen & Sorenson 1997, Hansen 1991]. We use a simple expression that includes a linear dependence on speed:

$$F_{ROL} = Mg\cos(tg^{-1}(\theta(t)))\left(C_{R1} + C_{R2}v\right) \qquad (5\text{-}5)$$

C_{R1}: first coefficient of rolling resistance.
C_{R2}: second coefficient of rolling resistance [sm^{-1}].

The coefficients of rolling resistance are determined empirically. Often for road-bound vehicles only C_{R1} is used.

The coefficient C_{R1} and C_{R2} for tyres and wheels depend on the design, materials, size and temperature of the wheels/tyres, and on the hardness and regularity of the road/rail surface. For tyres, the tyre pressure also influences the coefficients of rolling resistance. Some typical values for different vehicle types are given in Table 5-1.

Vehicle type	**Surface**					**Source**
	Con-crete	**Medium hard**	**Sand**	**Steel**		
	C_{R1}	C_{R1}	C_{R1}	C_{R1}	C_{R2}	
Passenger cars	0.001-0.015	0.08	0.30			Gillespie 1992
Heavy trucks	0.008-0.012	0.06	0.25			Gillespie 1992
Trains				0.0015-0.003	0.0000257	Jørgensen & Sorenson 1997; Banestyrelsen 2000

Table 5-1 Typical coefficients of rolling resistance for present vehicle types.

5.3.4 Air drag

Air drag is caused by the interaction between a moving vehicle and the air flowing around the vehicle. The interaction produces a force on the vehicle whose longitudinal component works against the direction of travel of the vehicle. Air drag is due in part to friction of the air on the surface of the vehicle and in the turbulent airflow around the vehicle (so called friction drag). In part to the way the friction alters the main flow down the back side of the vehicle creating pressure differences between the front and the back of the vehicle (form drag). With regard to vehicle design the overall drag on a vehicle depends on the following [Gillespie 1992]:

- The shape of the vehicle body.
- The size and shape of the objects who physically protrude from the basic form and trip the airflow, e.g. wheels, bogies, external mirrors and pantographs.
- The shape and location of the air intakes and the size of the internal air flows in the vehicle in connection with cooling and ventilation systems.
- The way the different cars in a train configuration fit together, e.g. with or without gaps.

Like in the case of rolling resistance a number of semi-empirical models of air drag exists. The most common is [Gillespie 1992; Jørgensen & Sorenson 1997]:

$$F_{AIR}(t) = \frac{1}{2}\rho C_D A v(t)^2 \qquad (5\text{-}6)$$

ρ: air density (roughly 1.2 kgm^{-3}).
C_D: dimensionless coefficient of drag of the vehicle in the direction of travel.
A: cross-sectional area of the vehicle [m^2].
$v(t)$: vehicle speed [ms^{-1}].

C_D is empirically determined by measuring the air drag in wind tunnels tests [Gillespie 1992]. When comparing vehicles with different cross-sectional areas the resistance area C_DA can be used. For trains C_D can be expressed as [Andersson & Berg 1999]:

$$C_D = C_P + C_L L \qquad (5\text{-}7)$$

C_P: the pressure difference coefficient covering the part of the air drag coefficient being independent of the length of the train. It depends mostly on the shape of the front and the end of the train.
C_L: the length resistance coefficient depending on skin friction between the air and the sides, roof, and bottom of the train, and on air drag from protruding objects [m^{-1}].
L: the length of the train [m]

Sometimes a term proportional to the speed is added to the expression for the air drag [Andersson & Berg 1999; Lukaszewicz 1995], but the main part of the air drag is covered by the quadratic term [Andersson 2000; Lukaszewicz 1995].

Wind also has importance for the air drag. As the direction and size of the wind is fluctuating, most measurements of C_D and simulations of the vehicle loads neglect the contribution from wind. When there is a wind, the expression for the air drag has to be modified in two respects:

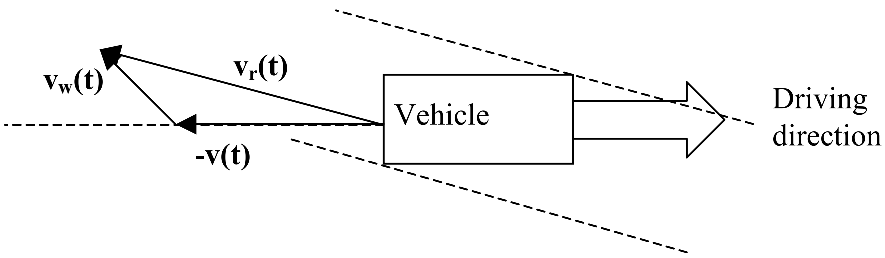


Figure 5-5 -v(t) is the negative of the vehicle velocity vector, $v_w(t)$ is the wind velocity vector, $v_r(t)$ is the relative air velocity vector as experienced from the vehicle.

1. It is the relative air velocity as experienced from the vehicle that has to be used, when calculating the air resistance. As seen from Figure 5-5 it is given by the sum of the negative of the vehicle velocity vector and the wind velocity vector.
2. If there is a side wind the incoming airflow experiences the vehicle as being broader, than is the case for still air, resulting in an increase in the product of the apparent

frontal area and the drag coefficient. Also the turbulence around the train can be increased as a result of side wind. These effects lead to an increase in the air drag in the presence of side wind, e.g. an 20-50 % increase in air drag for an attack angle of 10 degrees for a train [Andersson & Berg 1999].

Another undesirable property of side wind is the fluctuating side force on the vehicle resulting from the side wind, which tends to disturb the riding of the vehicle, and in the worst case can make the vehicle roll over.

Apart from air drag other aerodynamic phenomena are of importance in the design of vehicles, e.g. wind noise, the formation of pressure waves around vehicles driving with high speed leading to light objects being pulled along the train, aerodynamic forces on the pantographs, and other phenomena.

5.3.5 Running resistance of trains

The sum of the air drag and the rolling resistance of trains is called the running resistance. A very common empirical model for the running resistance are a second-order polynomial dependent on speed [Lukaszewicz 1995; Jørgensen & Sorenson 1997]:

$$F_{RUN} = B + Cv + Dv^2 \qquad (5\text{-}8)$$

It is generally accepted that the rolling resistance is covered by term B, and Cv in equation 5-8. The air drag is mainly covered by the term Dv^2, except air momentum drag believed to be covered by Cv. The magnitude of the coefficients B, C and D are determined experimentally [Lukaszewicz 1995], or from train configuration parameters. Comparing with the equations 5-5 and 5-6 it can be seen that $B = MgC_{R1}$, $C = MgC_{R2}$ and $D = ½\rho C_D A$.

5.3.6 Energy flows and energy sinks

Although equations 5-3, 5-4, 5-5 and 5-6 uses only first order approximations for each term, they are accurate enough for most analyses, and are the basic for almost all simulation tools of road-bound vehicles [Randall et al. 1998]. For rail bound vehicles equation 5-8 is commonly used.

In equation 5-1 the air drag and rolling resistances are always positive, which can be seen from equation 5-5 and 5-6. This reflects that these tractive forces consume mechanical energy and convert it to heat energy in irreversible processes. F_{ACC} and F_{GRA} on the other hand can be both positive and negative reflecting that the mechanical energy used to overcome these forces (when they are positive) goes to increasing the kinetic energy of the vehicle in case of F_{ACC} and the potential energy of the vehicle in case of F_{GRA}. The mechanical energy delivered at the wheels to overcome F_{ACC} and F_{GRA} (when they are positive) is therefore not lost immediately in irreversible processes, but stored as kinetic and potential energy of the vehicle. These kinetic and potential energies can in some cases be used to overcome the other tractive loads, e.g. in coasting and driving downhill, but often the kinetic and potential energies of the vehicle are lost as heat energy in the brakes.

There are three energy sinks that consume the mechanical power delivered to the wheels from the propulsion system: air resistance, rolling resistance, and the brakes of the vehicle. The energy lost in the brakes can in some propulsion systems be partly regenerated and used to propel the vehicle.

The importance of the driving cycle for the size of the vehicle loads can be seen from equation 5-2, the inertia force, involving the acceleration, equation 5-5, the rolling resistance, involving the vehicle speed, and equation 5-6, the air resistance, involving the vehicle speed squared.

5.4 The propulsion system

The propulsion system converts the energy in the fuel into mechanical and electrical energy and distributes mechanical energy to the wheels and electrical and/or mechanical energy to accessories. Often the propulsion system includes a sub system for onboard storage of fuel. Even though propulsion systems used in public transport modes exist in a lot of different configurations, the propulsion systems can, as mentioned in section 3.8, be perceived as being made up of a selection of a relatively limited number of subsystems, that can be combined in different ways (see Table 3-5). Figure 5-7 gives an example of a propulsion system configuration belonging to a series hybrid electric vehicle.

The sub systems are:

- **Electric vehicle subsystems**:
  - Electricity storage: batteries, fly wheels, ultracapacitors.
  - Electric motors/generators.
  - Pantographs or other equipment for continuously receiving electric energy during vehicle operation.
  - Power bus (often called controller/inverter systems).

- **Fuelled vehicle propulsion subsystems**:
  - Exhaust systems: catalytic converters, filters.
  - Fuel converters: internal combustion engines, fuel cells including reformers.
  - Fuel storage: tanks for gaseous or liquid fuels.
- **Transmission systems**

Apart from these subsystems a propulsion system also includes control systems for energy management and thermal management. The energy losses connected with thermal management are included in the energy losses of the subsystems in need of thermal control, i.e. motors, electricity storages, generators, fuel converters and reformers.

The energy efficiency of the propulsion system depends on the energy efficiencies of the subsystems. The energy efficiencies of some of the subsystems are strongly dependent on the operation profiles of the subsystems, e.g. internal combustion engines. This means that the development of efficient energy management strategies is important for achieving a good overall efficiency of the propulsion system.

The function of each subsystem is described in the following:

- **Electricity storage:** These systems store electrical energy onboard the vehicle. In electric buses and in some types of hybrid electric vehicles (HEVs) the electricity storages are recharged from the electricity grid. In conventional buses and some types of HEVs a fuel converter connected with a generator produces the recharge power.
- **Electric motors/generators:** The motor converts electrical energy into mechanical energy when in motoring mode, and vice versa when in generator mode. HEVs often include two motors in the propulsion system. One designed for generating electricity from the fuel converter, and the other designed for providing mechanical power to the transmission.
- **Exhaust system:** The exhaust from the fuel converter can be treated in an exhaust system to minimise the emission of local pollutants. The exhaust system if needed consists of a catalytic converter and/or a filter. The hot exhaust fumes provide the heat needed for catalysis of the pollutant components, so normally the energy use of the exhaust system is very low.
- **Fuel converters:** The function of a fuel converter is to convert the chemical energy in the fuel into useful energy in the form of mechanical or electrical energy. ICE's convert from chemical energy to mechanical energy and fuel cells from chemical energy to electrical energy. When fuel cells are used with other fuels than hydrogen a reformer is necessary. The reformer converts the fuel into a hydrogen rich gas.
- **Fuel storage:** The fuel system store the liquid or gaseous fuel used by the vehicle. In this study the losses of fuel during refuelling is included in the calculation of the energy efficiency of the fuel storages.
- **Power bus:** Consists of power electronics that control and modify the currents and voltages exchanged between the electric subsystems, i.e. the pantograph, motor, generator and electricity storage.
- **Transmission system:** The transmission system transmits the mechanical power from the fuel converter/motor systems to the driving wheels. Hubmotors[22] deliver torque to the wheels directly only involving a fixed transmission ratio between the motor and the wheel, thereby eliminating most of the parts involved in a conventional transmission system like the clutch, the gearbox, the transmission shaft and the differentials. In this case it can be said that the transmission system is electric, in that the power between the different subsystems of the propulsion system are exchanged via cables.

5.4.1 Classification of the propulsion systems in hybrid vehicles

The hybrid electric propulsion system can be designed in a lot of different ways. The power of the fuel converter relative to the power of the electric motor and the energy and power capacity of the electricity storage can vary a lot depending on the following design choices:

[22] Hubmotors are placed in the hub of the wheels.

- Series hybrid or parallel hybrid. In a series hybrid propulsion system it is only the electric motor that delivers torque to the driving wheels. The fuel converter is directly connected to a generator and used to produce electricity used in the electric motor or stored in a electricity storage. In a parallel hybrid propulsion system both the ICE and the electric motor can deliver torque to the driving wheels. Propulsion systems using fuel cells are always series hybrid, because the fuel cell only produces electricity. The series hybrid will usually have a larger electric motor than a parallel hybrid with comparable performance.
- Is the HEV dependent on the electricity grid for energy supply.
- The relative importance of the fuel converter to the electricity storage as the main power source, where the relationship for different types of vehicles is illustrated in Figure 5-6. The extreme cases are the EV on one hand, where all the power comes from the electricity storage, and the CV on the other hand where all power is delivered from the internal combustion engine. The “EV with extended travel range” is dependent on the electricity grid and is equipped with a little engine that extents the travel range. Normally these vehicles are made as series hybrid vehicles. The operating strategy assumes that all of the daily driving is done with the batteries as energy source, and the engine is seen as a backup. The power assist HEV is a parallel HEV where the electricity storage is very small. The electricity storage and the electric motor are used to give the fuel converter better operating conditions, by levelling out the driving loads. The travel range for the electricity storage alone is small, and all of the daily driving is done using the fuel converter as energy source either directly or by charging the electricity storage.

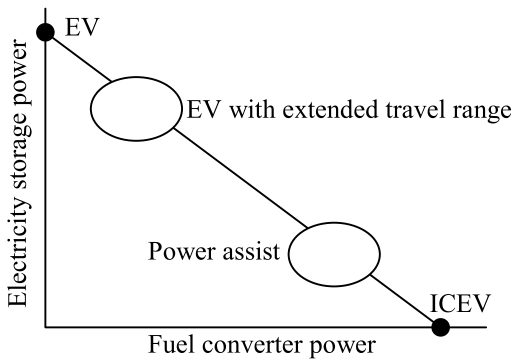


Figure 5-6 Illustration of the relative importance of the fuel converter versus the electricity storage as the power sources in the vehicle for different types of vehicles [Nelson 2000].

HEVs can belong anywhere between the above-mentioned two extreme cases. None of the hybrid electric cars and buses designed today depend on the electric grid for recharging, but some of them can drive a significant distance (10-20 km) on their batteries alone.

5.5 Energy consumption model in detail

Precise calculations of the energy consumption of a vehicle during a driving cycle consists in second by second simulations of the vehicle loads and the propulsion system efficiency. These simulations require rather detailed information about the subsystems of the propulsion system, e.g. the efficiencies of the engine and electrical motor as a function of speed and torque, and the charging/discharging efficiencies of the electricity storage as a function of the state of charge and the power requirements.

When considering improvements of the energy efficiency due to future technology development, considerable uncertainty is introduced. It can therefore be justified to calculate the energy consumption during a driving cycle with a more approximate and simplified algorithm using the average efficiencies of the subsystems. We have derived our own model for EVs and SHEVs inspired by a modelling approach formulated by Feng An and Marc Ross from University of Michigan [An & Ross 1993] for conventional vehicles.

5.5.1 Model of the vehicle loads during a driving cycle

We want an expression for the energy delivered to the driving wheels from the propulsion system during a driving cycle.

The net energy to the drive wheels during the driving cycle is given by:

$$\begin{aligned}
E_W &= \int_0^T P_W(t)dt = \int_0^T F_W(t)v(t)dt = \int_0^T \left(F_{ACC}(t) + F_{AIR}(t) + F_{ROL}(t) + F_{GRA}(t)\right)v(t)dt \\
&= \int_0^T (M_C m_{EFF} + M_P)a(t)v(t)dt + \int_0^T 0.5\rho C_D A v(t)^3 dt + \int_0^T Mg(C_{R1}v(t) + C_{R2}v(t)^2)dt \\
&\quad + \int_0^T Mg\sin(tg^{-1}(\theta(t)))v(t)dt \Rightarrow \\
E_W &= 0.5(M_C m_{EFF} + M_P)\left(v(T)^2 - v(0)^2\right) + 0.5\rho C_D AT < v^3 > \\
&\quad + MgT(C_{R1} < v > + C_{R2} < v^2 >) + Mg(h(T) - h(0))
\end{aligned} \qquad (5\text{-}9)$$

M_C, M_P, m_{EFF}, ρ, C_D, A, M, g, C_{R1}, C_{R2}, and $v(t)$ are defined in equations 5-2, 5-3, 5-4, 5-5, 5-6.
$P_W(t)$: the power at the drive wheels at the time t [W].
$F_W(t)$: the tractive force at the contact patch between the drive wheels and the ground [N].
T: the total time of the driving cycle [s].
$<v>$: the mean speed of the vehicle during the driving cycle [ms^{-1}].
$<v^2>$: the mean of v^2 during the driving cycle [m^2s^{-2}].
$<v^3>$: the mean of v^3 during the driving cycle [m^3s^{-3}].
$h(t)$: the height of the vehicle above sea level at the time t [m].

Looking at equation 5-9, the first term in the last line is the difference in the kinetic energy of the vehicle at the end of the driving cycle and at the start of the driving cycle. Assuming, as it is customary when making driving cycles, that the start and end speeds of the vehicle is zero, this term will be zero.

The second term is the tractive energy E_{AIR} used to overcome air resistance during the driving cycle:

$$E_{AIR} = 0.5\rho C_D A T < v^3 >$$

The third term in equation 5-9 is the tractive energy E_{ROL} used to overcome rolling resistance:

$$E_{ROL} = MgT(C_{R1} < v > + C_{R2} < v^2 >)$$

The fourth term in equation 5-9 is the difference in the potential energy of the vehicle between the end and the start of the driving cycle:

$$E_{POT} = Mg(h(T) - h(0)) = Mg\Delta h$$

where $\Delta h = h(T) - h(0)$ is the height difference between the end and the start of the driving cycle.

The net energy to the drive wheels is the sum of the energy delivered from the propulsion system, when $P_W(t)$ is larger than zero, and the energy flowing back into the vehicle when $P_W(t)$ is smaller than zero:

$$\begin{aligned} E_W &= E_{W,P>0} + E_{W,P<0} = \int_{P_W>0} P_W(t)dt + \int_{P_W<0} P_W(t)dt \\ &= E_{AIR} + E_{ROL} + E_{POT} \end{aligned} \qquad (5\text{-}10)$$

The energy flowing back into the vehicle ($E_{W,P<0}$), when $P_W(t)$ is smaller than zero, is either dissipated in the brakes and propulsion system, and/or regenerated and use to propel the vehicle. This term is named the braking energy during the driving cycle and designated with the symbol E_B.

The value of E_B in a given driving cycle can be calculated by calculating $E_{W,P<0}$, i.e. calculate $P_W(t)$in each time step of the driving cycle, and taking the sum of the negative values of $P_W(t)$. Alternatively E_B can be calculated by calculating $E_{W,P>0}$, and then subtract E_{ROL}, E_{AIR} and E_{POT}.

E_B is proportional to the tractive energy going into the kinetic and potential energies of the vehicle during the driving cycle. The size of the proportionality factor depends on how much of the kinetic and potential energy of the vehicle that is used to overcome rolling and air resistance, i.e. how fast the vehicle decelerates and how much the vehicle is coasting during the driving cycle.

The tractive energy being transformed into kinetic energy of the vehicle during the driving cycle can be approximated by the sum of the maximum kinetic energy of the vehicle in each subcycle (velocity peak) of the driving cycle [An & Ross 1993].

The tractive energy being transformed into potential energy of the vehicle during the driving cycle can be calculated by summing all the driving uphill during the driving cycle and adjust for the height difference between the end and the start of the driving cycle.

$$E_B = K\left(0.5(M_C m_{EFF} + M_P)N_S v_p^2 + Mg(\Delta H_{up} - \Delta h)\right) \quad (5\text{-}11)$$

$$v_p^2 = \frac{1}{N_S}\sum_{i=1}^{N_S}\left(v_{p,i}^2 - v_{v,i}^2\right)$$

$$\Delta H_{up} = \int_{\theta(t)>0}^{T} \sin(\theta(t))v(t)dt$$

K: factor correcting for the amount of potential and kinetic energy used to overcome rolling and air resistance.
N_S: the number of subcycles in the driving cycle.
v_p: the root-mean-square peak velocity over the driving cycle [ms^{-1}].
$v_{p,i}$: the maximum velocity of subcycle i [ms^{-1}].
$v_{v,i}$: the minimum velocity between subcycle i and $i+1$ [ms^{-1}].
ΔH_{up}: the amount of uphill driving during the driving cycle [m].

There are many speed fluctuations and velocity peaks in a driving cycle and sometimes it can be difficult to decide when to include a velocity peak in the calculation of v_p. A rule of thumb is that when the velocity-valley ($v_{v,i}$) is larger than two thirds of the velocity peak ($v_{p,i}$), the velocity peak can be omitted [An & Ross 1993].

From equation 5-11 it can be seen that E_B is approximately proportional to the total mass of the vehicle M.

Table 5-2 shows values of K for different vehicle concepts in different driving cycles (the vehicle parameters used are shown in Table 5-9). To show the sensitivity to a change in vehicle parameters, K has been calculated with zero and maximum passenger load, and it can be seen that K with good approximation can be considered a constant only dependent on the vehicle concept and the driving cycle.

Vehicle	Driving cycle[23]	M_P [kg]	K
Conv. 12 m bus	Line5suburbs_mod	6090	0.83
Conv. 12 m bus	Line5suburbs_mod	0	0.82
Conv. 12 m bus	Line5city_mod	6090	0.84
Conv. 12 m bus	Line5city_mod	0	0.84
S-train	LineA	0	0.81
S-train	LineA	42000	0.83
LRV Combino	LineLRV	0	0.87
LRV Combino	LineLRV	17640	0.87

Table 5-2 Calculated K values for different vehicle concepts in different driving cycles with different passenger load.

[23] See section 5.9 for a description of the driving cycles used in this study.

5.5.2 Model of the propulsion system

To get equations for the energy consumption of different types of propulsion systems, like EVs and SHEVs, the different operating modes of each type of propulsion system are analysed. The operating modes can be divided into three groups: power modes, i.e. operating modes where the propulsion system delivers power to the driving wheels, zero modes where the vehicle is stopped or is coasting, and braking modes where the power at the drive wheels is negative.

For propulsion systems with a electricity storage the change in the energy content of the electricity storage must in some way be included to give a correct calculation of the energy consumption of the vehicle. We make the simple assumption that the net energy drawn from the storage over the driving cycle is zero. This means that the energy out of the storage equals the energy into the storage multiplied with the average efficiency of the battery during the driving cycle.

The efficiency of an internal combustion engine is modelled by a simple but adequate approach taken from [An & Ross 1993; Ross 1997; Weiss et al. 2000], that uses two parameters to describe the efficiency of a given engine type. One parameter is the thermodynamic efficiency (fraction of the fuel chemical energy transferred to the engine's pistons as work), and the other is the friction mean effective pressure, which indicates how much of the work done on the pistons, that are lost in the engine due to friction:

$$\eta_T = \frac{P_{FRI} + P_P}{P_F} \Rightarrow \eta_T = \frac{E_{FRI} + E_P}{E_F}$$

$$P_{FRI} = \frac{f_{MEP} N V}{2} \Rightarrow E_{FRI} = \frac{f_{MEP} V}{2} \int_0^T N dt = \frac{f_{MEP} V}{2} \left(\sum_i < N_i > T_i \right) \quad (5\text{-}12)$$

η_T: the average thermal efficiency of the engine.
f_{MEP}: friction mean effective pressure of the engine [Pa].
V: the engine displacement equal to the swept volume of each cylinder times the number of cylinders [m3].
N: the engine speed [rps].
$<N_i>$: the average engine speed in engine operation mode i.
T_i: the time that the engine is in operation mode i [s].
P_{FRI}: the mechanical power used to overcome engine friction and to drive engine accessories [W].
P_P: the output mechanical power from the engine [W].
P_F: the power in the fuel [W].
E_{FRI}: the energy used to overcome engine friction during a driving cycle [J].
E_P: the mechanical energy delivered from the engine during a driving cycle [J].
E_F: the fuel consumption during a driving cycle [J].

The energy dissipated as engine friction (E_{FRI}) is proportional to the displacement volume of the engine and the number of revolutions of the engine. The number of revolutions of the engine is approximated with the average number of revolutions of the engine in different engine operating modes. The engine friction can be of three types [Ross 1997]: 1) rubbing of metal parts, like piston rings on cylinder walls, 2) gaseous friction, e.g. in valves, 3) friction in the engine accessories and their belt drives. The factor of 2 in the denominator of equation 5-12 is the number of crank-shaft revolutions per 4-stroke cycle [Ross 1997].

As a complement to the thermal efficiency of the engine a mechanical efficiency can be defined such that the product of the thermal and mechanical efficiency gives the total efficiency of the engine [Ross 1997]:

$$\eta_M = \frac{P_P}{P_{FRI} + P_P} \Rightarrow \eta_M = \frac{E_P}{E_{FRI} + E_P}$$
$$\eta = \eta_T \eta_M = \frac{E_P}{E_F} \qquad (5\text{-}13)$$

η_M is the fraction between the energy output of the engine and the work done on the pistons.

η is the total average efficiency of an engine in a given driving cycle.

η_M indicates how much of the work done on the pistons that is transformed into useful mechanical work on the crankshaft.

The available information about engines often consist of the maximum power output and the engine speed at maximum power output, the maximum torque and the engine speed at maximum torque, and the maximum efficiency of the engine given as the brake specific fuel consumption (b_{sfc}) in grams of fuel per kWh delivered from the engine. The engine speed and torque at the maximum efficiency is often not given. To make a connection between b_{scf} and the model parameters f_{MEP} and η_T, we assume that the maximum torque point with reasonable approximation can be said to be the working point of the engine with maximum efficiency[24]:

$$\eta_T \frac{P_{P,TMAX}}{0.5 f_{MEP} N_{TMAX} V + P_{P,TMAX}} = \frac{3600}{b_{SFC} h_{LV}} \qquad (5\text{-}14)$$

$P_{P,TMAX}$: the power output at maximum torque [W].
N_{TMAX}: the engine speed at maximum torque [rps].
b_{sfc}: the brake specific fuel consumption [g fuel/kWh].
h_{LV}: the lower heating value of the fuel [kJ/g].

Using the above mentioned assumptions we derive the equation for the energy consumption of a SHEV as an illustration of the methodology.

[24] This assumption is supported by the engine maps for CI engines in ADVISOR, where the engine efficiency at the maximum torque point is at most 2.7% lover than the maximum efficiency of the engine (see engine data files: FC_CI205, FC_CI171, FC_CI119, FC_CI67 in ADVISOR [NREL 2001]).

5.5.3 Energy consumption of a series hybrid electric vehicle with an internal combustion engine

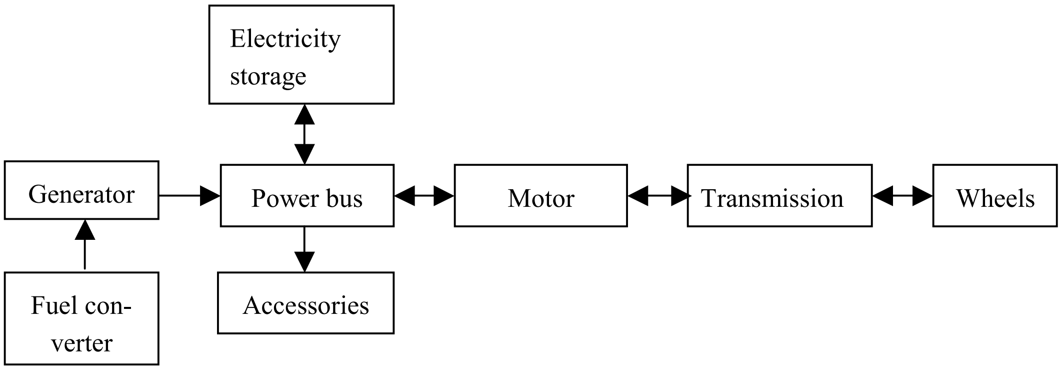


Figure 5-7 The configuration of the propulsion system of a series hybrid vehicle. The energy flows between subsystems are indicated with arrows.

Operating mode	Power at wheels	Power fuel converter	Power electricity storage	Description of operating mode
1	>0	>0	<0	Charging, power to wheels only from FC[25]
2	>0	>0	=0	No charging, power to wheels only from FC
3	>0	>0	>0	Power to wheels from both FC and ES
4	>0	=0	>0	Power to wheels only from ES (EV mode), FC stopped
5	=0	=0	>0	Vehicle stopped or coasting, power to accessories from ES, FC stopped.
6	=0	>0	<0	Vehicle stopped or coasting, charging, power to accessories from FC
7	<0	=0	<0	FC stopped or ideling, charging ES with regenerated braking power
8	<0	>0	<0	charging ES with both FC and regenerated braking power

Table 5-3 The operating modes of a series hybrid vehicle.

The eight operating modes described in Table 5-3 are defined by the combination of the power flows at the driving wheels, the fuel converter, and the electricity storage. Operating modes 1 to 4 are power modes, 5 to 6 are stopped modes, and 7 to 8 are braking modes.

Flow of energy in each of the operation modes

[25] FC = fuel converter, ES = electricity storage.

Mode 1:

$$E_{F,1} = \frac{1}{\eta_T}\left(E_{FRI,1} + \frac{1}{\varepsilon_G \varepsilon_{PB}}\left(\frac{E_{W,1}}{\varepsilon_M \varepsilon_T} + E_{A,1} + E_{E,IN,1}\right)\right) \qquad (5\text{-}15)$$

ε_G: average efficiency of the generator.
ε_M: average efficiency of the motor.
ε_T: average efficiency of the transmission.
ε_{PB}: average efficiency of the power bus.
$E_{F,i}$: fuel consumption in operating mode *i*.
$E_{W,i}$: energy to the wheels in operating mode *i*.
$E_{A,i}$: energy to accessories in operating mode *i*.
$E_{E,IN,i}$: energy flowing into the electricity storage in operating mode *i*.

Mode 2:

$$E_{F,2} = \frac{1}{\eta_T}\left(E_{FRI,2} + \frac{1}{\varepsilon_G \varepsilon_{PB}}\left(\frac{E_{W,2}}{\varepsilon_M \varepsilon_T} + E_{A,2}\right)\right) \qquad (5\text{-}16)$$

Mode 3:

$$E_{F,3} = \frac{1}{\eta_T}\left(E_{FRI,3} + \frac{1}{\varepsilon_G \varepsilon_{PB}}\left(\frac{E_{W,3} - E_{E,OUT,3}\varepsilon_{PB}\varepsilon_M \varepsilon_T}{\varepsilon_M \varepsilon_T} + E_{A,3}\right)\right) \qquad (5\text{-}17)$$

$E_{E,OUT,i}$: energy delivered from the electricity storage in operating mode *i*.

Mode 4:

$$E_{E,OUT,4} = \frac{1}{\varepsilon_{PB}}\left(\frac{E_{W,4}}{\varepsilon_M \varepsilon_T} + E_{A,4}\right) \qquad (5\text{-}18)$$

Mode 5:

$$E_{E,OUT,5} = \frac{E_{A,5}}{\varepsilon_{PB}} \qquad (5\text{-}19)$$

Mode 6:

$$E_{F,6} = \frac{1}{\eta_T}\left(E_{FRI,6} + \frac{1}{\varepsilon_G \varepsilon_{PB}}\left(E_{A,6} + E_{E,IN,6}\right)\right) \qquad (5\text{-}20)$$

Mode 7:

$$E_{E,IN,7} = E_{W,7} f_R \varepsilon_T \varepsilon_M \varepsilon_{PB}$$
$$E_{E,OUT,7} = \frac{E_{A,7}}{\varepsilon_{PB}} \qquad (5\text{-}21)$$

f_R: fraction of the energy at the wheels, when the vehicle is in braking mode, that is re-generated.

Mode 8:

$$E_{F,8} = \frac{1}{\eta_T}\left(E_{FRI,8} + \frac{1}{\varepsilon_G \varepsilon_{PB}} \left(E_{E,IN,FC,8} + E_{A,8} \right) \right) \qquad (5\text{-}22)$$

$$E_{E,IN,R,8} = E_{W,8} f_R \varepsilon_T \varepsilon_M \varepsilon_{PB} \qquad (5\text{-}23)$$

The time period with the vehicle in power mode (power at the wheels bigger than zero) is given by:

$$T_P = T_1 + T_2 + T_3 + T_4$$

T_i: the time of operating mode i [s].

The time period with the vehicle stopped or coasting is given by:

$$T_S = T_5 + T_6$$

The time period with the vehicle in braking mode (power at the wheels less than zero) is given by:

$$T_R = T_7 + T_8$$

Assume that the energy content in the electricity storage is the same in the end of the driving cycle as in the beginning:

$$E_{E,OUT,3} + E_{E,OUT,4} + E_{E,OUT,5} + E_{E,OUT,7} = \varepsilon_E \left(E_{E,IN,1} + E_{E,IN,6} + E_{E,IN,7} + E_{E,IN,FC,8} + E_{E,IN,R,8} \right)$$
$$\Leftrightarrow E_{E,OUT,3} = \varepsilon_E \left(E_{E,IN,1+6+FC8} + E_{E,IN,7} + E_{E,IN,R,8} \right) - E_{E,OUT,4} - E_{E,OUT,5} - E_{E,OUT,7} \qquad (5\text{-}24)$$

ε_E: average efficiency of the electricity storage.

where we have used the notation:

$$E_{X,1+2+4} = E_{X,1} + E_{X,2} + E_{X,4}$$

The total fuel consumption is:

$$E_F = E_{F,1} + E_{F,2} + E_{F,3} + E_{F,6} + E_{F,8}$$
$$= \frac{1}{\eta_T}\left(E_{FRI,1+2+3+6+8} + \frac{1}{\varepsilon_G \varepsilon_{PB}} \left(\frac{E_{W,1+2+3}}{\varepsilon_M \varepsilon_T} + E_{A,1+2+3+6} + E_{E,IN,1+6+FC8} - E_{E,OUT,3}\varepsilon_{PB} \right)\right) \quad (5\text{-}25)$$

Combining equation 5-24 and 5-25 we get:

$$E_F = \frac{1}{\eta_T}\left(E_{FRI,1+2+3+6+8} + \frac{1}{\varepsilon_G \varepsilon_{PB}} \left(\frac{E_{W,1+2+3}}{\varepsilon_M \varepsilon_T} + E_{A,1+2+3+6} + E_{E,IN,1+6+FC8}(1 - \varepsilon_E \varepsilon_{PB}) \right.\right.$$
$$\left.\left. - \varepsilon_E \varepsilon_{PB} E_{E,IN,7+R8} + E_{E,OUT,4+5+7}\varepsilon_{PB} \right)\right) \quad (5\text{-}26)$$

Inserting the expressions for $E_{E,IN,7}, E_{E,IN,R8}, E_{E,OUT,4}, E_{E,OUT,5}, E_{E,OUT,7}$ (equations 5-21, 5-23, 5-18 and 5-19 in equation 5-26 we get:

$$E_F = \frac{1}{\eta_T}\left(E_{FRI,1+2+3+6+8} + \frac{1}{\varepsilon_G \varepsilon_{PB}} \left(\frac{E_{W,1+2+3+4}}{\varepsilon_M \varepsilon_T} + E_{A,1+2+3+4+5+6+7+8} \right.\right.$$
$$\left.\left. + E_{E,IN,1+6+FC8}(1 - \varepsilon_E \varepsilon_{PB}) - f_R \varepsilon_E \varepsilon_{PB}^2 \varepsilon_M \varepsilon_T E_{W,7+8} \right)\right) \quad (5\text{-}27)$$

The energy delivered at the wheels from the propulsion system ($E_{W,1+2+3+4}$), when the vehicle is in power mode, is used to overcome air resistance, rolling resistance, the height difference between start and end of the driving cycle, and flows back into the vehicle, when the vehicle is in braking mode, where it is lost in the mechanical brakes or regenerated:

$$E_{W,1+2+3+4} = E_{AIR} + E_{ROL} + E_{POT} + E_{W,7+8} \quad (5\text{-}28)$$

We define $\varepsilon_P = \varepsilon_G \varepsilon_{PB} \varepsilon_M \varepsilon_T$ and $E_{W,7+8} = E_B$ (5-29)

The energy lost in the internal combustion engine due to friction can be approximated by:

$$E_{FRI} = E_{FRI,1+2+3+6+8} = \frac{1}{2} f_{MEP} V\left(< N_P > T_{P,FC} + < N_I > T_{I,FC} \right) \quad (5\text{-}30)$$

$<N_P>$: the average engine speed when the engine delivers power [rps].
$<N_I>$: the average engine speed when the engine is ideling [rps].
$T_{P,FC}$: the time that the engine delivers power [s].
$T_{I,FC}$: the time that the engine is ideling [s].

The auxiliary power is approximated with a constant power drawn from the power bus:

$$E_{A,1+2+3+4+5+6+7+8} = P_{AUX}(T_P + T_S + T_R) = P_{AUX} T \quad (5\text{-}31)$$

Inserting the equations 5-28, 5-29, 5-30 and 5-31 in equation 5-27, we get:

$$E_f = \frac{1}{\eta_T}\left(E_{FRI} + \frac{E_{AIR}}{\varepsilon_P} + \frac{E_{ROL}}{\varepsilon_P} + \frac{E_{POT}}{\varepsilon_P} + \frac{E_B(1 - f_R \varepsilon_E \varepsilon_{PB}^2 \varepsilon_M^2 \varepsilon_T^2)}{\varepsilon_P} + \frac{P_{AUX} T}{\varepsilon_G \varepsilon_{PB}} + \frac{E_{E,IN,1+6+FC8}\left(1 - \varepsilon_E \varepsilon_{PB}\right)}{\varepsilon_G \varepsilon_{PB}} \right) \quad (5\text{-}32)$$

Let α be the fraction of mechanical energy from the fuel converter used to charge the electricity storage relative to the total mechanical energy delivered from the fuel converter E_P (where E_P is equal to the terms in the brackets in equation 5-32 minus the E_{FRI} term):

$$\alpha = \frac{E_{E,IN,1+6+FC8}}{\varepsilon_G \varepsilon_{PB} E_P} \quad (5\text{-}33)$$

E_P can then be expressed as:

$$E_P = \frac{1}{\eta_T} \frac{1}{1 - \alpha(1 - \varepsilon_E \varepsilon_{PB})}\left(\frac{E_{AIR}}{\varepsilon_P} + \frac{E_{ROL}}{\varepsilon_P} + \frac{E_{POT}}{\varepsilon_P} + \frac{E_B(1 - f_R \varepsilon_E \varepsilon_{PB}^2 \varepsilon_M^2 \varepsilon_T^2)}{\varepsilon_P} + \frac{P_{AUX} T}{\varepsilon_G \varepsilon_{PB}} \right) \quad (5\text{-}34)$$

Finally the fuel consumption of a series hybrid vehicle can be expressed as:

$$E_F = \frac{E_{FRI}}{\eta_T} + \frac{1}{\eta_T \gamma}\left(\frac{E_{AIR}}{\varepsilon_P} + \frac{E_{ROL}}{\varepsilon_P} + \frac{E_{POT}}{\varepsilon_P} + \frac{E_B(1-\beta)}{\varepsilon_P} + \frac{E_{AUX}}{\varepsilon_{AUX}} \right) \quad (5\text{-}35)$$

$$\gamma = 1 - \alpha(1 - \varepsilon_E \varepsilon_{PB}) \quad (5\text{-}36)$$
$$E_{AUX} = P_{AUX} T$$
$$\beta = f_R \varepsilon_E \varepsilon_{PB}^2 \varepsilon_M^2 \varepsilon_T^2 .$$
$$\varepsilon_P = \varepsilon_G \varepsilon_{PB} \varepsilon_M \varepsilon_T$$
$$\varepsilon_{AUX} = \varepsilon_G \varepsilon_{PB}$$

In equation 5-35, the energy consumption of a SHEV has been distributed on six areas: 1) engine friction, 2) air resistance, 3) rolling resistance, 4) change in the potential energy, 5) energy lost in the brakes, 6) energy used by accessories. The calculation of the energy consumption uses a number of parameters to describe the driving cycle, vehicle and operating strategy of the vehicle, namely:

- 9 driving cycle parameters: T, D, $\langle v \rangle$, $\langle v^2 \rangle$, $\langle v^3 \rangle$, N_S, v_P, Δh, ΔH_{up}.
- 10 vehicle parameters: M_C, M_P, C_{R1}, C_{R2}, A, C_D, η_T, f_{MEP}, V, P_{AUX}.
- 5 parameters that depend on the interaction between the driving cycle and the design of the vehicle: ε_T, ε_M, ε_{PB}, K, m_{EFF}.

- 8 "mixed" parameters that depend on the interaction between the driving cycle, the vehicle design and the operating strategy of the vehicle: $T_{P,FC}$, $<N_P>$, $T_{I,FC}$, $<N_I>$ α, ε_G, ε_E, f_R.

5.5.4 Discussion of the relationship between the parameters T_{FC} and α

In this section the relationship between the time with the fuel converter on T_{FC}, α, and the chosen operating strategy will be discussed. The operating strategy of a series hybrid vehicle with an ICE determines the amount of power delivered from the fuel converter and electricity storage as a function of the instantaneous power demand at the power bus, the state of charge of the electricity storage and the efficiency and emission characteristics of the fuel converter. Basically, the goal is to make the fuel converter operate in the most efficient and low polluting part of its operating area, while keeping the state of charge of the battery within limits that secure the lowest discharge and charging losses and maintains battery life, and while delivering the needed amount of power to accessories and wheels. In order to minimise the emissions, the changes in the power output of the fuel converter should be kept reasonably low.

Looking at equation 5-30, it can be seen that the energy lost as friction in the engine is proportional to the number of revolutions of the engine and therefore proportional to the time that the fuel converter is on $T_{FC}=T_{P,FC}+T_{I,FC}$. One goal of the operating strategy will therefore be to minimise T_{FC}, especially the amount of time that the engine is ideling.

On the other hand, as we assume that the vehicle works independent of the electricity grid, the total amount of work delivered from the engine must equal E_P[26]:

$$E_P = < G_{FC} N_{P,FC} 2\pi > T_{P,FC} = < P_{FC} > T_{P,FC} \Leftrightarrow$$

$$< P_{FC} > T_{P,FC} = \frac{1}{\gamma}\left(\frac{E_{AIR}}{\varepsilon_P} + \frac{E_{ROL}}{\varepsilon_P} + \frac{E_{POT}}{\varepsilon_P} + \frac{E_B(1-\beta)}{\varepsilon_P} + \frac{E_{AUX}}{\varepsilon_{AUX}} \right) = \frac{H}{\gamma} \quad (5\text{-}37)$$

G_{FC}: the torque of the fuel converter [Nm].
H: the expression contained in the parenthesis in equation 5-37.

This means that if $T_{P,FC}$ is lowered, than the average power output from the engine must go up. H is only weakly dependent of the operating strategy, because the only parameters in H dependent on the operating strategy are ε_G (weakly dependent) and ε_E. The rest of the variables in H only depend on the driving cycle and the vehicle design.

The parameter γ describes the loss in efficiency due to losses in the electricity storage. γ is defined in equation 5-36, and depends on the efficiency of the electricity storage and the power bus, and on α, the amount of energy delivered from the engine that goes to the electricity storage. γ=0.96 if α =0.20, ε_E=0.85 and ε_{PB}=0.95, i.e. 4% of the total energy output from the fuel converter is lost in the electricity storage, corresponding to 19% of the energy input to the electricity storage from the fuel converter.

[26] Assuming that the state of charge of the electricity storage is the same in the end of the driving cycle as in the start.

Combining equation 5-24, and 5-33 α can be expressed as:

$$\alpha = \frac{E_{E,IN,1+6+FC8}}{\varepsilon_G \varepsilon_{PB} E_P} = \frac{E_{E,OUT,3+4+5+7}}{\varepsilon_E \varepsilon_G \varepsilon_{PB} E_P} - \frac{E_{E,IN,7+R8}}{\varepsilon_G \varepsilon_{PB} E_P}$$

Inserting the expression for E_P (equation 5-37), the expressions for the energy regenerated (5-21 and 5-23), the expression for γ(5-36), and isolating α one finds:

$$\alpha = \frac{\gamma E_{E,OUT,3+4+5+7}}{\varepsilon_E \varepsilon_G \varepsilon_{PB} H} - \frac{\gamma f_R \varepsilon_T \varepsilon_M \varepsilon_{PB} E_B}{\varepsilon_G \varepsilon_{PB} H} \Leftrightarrow \alpha = \frac{Z}{1 + ZQ}$$

where $Q = 1 - \varepsilon_E \varepsilon_{PB}$ and $Z = \frac{E_{E,OUT,3+4+5+7}}{\varepsilon_E \varepsilon_G \varepsilon_{PB} H} - \frac{f_R \varepsilon_T \varepsilon_M E_B}{\varepsilon_G H}$

All the terms in Q and Z, except $E_{E,OUT,3+4+5+7}$, are known. Operating modes 4, 5 and 7 are the EV operating modes, i.e. the operating modes where the accessories and driving wheels get their power entirely from the electricity storage. If it is known what parts of the driving cycle the vehicle drives in EV-mode, $E_{E,OUT,4+5+7}$ can be calculated exactly by summing up the power required at the driving wheels and to accessories in each time step. If only the distance driven in EV-mode, (D_{EV}) is known, $E_{E,OUT,4+5+7}$ can be approximated by assuming that the parts of the driving cycle, where the vehicle operates in EV-mode, resembles the rest of the driving cycle with regard to average speeds, values of the velocity peaks, and number of stops per unit distance.

We adopt the latter approach and assume the following:

1. The average driving speed[27] in EV-mode equals the average driving speed during the whole driving cycle.
2. Vehicle coasting can be neglected[28].
3. The engine is stopped when the vehicle is stopped[29].

The time that the vehicle spends in EV-mode is then given by:

$$T_{EV} = \frac{D_{EV}(T_P + T_R)}{D} + T_S$$

Assuming that the average power requirements at the wheels in EV-mode are approximately equal to the average power requirements at the wheels during the whole driving cycle, $E_{E,OUT,4+5+7}$ can be approximated by:

[27] The driving speed is the speed of vehicle when driving, i.e. the average driving speed during the driving cycle is given by $D/(T_P+T_R)$ assuming that vehicle coasting can be neglected.

[28] Vehicle coasting can not be neglected in real life driving, but in a model where the vehicle is forced to follow a specific driving cycle, vehicle coasting, i.e. the situation where the force at the driving wheels exactly cancels out, will happen very seldom.

[29] This assumption is reasonable in light of, that it is beneficial to reduce the time the fuel converter is on to reduce engine friction.

$$E_{E,OUT,4+5+7} = \frac{P_{AUX}T_{EV}}{\varepsilon_{PB}} + \frac{E_{W,4}}{\varepsilon_T \varepsilon_M \varepsilon_{PB}} = \frac{P_{AUX}T_{EV}}{\varepsilon_{PB}} + \frac{D_{EV} E_{W,1+2+3+4}}{D\varepsilon_T \varepsilon_M \varepsilon_{PB}}$$
$$= \frac{P_{AUX}T_{EV}}{\varepsilon_{PB}} + \frac{D_{EV}(E_{AIR} + E_{ROL} + E_{POT} + E_B)}{D\varepsilon_T \varepsilon_M \varepsilon_{PB}}$$

where we have used $E_{W,4} \approx D_{EV} E_{W,1+2+3+4} / D$ and equation 5-28.

$E_{E,OUT,3}$ is the energy delivered from the electricity storage, when the power from the engine is supplemented with the power from the electricity storage. No simple estimation of the size of $E_{E,OUT,3}$ can be made, but for a SHEV following a so-called "series power follower" operating strategy (see the caption to Figure 5-8 for an explanation of the series power follower strategy), and assuming that the vehicle is not operating as an EV during the driving cycle, the minimum size of $E_{E,OUT,3}$ can be estimated as:

$$E_{E,OUT,3} = \sum_{P_3>0} P_3(t)$$
$$P_3(t) = \frac{P_W(t)}{\varepsilon_{PB}\varepsilon_M \varepsilon_T} + \frac{P_{AUX}}{\varepsilon_{PB}} - P_{FC,MAX}\varepsilon_G \qquad (5\text{-}38)$$

$P_W(t)$: the power at the drive wheels at the time t [W] (see equation 5-9).

The approach is illustrated with the use of Figure 5-8. As can be seen from the figure, the size of $P_{FC,MAX}$ determine $E_{E,OUT,3}$. The size of $E_{E,OUT,5}$ is also given in the figure. It is the minimum size of $E_{E,OUT,3}$, because it is assumed that the engine will be able to deliver all necessary power between $P_{FC,MIN}$ and $P_{FC,MAX}$, but in reality it can happen that the engine is not allowed to regulate so fast as is required to follow the power demand from the power bus exactly.

If the vehicle operates as an EV during part of the driving cycle $E_{E,OUT,3}$ will be reduced. In accordance with the estimation of the energy consumption in EV-mode ($E_{E,OUT,4+5+7}$), the reduction of $E_{E,OUT,3}$ can be estimated as $1 - D_{EV} / D$.

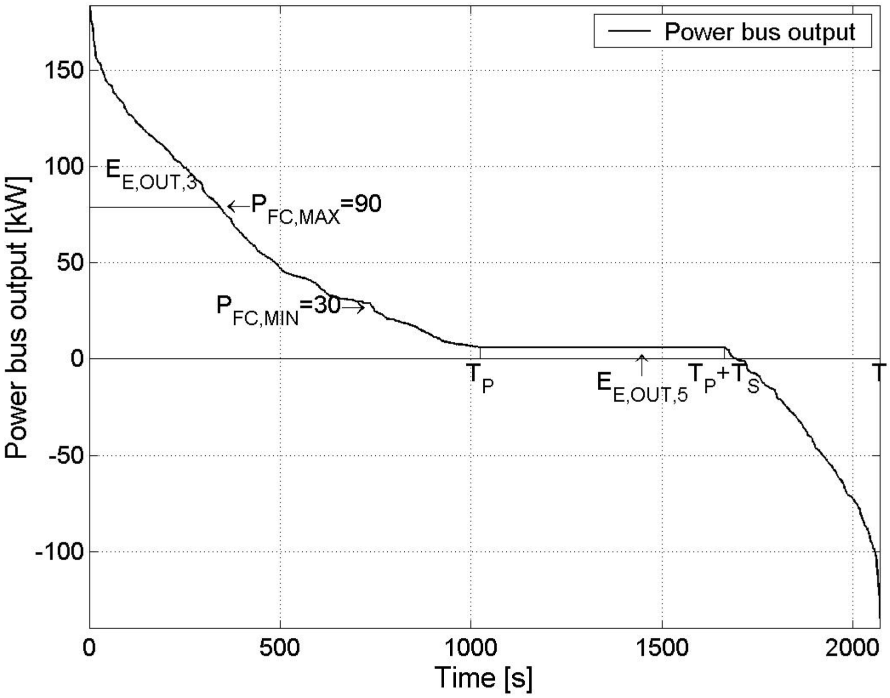


Figure 5-8 Illustration of the energy going out of the electricity storage in different operational modes. The plot shows the power output (or input when in braking mode) of the power bus calculated for a series hybrid bus driving on Line5suburbs_mod. The power bus power output has been sorted according to size. The SHEV follows a control strategy where the engine is kept within a minimum and maximum power limit $P_{FC,MIN}$ and $P_{FC,MAX}$. When the power required from the power bus is higher than $P_{FC,MAX}*\varepsilon_G*\varepsilon_{PB}$ additional power is delivered from the electricity storage. When the power required from the power bus is between $P_{FC,MIN}*\varepsilon_G*\varepsilon_{PB}$ and $P_{FC,MAX}*\varepsilon_G*\varepsilon_{PB}$ all the power is delivered from the engine, and finally when the power required from the power bus is lower than $P_{FC,MIN}*\varepsilon_G*\varepsilon_{PB}$ the surplus energy is delivered to the energy storage. The engine is assumed on in power mode, and it is assumed that the engine is stopped when the vehicle is stopped. The area between the plot of the power bus output and the horizontal line $P_{FC,MAX}$ = 90 is designated $E_{E,OUT,3}$, because the size of this area indicates how much energy is needed from the electricity storage in operation mode 3. Likewise with the area $E_{E,OUT,5}$.

Summing up α can be estimated with the expression:

$$\alpha == \frac{Z}{1+ZQ} \quad \text{where} \quad Q = 1 - \varepsilon_E \varepsilon_{PB} \quad \text{and}$$

$$Z = \frac{E_{E,OUT,3}}{\varepsilon_E \varepsilon_G \varepsilon_{PB} H}\left(1 - \frac{D_{EV}}{D}\right) - \frac{f_R \varepsilon_T \varepsilon_M E_B}{\varepsilon_G H} + \frac{P_{AUX}(T_S + {D_{EV}}/{D}(T_P + T_R))}{\varepsilon_E \varepsilon_G \varepsilon_{PB}^2 H} + \frac{D_{EV}(E_{AIR} + E_{ROL} + E_{POT} + E_B)}{D \varepsilon_P \varepsilon_E \varepsilon_{PB} H} \qquad (5\text{-}39)$$

where $E_{E,OUT,3}$ can be calculated with the use of equation 5-38 in the case of a SHEV following a series power follower strategy. α will therefore be higher the lower the maximum allowed power output from the engine, and the longer the vehicle drives as an EV.

Knowing the value of α, and assuming that engine idling can be ignored, i.e. $T_{I,FC} \approx 0$, the average power output of the fuel converter can be calculated using equation 5-37 with $T_{P,FC} = T - T_{EV}$.

The method presented above is used to determine α and $T_{P,FC}$ for the SHEVs analysed in this project.

Table 5-4 shows the results of model calculations for a series hybrid bus using the method presented in this section. As can be seen from the table the more passengers on the bus the higher a value of α, because the weight of the bus increases thereby increasing the power demands at the wheels, such that the electricity storage more often must deliver power to supplement the power output from the engine. When D_{EV} is zero and there are 18 passengers on-board the bus, α is slightly negative, meaning that the braking power regenerated is enough to recharge the batteries. Increasing D_{EV} increases α and reduces $T_{P,FC}$ as expected.

The fuel consumption is nearly independent of the value of D_{EV}, which means that the increased energy losses in the electricity storage when α gets bigger, is of the same size as the energy savings obtained by reduced engine friction connected with the reduced time the engine is on. In the calculation we have assumed that ε_E is constant, but in reality ε_E will decrease, when D_{EV} is increased, because larger power pulses are required of the electricity storage, when it is the only power source (EV-mode) than when it is supplemented by the engine. It is not possible to quantify this effect in the model, but it will slightly increase the energy consumption connected with large values of D_{EV}.

N_{PAS}	D_{EV} [km]	α	$T_{P,FC}$ [s]	$\langle P_{FC} \rangle$ [kW]	E_F [MJ/km]
18	0	-0.04	770	28.3	12.6
87	0	0.16	770	38.9	16.5
18	D/4	0.27	578	40.0	12.5
18	D/2	0.54	385	63.5	12.6

Table 5-4 The connection between the number of passengers (N_{PAS}), the distance driven in EV-mode (D_{EV}), the fraction of the energy delivered from the fuel converter that goes through the electricity storage relative to the total amount of energy delivered from the fuel converter (α), the time that the fuel converter delivers power ($T_{P,FC}$), the average power delivered from the fuel converter ($\langle P_{FC} \rangle$), and the energy consumption (E_F) of a series hybrid bus[30] driving in Line5city_mod.

[30] Parameters used to model the series hybrid bus: M_C=11209 kg, m_{eff}=1.1, ε_T=0.94, ε_G=0.90, ε_{PB}=0.95, ε_M=0.85, ε_E=0.85, C_{R1}=0.009, C_{R2}=0, A=6.75 m^2, C_D=0.8, p_{AUX}=1.5 kW, η_T=0.465, f_{MEP}=180 kPa.

5.5.5 Results for other types of propulsion systems

Similar calculations as the one done for SHEVs have been carried out for other types of propulsion systems and the results are given below.

SHEV with a fuel cell

The result for a SHEV with a fuel cell is the same as for the SHEV with ICE, except that the engine friction term is not present, there is no generator because the fuel cell produces electricity directly, and the thermal efficiency of the engine is replaced with the average efficiency of the fuel cell:

$$E_F = \frac{1}{\eta\,\gamma}\left(\frac{E_{AIR}}{\varepsilon_P} + \frac{E_{ROL}}{\varepsilon_P} + \frac{E_{POT}}{\varepsilon_P} + \frac{E_B(1-\beta)}{\varepsilon_P} + \frac{E_{AUX}}{\varepsilon_{AUX}}\right)$$

$\gamma = 1 - \alpha(1 - \varepsilon_E \varepsilon_{PB})$
$E_{AUX} = P_{AUX} T$
$\beta = f_R \varepsilon_E \varepsilon_P^2$.
$\varepsilon_P = \varepsilon_T \varepsilon_M \varepsilon_{PB}$ and $\varepsilon_{AUX} = \varepsilon_{PB}$
$\alpha = \dfrac{E_{E,IN,1+6+FC8}}{\varepsilon_{PB} E_P}$
η: the average efficiency of the fuel cell during the driving cycle.

EV with electricity storage

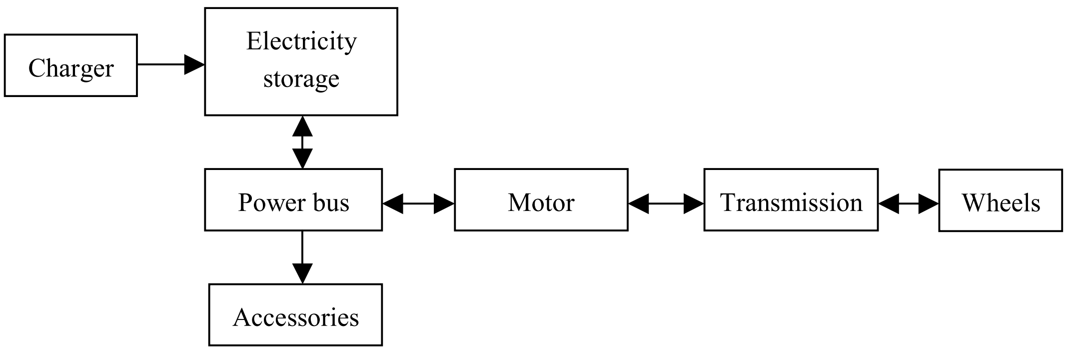


Figure 5-9 Subsystems and energy flows between subsystems in the propulsion system of an electric vehicle with electricity storage.

Operating mode	Power at wheels	Power charger	Power electricity storage	Description of operating mode
1	>0	=0	>0	Power to accessories and wheels from ES.
2	=0	=0	>0	Vehicle stopped or coasting, power to accessories from ES
3	<0	=0	<0	Charging ES with regenerated braking power
4	=0	>0	<0	Charging vehicle from stationary charger

Table 5-5 Operating modes for EV with electricity storage.

$$E_F = \frac{1}{\varepsilon_E}\left(\frac{E_{AIR}}{\varepsilon_P} + \frac{E_{ROL}}{\varepsilon_P} + \frac{E_{POT}}{\varepsilon_P} + \frac{E_B(1-\beta)}{\varepsilon_P} + \frac{E_{AUX}}{\varepsilon_{PB}}\right)$$

$$E_{AUX} = P_{AUX}T$$

$$\beta = f_R\varepsilon_P^2$$

$$\varepsilon_P = \varepsilon_{PB}\varepsilon_M\varepsilon_T$$

The conversion losses in the charger are included in the calculation of the fuel cycle efficiency.

EV with contact line

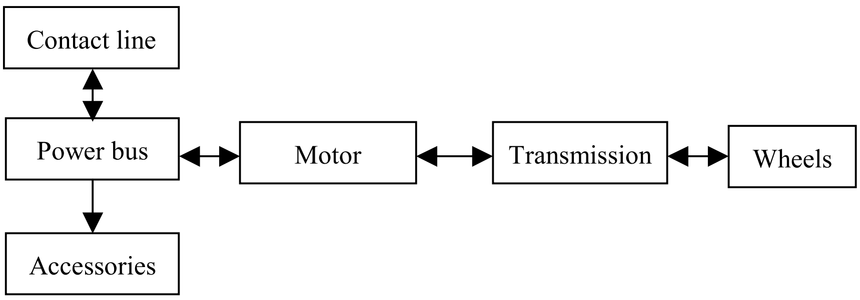


Figure 5-10 Configuration of an electric vehicle with contact line. Energy flows between subsystems are indicated with arrows.

Operating mode	Power at wheels	Power contact line	Description of operating mode
1	>0	>0	Power to accessories and wheels from contact line.
2	=0	>0	Vehicle stopped or coasting, power to accessories from contact line.
3	<0	<0	Regeneration of braking power that is sent out on the contact line to be used by other trains.

Table 5-6 Operating modes for EV with contact line.

$$E_F = \frac{E_{AIR}}{\varepsilon_P} + \frac{E_{ROL}}{\varepsilon_P} + \frac{E_{POT}}{\varepsilon_P} + \frac{E_B(1-\beta)}{\varepsilon_P} + \frac{E_{AUX}}{\varepsilon_{PB}}$$

$$E_{AUX} = P_{AUX}T$$

$$\beta = f_R \varepsilon_{CL} \varepsilon_P^2$$

$$\varepsilon_P = \varepsilon_{PB}\varepsilon_M\varepsilon_T$$

ε_{CL}: the efficiency of the contact line, equal to the ratio between the energy input to the vehicle and the energy input to the contact line.

Conventional vehicle

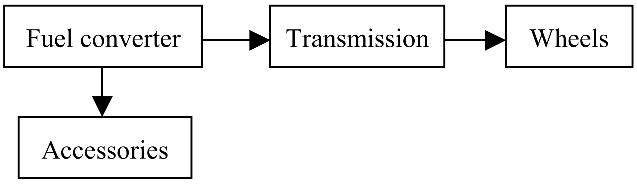


Figure 5-11 The configuration of the propulsion system of a conventional vehicle, where the small battery has been left out. The energy flows between subsystems are indicated with arrows.

$$E_F = \frac{E_{FRI}}{\eta_T} + \frac{1}{\eta_T}\left(\frac{E_{AIR}}{\varepsilon_T} + \frac{E_{ROL}}{\varepsilon_T} + \frac{E_{POT}}{\varepsilon_T} + \frac{E_B}{\varepsilon_T} + E_{AUX}\right) \quad (5\text{-}40)$$

$$E_{FRI} = \frac{f_{MEP}V}{2}\left(< N_I > T_I + < N_P > T_P\right)$$

$$E_{AUX} = P_{AUX}T$$

T: the total time of the driving cycle [s].

Operating mode	Power at wheels	Power fuel converter	Description of operating mode
1	>0	>0	Power to accessories and wheels from fuel converter.
2	=0	>0	Vehicle stopped or coasting, power to accessories from fuel converter.
3	<0	=0	Vehicle braking.

Table 5-7 The operating modes of a conventional vehicle.

5.5.6 Estimation of f_R

SHEVs and EVs of both types have the ability to regenerate braking energy. The braking energy at the wheels can either be dissipated in the mechanical brakes or used in the electric motor to regenerate braking energy. f_R is the fraction of the braking energy at the wheels being regenerated. The size of f_R depends on the design of the propulsion system and on the driving cycle.

The design of the propulsion system is important for the size of f_R in two respects. Firstly, as regenerative braking only can take place at the driving wheels, the position and number of driving wheels have importance. If the vehicle is backwheel or forwheel driven, it is in some braking situations necessary also to brake on the pair of wheels that is not driven, to secure the stability of the vehicle.

Secondly, the maximum regenerative power of the transmission, motor, power bus, and electricity storage determine the maximum braking power, that can be regenerated. This is illustrated in Figure 5-12, that for the driving cycle Line5suburbs_mod (see section 5.9) plots the braking power available at the wheels of the vehicle, at the motor (assuming a transmission efficiency of 0.95), and at the electricity storage, (assuming a variable motor efficiency including the power bus efficiency as explained in the caption of the figure). It can be seen that the amount of regenerated power gets smaller as it progresses up through the propulsion system, because of the efficiencies of the subsystems.

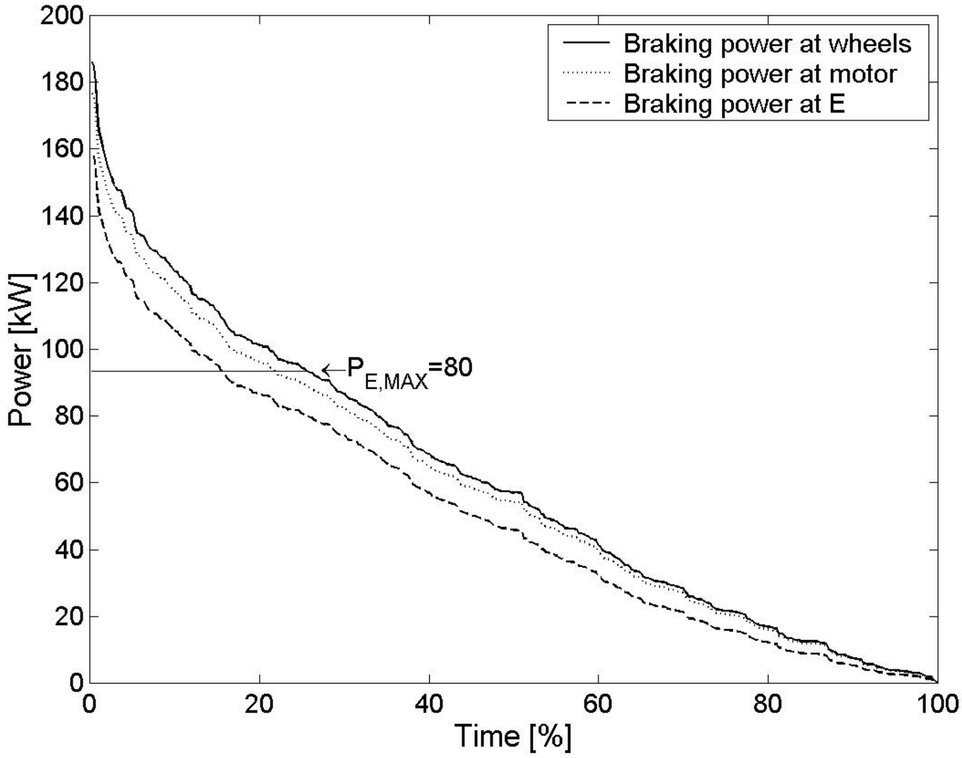


Figure 5-12 Plot of the braking power at the wheels, motor and electricity storage (E) for a series hybrid bus driving in the driving cycle Line5suburbs_mod. The motors peak regenerative power is 160 kW, and it is assumed that the efficiency of the motor in generator mode including the power bus efficiency is 0.70 at zero load (data taken from motor data file MC_AC75.m in ADVISOR [NREL 2001]) and increases linearly to 0.90 at half peak load (80kW). From half peak load to peak load the efficiency is assumed constant at 0.90.

The situation where the electricity storage limits the amount of braking energy that can be regenerated, has been illustrated in the figure in the form of the horizontal line designated $P_{E,MAX}$=80. It can be seen that the recharge limit of 80 kW limits the maximum braking power that can be regenerated to 94 kW (=80/(0.95*0.90)). The area between the line "Braking power at wheels" and the horizontal line "$P_{E,MAX}$=80", divided by the area below the line "Braking power at wheels", indicates how much of the braking power that can not be regenerated.

Plots like the one in Figure 5-12 can, supplemented with considerations about the amount of braking done on the driving wheels, be used to estimate f_R.

The driving cycle determines the size of the braking power at the wheels, i.e. the shape of the curve "Braking power at wheels" in Figure 5-12. If there are large decelerations in the driving cycle the maximum braking power at the wheels will be large, thereby making a larger fraction of the braking energy unavailable for regeneration due to limits in the maximum regenerative power of the subsystems in the propulsion system.

5.6 Calculation of key figures for the energy consumption

When the results of energy consumption calculations are presented and discussed, it is useful to define some key figures that can be compared for different vehicles. Two key figures have already been defined for ICEs namely the thermal and mechanical efficiency (see section 5.5.2). The most important key figure is the total efficiency of the propulsion system defined as the efficiency of the conversion of the fuel or electricity input to energy delivered at the wheels and accessories:

$$\eta_P = \frac{E_{VL}}{E_F} \quad \text{and} \quad E_{VL} = E_{AIR} + E_{ROL} + E_{POT} + E_B + E_{AUX}$$

η_P: the total efficiency of the propulsion system.
E_{VL}: the energy used in the vehicle loads.

It should be noticed that according to this definition the ability to regenerate braking energy is seen as an increase in the efficiency of the propulsion system, not as a decrease in the vehicle loads.

For the propulsion system type EV with contact line the recovery rate is an interesting number. The recovery rate is defined as the ratio between the energy delivered to the contact line from the vehicle in braking mode, and the energy delivered to the vehicle from the contact line in power mode.

5.7 Use of the model

Vehicle **Driving cycle**	**HT bus 12 m** **Line5city**	**HT bus 12 m** **Line5suburbs**	**S-train new** **Line A**	**Combino LRV** **LineLRV**
Subsystem efficiencies[31]				
ε_{PB}			0.95	0.95
ε_{M}			0.90	0.88
ε_{T}	0.72 (4-speed aut.)	0.75 (4-speed aut.)	0.98 (1-speed)	0.98 (1-speed)
Other parameters				
$<N_I>$[32]	15	15	-	-
$<N_P>$[32]	21	21	-	-
T_P	518	1003		
f_R	0	0	0.85[33]	0.85
m_{EFF}[34]	1.2	1.1	1.1	1.1
K	0.84	0.82	0.82	0.87

Table 5-8 "Mixed" parameters dependent on both the vehicle and the driving cycle.

The model presented above will be used to calculate the energy consumption of public transport modes with different propulsion systems and driving in different driving cycles.

As an example, the methodology will be used for calculating the energy consumption of three vehicles: 1) a conventional transit bus, 2) a local train of the type EV with contact line, 3) A light rail vehicle of the type Combino. The bus and the local train correspond to the type of vehicles being used in Greater Copenhagen. The vehicles represent the baseline vehicles of the present technology level. The local train will be named S-train, because it corresponds to the fourth generation of the S-train in Copenhagen.

The different parameters are specified in tables Table 5-8 and Table 5-9. The driving cycle parameters are specified in Table 5-12 (see section 5.9).

[31] The sub system efficiencies for the train is taken from [DSB 1999; DSB 2001 A]. The transmission of the bus is a 4-speed automatic. The efficiency of a 4-speed automatic transmission is estimated to 0.70 in city driving and 0.80 in highway driving [Weiss et al. 2000; Bradley 2000]. According to [Blumenthal et al. 2001] the efficiency of the propulsion system of the Combino is 0.82 in a "standard" driving cycle, i.e. the product of the power bus, motor and transmission efficiencies should be equal to this value.

[32] Estimated in an ADVISOR simulation using a 8.5 l, 205 kW engine.

[33] The maximum regenerative power of the motor is 1800 kW, which is used to estimate f_R.

[34] Value for bus/Line5city taken from [Bak 2000 A], value for bus/Line5suburbs based on own estimate, value for train taken from [Banestyrelsen 2000].

Vehicle name	Units	HT bus 12 m	S-train new	Combino LRV
Propulsion system type		Conventional	EV contact line	EV contact line
Passenger capacity:				
Seats		35	336	101
Total		87	600	252
Vehicle loads:				
M_C[35]	kg	11000	119000	43700
M_P[36]	kg	1260	11760	3500
C_{R1}		0.009	0.00205	0.00205
C_{R2}	sm^{-1}	0	0.0000257	0.0000257
A / C_D	m^2/	6.75[37] / 0.8	11.55 / 0.86	7.59[38] / 0.86
P_{AUX}	kW	3[39]	27[40]	11[41]
Fuel converter:[42]				
$\eta_T / f_{MEP} / V$	/kPa/l	0.465 / 180 / 9	-	-
Peak tractive power	kW	152	1778	741[43]

Table 5-9 Vehicle parameters. The values for the train are taken from [Banestyrelsen 2000] except for P_{AUX}. The values from the bus are based on information in [Teknologisk Institut 1999; Teknologisk Institut 2000; Bradley 2000; NREL 2001]. The values for the LRV is mainly taken from [Siemens 2001].

Figure 5-13 shows the energy consumption of the vehicles calculated with the model. The energy consumption of the conventional bus is 21.9 MJ/km in Line5city and 17.7 MJ/km in Line5suburbs. The unmodified driving cycles (see section 5.9) have been used to be able to compare the results with calculations from a vehicle simulation model made by the Technological Institute in Denmark called SEEK. Using the same parameters

[35] Including the weight of the driver (75 kg), and the weight of fuel (bus: 300 l diesel= 257 kg).

[36] In accordance with [Bradley 2000] we calculate the energy consumption at half-seated load. An average passenger weight of 70 kg is assumed.

[37] Height of bus 3.0 m, width 2.5 m, bus assumed 0.3 m above ground: A=2.5*(3.0-0.3).

[38] Height of LRV 3.5 m, width 2.3 m, LRV 0.2 m above the ground: A=2.3*(3.5-0.2).

[39] Mechanical load being driven by the engine [Bak 2000 A] (see section 9.4 for a discussion of accessory loads).

[40] P_{AUX} is estimated by looking at the extra energy consumption of S-trains in the winter compared to the summer, i.e. P_{AUX} include the power used for extra heating and lighting. The energy consumption is approximately 0.4-0.6 kWh/km larger in the winter than in the summer [DSB 1999], which distributed over the year gives an extra energy consumption of 0.2-0.3 kWh/km. We use a value of 0.25 kWh/km, which using the mean speed of 18.5 ms^{-1} in LineA gives a value of P_{AUX} = 16.7 kW. To this value we add 10 kW to take the base load used to ventilation, doors, etc. into consideration. The electrical power is delivered from the power bus.

[41] Assuming a value equal to 42% of the value used for the S-train, because the total passenger capacity of the LRV is 42% of the total passenger capacity of the S-train.

[42] The value of f_{MEP} is taken from [Weiss et al. 2000]. The value of V and η_T corresponds to a 169 kW Scania Euro 3 engine (DC9 01) [www.scania.com]. η_T is calculated on the basis of a minimum specific fuel consumption of 201 g/kWh (lower heating value of fuel = 43.0 kJ/g, maximum torque 1100 Nm at 1100 rpm). See equation 5-14 for the method used.

[43] The continuous power of the motors is 600 kW [Siemens 2001]. We assume the same peak power capability as the one given for the motors in the S-train, equal to 1.26 times the continuous power rating.

(M_C, C_{R1}, C_D, A, M_P,P_{AUX}) and a EURO III engine, SEEK calculates values of 22.0 for Line5city and 17.6 in Line5suburbs. The deviation between the results is below 1%.

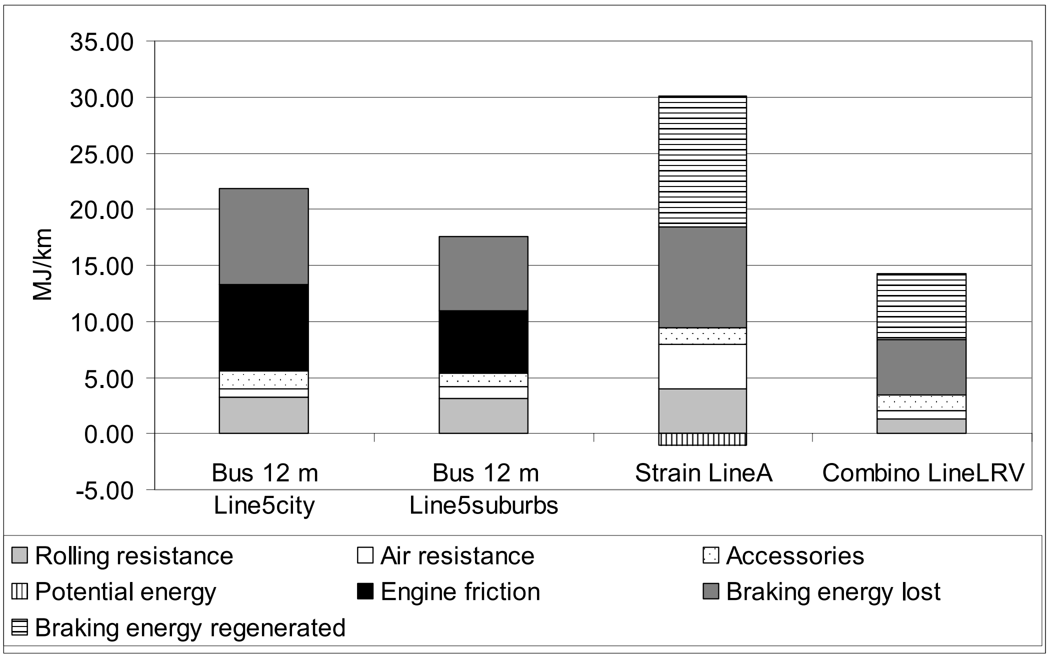


Figure 5-13 The energy consumption of a conventional bus and a local train in MJ/vehicle-km calculated with the model.

To compare the model with ADVISOR, simulations of a conventional bus driving in Line5city and Line5suburbs have been carried out in ADVISOR using the library of subsystems in ADVISOR to define the propulsion system and using the same vehicle load parameters as the ones in Table 5-9. The transmission efficiencies and average engine efficiencies calculated in ADVISOR have then been used in our model to be able to compare the results. Comparing ADVISOR and our model in this way, the results agree within 5%.

Looking at the figure it can be seen that the air resistance is relatively low compared to the other vehicle loads for buses driving in urban driving cycles. This is due to the low average speed involved in these driving cycles. The largest vehicle load is the braking energy for both bus and local train, reflecting that public transport modes have driving cycles with frequent stops, i.e. many accelerations involved. The engine friction constitutes approximately one third of the total energy consumption of the buses.

The energy consumption of the bus driving in the inner city driving cycle is 24 % higher than the energy consumption of the same bus driving in the suburbs driving cycle. This difference arises because the vehicle loads are 15% higher and the propulsion system efficiency 8% lower in Line5city compared to Line5suburbs (0.23 compared to 0.25). The braking energy is higher, because Line5city has more stops per distance than Line5suburbs (see Table 5-12), and the propulsion system efficiency is lower, because the efficiency of the transmission is lower, and because more energy is lost as engine friction. The mechanical efficiency of the engine (see equation 5-13) is 4% lower in Line5city compared to Line5suburbs.

The energy consumption of the local train is 17.4 MJ/km or 4.8 kWh/km. The potential energy is negative because the train is driving more downhill than uphill during the driving cycle. The propulsion system efficiency of the local train is 1.41 reflecting the large amount of braking energy regenerated, and the high efficiency of the subsystems in the propulsion system. The energy recovery rate of the local train is 0.41.

Measurements of the energy consumption of the S-train in real life driving done by DSB [DSB 1999] including contact line losses show an energy consumption between 3.0-3.5 kWh/km with a recovery rate of 0.39-0.45. It can be seen that the energy consumption calculated with the model is around 50% higher. Part of the difference probably arises, because the driving cycle used in the model is more demanding than the one experienced in real life driving (see section 5.9). According to [DSB 2001 A] driving 10% slower results in an energy saving of up to 1/3 of the energy consumed by the S-train. This is done by accelerating the vehicle with max power up to a certain point and then let the train coast until a vehicle speed where the braking can be done entirely with the use of the motors.

Another explanation can be that the vehicle load parameters (C_{R1}, C_{R2}, C_D) obtained from [Banestyrelsen 2000] are too large.

The energy consumption of the LRV Combino is 8.4 MJ/km or 2.3 kWh/km equal to 49.4 Wh/km/tons. The recovery rate is 0.42. Measurements of the energy consumption on a LRV of the Combino type (a shorter version) give an energy consumption of 46-55 Wh/km/tons and recovery rates of 0.31-0.42 [Blumenthal et al. 2001] in good agreement with the model.

To illustrate the influence of different parameters on the energy consumption, each parameter is reduced by 10 % while the other parameters are kept constant and the resulting change in the energy consumption is calculated.

Vehicle	**Driving cycle**	C_{R1}/C_{R2}	C_DA	M_C	**V**	P_{AUX}	ε_{PB}	ε_M	ε_T
Conv. bus	Line5city	-1.5	-0.4	-4.9	-3.5	-0.8	-	-	6.5
Conv- bus	Line5suburbs	-1.8	-0.6	-5.0	-3.2	-0.6	-	-	6.9
Combino LRV	LineLRV	-1.7	-1.0	-6.9	-	-1.7	23.9	24.2	23.9
S-train	LineA	-2.3	-2.2	-6.3	-	-0.9	25.3	24.3	24.3

Table 5-10 The influence of a 10% reduction in a parameter on the energy consumption of a conventional bus, local train and light rail vehicle.

The results are given in Table 5-10. For the conventional bus the most important parameters are the curb mass M_C, the displacement volume of the engine V, and the transmission efficiency ε_T. The curb mass is important because the braking energy and the rolling resistance together constitutes respectively 80% and 79% of the vehicle loads for the conventional bus driving in Line5city and Line5suburs, and both vehicle loads are proportional to the total mass of the vehicle. V shows the importance of the engine friction on the energy consumption. Reduction in the air resistance parameters (C_DA) has very little influence on the energy consumption.

For the local train and the LRV, it is remarkable, that a 10 % reduction in the efficiency of the motor, power bus or transmission results in a around 25 % increase in the energy consumption. The reason is that these efficiencies are involved not only, when power is delivered from the propulsion system, but also when power is regenerated, combined with the large amount of braking energy regenerated. The influence of the curb mass is even bigger than for the conventional bus, because there is no engine friction, which for the conventional bus is a large term independent of the curb mass.

5.8 Sizing of subsystems and calculation of the mass and cost of a vehicle

As mentioned in the previous paragraph the energy consumption of a vehicle depends on a number of parameters and variables that determine the vehicle loads and the subsystem efficiencies. To calculate the energy consumption, the curb mass of the vehicle must be determined, and to estimate f_R the peak power of the transmission, motor and battery must be known.

In this section a method for determining the curb mass and cost of a vehicle and the sizes of the subsystems in the propulsion system is presented. The method is based on the approaches described in [Cuenca et al. 1999; An et al. 2000].

For each vehicle concept the basic approach is to ensure that the performance of future vehicles equals the performance of the present vehicles within the same vehicle class. This is done by ensuring that the tractive power capability per mass of the future vehicles equals the tractive power capability per mass of the vehicles of today. Next for a given type of propulsion system the required tractive power capability is used to determine the required peak power of each subsystem (or storage capacity in case of fuel and electricity storages). The peak power or storage capacity of a subsystem determines the mass and cost of the subsystem with the use of specific power, energy and price parameters. By adding the mass of each subsystem the mass of the propulsion system is determined.

The glider mass of the vehicle, i.e. the mass of the vehicle exclusive the mass of the propulsion system, is determined as the glider mass of a reference vehicle plus 15% of the weight difference between the curb mass of the vehicle under consideration and the curb mass of the reference vehicle. The 15% of the mass difference is added to take the increase or decrease in the weight of the necessary support structures relative to the reference vehicle into account. This approach and the choice of 15% are taken from [Ogden et al. 1999].

Finally the mass of the vehicle are determined by adding the mass of the propulsion system to the glider mass of the vehicle. Similar calculations are done to arrive at the cost of the vehicle.

5.8.1 Performance criteria for a vehicle

The performance criteria for a vehicle consist in a combination of top speed criteria, gradeability criteria[44], acceleration criteria[45], and startability criteria[46] [Bradley 2000]. These performance criteria must normally be fulfilled at the gross vehicle weight rating[47]. Apart from these criteria there are also braking requirements and environment requirements, i.e. the ability to operate within certain temperature, humidity and altitude intervals, but they are not taken into account in this project.

Some of the performance criteria (startability and grade) are mainly requirements on the torque delivered at the wheels of the vehicle, i.e. the fulfilment of these criteria do not require a high power output from the propulsion system but rather a high torque at a low speed. In our approach we only look at the maximum power requirement, and assumes that the torque requirements can be fulfilled by a proper choice of transmission ratios.

Of the tractive forces only the air resistance is independent of the total mass of the vehicle, whereas the acceleration, grade and rolling resistance forces all are proportional to the total mass (see section 5.3). The maximum air resistance constitutes around 18% of the peak tractive power capability for a conventional bus and 13% for an S-train[48]. As the air resistance constitutes a small fraction of the tractive power required in most driving situations, it can with good approximation be assumed that vehicles with the same tractive power capability per maximum mass, have the same performance [An et al. 2000; Weiss et al. 2000]. Using this assumption, the tractive power capability of a vehicle is calculated as:

$$P_{W,MAX} = \left(M_C + M_P\right) \frac{P_{W,MAX,B}}{M_{C,B} + M_{P,MAX,B}} = a\left(M_C + M_P\right)$$
$$a = \frac{P_{W,MAX,B}}{M_{C,B} + M_{P,MAX,B}} \qquad (5\text{-}41)$$

a: the specific peak tractive power of the baseline vehicle [kW/tons].
$P_{W,MAX}$: the peak tractive power capability of the new vehicle [kW].
$P_{W,MAX,B}$: the peak tractive power capability of the baseline vehicle [kW].
M_C: the curb mass of the new vehicle [kg].
$M_{C,B}$: the curb mass of the baseline vehicle [kg].
$M_{P,MAX,B}$: the maximum passenger load of the baseline vehicle [kg].
M_P: the maximum passenger load of the new vehicle [kg].

Table 5-11 shows values of a for different vehicle concepts and the assumptions used in the calculation of a. These values are used as the baseline values in this study.

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[44] The ability to maintain a given constant speed on a given grade for a certain amount of time.
[45] The ability to accelerate to a certain top speed within a certain time on level ground.
[46] The ability to start the vehicle on a certain grade.
[47] The maximum allowed weight of the vehicle including load.
[48] Using the vehicle parameters specified in Table 5-9 and assuming a maximum speed of 80 km/h of the bus and 120 km/h of the S-train.

Vehicle concept	12 m bus	18 m bus	Local train	LRV
Curb mass/total passenger load [tons]	11.0/6.1	16.8/10.5	124.6/42.0	43.7/17.6
Max efficiency transmission [in/out]	0.9	0.9	0.98	0.98
Engine/Motor peak output power [kW]	169	220	1814	756
a (peak tractive power capability per maximum mass) [kW/tons]	8.9	7.3	10.7	12.1

Table 5-11 The specific peak tractive power (a) of different vehicle concepts and the values of the parameters used in the calculation of the specific peak tractive power.

The maximum tractive power required at the wheels is used to size the subsystems in the propulsion system by requiring that the peak output power of each subsystem matches the maximum tractive power at the wheels, and taking into consideration the efficiencies involved in the transmission of power from the subsystems to the wheels. The efficiencies used in the determination of the subsystem efficiencies refer to the transmission, motor, power bus and generator peak efficiencies, because these subsystems are most efficient at maximum load.

For a series hybrid vehicle the peak power delivered at the wheels will be delivered from both the fuel converter and the electricity storage. Therefore an additional criteria is needed to determine the size of the fuel converter. In accordance with [An et al. 2000] we have for buses chosen to require that the vehicle should be able to drive 80 km/h on level ground without requiring power from the electricity storage. This criteria is chosen to secure that the vehicle can drive long distances with high speed, a situation that can arise when the vehicle is transferred to another route. This criteria should be fulfilled at zero passenger load, because the long distance driving at high speed normally will only take place in situations without passengers.

The fuel storage system present in conventional and hybrid electric propulsion systems will be sized to allow for 19 hours of operation between refuelling to allow the vehicle to operate for a whole day without refuelling.

The electricity storage systems present in EVs with electricity storage will be sized to allow for at given number of hours of operation between recharging. The electricity storage systems present in series hybrid vehicles will be sized according to two criteria:

1. A power criteria where the sum of the peak power from the electricity storage and the fuel converter must be enough to deliver the required tractive power at the wheels.
2. An energy criteria where the electricity storage is sized according to a given EV range, i.e. the energy storage must be able to provide enough energy to power the vehicle over a given distance with the fuel converter stopped.

5.8.2 The mass of a series hybrid vehicle with internal combustion engine

As an example of the methodology used, the sizes of the subsystems in the propulsion system and the curb mass of the vehicle is calculated for a series hybrid vehicle with a internal combustion engine.

The curb mass of the series hybrid vehicle is given by:

$$M_C = M_{GL,REF} + M_{SUP} + M_{FC} + M_G + M_E + M_{PB} + M_M + M_T + M_{FSTO} \qquad (5\text{-}42)$$

$M_{GL,REF}$: the glider mass of the reference vehicle [kg].
M_{SUP}: the mass of the support structures added or subtracted relative to the reference vehicle [kg].
M_{FC}: the mass of the fuel converter [kg].
M_G: the mass of the generator [kg].
M_E: the mass of the electricity storage [kg].
M_{PB}: the mass of the power bus [kg].
M_M: the mass of the electric motor [kg].
M_T: the mass of the transmission [kg].
M_{FSTO}: the mass of the fuel storage [kg].

The mass of the support structures is given by:

$$M_{SUP} = k_{SUP}\left(M_C - M_{C,REF}\right) \qquad (5\text{-}43)$$

k_{SUP}: the fraction of the weight difference between the curb mass of the vehicle and the curb mass of the reference vehicle that is used to support structures.
$M_{C,REF}$: the curb mass of the reference vehicle [kg].

The mass of the fuel storage is given by:

$$M_{FSTO} = \frac{E_{F,H} T_{FSTO} k}{s_{FSTO}} \qquad (5\text{-}44)$$

T_{FSTO}: the number of hours that the vehicle should be able to operate between refuelling [h].
k: a general design factor introduced to secure that the subsystems are sized large enough. A value of 1.1 is used in this project.
s_{FSTO}: the specific energy of the fuel storage under consideration [MJ/kg]
$E_{F,H}$: the design fuel consumption of the vehicle per hour [MJ/h].

For a given driving cycle the fuel consumption per hour is given by $E_{F,H} = E_F/T$, so the design fuel consumption can be estimated by looking at the fuel consumption in different driving cycles and choosing the largest value of the fuel consumption per hour. In this project the fuel consumption per hour of a vehicle with maximum passenger load operating in Line5_mod is used as the design fuel consumption for all types of fuel storages.

The mass of the fuel converter is given by:

$$M_{FC} = \frac{P_{FC,MAX}}{q_{FC}}$$

$$P_{FC,MAX} = k\left(\frac{P_{W,V_{FC}}}{\varepsilon_{P,MAX}} + \frac{P_{AUX}}{\varepsilon_{AUX}}\right) \qquad (5\text{-}45)$$

$$P_{W,V_{FC}} = M_C g(C_{R1} v_{FC} + C_{R2} v_{FC}^2) + 0.5\rho A C_D v_{FC}^3$$

$\varepsilon_{P,MAX}$: instead of average values of the subsystem efficiencies peak values are used in the calculation of $\varepsilon_{P,MAX}$.
$P_{FC,MAX}$: the peak power of the fuel converter [W].
q_{FC}: the specific power of the fuel converter [W/kg].
$P_{W,vFC}$: the tractive power at the wheels when the vehicle is driving at the constant speed v_{FC} [W].
v_{FC}: the constant speed used to determine the size of the fuel converter [ms^{-1}].

It turns out to be advantageous to express the peak power of the fuel converter in the following form:

$$P_{FC,MAX} = k(dM_C + f)$$

$$d = \frac{g(C_{R1} v_{FC} + C_{R2} v_{FC}^2)}{\varepsilon_{P,MAX}} \qquad (5\text{-}46)$$

$$f = \frac{P_{AUX}}{\varepsilon_{AUX}} + \frac{0.5\rho A C_D v_{FC}^3}{\varepsilon_{P,MAX}}$$

The mass of the electricity storage is sized, both according to an energy capacity criteria securing that the vehicle can drive a certain distance as an EV, and according to a power criteria securing that the sum of the peak power from the fuel converter and battery is enough to deliver the peak tractive power at the wheels.

The energy capacity criteria is given by:

$$M_E = \frac{e_E D_E k}{r_{DC} s_E} \qquad (5\text{-}47)$$

D_E: the required EV range [km].
r_{DC}: discharge ratio: the fraction of the maximum energy content of the electricity storage that the vehicle is assumed to use during the operation as an EV.
s_E: the specific energy of the electricity storage [kJ/kg].
e_E: the design electricity consumption per km of the vehicle in EV-mode [kJ/km].
e_E can be estimated as $e_E = \frac{P_{AUX}}{<v> \varepsilon_{PB}} + \frac{E_W}{D \varepsilon_T \varepsilon_M \varepsilon_{PB}}$ using values from a innercity driving cycle (assuming that the vehicle will operate as an EV preferentially in the inner city).

The power capacity criteria is given by:

$$M_E = \frac{P_{W,MAX}}{\varepsilon_{PB,MAX}\varepsilon_{M,MAX}\varepsilon_{T,MAX} q_E} + \frac{P_{AUX}}{\varepsilon_{PB} q_E} - \frac{P_{FC,MAX}\varepsilon_{G,MAX}}{q_E} \qquad (5\text{-}48)$$

$\varepsilon_{G,MAX}$: the peak efficiency of the generator.
$\varepsilon_{PB,MAX}$: the peak efficiency of the power bus.
$\varepsilon_{M,MAX}$: the peak efficiency of the motor.
$\varepsilon_{T,MAX}$: the peak efficiency of the transmission.
q_E: the specific power of the electricity storage [W/kg].

The peak tractive power required at the wheels is given by equation 5-41.

The generator is sized to match the peak power output from the fuel converter:

$$M_G = \frac{kP_{FC,MAX}\varepsilon_{G,MAX}}{q_G} \qquad (5\text{-}49)$$

q_G: the specific power of the generator [W/kg].
The power bus and motor are sized to match the peak tractive power at the wheels, and the transmission is sized to match the peak power output from the motor:

$$M_{PB} = \frac{P_{W,MAX}}{\varepsilon_{M,AMX}\varepsilon_{T,MAX} q_{PB}} + \frac{P_{AUX}}{q_{PB}} \qquad (5\text{-}50)$$

$$M_M = \frac{P_{W,MAX}}{\varepsilon_{T,MAX} q_M} \quad \text{and} \quad M_T = \frac{P_{W,MAX}}{\varepsilon_{T,MAX} q_T} \qquad (5\text{-}51)$$

q_{PB}, q_M and q_T are respectively the specific power of the power bus, the specific power of the motor and the specific power of the transmission [W/kg].

The two criteria for the size of the electricity storage give two equations for the curb mass. Starting with the power criteria the expression for the curb mass is derived by inserting the expressions for the support structures (5-43), fuel converter (5-45), the generator (5-49), the electricity storage (5-48), the power bus (5-50), the motor and transmission (5-51) into the equation for the curb mass 5-42, and then using the equation for the maximum power at the wheels (5-41) and the maximum power of the fuel converter (5-46):

$$
\begin{aligned}
M_C &= P_{W,MAX}\left(\frac{1}{\varepsilon_{PB,MAX}\varepsilon_{M,MAX}\varepsilon_{T,MAX}q_E}+\frac{1}{\varepsilon_{M,MAX}\varepsilon_{T,MAX}q_{PB}}+\frac{1}{\varepsilon_{T,MAX}q_M}+\frac{1}{\varepsilon_{T,MAX}q_T}\right)\\
&\quad + P_{AUX}\left(\frac{1}{\varepsilon_{PB}q_E}+\frac{1}{q_{PB}}\right)+P_{FC,MAX}\left(\frac{1}{q_{FC}}+\frac{k\varepsilon_{G,MAX}}{q_G}-\frac{\varepsilon_{G,MAX}}{q_E}\right)+M_{GL,REF}+M_{SUP}+M_{FSTO}\\
&= M_{GL,REF}+M_{FSTO}+k_{SUP}\left(M_C-M_{C,REF}\right)+\left(M_C+M_P\right)ae_1+P_{AUX}e_2+\left(dM_C+f\right)ke_3 \Leftrightarrow\\
M_C &= \frac{M_{GL,REF}+M_{FSTO}-k_{SUP}M_{C,REF}+ae_1M_P+P_{AUX}e_2+fke_3}{1-k_{SUP}-ae_1-dke_3}
\end{aligned}
$$

where

$$
\begin{aligned}
e_1 &= \frac{1}{\varepsilon_{PB,MAX}\varepsilon_{M,MAX}\varepsilon_{T,MAX}q_E}+\frac{1}{\varepsilon_{M,MAX}\varepsilon_{T,MAX}q_{PB}}+\frac{1}{\varepsilon_{T,MAX}q_M}+\frac{1}{\varepsilon_{T,MAX}q_T}\\
e_2 &= \frac{1}{\varepsilon_{PB}q_E}+\frac{1}{q_{PB}}\\
e_3 &= \frac{1}{q_{FC}}+\frac{k\varepsilon_{G,MAX}}{q_G}-\frac{\varepsilon_{G,MAX}}{q_E}
\end{aligned}
$$

In the same manner the expression for the curb mass using the energy capacity criteria is:

$$
\begin{aligned}
M_C &= M_{GL,REF}+M_{SUP}+M_{FSTO}+M_E+P_{W,MAX}\left(\frac{1}{\varepsilon_{M,MAX}\varepsilon_{T,MAX}q_{PB}}+\frac{1}{\varepsilon_{T,MAX}q_M}+\frac{1}{\varepsilon_{T,MAX}q_T}\right)+P_{AUX}\left(\frac{1}{q_{PB}}\right)\\
&\quad + P_{FC,MAX}\left(\frac{1}{q_{FC}}+\frac{k\varepsilon_{G,MAX}}{q_G}\right)\\
&= M_{GL,REF}+M_{FSTO}+M_E+k_{SUP}\left(M_C-M_{C,REF}\right)+\left(M_C+M_P\right)ae_1+P_{AUX}e_2+\left(dM_C+f\right)ke_3 \Leftrightarrow\\
M_C &= \frac{M_{GL,REF}+M_{FSTO}+M_E-k_{SUP}M_{C,REF}+ae_1M_P+P_{AUX}e_2+fke_3}{1-k_{SUP}-ae_1-dke_3}
\end{aligned}
$$

where

$$
\begin{aligned}
e_1 &= \frac{1}{\varepsilon_{M,MAX}\varepsilon_{T,MAX}q_{PB}}+\frac{1}{\varepsilon_{T,MAX}q_M}+\frac{1}{\varepsilon_{T,MAX}q_T}\\
e_2 &= \frac{1}{q_{PB}}\\
e_3 &= \frac{1}{q_{FC}}+\frac{k\varepsilon_{G,MAX}}{q_G}
\end{aligned}
$$

The final value of the curb mass is taken as the largest of the two values for the curb mass calculated above. The masses and peak powers of the subsystems can now be calculated “backwards” using the value for the curb mass in the equations for the masses of the subsystems. Having calculated the peak powers and energy capacities, the costs of the subsystems can be calculated with the use of specific prices[49].

5.8.3 Calculation of the mass of vehicles with other propulsion systems

The same methodology as the one used for a SHEV with ICE has been used to derive expressions for the calculation of the curb mass of vehicles with other propulsion systems. The results are summarised in this section.

For all propulsion systems the expression for the peak tractive power required at the wheels is the same as the one given for a SHEV with ICE (equation 5-41).

SHEV with fuel cell

The results for the SHEV with fuel cell correspond to the ones given for a SHEV with ICE, except that there is no generator in the propulsion system. Only the power criteria is used to size the electricity storage, because the emissions from the fuel cell are so low that no EV range is required. The results are:

$$M_C = \frac{M_{GL,REF} + M_{FSTO} - k_{SUP}M_{C,REF} + ae_1M_P + P_{AUX}e_2 + fke_3}{1 - k_{SUP} - ae_1 - dke_3}$$

$$e_1 = \frac{1}{\varepsilon_{PB,MAX}\varepsilon_{M,MAX}\varepsilon_{T,MAX}q_E} + \frac{1}{\varepsilon_{M,MAX}\varepsilon_{T,MAX}q_{PB}} + \frac{1}{\varepsilon_{T,MAX}q_M} + \frac{1}{\varepsilon_{T,MAX}q_T}$$

$$e_2 = \frac{1}{\varepsilon_{PB}q_E} + \frac{1}{q_{PB}}$$

$$e_3 = \frac{1}{q_{FC}} - \frac{1}{q_E}$$

$$P_{FC,MAX} = k(dM_C + f)$$

$$d = \frac{g(C_{R1}v_{FC} + C_{R2}v_{FC}^2)}{\varepsilon_{PB,MAX}\varepsilon_{M,MAX}\varepsilon_{T,MAX}}$$

$$f = \frac{P_{AUX}}{\varepsilon_{AUX}} + \frac{0.5\rho AC_Dv_{FC}^3}{\varepsilon_{PB,MAX}\varepsilon_{M,MAX}\varepsilon_{T,MAX}}$$

$$M_E = \frac{P_{W,MAX}}{\varepsilon_{PB,MAX}\varepsilon_{M,MAX}\varepsilon_{T,MAX}q_E} + \frac{P_{AUX}}{\varepsilon_{PB}q_E} - \frac{P_{FC,MAX}}{q_E}$$

The mass and size of the fuel storage is determined in the same way as done for the SHEV with ICE (equation 5-44). After the calculation of the curb mass the mass and

[49] Assuming that the price of a subsystem is proportional to the peak power or energy capacity of the subsystem. This assumption is done for simplicity and because we lack price data to make more realistic models of the connection between size of a subsystem and price.

peak power of the power bus, motor and transmission can be calculated by using equations 5-50 and 5-51.

EV with electricity storage

The electricity storage is designed to have a given number of operating hours between recharging:

$$M_E = \frac{E_{E,H} T_E k}{r_{DC} s_E}$$

$E_{E,H}$: the energy delivered from the electricity storage per hour [J/h].
T_E: the operating hours between recharge [h].
For a given driving cycle $E_{E,H}$ is given by $E_{E,H} = \frac{P_{AUX}}{\varepsilon_{PB}} + \frac{E_W}{T \varepsilon_T \varepsilon_M \varepsilon_{PB}}$. In this way $E_{E,H}$ can be calculated for different driving cycles to get an impression of a suitable value.

$$M_C = \frac{M_{GL,REF} + M_E - k_{SUP} M_{C,REF} + a e_1 M_P + P_{AUX} e_2}{1 - k_{SUP} - a e_1}$$

$$e_1 = \frac{1}{\varepsilon_{M,MAX} \varepsilon_{T,MAX} q_{PB}} + \frac{1}{\varepsilon_{T,MAX} q_M} + \frac{1}{\varepsilon_{T,MAX} q_T}$$

$$e_2 = \frac{1}{q_{PB}}$$

After the calculation of the curb mass, the mass and peak power of the power bus, motor and transmission can be calculated by using equation 5-50 and 5-51.

EV with contact line

The results for the EV with contact line are equal to the results for the EV with electricity storage, except that there is no electricity storage:

$$M_C = \frac{M_{GL,REF} - k_{SUP} M_{C,REF} + a e_1 M_P + P_{AUX} e_2}{1 - k_{SUP} - a e_1}$$

$$e_1 = \frac{1}{\varepsilon_{M,MAX} \varepsilon_{T,MAX} q_{PB}} + \frac{1}{\varepsilon_{T,MAX} q_M} + \frac{1}{\varepsilon_{T,MAX} q_T}$$

$$e_2 = \frac{1}{q_{PB}}$$

Conventional vehicle

In a conventional vehicle the weight of the starter battery is included separately, because in other propulsion systems like SHEV the electricity storage replaces the starter battery. The weight of the fuel storage is determined as in equation 5-44, and the weight of the transmission is determined as in equation 5-51.

$$M_C = M_{GL,REF} + M_{SUP} + M_{FSTO} + M_E + M_{FC} + M_T$$

M_E: the weight of the starter battery [kg].

$$M_{FC} = \frac{P_{W,MAX}}{\varepsilon_{T,MAX} q_{FC}} + \frac{P_{AUX}}{q_{FC}}$$

$$M_C = \frac{M_{GL,REF} + M_{FSTO} + M_E - k_{SUP} M_{C,REF} + ae_1 M_P + P_{AUX} e_2}{1 - k_{SUP} - ae_1}$$

$$e_1 = \frac{1}{\varepsilon_{T,MAX} q_{FC}} + \frac{1}{\varepsilon_{T,MAX} q_T}$$

$$e_2 = \frac{1}{q_{FC}}$$

5.9 Driving cycles

In this section the driving cycles used in this project are introduced. Different driving cycles are used for different vehicle concepts, because the interaction with the surrounding traffic system is different for different vehicle concepts (see section 3.7).

For buses a driving cycle based on measurements of the driving done on Line 5 in Copenhagen is used. Line 5 has been split up into two driving cycles an inner city driving cycle and a suburbs driving cycle, where the inner city driving cycle has lower average speed and more frequent stops than the suburb driving cycle (see Table 5-12). The driving cycles are taken from [Teknologisk Institut 2000]. Both driving cycles have very high decelerations up to –6.44 ms^{-2} for line5city and –6.67 ms^{-2} for line5suburbs, where as the accelerations are only up to 1.28 ms^{-2}. Decelerations of this magnitude are far higher than the deceleration allowable from passenger comfort considerations. [Overgaard 2001] estimate the maximum allowable deceleration to be –1.75 ms^{-2}. As lower decelerations are preferential when considering regeneration of braking energy, the driving cycles are modified such that the maximum decelerations encountered are –1.75 ms^{-2}, by making the braking of the buses more smooth. Thereby increasing the duration of the driving cycles with 4.0% in both cases (see Table 5-12). The modified driving cycles are named Line5city_mod for the inner city driving cycle and Line5suburbs_mod for the suburbs driving cycle. The two driving cycles combined into one, i.e. the whole of Line5, is named Line5_mod. Figure 5-14 shows a plot of Line5city_mod.

	Unit	Sym-bol							
Vehicle concept			Bus	Bus/LRV	Bus	Bus/LRV	Bus	LRV	Local train
Name of driving cycle			Line5inner city	Line5suburbs	Line5city_mod	Line5suburbs_mod	Line5_mod	LineLRV	Line A
Time of driving cycle	s	T	1137	1991	1183	2072	3255	732	2982
Length [m]	m	D	4560	11150	4645	11319	15964	6000	55310
Number of subcycles		N_S	26	39	26	39	65	12	22
Mean speed	m/s	$\langle v \rangle$	4.01	5.6	3.93	5.46	4.90	8.2	18.54
Mean of v^2	m2/s2	$\langle v^2 \rangle$	33.41	57.49	32.32	55.49	47.07	100.42	415.8
Mean of v^3	m3/s3	$\langle v^3 \rangle$	309.49	635.5	298.2	611.6	497.7	1287.5	9996
Max speed	km/h	v_{max}	44.61	50.01	44.61	50.01	50.01	50.5	100
Max acc	m2/s	a_{max}	1.25	1.28	1.25	1.28	1.28	1.31	1.43
Max dec	m2/s	d_{max}	-6.44	-6.67	-1.75	-1.75	-1.75	-1.73	-1.25
Power time	s	T_P	518	1003	512	997	1509	420	1800
Stopped time	s	T_S	417	638	413	640	1053	168	6
Braking time	s	T_R	202	350	258	435	693	144	1176
Height difference	m	Δh	0	0	0	0	0	0	-36.2
Sum of uphill driving	m	ΔH_{up}	0	0	0	0	0	0	124.4
Root mean square peak speed	m/s	v_p	9.11	11.04	9.11	11.04	10.31	14.0	24.74
Braking constant		K	0.84	0.82	0.84	0.82	0.83	0.87	0.82

Table 5-12 Driving cycle parameters for the driving cycles used in the project.

For the local train we use a driving cycle taken from the simulation programme K-tid used to simulate the performance of S-trains operating in Greater Copenhagen [Banestyrelsen 2000]. The driving cycle corresponds to an S-train driving (fast) on line A. The duration of the driving cycle is 2982 s, whereas the scheduled timetable for line A is 3960 s. Assuming that each stop at a station has a duration of 15 s, the scheduled driving time of line A is 3630, i.e. 648 s longer than the driving cycle used in this project. Figure 5-15 shows a plot of the driving cycle named lineA.

Finally, for the light rail vehicles no measured driving cycle could be found, so a driving cycle was constructed having 500 meter between stops, a maximum speed of 50 km/h and a average speed of 30 km/h. The LRV is assumed to accelerate with near maximum power up to the maximum speed, then let the vehicle coast until it is braked with regenerative braking power. The mechanical brakes help with the braking the last meters before a stop, but the maximum deceleration is limited to -1.75 ms^{-2}. The LRV Combino was used in the construction of the driving cycle. The driving cycle is shown in Figure 5-16.

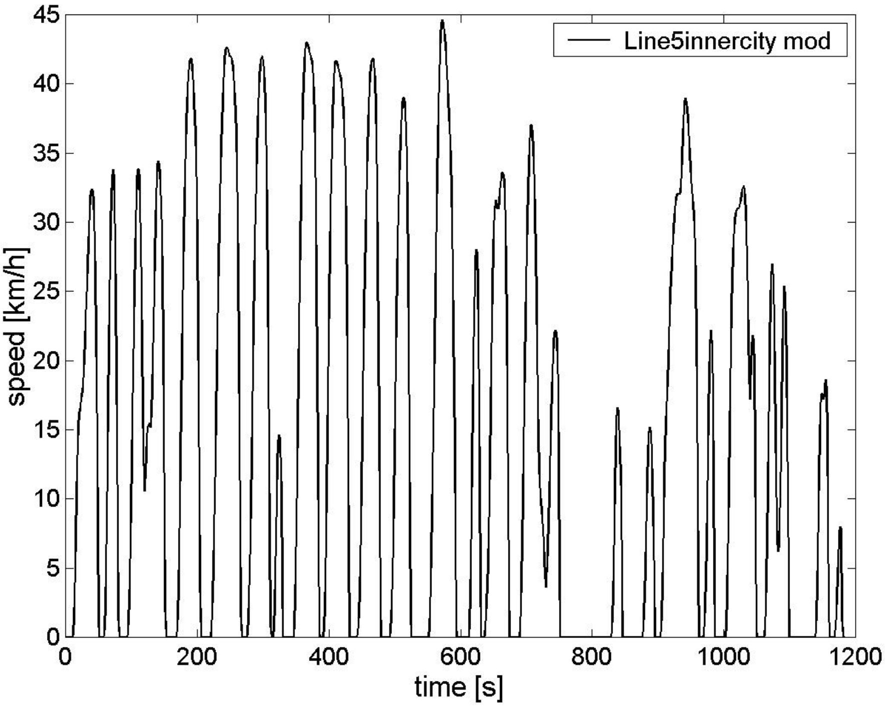

Figure 5-14 Plot of the driving cycle Line5city_mod.

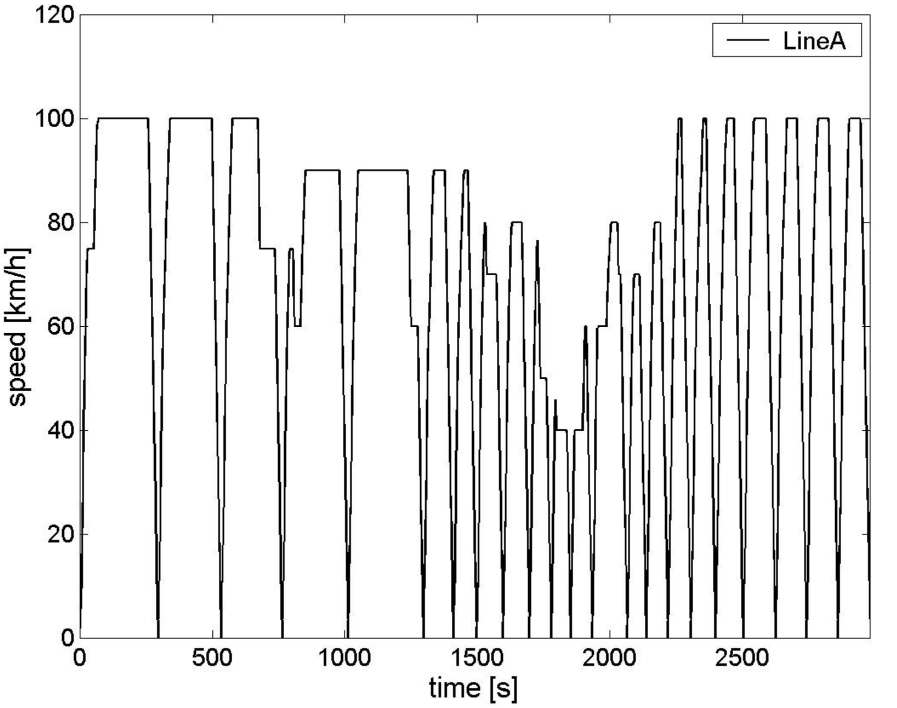

Figure 5-15 Plot of the driving cycle used for local trains LineA.

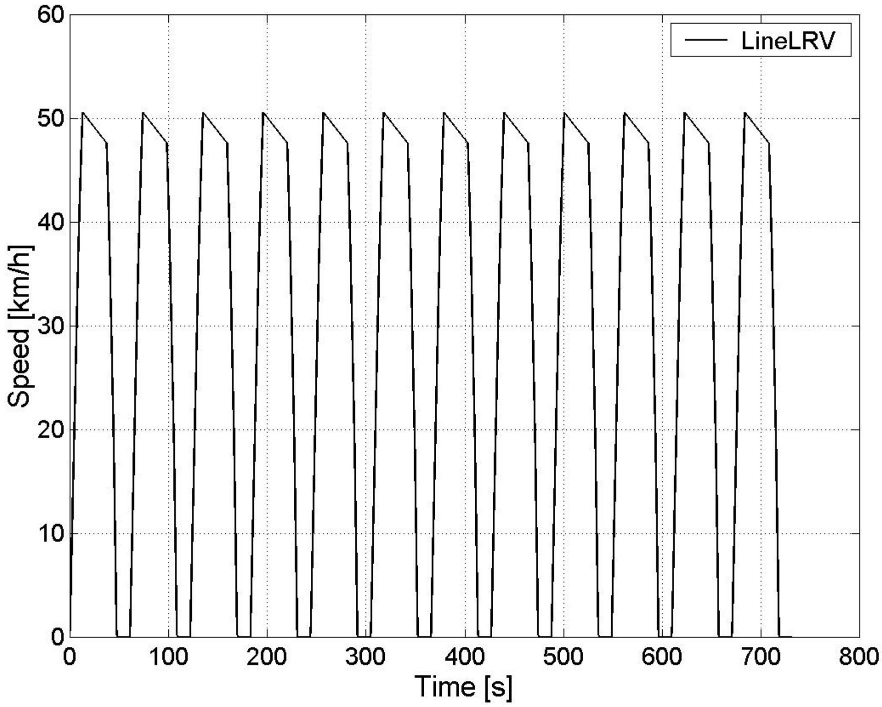

Figure 5-16 Driving cycle for a light rail vehicle, lineLRV.

6. Technology analysis method

This chapter presents the technology analysis method used in this study. It begins with an overview of the theories and methods potentially involved in technology analysis. Next the approach used in this study is presented.

6.1 Overview of theories and methods

Analysing the future development and impact of a technology or a group of technologies is a multidisciplinary research area that potentially involves methods and theories belonging to the fields of sociology, economics, decision theory, engineering and planning. The theoretical and conceptual framework covers four research areas:

1. **Innovation studies:** This area is concerned with the basic understanding of technology, technological innovations and industrial dynamics. Questions like "what is technology", "how does technological innovation take place" are studied.
2. **Technology assessment studies** analyse the impacts on society that the deployment of a technology will have. A wide range of impacts can be considered, e.g. environmental, safety and societal consequences. The basic research question is "what impacts do the large-scale introduction of this/these technologies have on society". There is no established theoretical framework in this research area, but different methods are used like modelling studies and expert surveys [Davison et al. 1997].
3. **Technology foresight studies** are concerned with the development of a technology. The barriers and problems connected with developing the technology into a technological competitive product and obtaining a large share of the market are analysed. Further more possible measures and developments that will favour the deployment of the technology are studied. The two basic research questions are "what barriers and drivers exist for the market success of this/these technologies" and "what policy options exist for helping this/these technologies get into the market". Common approaches in this area are Delphi studies[50], scenario building[51] and trend analyses[52].
4. **Technology comparison and choice studies** are as the name indicates concerned with the comparisons between alternatives (technologies, desired developments, etc.). The comparisons build on the impact assessments and the technology foresigths and are based on a set of values and objectives. Theories from decision theory

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[50] A Delphi studie is based on questionaires sent to a selected panel of experts. By answering the questionaires the experts express their opinion on the future development and potential of a number of technologies. Both the time frame and the technologies included can vary considerable. The Delphi process consists of several rounds of dialogue, where the results from the questionaries in each round are communicated to the participants in order to achieve consensus after the final round. Delphi studies have been carried out in Japan since the 1970´s and in a number of European countries in the 1990's, e.g. France, Germany, UK.

[51] Technology scenarios can be defined as stories describing different but equally plausible futures. They are developed using techniques that systematise the perceptions of alternative futures.

[52] A trend analyse is a forecasting method based on analysing historical trends in the topic under consideration. Projecting the historical trends into the future makes a forecast. This often results in so called business as usual scenarios.

are used. In recent years a number of multi-criteria analysis methods have been developed and applied for policy purposes in different contexts.

In practice many studies of the impact of future technologies (including this study) involve elements from technology assessment, foresight and comparison studies.
As discussed in section 4.1.2 there is a close relationship between the future performance of a technology, i.e. the impacts of the technology, and the market success of the technology, therefore the technology assessment study and the technology foresight study are closely linked. The relationship is such that you can not make a technology foresight study without also making a technology assessment study[53], but you can make a technology assessment study without making a technology foresight study. The latter can be done by just assuming that the technology has obtained a certain technological maturity level corresponding to a given interval on the learning curve, and corresponding to a certain production level and market share. This approach is used in this study.

6.2 Framework for the technology assessment

The main focus of this study is a technology assessment of the characteristics of hardware technologies of importance for the energy consumption and GHG emissions of public transport modes. Other characteristics of importance for the performance and market success of the technologies are also taken into account.

6.2.1 Characteristics of technologies

The following characteristics of a given technology is included in the technology assessment:

- Cost or price characteristics (investment and fuel costs), where as the maintenance costs are left out of the technology assessment, except for the battery replacement costs that are included in the assessment.
- Durability and lifetime characteristics, i.e. the resistance against misuse and the lifetime measured in years and in the number of working cycles or working hours. These parameters do have a significant influence on the overall costs of using a technology.
- Energy consumption.
- Environmental characteristics:
  - Emissions of the GHG: CO_2, CH_4 and N_2O.
  - Emissions of the following regulated air pollutants: particles, NO_X, CO, NMHC.
  - Land use of renewable energy sources.

With regard to the costs of a technology, it should be noted when quoting figures that there is a difference between the manufacturing costs of a technology, the costs paid by the vehicle producer buying the technology from a supplier or producing the technology

[53] This is because the analysis of the barriers and drivers for the market introduction of the technology needs an at least qualitative picture of the performance of the technology, i.e. what the impacts of the technology are.

in house, and the costs paid by the vehicle buyer. The manufacturing costs include the cost of the elements of the technology plus the costs for assembly and testing of the technology. The price paid by the vehicle producer often called the original equipment manufacturer (OEM) is the manufacturing cost plus a overhead taking into account the profit of the supplier and the costs the supplier has to research and development, administration, insurance, sales and marketing of his business. This overhead can be calculated as a certain fraction of the manufacturing costs, e.g. in [Cuenca et al. 1999] 25% of the manufacturing costs is added to the manufacturing costs to get to the final OEM price.

The same goes for the price difference between the price for the OEM and the retail price for the vehicle buyer. The vehicle buyer only sees a total price for the vehicle, but this price can be seen as a sum of the OEM costs of the components constituting the vehicle plus an overhead covering sales and marketing, administration, depreciation, research and development and a profit.

In this project we use the price paid by the OEM when evaluating specific technologies, and then add a certain overhead to get to the total vehicle price when evaluating on the vehicle level.

All costs and prices are expressed in 1999 $US. Published costs expressed in dollars of other years (up to year 2000) were adjusted to 1999 dollars using the US Consumer price index. Exchange rates of 1 $US = 7.0 DKK, 1 $US = 8.0 SEK was used. The prices are exclusive of taxes.

6.2.2 Technological maturity levels

It is important when comparing technologies and estimating the future performance of a technology to known the present technological maturity of the technology. It can give erroneous results to compare the performance of a vehicle incorporating advanced, not yet market ready technologies with the performance of a vehicle using standard technologies on the market, especially when comparing different vehicle concepts.

Inspired by [Jørgensen 1997] the technological maturity of a technology is estimated by assigning a technology level to the technology. Five technology levels are defined, two for technologies already on the market, and three for technologies still in the prototype/laboratory stage:

1. **Small scale production (SS):** represents technologies that are on the market but in small numbers such that the cost benefits of mass production can not be reaped, i.e. they are still on the upper-left half of the learning curve (see section 4.1.2).
2. **Large scale production (LS):** represents technologies on the market in large numbers and produced with industrial mass production techniques, i.e. they have entered down of the learning curve, and is situated in the middle or right part of the learning curve (see section 4.1.2).
3. **Short term/Prototype (S):** represents technologies that are close to commercialisation and do not face engineering constraints. There are certain uncertainties linked to them due to limited experiences with large-scale production (manufacturing risks)

and commercial risks (0-5 years). They have not started the technological learning process yet.

4. **Medium term (M):** represents technologies in advanced stages of development, but needing a certain technical development before being available for production, typically realistic within about 5-15 years. They have not started the technological learning process yet.
5. **Long term (L):** Breakthrough technologies that are still in the laboratory (> 15 years). They have not started the technological learning process yet.

6.2.3 Time frame

The technology assessment analyses the present status of the technology, i.e. the values of different parameters of the technology today, and the improvement potentials of the technology in the future. The time frame for the assessment is 20 years i.e. includes technologies that have a chance for being on the market at the latest in 2020.

To evaluate the improvement potentials of a technology, the performance of the technology today (1999), in the short term (2005), and in the long term (2020) is estimated. For technologies belonging to one of the four technology levels: small scale, short term, medium term and long term, the future performance is estimated under the assumption that the technologies will gain a share of the market and achieve sufficient high production volumes to be able to "go down the learning curve".

6.2.4 Bundling and selection of technologies

In section 3.3 the hardware technologies of importance for the energy consumption and GHG emissions were divided into three classes:

- Fuel cycles
- Propulsion systems
- Vehicle concepts (i.e. vehicle loads and seat configurations)

The technologies included in the class of fuel cycles are analysed in a more aggregated manner than the technologies included in the propulsion system. Because each fuel cycle consists of many technologies, it is chosen to look at the resulting performance of the whole fuel cycle without giving data about the individual technologies. The same goes for the vehicle load reduction technologies, where the possible reduction in vehicle load parameters is analysed without going into details about individual technologies. In contrast to this the technologies included in the propulsion systems are treated individually, and the resulting performance of a propulsion system emerges by combining a given selection of sub technologies.

A large number of technologies have a potential for improving the propulsion system efficiency and reducing the vehicle loads. Therefore it is necessary to bundle the technologies together into appropriate technology bundles[54]. This is done according to the

[54] The term bundling is adopted from the FANTASIE project [Davison et al. 1997].

model of the energy consumption in a vehicle presented in chapter 5, such that each sub-system in the propulsion system and each vehicle load parameter constitute a technology bundle:

Propulsion system:
- Electricity storage systems.
- Fuel converters: internal combustion engines, fuel cell + reformer.
- Fuel storage.
- Electric motor/generator.
- Power electronics.
- Transmission system.

Vehicle loads:
- Weight savings.
- Rolling resistance.
- Air drag.
- Auxiliary loads.

To keep the technology analysis as small and manageable as possible the technologies included in each bundle need to be selected carefully to keep the number of technologies as low as possible. This means that the selection of technologies are not done with the aim of being complete, i.e. include all technologies existing in a given bundle, but more with the aim of illustrating the improvement potentials in a given bundle by selecting the most promising technologies.

6.2.5 Analysis of integrated technology packages at the vehicle level

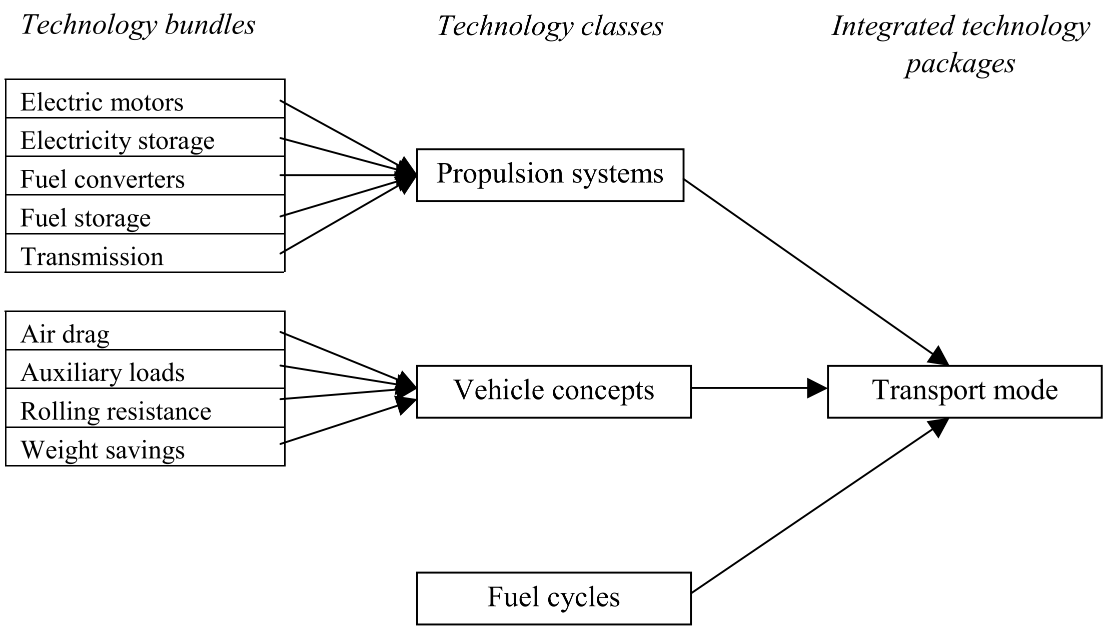

Figure 6-1 Construction of transport modes by combining the results of the analyses of fuel cycles, propulsion systems and vehicle concepts.

The results from the technology analysis of propulsion sub systems and vehicle loads are used to the construction of integrated technology packages at the vehicle level, i.e. a light weight, series hybrid bus.

The integrated technology packages are constructed by combining the results obtained from the analysis of fuel cycles, propulsion sub systems and vehicle loads. For each technology group the most promising short term, and long term technologies are selected, and these technologies are used to put together short term and long term versions of a transit bus, LRV and a local train. For each time frame vehicles with different passenger capacity is constructed. The approach has been illustrated in Figure 6-1.

6.2.6 Analysis framework

The same framework is used for all technology bundles to analyse the technological performance, the maturity and the improvement potentials of the technologies in a given technology bundle.

The framework is given by the following list of questions:

Description of the technology bundle:

- What parameters are important when evaluating the technology bundle? Why are they important (environment, convenience, cost, security, vehicle/propulsion system design)?
- How is the interaction between the propulsion system/operating strategy and the performance required of the technology?
- How does the development of the technology bundle influence the development of propulsion systems and vehicle types?
- How is the further subdivision of the technology bundle?

Description of the technologies:

- What is the design and working principle of the technologies? What are the design trade-offs between parameters? Important things to take into account when comparing and stating values?
- What is the technological maturity of the technology?
- What is the development potential of the technology? What are the possibilities for improvement (performance, price/performance)?
- Evaluation of the technology: what is the value of parameters today and in the future, what are the advantages and the disadvantages of the technology?

6.3 Treatment of uncertainty

The parameter values chosen to represent a given propulsion system technology, fuel cycle or vehicle load can only be determined with uncertainty. The reasons for the uncertainty are twofold. Firstly each technology exists in a lot of different designs and sizes with each design and size having a unique set of parameter values. The many individual designs of a given technology therefore give rise to dispersion in the values of technology parameters. This is even worse in the case of the parameters describing fuel cycles, where the values of the parameters arise as a result of the interaction of many different technologies. Secondly evaluating the performance of technologies in the future introduces uncertainty, because the future development of a technology can only be determined using educated guesses.

The uncertainty connected to each parameter value is also uncertain meaning that the size of the uncertainty can not be determined empirically like it is possible in measurements of physical phenomena.

Sometimes estimates of the dispersion in a parameter value are given in the literature. Another approach giving a rough estimate of the dispersion in the value of a parameter is by looking at the dispersion in the values found in the literature. These two approaches supplemented with estimates based on own calculations have been used to determine the dispersion in the parameter values for the fuel cycles.

For the vehicle load parameters and the many propulsion system parameters it was not possible to estimate the dispersion in the values of all parameters. Therefore for the sake of consistency it was decided not to give an indication of the dispersion in the values of these parameters.

The uncertainty in the values of technology parameters will make the results calculated for the transport modes uncertain. Sensitivity analysis of the results is carried out by varying the values of key parameters.

7. Fuel cycles

A fuel cycle is the path from primary energy to energy delivered to the fuel storage in the vehicle with primary focus on the conversion and distribution processes [Weiss et al. 2000]. In this section the processes involved in converting the primary energy into a fuel and providing the fuel in the fuel dispenser at the demanded pressure and temperature levels are analysed with emphasis on the energy consumption involved. The processes involved in the fuel cycle are:

- Primary energy (i.e. energy feedstock) extraction/production, transportation and storage.
- Fuel production (i.e. conversion of the feedstock), transportation, storage and distribution of the fuel.

Analysing the fuel cycle efficiency can be seen as a partial life cycle analysis of the energy consumption and CO_2 emission connected with the consumption of the fuels. The LCA is limited because the energy consumption and CO_2 emission involved in the construction of the equipment used to extract, convert and distribute the fuels are excluded from the analysis.

The energy losses associated with the production and distribution of fuels to the vehicles are:

- Losses connected with the conversion steps involved in the fuel cycle, where one energy carrier is converted into another. For diesel these losses are refinery losses when crude oil is refined into diesel. For the fuel cycle "natural gas to liquid hydrogen" the conversion steps are steam reforming of natural gas to gaseous hydrogen, and liquidation of gaseous hydrogen into liquid hydrogen. According to the laws of thermodynamics, there are always losses connected with converting energy[55] under practical conditions, but the sizes of the losses differ a lot between different conversion steps.
- Losses connected with the energy consumption of the accessories needed for extraction, conversion and distribution of the fuels. One example is the energy consumption of the oilrig that extracts the crude oil from the underground. Another example is the energy consumption of the machines involved in planting, harvesting and distributing the biomass from an energy forest.
- Losses where the energy is not utilised, e.g. boil off losses connected with liquid hydrogen storage, flaring of natural gas in connection with natural gas and crude oil extraction, methane emissions in connection with the extraction of coal.

7.1 Modelling fuel cycle processes

A number of studies analyse the energy efficiencies of fuel cycle processes [see Wang 1999 for a review]. This short introduction to the methods used when analysing fuel cy-

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[55] If ideal thermodynamic conditions are assumed some conversion steps can be done without losses, e.g. the conversion between electricity and mechanical energy. In practice the conversion has to proceed with reasonably speed giving a certain minimum power output, meaning that the processes evolves under far from ideal thermodynamic conditions.

cles are based on two large studies of fuel cycles, namely the pioneering fuel-cycle study by Mark A. Delucchi developed in the period 1991-1993 and revised in 1997 [Delucchi 1997], and the **G**reenhouse gases, **R**egulated **E**missions and **E**nergy use in **T**ransportation (GREET) fuel-cycle model under ongoing development at Argonne National Laboratory since 1996 [Wang 1999].

As a fuel cycle involves a lot of technologies, it is not feasible to threat each technology separately. Instead the fuel cycle is separated into a number of stages and the energy efficiency of each stage is estimated. In GREET four stages are used:

1. Production/Extraction of the energy feedstock.
2. Transportation and storage of the energy feedstock.
3. Fuel production.
4. Transportation, storage and distribution of the fuel.

[Delucchi 1997] uses the same division into stages, except that stage four is divided into two stages:

4. Transportation, storage and distribution of the fuel.
5. Fuel dispensing (including pumping energy for liquid fuels, and energy used to compress or liquefy natural gas and hydrogen).

In each stage the amount of process energy used to deliver one unit of fuel at the next stage is calculated. Furthermore to calculate the emissions the total amount of process energy is divided into different process fuels like electricity, gasoline, diesel, natural gas, and the process fuels are attributed to different combustion technologies.

Some fuel production processes produce different co-products that must be ascribed an energy value. Examples are production of surplus steam from the production of hydrogen from natural gas that can be used by nearby plants or buildings, surplus production of electricity from ethanol plants using wood, and the production of different kinds of animal feeds from ethanol plants using corn. The attribution of the energy values to the co-products can be done by different methods[56] giving different results [Wang 1999].

The energy efficiency of each stage is estimated on the basis of historical data for the stage, e.g. historical data for the energy consumption of a oil rig, or on the basic of models of the physical processes taking place in the stage. Often a number of different technologies doing the same thing exist and the technology mix used in the stage needs to be decided, e.g. a number of different oil extraction technologies exist (conventional extraction methods, artificial lift methods, enhanced oil recovery methods) with different energy consumption [Wang 1999]. With regard to electricity production the choice of power generation technologies producing the electricity can have significant influence on the total energy efficiency of fuel cycles having electricity as an important process fuel, like production of compressed hydrogen gas from water via electrolysis. In the stages involving transportation, storage and distribution of feedstocks or fuels assumptions have to be made about the transportation distances and storage times involved. The choice between using marginal or average values for a fuel stage (see appendix B for a discussion of the marginal versus average approach) can also have significant impact on the results achieved. For example using the marginal approach the increased use of elec-

[56] [Wang 1999] mention that most studies have used one of the following five methods: 1) weight-based, 2) energy content, 3) product displacement, 4) market value, or 5) process energy approach.

tric vehicles in the vehicle sector will in some cases necessitates upgrading of the local distribution grid, thereby increasing the costs connected with distribution of electricity considerably compared to a situation without this upgrading [Johansson & Åhman 1999].

In general the energy consumption and emissions associated with the manufacturing of chemicals used in the fuel cycle (e.g. the catalysts used in reforming processes) are not included in the fuel cycle analysis. One exception for this rule is the energy consumption and emissions associated with manufacturing of fertilisers, herbicides and pesticides used when growing biomass.

7.2 Area use of renewable energy sources

For fuels extracted from renewable energy sources the area use connected with producing one MJ of a specific fuel can be calculated. The area use in square meters is used as a measure of the efficiency of the renewable fuels cycle. For solar cells and biomass the area use per MJ produced indicate, how effective the energy in the sun falling on that area is utilised. Such a clear interpretation can not be done in the case of wind and hydropower. However the area use is an important indicator on the impact that the production of the renewable fuels has on the surroundings.

The area use of renewable energy sources are expressed as the energy content in the fuel produced on one square meter in one year, or MJ fuel/m^2/year, minus the energy inputs to the production process. We have chosen to include the energy used to the production of the extraction and accessory equipment, as it is significantly higher for solar cells than for wind turbines and farming machinery. As the energy content in the solar radiation, the average wind speeds and the conditions for growth varies considerably from place to place, the results are very site dependent, and figures are given for Danish site conditions. This puts solar power in a relatively worse position compared with biomass and wind power[57].

The area use of wind turbines can be defined in different ways. The wind turbine foundations and access roads typically occupy less than one percent of the total area of a wind park [Danish Wind Turbine Manufacturers Association 2001]. The rest of the area can be used for farming and grazing. Even less area is used in the case of offshore wind parks. On the other side the possible uses of the area have been restricted as a consequence of the wind park, e.g. no tall objects can be placed on the area without lowering the energy production from the wind park and there will be noise from the wind turbines. Therefore we have chosen to calculate the area use of a wind park as the area of a square with side lengths of five times the rotor diameter, in that a typically spacing between wind turbines in a wind park is five rotor diameters apart.

[57] The yearly solar radiation in the southwest of the United States is approximately twice as big as in Denmark [RREDC 2001]

Technology	Site conditions	Energy inputs [% of yearly production]	Net energy production [MJ/m2/year]	Source
Wind park, 600 kW, rotor diameter 44 m	Roughness class 1 ⇒ 2322 full load hours per year, average spacing 5 rotor diameters	3.2	100	[Krohn 1997]
Wind park, 1.5 MW, rotor diameter 64 m	Roughness class 0 ⇒ 3350 full load hours per year, average spacing 5 rotor diameters	3.0	171	[Krohn 1997]
Solar cell farms, efficiency 10%, 75% of area used for solar cells, 25% used for access roads and space between modules	Danish site, inclination of 45 degrees measured relative to the horizontal plane oriented towards south, incident solar radiation 1200 kWh/year	25	324	[Energistyrelsen 2000 B]
Wood for methanol, e.g. short rotation poplar	Danish site, yield 10 dry tons/ha/year	10	18	[Hall & Scrase 1998, Steen et. al 1997]

Table 7-1 The area use of different renewable energy technologies. Wind power and solar cells deliver high value energy in the form of electricity, whereas wood is low value energy, because there are relatively large losses connected with converting wood to methanol.

For solar cells in a large farm there must be some spacing between modules to enable service. On the other hand the modules are inclined with respect to the horizontal, therefore taking up less space than the area of the solar cells. It is assumed that for a inclination of 45 degrees these two effects are approximately equal, meaning that 25% of the area is used for service space (cos(45) = 0.76).

The results in Table 7-1 shows that with these assumptions solar cells produce most energy per area, around 2-3 times more than wind power and 18 times more than biomass. Making the efficiency of biomass to liquid fuels even worse is the fact, that there are considerably losses connected with converting biomass into biofuels (40% of the energy content lost or more), whereas the losses connected with using electricity to transportation purposes are much smaller (8% transmission losses plus charging losses). The main point is that the conversion of solar energy in biomass via photosynthesis is quite inefficient, and the production of biofuels therefore requires large areas. Finally it has to be remembered that the main part of the area taken up by on-shore windmills also can be used as grazing areas or for growing crops.

7.3 Characteristics of fuel cycles

The fuel cycles are analysed with regard to the following characteristics:

- Emission of greenhouse gases, i.e. CO_2, CH_4 and N_2O.
- Energy consumption of the fuel cycles.
- Costs of producing and distributing the fuels.

Apart form these characteristics the technical problems and market uncertainty connected to the use of the fuels is evaluated.

The emission of GHG are summarised in a single number by calculating the CO_2 equivalents of CH_4 and N_2O using values of 1 g N_20 = 310 g CO_2 eqv. and 1 g CH_4 = 21 g CO_2 eqv. [Wang 2000].

The emissions of regional and local air polluting compounds like SO_2, NO_x, CO, VOC and particles in connection with the production and distribution of fuels are not included in the analysis of fuel cycles. This is because most of the emissions to the air take place outside cities, and therefore are not as important for the urban air quality as the vehicle emissions. Another reason is that the emissions typically come from point sources like refineries and power plants, where emission reduction treatment can be applied to a reasonable cost, as it is done in the Danish power sector with reduction of SO_2 and NO_X.

The analysis is based on a literature review with the GREET model as the main source [Wang 1999].

7.4 Choice of fuel cycles

The following fuel cycles are analysed:

Time frame	Propulsion system
Short term (2005)	Rape methyl ester (RME) produced from rape. Compressed natural gas (CNG) produced from natural gas.
Both short and long term	Electricity (EL) produced from wind power. Electricity produced from natural gas. Diesel produced from petroleum.
Long term (2020)	Compressed hydrogen (CH_2) produced at refueling stations via electrolysis from electricity produced from wind power. Compressed hydrogen produced at refueling stations from natural gas. Methanol (MeOH) produced from wood or grass. Methanol produced from natural gas extracted at remote places. Gasoline produced from petroleum.

Table 7-2 The fuel cycles included in this study.

Table 7-2 specifies the fuel cycles included in this study. Diesel is included because it will be the benchmark fuel for buses in the short to long term (2005-2020). The diesel quality is assumed to be with a very low sulphur content (so-called reformulated diesel) in that both United States[58] and the European Union[59] are putting forward progressively tighter fuel quality standards. The diesel quality in Denmark already has a sulphur content of 50 ppm. The move towards diesel with lower sulphur content is caused by the connection between sulphur and the formation of particulates that are considered a serious air pollutant. Furthermore is sulphur a problem for the operation of exhaust gas cleaning technologies such as NO_X storage catalysts and particulate or filters [European Environmental Bureau 2000].

Compressed natural gas (CNG) is included as an example of other fossil fuels than diesel and gasoline. Gasoline (reformulated), methanol and compressed gaseous hydrogen (CH_2) are included because they are among the fuel candidates for fuel cell vehicles. Both methanol and CH_2 can be produced either from fossil feedstocks or from renewable energy. Natural gas is chosen as an example of a fossil feedstock, and CH_2 production via electrolysis using wind power electricity and methanol production based on biomass are chosen as examples of renewable energy fuel cycles.

Apart from the choice of feedstock used to produce CH_2, the fuel infrastructure is also of importance when analysing the production of hydrogen. In the case of hydrogen production from natural gas, the hydrogen can either be produced at large reforming plants and then distributed to the refueling sites via pipelines, a so-called central hydrogen production, or alternatively the natural gas can be delivered to the refueling sites via pipelines, where the hydrogen is produced using small-scale reformers (so-called onsite reforming). In [Ogden et al. 1999] different fuel infrastructures are analysed and compared over a range of refueling station sizes, i.e. over a range of demand cases. At every scale of production the onsite production of hydrogen is the lowest cost option assuming that advanced reformer technology is used [Ogden et al. 1999]. We have therefore chosen only to include the onsite production of hydrogen at the refueling sites in the analysis.

Methanol is furthermore included together with methyl ester produced from rape oil (RME) as examples of biofuels, i.e. fuels produced from biomass. Electricity (EL) is included because of the existence of EVs. As the greenhouse emissions are very dependent on the feedstock used to produce electricity, we have included natural gas and wind power as examples of a fossil and a renewable source of electricity.

Liquid hydrogen is also a candidate for fuel cell vehicles. The advantage of liquid hydrogen compared to compressed hydrogen is that the storage of liquid hydrogen takes up less volume than the onboard storage of compressed hydrogen. The disadvantage is that the liquidation of hydrogen uses a lot of energy (around 30-40% of the energy content of the produced liquid hydrogen), giving an energy efficiency of liquid hydrogen storage of around 60% compared with an energy efficiency of compressed hydrogen of around 90%. The prototypes of fuel cell buses have used on-board storage of compressed hydrogen in tanks placed on the roof of the buses. We have chosen to leave out liquid hy-

[58] The US Environmental Protection Agency has announced actions that will reduce the sulphur content of highway diesel to 15 ppm in 2006 [EPA 2000].

[59] The Auto-Oil 1 legislation (98/70/EC) requires EU-wide availability of gasoline and diesel with a sulphur content of 50 ppm in 2005 [European Environmental Bureau 2000].

drogen, because the volume issue is not considered as critical for the large vehicles used in the public transport modes as it is for cars.

Properties of the fuels assessed are shown in Table 7-3 and Table 7-4 and are used throughout this report.

Fuel/Raw material	Density	Lower heating value		Carbon content		Sulphur content
	kg/l	GJ/ton	GJ/m^3	wt%	$kgCO_2/GJ$[60]	wt ppm
Diesel	0.856	41.7	35.7	87.0	76.5	15-50
Gasoline	0.738	42.7	31.5	83.5	71.7	30
LPG	0.528	44.3	23.4	82	67.8	0
MeOH	0.792	20.1	15.9	37.5	68.5	0
RME	0.884	36.9	32.7	78	77.4	0
NG		45.3		74	60.0	7
H_2[61]		120		0	0	0

Table 7-3 Fuel properties taken from [Wang 2000] except the values for hydrogen taken from [Jørgensen & Schleisner 2001]. Values for gasoline is set to the values for CARFG2 in [Wang 2000], and values for diesel is set to the values for reformulated diesel in [Wang 2000].

Fuel	20 MPa	25 MPa	34.4 MPa	50 MPa
NG	197	223		
H_2	14.5	18.0	23.1	32.2

Table 7-4 Density in kg/m^3 of natural gas (methane) and hydrogen at different pressures. Values for hydrogen at 25°C taken from [Niehues & Edwards 2000]. Values for methane at 21°C derived from [Dynetek 2001].

7.5 Description of the fuel cycles

These descriptions are mainly derived from [Wang 1999]. The description is divided into two. A description of the feedstock stages of the three feedstocks: crude oil, natural gas and biomass, and a description of the fuel stages of the fuels.

7.5.1 Extraction, transport and storage of crude oil

The crude recovery stage of the petroleum fuel cycle includes well drilling, oil extraction, oil gathering through gathering pipes, crude treatment in production fields, and crude storage in production fields. Different oil extraction techniques exist with different energy consumption required for oil recovery. Crude oil is brought to the surface with a

[60] Assuming that all carbon in the fuel is combusted to CO_2.

[61] Values for hydrogen at a pressure of 1 atm and a temperature of 20 °C.

mixture of oil, water and gas, which must be separated from the crude in on-site treatment facilities before the crude can be put through pipelines. In connection with oil and gas production NG is vented and flared.

The crude transportation and storage stage includes transportation of crude from oil fields to central storage terminals, storage at the terminals, transportation from the terminals to petroleum refineries, and storage at refineries. The transportation from the oil fields to the central storage terminals take place with small-size pipelines and tank trucks, and the bulk transportation of crude to petroleum refineries take place with ocean tankers (for inter-continent transportation) and/or pipelines (for intra-continent transportation).

7.5.2 Extraction, transport and storage of natural gas

In the extraction stage NG is recovered and collected from NG and oil fields. Collected NG is then delivered through pipelines to NG processing plants, where high-value liquids (e.g. natural gasoline, propane, butane) are separated from NG, and impurities (e.g. sulfur compounds and CO_2) are stripped from NG to produce pipeline quality NG. During the transport and storage stage the NG is compressed to a pressure of 50-80 bar and transported from the processing plants to local distribution companies via pipelines. Storage facilities are necessary for the NG industry during off-peak demands periods. Gas is stored in underground facilities such as salt caverns or at aboveground liquid NG facilities.

7.5.3 Production, transport and storage of biomass

Biomass used to production of biofuels can be classified in different groups:

- **Residues:** can be forest residues from the logging of roundwood[62], or agricultural residues that is left over from the production of food crops, either left on the field (e.g. straw) or generated in the different processing steps the food crops undertake (e.g. bagasse from the production of sugar from sugar cane). The forest residues are both smaller branches and trees unsuitable for roundwood production left on the logging site, but also sawdust and other residues generated at mills and manufacturing facilities where the wood is converted into consumer products.
- **Energy crops:** are plants that are grown specifically to be used as a energy source. These crops can be divided into two groups:
    - Traditional agricultural crops like corn, sugar cane and rape that are used to produce liquid biofuels like ethanol and rape methyl ester. This is annual crops where the plant constituents used to produce biofuels are oil (rape), sugar (sugar cane and sugar beet) and starch (corn). The experience with large scale farming of these crops is huge.
    - Dedicated energy crops are plants that are especially good as energy crops, but usually can not be used to other purposes like the agricultural crops. The dedicated energy crops consist mostly of perennial woody plants (trees) and perennial

[62] Roundwood is the trunks and large branches of the harvested trees.

herbaceous plants (grasses). The main constituent in the plants suitable for biofuel production (e.g. ethanol and methanol) is cellulose. The trees are typically grown in so-called short-rotation intensive-culture (SRIC) plantations, where the trees are harvested every 3-8 years, with replanting every 15 to 30 years [Hall et al. 1993]. There are typically three cuts for each planting, one from a planted rotation and two from coppice rotations, with regrowth from the stump after the first two cuts. Often used species are Eucalyptus and different types of Willow. The herbaceous plants (e.g. switchgrass) are harvested every six to 12 months but replanted less often - perhaps only once a decade. The experiences with the large scale farming of dedicated energy crops are still rather small [Hall et al. 1993]. Field-trials and other work is going on in many countries with the aim of finding the species most suited as energy crops, and finding the most economically and environmentally friendly way of farming them.

The production stage of the biomass feedstock consists in planting, managing and harvesting the biomass. The managing involves controlling weeds, pests and diseases by mechanical and chemical means, securing a good nutrients balance in the soil by adding fertilisers and by other means[63], and securing adequate water supply.

When the biomass is harvested it is usually stored for some time to reduce the moisture content of the biomass. It can be stored at the harvest site (in some cases just by leaving the biomass on the ground for some time) or collected together and stored a more central place. From the storage the biomass is transported by trucks and ships to the fuel production plants.

The energy consumption and emissions associated with manufacturing and transport of fertilisers and pesticides are included in the calculations of the energy consumption and emissions of the biomass fuel cycles [Wang 1999; Delucchi 1997].

7.5.4 Production, transport, storage and distribution of diesel and gasoline

The fuel production stage consists of refining of the petroleum at refineries to diesel and gasoline.

The transport, storage and distribution stages of diesel and gasoline include transportation to bulk terminals (primarily via pipelines), storage at the terminals, and distribution to refueling stations (primarily via tank trucks).

The fuel dispensing stage includes the electricity consumption of fuel pumps.

7.5.5 Production, transport, storage and distribution of CNG, MeOH, CH_2, EL

NG to CNG

[63] E.g. intercropping the primary crop with nitrogen-fixing species can make a plantation self-sufficient in Nitrogen [Hall et al. 1993].

NG is distributed to the CNG refueling stations in pipelines. CNG is stored onboard the vehicles at a pressure of about 200 bar. To achieve this requires a pressure in the storage tanks at the CNG refueling station of about 250 bar, which requires a initial compression to about 270 bar [Wang & Huang 1999].

NG to MeOH
Methanol is produced at methanol plants usually by steam methane reforming (SMR). First SMR is used to produce a gaseous mixture of H_2, CO, H_2O and CO_2 (called syngas) from NG. The syngas is then synthesised into methanol. Methanol plants are generally able to generate some excess amount of steam that can be exported to nearby plants. Other reforming techniques exist, e.g. partial oxidation reforming (POX) [Wang 1999].

The produced methanol is transported via pipelines to bulk terminals for storage and distribution, and then transported to refueling stations via trucks. Imported methanol is transported via ocean tankers to major ports and then transported to inland bulk terminals via pipelines or tank trucks.

NG to CH_2
H_2 is produced from NG by different reforming techniques, i.e. SMR, POX, autothermal reforming and plasma reforming. The majority of large-scale H_2 plants still employ SMR. H_2 plants can generate surplus amounts of steam that can be exported if suitable purchasers exist nearby (e.g. nearby chemical plants).

H_2 can either be produced in large-scale plants located near NG fields or large NG storages, or produced locally at the H_2 refueling stations. In the first case the produced H_2 is compressed and transported through pipelines to refueling stations, where it is further compressed to 300-500 bar.

In the second case NG is distributed to the H_2 refueling stations in pipelines, where it is reformed into H_2 in small-scale SMR units. The H_2 produced in this way is then compressed and stored as CH_2.

NG to EL
NG is distributed to power plants via pipelines, where EL is produced in NG fired gas motors, gas turbines, combined-cycle turbines[64] or fuel cells. The power plants can either produce EL and heat to a district heating system, so-called combined power and heat plants, or only produce EL. The produced electricity is distributed in the power grid. The transmission and distribution costs are estimated to 0.02 $/kWh [EIA 2001; Dansk Energi 2001]. Finally the electricity is delivered to the EVs by the use of a battery (electricity storage) charger.

7.5.6 Production, transport, storage and distribution of RME and methanol

Rape seed to methyl ester

[64] The combined cycle power plant combine a gasturbine with a steam turbine to enhance the efficiency of the power production.

Rape seed is harvested and transported to RME production plants in trucks. At the production plants the seeds are crushed and the rape oil is extracted from the crushed seeds. The left overs from the crushing process can be sold as a high value animal feed product. Next the rape oil is converted to methyl ester in a so-called transesterification process, where constituents in the rape oil react with methanol in the presence of a catalyst. Finally the RME is transported to the refueling stations in trucks.

Wood/Grass to methanol
The biomass feedstock is transported to the methanol production plants by truck or boat, where it is converted into methanol by gasification to synthesis gas and methanol synthesis [Ecotraffic 1992]. The produced methanol is stored in terminals and distributed to the refueling stations using coastal shipping, barges, pipeline and/or road tankers.

7.5.7 Production and distribution of EL from windpower

EL is produced by the wind turbines, distributed via the power grid, and delivered to the EVs by a battery (electricity storage) charger.

7.6 Results

The results of the analysis of the fuel cycles are presented in a number of data sheets, one for each fuel cycle. The parameters presented in a data sheet are:

- The energy efficiency of the fuel cycle defined as the ratio between the energy content in one unit of fuel and the total primary energy input connected with producing one unit of fuel (including the energy content in the fuel). Both energy input from fossil fuels and energy input from renewable energy sources are included in the calculation of the energy efficiency.
- The process energy used to produce one GJ of fuel, i.e. the energy lost during the different fuel stages. Again both process energy coming from fossil fuels and process energy coming from renewable energy sources are included. The connection between the process energy and the energy efficiency is given by:
  Energy efficiency=Energy content in fuel/(Energy content in fuel + Process energy)
- The emissions of the GHG CO_2, CH_4 and N_2O during the different fuel stages. Only the emissions from the use of fossil fuels are included, i.e. the emission of CO_2 from the use of straw in the production of RME is not included.
- The cost of one GJ of fuel delivered to the vehicle exclusive of taxes.
- A rough estimation of the present barriers existing for widespread use of the fuel. The barriers are divided into technical problems, which must be solved before the fuel can be competitive, and the uncertainty connected to the development of a market for the fuel.

The values of the parameters are estimated in the status year 1999, short term (2005) and long term (2020).

	Units	1999	2005	2020
Fuel cycle ID		RME_1999	RME_2005	
Technology level		Large scale		
Energy consumption[65]				
Energy efficiency	%	63 ± 5	63 ± 5	
Total process energy	GJ/GJ fuel	0.6 ± 0.1	0.6 ± 0.1	
Emissions[65]				
CO_2 emissions[66]	kg/GJ fuel	32 ± 10	32 ± 10	
CH_4 emissions	g/GJ fuel	<<1	<<1	
N_2O emissions	g/GJ fuel	3	<1	
GHG	kg/GJ fuel	33 ± 10	32 ± 10	
Area use	m^2/GJ fuel	280 ± 40[67]	280 ± 40	
Costs	$/GJ fuel	10.4 ± 2.2[68]	10.4 ± 2.2	
Future development				
Technical problems		None		
Market uncertainty		High[69]		
Time to market	Years	0		

Table 7-5 Rapeseed oil to methyl ester (RME).

[65] [Lewis 1997; Ecotraffic 1992].

[66] The value for the CO_2 emissions depends among other things on the assumption done about the kind of process energy used in the esterification process. In the lower values for the CO_2 emissions rape straw or other biomass is used for process energy, whereas in the higher values natural gas is used as process energy.

[67] The production of RME is 1100 ± 150 l/ha [Lewis 1997; Bugge 2000]. Apart from RME there will be produced approximately 1700 kg/ha cattle cake plus 120 kg/ha pure glycerine [Lewis 1997].

[68] The costs of distributing RME from the production plant to refueling sites are assumed the same as the distribution costs of diesel 1.22 $/GJ [Weiss et al. 2000]. The production price is set to 2.1 ± 0.5 DKK/l RME [Bugge 2000; Energistyrelsen 1997].

[69] RME is not competitive with diesel with regard to price. The size of the market therefore depends on the subsidies given to RME from government and the evolution in the price of diesel.

	Units	Status	2005	2020
Fuel cycle ID				MeOH_Wood_2020
Technology level		Short term		
Energy consumption[70]				
Energy efficiency[71]	%			0.50 ± 0.05
Total process energy	GJ/GJ fuel			1.0 ± 0.2
Emissions[72]				
CO_2 emissions	kg/GJ fuel			15.4 ± 7
CH_4 emissions	g/GJ fuel			25 ± 25
N_2O emissions	g/GJ fuel			3.5 ± 3
GHG	kg/GJ fuel			17.0 ± 8
Area use[73]	m^2/GJ fuel			110
Costs[74]	$/GJ fuel			19 ± 6
Future development				
Technical problems		Small		
Market uncertainty		High[75]		
Time to market	Years			

Table 7-6 Wood/Grass to methanol.

[70] [Steen et al. 1997; Delucchi 1997; Jørgensen & Schleisner 2001].

[71] Defined as the energy content in the produced methanol relative to the total energy input.

[72] [Ecotraffic 1992; Delucchi 1997; Johansson & Åhman 1999].

[73] Assuming a yield of 10 Dry tons/ha for a energy forest with a energy input of 10% to cultivate, harvest, store and transport the crop, and a energy content of 20 GJ/dry tons of wood.

[74] Using a cost of 550 SEK/MWh fuel for the production and distribution of methanol from biomass [Johansson & Åhman 1999] and assuming an exchange rate of 1 US$ = 8 SEK. An uncertainty in the cost of methanol of ± 30% is assumed.

[75] The market for refueling stations selling methanol depends both on the market success of fuel cell vehicles and on the choice of fuel to the fuel cell vehicles.

	Units	1999	2005	2020
Fuel cycle ID		Diesel_1999	Diesel_2005	Diesel_2020
Technology level		Large scale		
Energy consumption[76]				
Energy efficiency	%	87 ± 5	87 ± 5	87 ± 5
Total process energy	GJ/GJ fuel	0.15 ± 0.06	0.15 ± 0.06	0.15 ± 0.06
Emissions[77]				
CO_2 emissions	kg/GJ fuel	11 ± 4	11 ± 4	11 ± 4
CH_4 emissions	g/GJ fuel	85 ± 25[78]	85 ± 25	85 ± 25
N_2O emissions	g/GJ fuel	0.2	0.2	0.2
GHG	kg/GJ fuel	13 ± 5	13 ± 5	13 ± 5
Costs[79]	$/GJ fuel	6.7 ± 2.2	6.7 ± 2.2	6.7 ± 2.2
Future development				
Technical problems		None		
Market uncertainty		Very low		
Time to market	Years	Already on the market		

Table 7-7 Petroleum to reformulated diesel (RFD).

[76] [Wang 2000; Weiss et al. 2000; Delucchi 1997]. The potentials for improving the energy efficiency are considered small, because the fuel cycle consists of mature technologies, and the existing and future demands to the fuel quality will increase the energy consumption of the refining off setting improvements in the energy efficiency.

[77] [Wang 2000; Weiss et al. 2000; Delucchi 1997; Lewis 1997].

[78] [Lewis 1997] estimates a value of 16 g/GJ, and Wang 2000 calculates a value of 101 g/GJ.

[79] The estimate of the cost is based on a crude oil price of 22 $/barrel with a possible variation of ± 10 $/barrel [Weiss et al. 2000].

	Units	1999	2005	2020
Fuel cycle ID		Gasoline_1999	Gasoline_2005	Gasoline_2020
Technology level		Large scale		
Energy consumption[80]				
Energy efficiency	%	81 ± 2	81 ± 2	81 ± 2
Total process energy	GJ/GJ fuel	0.23 ± 0.04	0.23 ± 0.04	0.23 ± 0.04
Emissions[81]				
CO_2 emissions	kg/GJ fuel	18 ± 2	18 ± 2	18 ± 2
CH_4 emissions	g/GJ fuel	118 ± 10	118 ± 10	118 ± 10
N_2O emissions	g/GJ fuel	0.3	0.3	0.3
GHG	kg/GJ fuel	21 ± 2	21 ± 2	21 ± 2
Costs[82]	$/GJ fuel	8.3 ± 2.7	8.3 ± 2.7	8.3 ± 2.7
Future development				
Technical problems		None		
Market uncertainty		Very low		
Time to market	Years	Already on the market		

Table 7-8 Petroleum to reformulated gasoline (RFG).

[80] [Wang 2000; Weiss et al. 2000; Delucchi 1997]. The potentials for improving the energy efficiency are considered small, because the fuel cycle consists of mature technologies, and the existing and future demands to the fuel quality will increase the energy consumption of the refining off setting improvements in the energy efficiency.

[81] [Wang 2000; Weiss et al. 2000; Delucchi 1997; Lewis 1997].

[82] The estimate of the cost is based on a crude oil price of 22 $/barrel with a possible variation of ± 10 $/barrel [Weiss et al. 2000].

	Units	1999	2005	2020
Fuel cycle ID		CNG_1999	CNG_2005	
Technology level		Small scale[83]		
Energy consumption[84]				
Energy efficiency	%	87 ± 0.04	87 ± 0.04	
Total process energy	GJ/GJ fuel	0.15 ± 0.05	0.15 ± 0.05	
Emissions[85]				
CO_2 emissions	kg/GJ fuel	12 ± 2	12 ± 2	
CH_4 emissions	g/GJ fuel	250 ± 50	250 ± 50	
N_2O emissions	g/GJ fuel	0.3 ± 0.2	0.3 ± 0.2	
GHG	kg/GJ fuel	17 ± 3	17 ± 3	
Costs[86]	$/GJ fuel	8.2 ± 1	8.2 ± 1	
Future development				
Technical problems		None		
Market uncertainty		Medium		
Time to market	Years	Already on the market		

Table 7-9 Natural gas to CNG.

[83] Around 1226 CNG refueling stations in USA [NAVC 2000 B].
[84] [Ecotraffic 1992; Delucchi 1997; Wang 2000].
[85] [Wang 2000; Ecotraffic 1992; Delucchi 1997].
[86] Costs of piped natural gas in 2005 4.2 $/GJ [Energistyrelsen 2001], CNG service station costs 4.0 $/GJ [Weiss et al. 2000].

	Units	1999	2005	2020
Fuel cycle ID		EL_Wind_1999	EL_Wind_2020	EL_Wind_2020
Technology level		Large scale		
Energy consumption				
Energy efficiency[87]	%	87 ± 2	87 ± 2	87 ± 2
Total process energy	GJ/GJ fuel	0.14 ± 0.02	0.14 ± 0.02	0.14 ± 0.02
Emissions				
CO_2 emissions	kg/GJ fuel	0	0	0
CH_4 emissions	g/GJ fuel	0	0	0
N_2O emissions	g/GJ fuel	0	0	0
GHG	kg/GJ fuel	0	0	0
Area use	m^2/GJ fuel	10[88]	8[89]	6[90]
Costs[91]	$/GJ fuel	20.7 ± 1.7	20.1 ± 1.7	17.4 ± 1.3
Future development				
Technical problems		None		
Market uncertainty		Low[92]		
Time to market	Years	Already on the market		

Table 7-10 Electricity produced from wind power to electricity at the 0.4 kV level.

[87] The transmission and distribution losses are set to 8% [Wang 2000]. The conversion of AC power from the power grid to DC power feed to the electricity storage is assumed to be done with 95% efficiency. When the power is used by vehicles getting electricity from a contact line the distribution losses in the contact line is assumed to be 5%.

[88] Assumptions: Wind park consisting of 600 kW wind turbines with a rotor diameter of 44 m and with a average spacing of 5 rotor diameters. Roughness class 1 giving 2322 full load hours a year [Krohn 1997].

[89] Assumptions: Wind park consisting of 1500 kW wind turbines with a rotor diameter of 64 m and with a average spacing of 5 rotor diameters. Roughness class 1 giving 2322 full load hours a year [Krohn 1997].

[90] Assumptions: Off shore wind park consisting of 2500 kW wind turbines with a rotor diameter of 89 m and with an average spacing of 5 rotor diameters. Roughness class 0 giving 3839 full load hours a year [Andersen & Fuglsang 1996].

[91] Production price [Andersen & Fuglsang 1996]: 0.05 ± 0.006 $/kWh in 1999, 0.047 ± 0.006 $/kWh in 2005, 0.038 ± 0.004 $/kWh in 2020, transmission and distribution costs estimated to 0.02 $/kWh. Cost of recharge station to a fleet of buses 0.005 $/kWh [Johansson & Åhman 1999]. As wind power constitutes a fluctuating and only partly predictable power production technology, there will be additional costs associated with back-up power plants and electric storage technologies, in areas where wind power constitutes a large share of the electricity production. These costs are not included in the above values.

[92] The concern over the greenhouse effect combined with wind turbines being the cheapest of the electricity producing renewable technologies (except hydro power) mean that the market projections of wind power are very positive.

	Units	1999	2005	2020
Fuel cycle ID		EL_NG_1999	EL_NG_2020	EL_NG_2020
Technology level		Large scale		
Energy consumption				
Energy efficiency[93]	%	44 ± 2	46 ± 2	48 ± 2
Total process energy	GJ/GJ fuel	1.3 ± 0.1	1.2 ± 0.1	1.1 ± 0.1
Emissions[94]				
CO_2 emissions	kg/GJ fuel	124.8	120.4	114.3
CH_4 emissions	g/GJ fuel	374	361	343
N_2O emissions	g/GJ fuel	2.4	2.2	2.1
GHG	kg/GJ fuel	133 ± 7	129 ± 7	122 ± 7
Costs[95]	$/GJ fuel	19.4 ± 2.8	18.4 ± 2.8	17.4 ± 2.8
Future development				
Technical problems		None		
Market uncertainty		Low		
Time to market	Years	Already on the market		

Table 7-11 Natural gas to electricity at 0.4 kV level, combined cycle plants with no district heat production.

93 Energy efficiency of the extraction, storage and distribution of natural gas 0.92 [Wang 1999]. Energy efficiency of the distribution of power 0.92. Efficiency of electricity generation in combined cycle plants: 1999: 0.55; 2005 0.57: 2020 0.60 [Weiss et al. 2000; Energistyrelsen 1995]. Efficiency of conversion of AC power from the power grid to DC power feed to the electricity storage 0.95. When the power is used by vehicles getting electricity from a contact line the distribution losses in the contact line is assumed to be 5%.

94 [Wang 2000].

95 Transmission and distribution costs 0.02 $/kWh. Production costs of combined cycle, natural gas plant: 1999: 0.044 $/kWh; 2005 0.042 $/kWh [EIA 2001]; 2020 0.038 $/kWh [EIA 2001]. A variation of the natural gas price of ± 1.4 $/GJ gives a variation in the production price of ± 0.01 $/kWh [own calculations]. Cost of recharge station to a fleet of buses 0.005 $/kWh [Johansson & Åhman 1999].

	Units	Status	2005	2020
Fuel cycle ID				CH2_NG_2020
Technology level		Medium term		
Energy consumption				
Energy efficiency	%			54 ± 3
Total process energy	GJ/GJ fuel			0.85 ± 0.10
Emissions[96]				
CO_2 emissions	kg/GJ fuel			118 ± 7
CH_4 emissions	g/GJ fuel			190 ± 60
N_2O emissions	g/GJ fuel			0.8
GHG	kg/GJ fuel			125 ± 7
Costs[97]	$/GJ fuel			16± 6
Future development				
Technical problems		Medium		
Market uncertainty		High[98]		
Time to market[99]	Years	Prototypes in 2005. Niche market deployment in 2010		

Table 7-12 Natural gas to compressed hydrogen (350 bar) produced at refueling stations.

[96] [Weiss et al. 2000; Wang 2000].

[97] [Weiss et al. 2000] estimate a cost of 19 $/GJ. [Ogden et al. 1999] estimate a price between 12-20 $/GJ for hydrogen stations with a capacity between 10000-57000 m^3 H2/day.

[98] The market for refueling stations producing hydrogen depends both on the market success of fuel cell vehicles and on the choice of fuel to the fuel cell vehicles.

[99] In 2010 there could be fleets of fuel cell buses with onboard storage of compressed hydrogen.

	Units	Status	2005	2020
Fuel cycle ID				CH2_Wind_2020
Technology level		Medium term		
Energy consumption				
Energy efficiency[100]	%			70 ± 5
Total process energy	GJ/GJ fuel			0.43 ± 0.10
Emissions				
CO_2 emissions	kg/GJ fuel			0
CH_4 emissions	g/GJ fuel			0
N_2O emissions	g/GJ fuel			0
GHG	kg/GJ fuel			0
Costs[101]	$/GJ fuel			36 ± 10
Future development				
Technical problems		Medium		
Market uncertainty		High[102]		
Time to market[103]	Years			

Table 7-13 Compressed hydrogen produced from electricity produced from wind power at refueling stations.

[100] The distribution of electricity to the electrolysis plant is done with a efficiency of 0.92. The compression of hydrogen with electric compressors has a efficiency of 0.90 [Wang 2000]. The efficiency of the electrolysis plant is 0.78 for alcaic electrolysis [Jørgensen & Schleisner 2001] and 0.92 for solid polymer electrolysis [Jørgensen & Schleisner 2001]. We assume a mix of these technologies and use an electrolysis plant efficiency of 0.85.

[101] [Ogden et al. 1999] estimate a price between 24-27 $/GJ compressed hydrogen for hydrogen stations with onsite electrolysis assuming a electricity price of 0.03 $/kWh. Using an electricity price of wind power of 0.05 $/kWh including transmission and distribution gives a price of 36 $/GJ.

[102] The market for refueling stations producing hydrogen depends both on the market success of fuel cell vehicles and on the choice of fuel to the fuel cell vehicles.

[103] In 2010 there could be fleets of fuel cell buses with onboard storage of compressed hydrogen.

	Units	Status	2005	2020
Fuel cycle ID				MeOH_NG_2020
Technology level		Short term		
Energy consumption[104]				
Energy efficiency	%			64 ± 2
Total process energy	GJ/GJ fuel			0.56 ± 0.06
Emissions[105]				
CO_2 emissions	kg/GJ fuel			21.5 ± 2
CH_4 emissions	g/GJ fuel			135 ± 5
N_2O emissions	g/GJ fuel			0.3
GHG	kg/GJ fuel			24 ± 2
Costs[106]	$/GJ fuel			7.3 ± 2.3
Future development				
Technical problems		Small		
Market uncertainty		High[107]		
Time to market	Years			

Table 7-14 Remote natural gas to methanol[108].

[104] [Weiss et al. 2000; Wang 2000].

[105] [Weiss et al. 2000; Wang 2000].

[106] [Weiss et al. 2000; Ogden et al. 1999].

[107] The market for refueling stations selling methanol depends both on the market success of fuel cell vehicles and on the choice of fuel to the fuel cell vehicles.

[108] It is assumed that the methanol is produced in new large plants located where large quantities of low-price gas are available. A gas price of 0.50 $/GJ ± 0.50 $/GJ is assumed [Weiss et al. 2000].

8. Propulsion systems

In this chapter the sub systems of importance for the energy efficiency of the propulsion system are analysed. The sub systems are divided into the following technology bundles:

- Electric motor/generator
- Electricity storage
- Fuel converters, where fuel cells and internal combustion engines are analysed in separately sections.
- Fuel storage.
- Power electronics i.e. the inverter controller.
- Transmission systems.

The subsystems are analysed with a focus on the parameters needed to estimate the mass and price of the subsystems and the energy efficiency of the subsystems according to the model presented in chapter 5, i.e. with a focus on the specific power or specific energy, the specific price and the average energy efficiency of the subsystems.

Most of the technology assessments of propulsion systems found in the literature are concerned with propulsion system technologies to cars. The findings in these studies with regard to the specific power and specific price of different subsystems can only with caution be used for public transport modes. The reason is twofold.

Firstly the driving cycles and lifetime number of operating hours are much more demanding for urban public transport modes than for cars. The lifetime number of operating hours for a transit bus is around 50000-65000 hours[109] whereas the lifetime number of operating hours for a car is 4000-6000 hours[110]. The lifetime number of operating hours for a LRV and a local train is even higher than for the bus, because the lifetime of these vehicles is higher (around 30 years). The driving cycles of public transport modes have more accelerations from standstill per distance compared to the driving cycles for cars, which do not stop frequently to pick up passengers. These two factors together results in a much higher durability required of the technologies used in public transport compared to the durability of the technologies used in cars. The high durability required will add extra weight and/or cost to the technologies relative to the same technologies used in cars.

Secondly compared with cars the production volumes involved when manufacturing buses, LRVs and local trains are much smaller, which will increase the price of the propulsion system technologies relative to the price for the same type of technologies used in cars [An et al. 2000].

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[109] 14-16 hours a day, 300-340 days a year, 12 years lifetime.

[110] Lifetime driving distance 200000-300000 km with average speed of 50 km/h.

8.1 Electric motor/generator

The electric motor can operate in two modes: a motoring mode where the motor uses electricity and produces mechanical energy, and a regenerative or generator mode where the motor uses mechanical energy and produces electricity. The output torque and speed of the motor in motoring mode are regulated by varying the voltage and/or frequency of the electrical power input to the motor, which is done by the inverter.

The most important evaluation parameters are the weight, the average energy efficiency, the price, and the lifetime/reliability. Other parameters that must be taken into account when evaluating the electrical motors are the volume, maximum torque of the motor (start-up torque) and the maintenance requirements.

The specific power of the motor in motoring mode is the ratio between the maximum power output of the motor and the total weight of the motor. The maximum power that can be delivered or regenerated in short time spans is considerably larger (around 30-70 % [UQM 2001, Cuenca et al. 1999]) than the maximum power that can be delivered or regenerated continuously[111]. Electric motors in vehicles are only required to deliver large amounts of power in short time spans such as acceleration from stand still to a certain speed. Therefore it is logical to use the intermittent or peak maximum power output when evaluating the specific power. The peak power output can be different in the generator operation mode than in the motoring mode [Bavard & Gayed 2000].

The larger the maximum torque required of a motor the larger the size and weight, because the maximum torque determines the stresses and forces the motor must be able to withstand. As it is the maximum torque at the wheels of the vehicle that are of interest, the maximum motor torque requirement can be lowered by choosing a large transmission ratio between the motor and the wheels. The higher the transmission ratio of the transmission the more expensive and larger the transmission, so there is a trade-off to be done when designing the motor and transmission. For a one-speed transmission the connection between the maximum vehicle speed and the maximum motor speed is given by:

$$v_{M,MAX} = \frac{N_T v_{W,MAX}}{2\pi R} \qquad (8\text{-}1)$$

$v_{M,MAX}$: the maximum speed of the motor [rps].
N_T: the transmission ration of the transmission.
$v_{W,MAX}$: the maximum speed of the vehicle [ms^{-1}].
R: the radius of the driving wheels [m].

Therefore for a given required maximum speed of the vehicle increasing the transmission ratio means increasing the required maximum speed of the motor.

[111] This is because the constraint on the continuous operation is to avoid that the motor overheats due to the generated heat in the motor, but as the motor has some heat capacity, it can be operated above the continuous operation limit in short time spans.

The power output of a motor in motoring mode is given as the product between the motor speed in rad/s and the motor torque in Nm. From this follows that high speed motors do not require such a large torque output as do low speed motors to achieve a given power output, and high speed motors will therefore have higher specific power and power density than low speed motors[112].

It is important when evaluating the specific power of the motor to include the cooling system. In general liquid cooled motors and inverters have higher specific power than air cooled motors, but are more expensive [Bradley 2000]. Some motor designs do not need a cooling system but are self-ventilating [Blumenthal et al. 2001].

The specific price of the motor is measured in this project as the ratio between the total price of the motor as paid by the vehicle manufacturer (OEM price) and the maximum peak power output of the motor in motoring mode, i.e. in units of $/kW.

The instantaneous energy efficiency of a motor depends on the operation point of the motor and can be expressed as a function of the instantaneous motor speed and torque. The lower the power output the lower the efficiency. The average efficiency of a motor is calculated by averaging the energy efficiency of the motor in each time step over a driving cycle. The average efficiency depends on the driving cycle and the characteristics of the motor. As shown in Table 5.10 the average energy efficiency of the motor is very important for the energy consumption of EVs and HEVs driving in driving cycles with large amounts of braking energy.

About half of a motors full-load losses are I^2R or resistive, and most of the rest are magnetic (or core) losses [E Source 1999]. Therefore increasing the average voltage level used to power the motor means decreasing the losses, in that the current in the motor is reduced.

8.1.1 Description of the motor technologies

Two general motor types are included in this evaluation: 1) the asynchronous induction motor type (IM), 2) the synchronous permanent magnet motor type (PM motor). The motor types are described below.

The three-phased alternating current induction motors are the state-of-the-art for use in trams and trains [Siemens 2000 A]. The working principle is that the alternating current in the stator induces an electromotive force in the rotor. The development in power electronics used to control the induction motor has made this motor type cheaper and more efficient. Induction motors are robust and require little maintenance.

The permanent magnet motor type (PM motor) has entered into the vehicle market in the last five years and is mainly being used in cars. The hybrid cars on the market today like the Toyota Prius and the Honda Insight uses the PM motor. In this motor type the rotor windings are eliminated by using a permanent magnet as the rotor. This motor type

[112]Because as before mentioned the higher the maximum torque requirement of the motor the larger the motor size and weight.

therefore requires high performance magnets, and presently neodymium-iron-boron (Nd-Fe-B) magnets are used [Winter 1998].

The switched reluctance motor (SR motor) is mentioned by some as a future interesting candidate for traction purposes [Moore & Lovins 1995], and could have been included in this assessment. As with the PM motor, the SR motor only has windings on the stator, and the rotor is made exclusively of steel laminates. The rotor moves in a rotating magnetic field created by switching the poles of the stator on and off according to a certain algorithm. [Moore & Lovins 1995] claims that this motor type has the potential to outperform the induction and PM motor, but [Winter 1998] indicate that the energy efficiency and price of the SR motor lies in between the energy efficiency and price of the induction motor and the PM motor. Therefore and because the information in the literature about the use of this motor in vehicle applications is very little, this motor type is omitted from the assessment.

8.1.2 Evaluation and comparison of the motor types

When evaluating the motor types it has to be taken into consideration that the motors will be used in large public transport modes. The majority of sources about motor type performance and costs investigate motors aimed at electric and hybrid cars, i.e. smaller motors with smaller requirements towards durability.

Especially the costs of the larger motors aimed at public transport modes is considerably larger than the costs of electric motors to cars. The present cost paid by a vehicle manufacturer of a electric motor to a car is around 6 $/kW [National research council 2000], whereas the present OEM price of a electric motor to a 12 m bus is estimated to around 25 $/kW [An et al. 2000]. The higher price is due to the low production volumes and high durability required of the electric motors used in transit buses. No information about the price of electric motors used in trams and trains has been found in the literature, so it is assumed that the price is the same as the price for electric motors in buses.

The present performance and development potential of induction and PM motors is estimated in Table 8-1 and Table 8-2. The most important conclusions are:

The differences in the specific power of the different motor types seem to be quite small [Winter 1998; Wang et al.1997; Moore & Lovins 1995] with at least as much variation between specific designs of each type as between types.

The PM motor is more expensive than the induction motor mainly because the permanent magnets are expensive [Cuenca et al. 1999; Winter 1998].

The PM motor is more energy efficient than the induction motor, because there are no windings in the rotor and therefore no ohmic losses in the rotor. The average energy efficiency of the PM motor is around 5% higher than the average energy efficiency of the induction motor depending on the driving cycle used and the specific motor design [Winter 1998].

The energy efficiency of the motor is already very high, so there is not much room for improvement. We have assumed a 2% improvement in the energy efficiency from now to 2020. A shift from induction motors to PM motors will give an efficiency gain of 5%. The largest improvement potentials for this technology lies in a reduction in the OEM price by increased production volumes. The increased production volumes can be achieved if hybrid vehicles get a large share of the transit bus market in the future. The technology bundle will also benefit from a success of hybrid cars in the future market place, which will lead to larger production volumes for electric motors of smaller size. [An et al. 2000] estimate a decrease in the extra costs connected with vehicle hybridisation of around 50-60% from 2005 to 2020. Assuming that this cost reduction applies to all components in the hybrid powertrain the price of the motor can be reduced with around 50%.

	Units	Status	2005	2020
Motor ID		IM_1999_train /IM_1999	IM_2005	IM_2020
Technology level		Small scale[113]		
Weight				
- specific power	(kW peak)/kg[114]	0.227[115]/0.5	0.6	1.0
Energy efficiency[116]				
- peak efficiency	out/in	0.94	0.94	0.96
- avg. eff in line5city_mod	out/in	0.88[117]	0.88	0.90
- avg. eff in line5suburbs_mod	out/in	0.89[117]	0.89	0.91
- avg. eff in lineA	out/in	0.90[118]	0.90	0.92
Durability				
- number of operating hours[119]	h	65000	65000	65000
Economy				
- specific OEM price[120]	$/kW peak	30	25	12.5[121]
Future development				
- Technical problems		None		
- Market uncertainty		Very low		
- Time to market	Years	Already on the market		

Table 8-1 Induction motor used in public transport modes.

113 The number of LRVs and local trains produced each year is rather small.

114 The specific power of the motor in motoring mode is in this project measured as the ratio between the intermittent peak power output of the motor and the total weight of the motor.

115 The weight of one of the 180 kW continuously (227 kW peak) induction electric motor including transmission in a S-train is 1225 kg [Pedersen 2001], i.e. a specific power of 0.227 kW/kg if we assume that the electric motor weighs 1000 kg, and the transmission the rest (225 kg).

116 As the induction motor is a mature technology and the energy efficiency already is high, the potentials for improvement of the energy efficiency from now to the year 2020 are considered small. An improvement of 2% in the energy efficiency is assumed.

117 Value found in a ADVISOR simulation of a SHEV bus using the motor data of a 75 kW induction motor and assuming a constant efficiency of the inverter controller of 0.95 (not included in the value for the motor).

118 [DSB 2001 A].

119 The AC induction motors and power electronics used in the new generation of S-trains in Greater Copenhagen will last around 2,5 Mkm, which assuming an average speed of 40 km/h gives 62500 operating hours [DSB 2001 A].

120 [Bradley 2000] estimates that the present retail price is 100$/(kW peak) for a total drive motor package to heavy-duty vehicles consisting of motor, inverter and gear reduction, and says that large production volumes should lead to substantial reduction in parts costs. [An et al. 2000] gives separate prices for motor, inverter and gear reduction, but the sum of their prices adds up to 80-90 $/kW peak at the retail level in reasonable agreement with [Bradley 2000]. The OEM price of 25 $/kW given by [An et al. 2000] is used for the year 2005.

121 Assuming a 50% reduction compared with year 2005 due to larger production volumes in 2020, because the hybrid buses have gained a significant share of the transit bus market.

	Units	Status	2005	2020
Motor ID		PM_1999	PM_2005	PM_2020
Technology level		Small scale[122]		
Weight				
- specific power	(kW peak)/kg	0.8[123]	0.9	1.1
Energy efficiency[124]				
- peak efficiency	out/in	0.96[125]	0.96	0.98
- avg. eff in line5innercity		0.93[126]	0.93	0.94
- avg. eff in line5suburbs		0.94[126]	0.94	0.95
- avg. eff in lineA		0.94	0.94	0.95
Durability				
- number of operating hours	h	65000	65000	65000
Economy				
- specific OEM price[127]	$/kW peak	35	30	15[128]
Future development				
- Technical problems		Small		
- Market uncertainty		Low[129]		
- Time to market	Years	Already on the market		

Table 8-2 Permanent magnet motor used in public transport modes.

[122] LRVs and local trains presently use induction motors. PM motors are used in hybrid cars like the Toyota Prius and the Honda Insight.

[123] [UQM 2001] gives a value of 1.16 kW/kg for their 100 kW PM motor designed for large EV/HEV applications.

[124] The possibilities for improving the energy efficiency from now to the year 2020 are considered small, because the PM motor already has a very high efficiency. An improvement in the energy efficiency of 1% is used.

[125] [UQM 2001] gives a peak efficiency of their 100 kW PM motor plus inverter/controller of 0.94 at a voltage level of 300 V. Assuming a peak efficiency of the inverter/controller of 0.98 gives a peak efficiency of the motor of 0.96.

[126] Value found in a ADVISOR simulation of a SHEV bus using the motor data of a 100 kW PM motor from [UQM 2001] and assuming a constant efficiency of the inverter controller of 0.95 (not included in the value for the motor).

[127][Winter 1998] estimate the price of a PM motor with inverter to be 20% larger than a induction motor. [Cuenca et al. 1999] estimate the price difference to be 46%. Both sources are investigating electric motors used in cars. We assume a price difference of 20% and use the value of 25 $/kW in 2005 for a induction motor to find the price of the PM motor.

[128] Assuming a 50% reduction compared with year 2005 due to larger production volumes in 2020, because the hybrid buses have gained a significant share of the transit bus market.

[129] With the strong competition from the induction motor, it is uncertain if the PM motor will be used in heavy-duty vehicles.

8.2 Power electronics

The power electronics technology bundle consists of the inverter controller or in short the inverter, which is an assembly of different power electronics components. These components regulate and modify the power exchanged between the electric subsystems in the propulsion system[130]. Apart from this the inverter also supplies power to the accessories, which involves the conversion of DC power at high voltage to DC or AC power at low voltage levels.

The important evaluation parameters for the inverter are the specific power, energy efficiency, specific price and durability. The specific price of the inverter is the ratio between the OEM price of the inverter and the maximum power output of the inverter. Inverters can be liquid or air cooled with the highest specific power achieved for the liquid cooled.

The instantaneous energy efficiency of the inverter depends on the power output of the inverter. It is in general high and the average energy efficiency of the inverter during a driving cycle is around 0.95 [Weiss et al. 2000; NREL 2001].

8.2.1 Improvement potentials of the power electronics

The power electronics bundle is evaluated in Table 8-3. It can be seen that the energy efficiency is already very high so only a modest improvement can be expected, and a 1% improvement is assumed. The specific power can probably be increased substantially due to integrated designs and the use of new materials with improved thermal properties [National Research Council 2000; Chalk 2000], but estimates of the improvement potential for this parameter have been difficult to find in the literature. As with the electric motors the specific price can be decreased with larger production volumes, and a reduction of 50% between the year 2005 and 2020 is assumed based on the estimates in [An et al. 2000].

[130] The power exchanged between the contact line and the motor in EVs with contact line, the power exchanged between the electricity storage system and the motor in EVs with electricity storage, and the power exchanged between the generator, motor and electricity storage system in SHEVs.

	Units	Status	2005	2020
Power bus ID		PB_1999_train/ PB_1999_LRV/ PB_1999	PB_2005	PB_2020
Technology level		Small/large scale[131]		
Weight				
- specific power	kW/kg	0.32/0.75/1[132]	1.5	3[133]
Energy efficiency				
- peak efficiency	out/in	0.98[134]	0.98	0.98
- avg. eff	out/in	0.95	0.95	0.96[135]
Durability				
- number of operating hours	h	65000	65000	65000
Economy				
- specific OEM price[136]	$/kW peak	40	37	19[137]
Future development				
- Technical problems		Small		
- Market uncertainty		Low		
- Time to market	Years	Already on the market		

Table 8-3 Power electronics.

[131] The number of LRVs and local trains produced each year is relatively low, which makes the production volumes for the specific power electronic packages used in heavy-duty vehicles small. On the other hand many of the individual power components are already in high-volume production today due to their use in other areas [Cuenca et al. 1999].

[132] [National Research Council 2000] gives a value of 4 kW/kg for cars. [UQM 2001] gives a value of 15.9 kg for the inverter controller used with the 100 kW PM motor exclusive the cooling system. Assuming that the cooling system weighs 10 kg gives a specific power of 4 kW/kg. The traction and auxiliary inverters in a LRV have a specific power of 0.75 kW/kg [Niehues & Edwards 2000], and the traction and auxiliary inverters in a S-train including the braking resistance have a specific power of 0.32 kW/kg [Pedersen 2001].

[133] A inverter with a specific power of 11 kW/kg has been developed by Oak Ridge National Laboratories [USCAR 2001].

[134] [Blückert et al. 2000].

[135] The possibilities for improving the energy efficiency from now to the year 2020 are considered small, because the power electronics already has a very high efficiency. An improvement in the energy efficiency of 1% is used.

[136][An et al. 2000] gives a value for the inverter in 2005.

[137] Assuming a 50% reduction compared with year 2005 due to larger production volumes in 2020, because hybrid cars and hybrid buses have gained significant shares of their markets.

8.3 Electricity storage

8.3.1 Description of the electricity storage bundle

A storage system for electricity is today part of most types of propulsion systems in the form of the starter battery for road bound vehicles, or a battery providing backup power in LRVs and local trains. However the propulsion systems found in EVs and HEVs need electricity storages with much larger energy and power capacity than those found in conventional vehicles.

The performance required of the electricity storage depends on the overall design of the propulsion system. In an EV with electricity storage the electricity storage must provide all the energy and power required during operation, which requires a large power and energy capacity of the storage system. Experiences with designing and operating EVs have shown that it is the energy demand that determines the weight of the electricity storage. Therefore in EVs the electricity storage can be named an electric **energy** storage system.

In a HEV with power assist (see section 5.4.1) the average demand for energy is usually delivered from the fuel converter such that the function of the electricity storage is more to provide extra power and to store braking energy. The weight of the electricity storage is therefore determined by the power demands during charge and discharge. In this case the electricity storage can be named an electric **power** storage system.

The duty cycles of the electricity storages also depend on the type and design of the propulsion system. In an EV the electricity storage is discharged to a low state of charge frequently, and charged to 100% SOC at the recharge stations to secure the largest driving range between recharges. The duty cycle of an electricity storage in an EV is therefore characterised by many deep discharge cycles.

In contrast to this the electricity storage in a HEV experiences small state of charge variations around a certain SOC level as the electricity storage undergoes charge/discharge cycles during regenerative braking and accelerations. The charge/discharge cycles are low in energy content, but the power of the charge/discharge pulses is often relatively high. The electricity storage is operated at a SOC level near 0.50, such that the electricity storage neither goes into deep discharge (below ~ 0.20 SOC) or overdischarge (below 0% SOC) nor enter into overcharging (above ~ 0.80 SOC), when delivering the charge/discharge surges required during the driving cycle [Nelson 2000].

Parameter	Dependence on operating conditions	Significant for (technology attributes)	Significant for (vehicle attributes)
Specific energy [Wh/kg]	discharge/charge rates[138]	- weight (energy storage)	- driving range (EV) - weight (EV)
Specific power (both discharge and charge power) [W/kg]	- state of charge (SOC) - temperature[139] - duration of pulse[140]	- weight (power storage)	- acceleration - regeneration of braking energy
Energy density [Wh/litre]	discharge/charge rates	- volume (energy storage)	- passenger and luggage space (EV)
Power density [W/litre]	- state of charge (SOC) - temperature - duration of pulse	- volume (power storage)	- passenger and luggage space (HEV)
In use energy efficiency [output/input]	- discharge/charge rates - SOC		- energy consumption when driving
Self discharge [% loss cap./hour]			- overall energy consumption
Thermal loss [W/kWh]	- working temp. of battery		- overall energy consumption
Cycle life [cycle][141]	- size of cycle - temperature[142]	- overall cost	- overall cost - service demand
Calendar life [year]		- overall cost	- overall cost - service demand
Discharge/charging sensitivity	- overcharging - overdischarging - memory effect[143]	- strictness of operational procedures - service demand	- convenience - service demand
Charging time [hours]			- convenience
Fast charging capability			- daily driving range (EV)
Operating temperature range		- start up time	convenience
Capital cost [$/kWh or $/kW]		- overall cost	- overall cost
Recycling issues		- resource use	

Table 8-4 Evaluation parameters for electricity storages and the influence each parameter has on the attributes of the electricity storages and on the attributes of a vehicle using an electricity storage [Anderman et al. 2000; Åhman 1999; Andersson & Johansson 2000; Nelson 2000].

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[138] The capacity of a battery depends on the discharge/charge rates such that higher discharge/charge rates give a lower capacity [Linden 1995].

[139] For some battery types, e.g. lead-acid batteries, the power capacity decreases strongly when the temperature of the battery is below 0 °C [Anderman et al. 2000].

[140] The power of a discharge or a charge depends on the duration of the discharge/charge pulse, such that the longer the pulse the lower the available power.

[141] The cycle life is measured in the number of charge/discharge cycles of a specified size (measured in Wh) before the performance of the electricity storage is degraded so much that it is discarded. The degradation criteria of United States Advanced Battery Consortium are that the battery is discarded, when the power and energy capacities are degraded to below 80 % of their initial values [Anderman et al. 2000].

[142] For many battery types, e.g. LiIon, NiMH, Lead-acid, the cycle life is reduced when the battery temperature is above 40-50 °C [Anderman et al. 2000].

[143] The memory effect is the degradation in energy and power capacity of a battery, when it is operated without deep discharges to a least 20 % SOC at frequent time intervals. NiMH and Ni/Cd batteries have a memory effect [Linden 1995].

A lot of parameters are involved in the evaluation of the performance and usability of electricity storages and the most important are listed in Table 8-4. With regard to the energy consumption of electricity storages the most important parameter is the average energy efficiency, i.e. the energy efficiency during a driving cycle. It depends strongly on the duty cycle of the electricity storage during the driving cycle, i.e. the variation of the state of charge (SOC) with time during the charge-discharge cycle. Other important parameters is the price and weight of the electricity storage, which is determined by respectively the specific price and the specific power or specific energy. Also the durability/lifetime are very important for the economy of EVs and HEVs, because the cycle life and calendar life determine how often the electricity storages need to be replaced.

Experiences with EVs have shown that the weight and cost of the electricity storage constitute the most important technological problems facing the development of EVs, i.e. the future development of the electricity storage are crucial to the future development of EVs. The electricity storage in a HEV is typically much smaller than in an EV which reduces the weight and cost problems, but the cost of the electricity storage is still one of the main reasons for the added cost of a hybrid propulsion system relative to an conventional propulsion system. Cost reductions of the electricity storage are therefore also important for the development of hybrid propulsion systems [Anderman et al. 2000].

Storage systems for electricity can be bundled into the following technology groups: batteries, fly wheels and ultra capacitors.

8.3.2 Design and working principle of batteries, fly wheels and ultracapacitors

Batteries

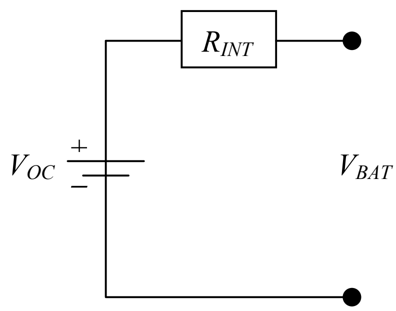

Figure 8-1 The battery model in ADVISOR [NREL 2001]. The open circuit voltage V_{OC} is connected in series with the internal resistance R_{INT}. Both V_{OC} and R_{INT} are functions of the state of charge of the battery. R_{INT} is also dependent on the direction of the current (charging/discharging) and the temperature. V_{BAT} is the voltage across the battery terminals.

A battery stores and delivers electrical energy through near reversible electrochemical reactions. It consists of the following main parts:

1. The anode or negative electrode, which gives up electrons to the external circuit and is oxidised during discharge.

2. The cathode or positive electrode, which accepts electrons from the external circuit and is reduced during discharge.
3. The electrolyte – the ionic conductor – which provides the medium for transfer of ions between the anode and cathode and is an insulator for transfer of electrons. Typically a liquid with dissolved salts, acids or alkalis to impart ionic conductivity.

Batteries are very complex devices, but a simple battery model is given in **Figure 8-1**. The instantaneous efficiency of the battery assuming 100% coulombic efficiency is given by:

$$e_{BAT} = \begin{cases} \dfrac{P_{OUT}}{P_{OUT}+P_{LOSS}} = \dfrac{V_{OC}I - R_{I,D}I^2}{V_{OC}I - R_{I,D}I^2 + R_{I,D}I^2} = 1 - \dfrac{R_{I,D}I}{V_{OC}} & \text{for} \quad I > 0 \\ \dfrac{P_{IN}-P_{LOSS}}{P_{IN}} = \dfrac{-V_{OC}I + R_{I,C}I^2 - R_{I,C}I^2}{-V_{OC}I + R_{I,C}I^2} = \dfrac{V_{OC}}{V_{OC} - R_{I,C}I} & \text{for} \quad I < 0 \end{cases} \qquad (8\text{-}2)$$

e_{BAT}: the instantaneous efficiency of the battery.
P_{OUT}: the discharge power out of the battery [W].
P_{LOSS}: the power loss in the battery due to the internal resistance [W].
P_{IN}: the charge power at the battery terminals [W].
$R_{I,C}$: the internal resistance when the battery is charged [ohms].
$R_{I,D}$: the internal resistance when the battery is discharged [ohms].
I: the current running in the battery [A].
V_{OC}: the open circuit voltage of the battery, i.e. the voltage when there is no currents running in the battery [V].

As can be seen from equation 8-2 the larger the charging or discharging current I, the lower the instantaneous efficiency. The variations of $R_{I,C}$, $R_{I,D}$ and V_{OC} with SOC are characteristics of a battery. In general the internal charge resistance gets relatively higher when the SOC gets high, and the internal discharge resistance gets relatively higher when the SOC gets low [NREL 2001].

The connection between the currents required of the battery and the efficiency of the battery is important to keep in mind, when quoting specific power values for a battery type. Often the specific power of a battery is determined at the so-called matched impedance condition at which $P_{OUT} = P_{LOSS}$, i.e. one-half the energy of the discharge is in the form of electricity and one-half is in heat [Burke 2000]. The maximum discharge power at the matched impedance condition (P_{MI}) is the highest power a battery can deliver, i.e. the specific power found in this operating point is the highest specific power of the battery. The maximum discharge powers at higher efficiencies will be smaller than the maximum discharge power at the matched impedance condition. Using the simple battery model seen in **Figure 8-1**, the connection between the power of the discharge pulse (P_{OUT}), the efficiency of the discharge pulse (e_{BAT}), and P_{MI} is given by [Burke 2000]:

$$P_{OUT} = 4e_{BAT}(1-e_{BAT})P_{MI} \quad \text{where} \quad P_{MI} = \frac{V_{OC}^2 R_{I,D}}{4} \qquad (8\text{-}3)$$

Using equation 8-3, it can be seen that the size of the maximum discharge pulse with 0.90 efficiency is 0.36 times the power pulse measured at the matched impedance condition. A similar relation can be derived for the connection between the charging power at the matched impedance condition, and the efficiency and power of a charging pulse at another operating point. Therefore when determining the size of a battery pack used in a HEV, i.e. a battery pack that must be able to deliver high power levels with high efficiencies, the specific power at the matched impedance condition should not be used, but a significantly smaller specific power.

The approach taken in this project is to use the specific power at the matched impedance condition in the analysis of the battery technologies (i.e. in this section). When sizing the batteries in the vehicle model (see section 5.8), the specific power of the chosen battery type will be scaled according to the energy efficiency assumed for the battery with the use of equation 8-3:

$$M_{BAT} = \frac{P_{BAT,MAX}}{q_{BAT}} = \frac{P_{BAT,MAX}}{4e_{BAT}(1-e_{BAT})q_{MI,BAT}} \qquad \text{(8-4)}$$
$$e_{AVG,BAT} \approx e_{BAT}^2$$

M_{BAT}: the mass of the battery [kg].
$P_{BAT,MAX}$: the peak battery power required [kW].
q_{BAT}: the specific power of the battery at the discharge efficiency e_{BAT} [kW/kg].
$q_{MI,BAT}$: the specific power of the battery at the matched impedance condition [kW/kg].
$e_{AVG,BAT}$: the average efficiency of the battery in the driving cycle.

E.g. if the average efficiency of the battery during a driving cycle is assumed to be 0.80, the efficiency of the maximum discharge pulse must be $\sqrt{0.80} = 0.89$, and the specific power is 0.38 times the specific power at the matched impedance condition.

Equation 8-4 can also be used the other way round, i.e. assuming a certain mass of the battery, and then using 8-4 to determine the efficiency achievable with this battery type.

When designing a battery there is a trade off between achieving high specific energy and high specific power in that high specific power need large electrode surfaces and current collectors, which increase the amount of inactive material in the battery [Linden 1995]. There is also a trade off between high specific energy and high cycle life because thicker electrodes weigh more but enhance the cycle life [Anderman et al. 2000 p. 109]. Often a battery manufacturer produces a given battery type in several designs, one design for EV-applications with high specific energy, and other high power designs for HEV-applications [Anderman et al. 2000]. Therefore when analysing and comparing the performance of different battery types care has to be taken to distinguish between high energy (EV) and high power (HEV) battery designs.

The distinction between batteries used in EVs and batteries used in HEVs is also important, because as before mentioned the duty cycles of the batteries are very different in HEVs than in EVs, which can have a significant influence on the energy efficiency and the durability of the batteries. In HEVs part of the operating strategy is to keep the state of charge of the batteries within limits corresponding to the most energy efficient operating area of the batteries, i.e. within limits where the internal resistance in charging and discharging modes is relatively low. The limits chosen depend on the type of propulsion system and the battery characteristics[144]. In EVs the battery SOC can not be restricted without decreasing the driving range of the EVs.

Another important thing when comparing the performance is to distinguish between the values of the performance parameters for a single battery cell, a module consisting of several cells put together, or a battery pack with associated thermal & electrical control/management systems. In each stage additional weight and volume are added that lowers the specific energy and power, and the energy and power density.

Ultracapacitors

Ultracapacitors stores energy as electrostatic charge in a polarised layer at the interface between an ionically conducting electrolyte and a conducting electrode. Though it is an electrochemical device there are no chemical reactions involved in its energy storage mechanism. This mechanism is highly reversible, giving the ultracapacitor excellent cycle life and high durability also when delivering frequent high power pulses.

Ultracapacitors have very low specific energy and very high specific power and are therefore most suited to electric power storage systems (load-levelling devices) in HEVs either in combination with a battery or alone. If combined with a battery the ultracapacitor can provide the peak power capacity relaxing the power demands on the battery.

The voltage of a ultracapacitor is proportional to the charge stored in the ultracapacitor. This means that the available energy from the ultracapacitor is reduced, e.g. if the minimum controller voltage is 50% of the maximum, then only 75% of the stored energy can be removed before the voltage is halved.

Flywheels

Flywheels store kinetic energy within a rapidly spinning wheel-like rotor or disk. Modern flywheels employ a high-strength composite rotor, which rotates in a vacuum chamber to minimise aerodynamic losses. A motor/generator is mounted on the rotor's shaft both to spin the rotor up to speed (charging) and to convert the rotor's kinetic energy to electrical energy (discharging). A high-strength containment structure houses the rotating elements and magnetic low-energy-loss bearings stabilise the shaft. Interface electronics are needed to convert the alternating current to direct current, condition the power, and monitor and control the flywheel.

Flywheels have many of the same characteristics as ultracapacitors the most important being high specific power and excellent cycle life. The specific energy is low compared to batteries but higher than the specific energy of ultracapacitors. Ultimately, flywheels could store amounts of energy comparable to batteries [Moore & Lovins 1995].

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[144] For example the default SOC range in ADVISOR for the Toyota Prius parallel hybrid is 0.45-0.75 SOC and for a series hybrid is 0.4-0.8 SOC [NREL 2001].

8.3.3 Selection of electric storage technologies for evaluation

Batteries are classified according to the materials used for the anode, cathode and electrolyte. Quite a lot of different battery types have been investigated for use in EVs, but only a few have made it out of the laboratory and into the EVs [Andersson & Johansson 2000].

Based on information in [Anderman et al. 2000; Andersson & Johansson 2000; Jørgensen & Nielsen 1998] the following four battery types have been selected for analysis in this work: lead-acid (PbAcid), nickel-metal hydride (NiMH), lithium-ion (LiIon) and lithium-polymer (LiPo).

PbAcid are the most mature technology that has been used in the first generations of EVs, but lately has been replaced by other battery types because of the low specific energy and low cycle life of the PbAcid batteries. The valve regulated lead acid battery (VRLA) is the most resent innovation in lead-acid battery technology. It is a sealed battery, where the need for periodic water addition is eliminated, and it is an interesting candidate for HEV batteries [Nelson 2000; Anderman et al. 2000; Kalhammer 2000].

NiMH, LiIon and LiPo were chosen in [Anderman et al. 2000] as the most interesting battery types for EVs in the short to medium term and are therefore included in this analysis. They are also the battery types that the United States Advanced Battery Consortium (USABC) is concentrating on. NiMH is the battery of choice in HEVs and to some extent EVs for the time being. LiIon batteries for EVs and HEVs are still in the prototype stage but have high specific energy. LiPo batteries are still in the laboratory stage but because of the used materials and the selected production techniques have a potential for high specific energy and low cost.

Ni/Cd batteries are used in the EVs from Peugeot, Renault and Citroén, but they will probably be replaced with NiMH batteries in the future, because of their relatively low specific energy and the perceived environmental and health risks connected to the use of Cadmium. SAFT the only major manufacturer of Ni/Cd batteries has terminated their development of this battery type. Therefore Ni/Cd is left out of this analysis.

Ultracapacitors and flywheels are included in the analysis, because they offer potentially very high specific power and energy efficiency. At least one manufacturer has started selling ultracapacitors to vehicle manufacturers [PowerCache 2001], so they will probably be introduced in prototype vehicles within the next year. The development of flywheels for use in vehicles still face serious technical difficulties and very few development resources are used in this area [Wahlström 1999].

8.3.4 Evaluation of electricity storage technologies

The electricity storage technologies are evaluated in Table 8-6 to Table 8-11. The duty cycles assumed for EV batteries when quoting energy efficiencies and durability values are deep discharge duty cycles (from 1.0 SOC to ~ 0.2 SOC), where as the duty cycles for HEV batteries are small SOC variations (below ± 0.25 SOC) around a certain SOC level (~ 0.50 SOC). The specific power of a battery is measured at the matched impedance condition, where as the specific power of the ultracapacitor is measured at a 0.95 discharge efficiency.

Technology	Advantages	Disadvantages
Pb/Acid	- relatively low capital cost. - high specific power. - possibility for fast partial recharging. - well-established collection and recycling systems.	- low specific energy. - low calendar and cycle life. - loss of power capacity at low temperatures. - sensitive to mishandling. - no major improvement in specific energy can be expected.
Ni/MH	- excellent cycle life. - medium specific energy. - good performance at low temperatures. - good resistance against misuse. - possibility for fast recharging. - many manufacturers.	- high initial cost. - no potential for achieving USABCs[145] target costs due to the costs of the materials. - major increases in specific energy are unlikely.
Li/Ion	- high specific energy. - high power. - high energy efficiency. - low self-discharge. - potential for good cycle life.	-difficult to achieve high calendar life (typically only 2-3 years at present). - do not pass all abuse tests at present. - high cost. - high charging/discharging sensitivity.
Li/Polymer	- high specific energy. - no material constraints. - low service demand. - potentially low cost.	- still in the experimental stage. - cycle life needs to be improved.
Ultracapacitors	- very high specific power. - fast charge and discharge capabilities. - very high energy efficiency. - excellent temperature performance. - excellent cycle life. - easy determination of SOC.	- very low specific energy.
Flywheels	- very high specific power. - fast charge and discharge capabilities. - very high energy efficiency. - excellent temperature performance. - excellent cycle life. - easy determination of SOC.	- low specific energy. - still in the laboratory phase. - security concerns.

Table 8-5 Advantages and disadvantages of the technologies.

In general the information given in the tables about the development in the performance and cost of the technologies in the long term is highly uncertain. The more immature a technology the more uncertain the information about the technology. The cost figures quoted are very dependent on the production volumes achieved, which has been indicated in the tables.

[145] USABC: the United States Advanced Battery Consortium.

Table 8-5 summarises the advantages and disadvantages of the technologies. In general it can be said, that ultracapacitors, and high power versions of PbAcid and NiMH are interesting candidates for use in power assist HEV applications in the short term. EVs and HEVs with a significant EV range will use high energy version of NiMH in the short term, or PbAcid batteries because of their low cost.

Assuming that the durability of LiIon and LiPo can be substantially increased to a level close to the durability of NiMH, LiIon together with ultracapacitors, flywheels, and PbAcid batteries appear the most suited for power assist HEVs in the long term, and LiPo and LiIon appear most suited for EVs and HEVs with significant EV range in the long term.

	Units	Status	2005	2020
Electricity storage ID		PbAcid_EV_1999/ PbAcid_HEV_1999	PbAcid_EV_2005/ PbAcid_HEV_2005	PbAcid_EV_2020/ PbAcid_HEV_2020
Technology level		Small scale		
Weight				
- specific energy[146]	Wh/kg	30/22	35/22	35/25
- specific power[147]	kW/kg	0.30[148] /0.5[149]	0.40 /0.6	0.60/1.0
Energy efficiency				
- avg. eff	out/in	0.80/est.[150]	0.82/ est.[150]	0.85/ est.[150]
Durability				
- Calendar life	Years	3/3	4/4	6/6
- Cycle life	Cycles	300/	400/	750[151]/
Economy				
- specific price power	$/kW	45/13	20/8	11/4
- specific price energy	$/kWh	275/300	125[152]/225	100/130
Future development				
- Technical problems		Small		
- Market uncertainty		Medium		
- Time to market	Years	Already on the market		

Table 8-6 Lead Acid battery technology [Nelson 2000; An et al. 2000; Anderman et al. 2000; Burke 2000; ALABC 2001; Ogden et al. 1999; Olson & Sexton 2000].

General advantages of the PbAcid battery technology:

- Fast recharging capability: to 50% SOC in 5 minutes and 80% SOC in 15 minutes [Anderman et al. 2000].
- Well established collection and recycling systems.

[146] At the C/3 rate, i.e. the energy available from a fully charged battery when discharged with a constant current over three hours.
[147] At the matched impedance condition i.e. 50 % efficiency of the discharge pulse.
[148] At 20-25 °C, 20% SOC and 10 s power pulse [Anderman et al. 2000; Burke 2000].
[149] Even higher specific power can be achieved, i.e. a battery produced by Bolder has a specific power of 2.33 kW/kg [Burke 2000].
[150] There is a trade-off between battery size and average efficiency of the battery. Equation 8-4 will be incorporated in the model for the energy consumption of a vehicle and used to calculate the battery mass for a given average battery efficiency.
[151] In research and development projects a cycle life of up to 1000 cycles have been achieved [ALABC 2001]. “Industrial grade” lead-acid batteries used in off-road applications like forklift trucks have specific energy of 25 Wh/kg, calendar life of 5-10 years, and up to 1500 deep-discharge cycles for a price of 150-200 $/kWh [Anderman et al. 2000].
[152] For production levels above 10000 EV packs/year [Anderman et al. 2000].

	Units	Status	2005	2020
Electricity storage ID		NiMH_EV_1999/ NiMH_HEV_1999	NiMH_EV_2005/ NiMH_HEV_2005	NiMH_EV_2020/ NiMH_HEV_2020
Technology level		Small scale		
Weight				
- specific energy[153]	Wh/kg	60/45	60/45	75/55
- specific power	kW/kg	0.25[154]/0.5	0.3/0.6	0.4/0.8
Energy efficiency				
- avg. eff	out/in	0.75/ est.[155]	0.75/ est.	0.80/ est.
Durability				
- Calendar life	Years	5/5	7/7	10/10
- Cycle life	Cycles	1500 ± 500/	1500 ± 500/200000[156]	2000 ± 500/
Economy				
- specific price power	$/kW	240/	94/51	47/20
- specific price energy	$/kWh	1000/	393[157]/685	250[158]/300
Future development				
- Technical problems		Small		
- Market uncertainty[159]		Medium/Small		
- Time to market	Years	Already on the market		

Table 8-7 Nickel Metal Hydride battery technology [Anderman et al. 2000; Chau et al. 1999; Kalhammer 2000; Burke 2000; An et al. 2000].

[153] At the C/3 rate.

[154] At 20-25 °C, 0.20 SOC, 30 s power pulse.

[155] There is a trade-off between battery size and average efficiency of the battery. Equation 8-4 will be incorporated in the model for the energy consumption of a vehicle and used to calculate the battery mass for a given average battery efficiency.

[156] The battery manufacturer VARTA has developed a prototype NiMH battery capable of 200000 shallow cycles, where the SOC vary 4% in each cycle [Kalhammer 2000].

[157] Assuming a production volume of 10000 EV packs/year [Anderman et al. 2000].

[158] Assuming a production volume of 100000 EV packs/year [Anderman et al. 2000].

[159] The market uncertainty of NiMH EV batteries is medium due to the general uncertainty about the future market for EVs. The market uncertainty for NiMH HEV batteries is small, because they are already used in the two hybrid electric cars on the market today: the Toyota Prius and the Honda Insight.

	Units	Status	2005	2020
Electricity storage		LiIon_EV_1999/	LiIon_EV_2005/	LiIon_EV_2020/
ID		LiIon_HEV_1999	LiIon_HEV_2005	LiIon_HEV_2020
Technology level		Short term		
Weight				
- specific energy[160]	Wh/kg	110/80	110/80	110/80
- specific power	kW/kg	0.50[161]/1.0	0.60/1.0	0.90/1.5
Energy efficiency				
- avg. eff	out/in	0.80/ est.[162]	0.80/ est.	0.85/ est.
Durability				
- Calendar life	Years	3 /3	4 /4	6/6
- Cycle life	Cycles	600/	600/	1500/
Economy				
- specific price power	$/kW	660/320	300/160	34/16
- specific price energy	$/kWh	3000/4000	1500/2000	275[163]/300
Future development				
- Technical problems				
- Market uncertainty				
- Time to market	Years			

Table 8-8 Lithium Ion battery technology [Anderman et al. 2000; Nelson 2000; Kalhammer 2000].

[160] At the C/3 rate.

[161] At 0.20-0.50 SOC, 10-30 s duration of power pulse, 20-25 °C.

[162] There is a trade-off between battery size and average efficiency of the battery. Equation 8-4 will be incorporated in the model for the energy consumption of a vehicle and used to calculate the battery mass for a given average battery efficiency.

[163] Assuming a production volume of 100000 EV battery packs per year [Anderman et al. 2000].

	Units	Status	2005	2020
Electricity storage ID		LiPo_EV_1999/ LiPo_HEV_1999	LiPo_EV_2005/ LiPo_HEV_2005	LiPo_EV_2020/ LiPo_HEV_2020
Technology level		Medium term		
Weight				
- specific energy[164]	Wh/kg	120/		120/80
- specific power	kW/kg	0.30[165]/		0.40[166]/0.7
Energy efficiency				
- avg. eff	out/in	0.85/		0.85/est. [167]
Durability				
- Calendar life	Years	>3/		6/6
- Cycle life	Cycles	400/		1000/
Economy				
- specific price power	$/kW			60/30
- specific price energy	$/kWh			200/250
Future development				
- Technical problems		Medium		
- Market uncertainty				
- Time to market	Years	>8		

Table 8-9 Lithium Polymer battery technology [Anderman et al.; Nelson 2000; Kalhammer 2000].

[164] At the C/3 rate.

[165] At 0.20 SOC, 30 s power pulse, 20-25 °C.

[166] At 0.20 SOC, 30 s power pulse, 20-25 °C.

[167] There is a trade-off between battery size and average efficiency of the battery. Equation 8-4 will be incorporated in the model for the energy consumption of a vehicle and used to calculate the battery mass for a given average battery efficiency.

	Units	Status	2005	2020
Electricity storage ID		Ultra_1999	Ultra_2005	Ultra_2020
Technology level		Small scale		
Weight				
- specific energy[168]	Wh/kg	2	3	7
- specific power[169]	kW/kg	0.5	0.7	1.5
Energy efficiency				
- avg. eff	out/in	0.92	0.92	0.94
Durability				
- Calendar life	Years			
- Cycle life	Cycles	750 K	750 K	1000 K
Economy				
- specific price power	$/kW			7
- specific price energy	$/kWh	10000	8000	1000[170]
Future development				
- Technical problems				
- Market uncertainty				
- Time to market	Years			

Table 8-10 Ultracapacitor technology [Burke 2000; Chau et al. 1999].

168 The specific energy of single ultracapacitors are from 1-6 Wh/kg at present [Burke 2000], but making an ultracapacitor pack consisting of several ultracapacitors connected in series with control electronics, cooling system and enclosure adds extra weight. Around 70% of the weight of an ultracapacitor pack consisting of 149 ultracapacitors is the weight of the ultracapacitors themselves and the remaining 30% is the weight of additional components use to control, cool and enclose the ultracapacitors [ISE Research 2001]. The specific energy of the ultracapacitor pack is 2.1 Wh/kg [ISE Research 2001].

169 At discharge rates giving a discharge efficiency of 0.95. The matched impedance specific power is 5.0 kW/kg [Burke 2000].

170 This is the cost target of a ultracapacitor development programme established by the US Department of Energy [Chau et al. 1999]. Achieving this target will require the use of cheaper materials than those presently used [Burke 2000]. The present price is around a factor of ten higher than the cost target [Burke 2000].

	Units	Status	2005	2020
Electricity storage ID		Flywheel_1999		Flywheel_2020
Technology level		Medium term		
Weight				
- specific energy	Wh/kg	14		40
- specific power	kW/kg	0.80		1.0
Energy efficiency				
- avg. eff	out/in	0.90		0.92
Durability				
- Calendar life	Years			Lifetime of bus
- Cycle life	Cycles	> 100 K		Lifetime of bus
Economy				
- specific price power	$/kW			
- specific price energy	$/kWh			
Future development				
- Technical problems		Medium		
- Market uncertainty		Large		
- Time to market	Years			

Table 8-11 Flywheel technology [Chau et al. 1999; Moore & Lovins 1995].

8.4 Fuel converters

The function of the fuel converter is to convert liquid or gaseous fuel to mechanical or electrical energy. A classification of fuel converters is shown in Table 3-6. The classification consists of five basic types of fuel converters: Spark ignition internal combustion engines (SI ICEs), compression ignition internal combustion engines (CI ICEs), gas turbines, sterling engines and fuel cells. The first four of the mentioned fuel converter types use combustion of a fuel to produce mechanical energy, where as the fuel cell uses electrochemical conversion of a fuel to produce electricity.

The evaluation parameters for this technology bundle are the following:

- Cost of the fuel converter measured as the ratio between the total price and the power output of the fuel converter, i.e. in units of $/kW.
- The volume and weight of the fuel converter measured as the power density (kW/l) and the specific power (kW/kg).
- The average energy efficiency of the fuel converter over a driving cycle. As for electrical motors the instantaneous energy efficiency of a fuel converter is dependent on the working conditions of the fuel converter. For combustion engines this dependency can be expressed in a engine map given the efficiency of the engine as a function of engine speed an output torque. For fuel cells the energy efficiency is a function of the electrical power output of the fuel cell. In this project the efficiency of a ICE is modelled with two parameters: the thermodynamic efficiency (η_T) and the frictional mean effective pressure f_{MEP} (see section 5.5.2).
- The emissions of air pollutants from the fuel converter, which is highly dependent on the working conditions.
- Other issues like reliability and durability, driveability issues (start-up-time, transient response for rapid acceleration), the operating limits with regard to temperature.

Spark ignition or compression ignition internal combustion engines with an automatic or manual gearbox constitute the baseline propulsion system in road-bound vehicles today. All new types of propulsion systems (electric, hybrid electric) and fuel converters (fuel cells, gas turbines) get their performance evaluated against the SI ICE or CI ICE. The developments of the SI ICE and CI ICE are therefore very important for the developments of all types of propulsion systems, both those propulsion systems that actually features an SI/CI ICE as part of the propulsion system, and those with other types of fuel converters.

8.4.1 Emissions from fuel converters

A lot of different chemical compounds can be present in the exhaust gases from a ICE. Some of these have attracted attention, because they are considered harmful to humans and/or to the environment. Among the harmful substances some have been put under regulation in an attempt to lower the emissions of these compounds. This is done by issuing emission standards giving limits for the emissions of specific compounds (or group of compounds) from new engines (or vehicles) introduced to the market from a given year. For heavy-duty engines used in trucks and buses the emissions are measured as grams per kWh mechanical energy output from engines being used in specified duty grams per kWh mechanical energy output from engines being used in specified duty cycles. The most common regulated compounds are carbon mono-oxide (CO), nitrogen oxides (NO_X)[171], hydrocarbons (HC)[172], which often are divided into non methane hydrocarbons (NMHC) and methane, and finally particulate matter (PM)[173]. Table 8-12 gives the values for different emission standards.

Emission types	CARB[174]	EPA[175]	Euro III ETC[176]	Euro IV ETC	Euro V ETC
Applies to model year	2004-2006	from 2007	from Oct 2001	from Jan 2006	from Oct 2009
CO	6.7		5.45	4.0	4.0
Formaldehyde	0.013				
Methane			0.82	0.55	0.55
NMHC	0.067	0.19	0.78	0.55	0.55
NO_X	0.67	0.27	5.0	3.5	2.0
PM[177]	0.013	0.013	0.16	0.03	0.03

Table 8-12 European and American emission standards for heavy-duty engines used in trucks and buses [CARB 2001; EPA 2000; Teknologisk Institut 2000]. All values are g/kWh engine output.

The emissions from a vehicle depend on a lot of parameters. The size, design, age, temperature and maintenance of the engine in the vehicle, the duty cycle of the engine (i.e. the driving cycle of the vehicle) and the properties of the fuel used all have importance [Winther 1998]. The use of exhaust aftertreatment devices also is very important. Often there is a trade-off between different emission compounds when optimising an engine, i.e. in a diesel engine the minimisation of the emission of NO_X makes the emission of PM larger [Gaines et al. 1998].

All in all the emissions from an engine is very hard to model. The approach chosen in this project is very simple. For each fuel converter type and time frame a set of emission values in units of g/kWh fuel converter output is estimated. Then in the vehicle model

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171 Mainly NO and NO_2 [Winther 1998].

172 Hydrocarbons are organic compounds consisting only of H and C atoms. Often all volatile organic compounds (VOC), i.e. compounds that consist of H, C and other types of atoms are included in this group [Winther 1998].

173 Particulate matter is small solid components in the air. They can be divided into three groups after their size with ultrafine particles having a diameter from 0.01-0.1 micrometer, fine particles having a diameter from 0.1-2.5 micrometer, and coarse particles with a diameter above 2.5 micrometer [Trafikministeriet & Færdselsstyrelsen 2001]. In an emission standard PM_X indicate that only particulate matter up to a certain diameter X is included in the emission standard.

174 The emission standard in California for model year 2004-2006 public transit buses and bus engines fuelled by diesel, methanol, natural gas and LPG [CARB 2001].

175 Emission standard for model year 2007-2010 heavy-duty highway vehicles and engines [EPA 2000].

176 ETC is an engine test cycle with transient loads.

177 In the European emission standards the particulates are measured by collecting them on a filter. Therefore the particulates measured include all sizes of particulates up to a diameter of 25 micrometer [Trafikministeriet & Færdelsstyrelsen 2001].

(see section 5.5) the fuel converter output over a driving cycle is calculated, and this is used to calculate the emissions during the driving cycle.

There are two basic approaches to reducing the emissions from a ICE:

Firstly reduce the engine-out emissions by using a cleaner burning fuel and/or by changes in the engine design. A resent development in the engine design are the use of exhaust gas recirculation (EGR), where some of the exhaust gas is recirculated into the combustion cylinder which reduces the combustion temperature with associated reduction in the NO_X emission. With regard to cleaner fuels the development goes toward diesel or other fuels with very low levels of sulphur (10-20 ppm).

Secondly to use aftertreatment devices that reduce the amounts of emission compounds in the exhaust gas from the engine.

There exist several technologies for the reduction of NO_X from engines used in vehicles like NO_X adsorber catalysts, urea selective catalytic reduction, HC selective catalytic reduction and plasma-assisted NO_X catalysis [Bradley et al. 2000]. Most of the technologies are still in the prototype stage or early commercialisation and need further development to achieve high reduction efficiencies in real life duty cycles, high durability and low fuel economy penalty. With further development the fuel economy penalty is expected to be below 5% [Bradley et al. 2000]. At present the reduction efficiencies of both the NO_X adsorber catalysts and the urea selective catalytic reduction are very sensitive to sulphur with efficiency decreasing quickly with fuels containing 16 ppm or more sulphur [Bradley et al. 2000]. Use of these devices therefore may require ultra low fuels or the use of sulphur traps.

The technologies for reduction of PM from diesel engines are based on removal of PM from the exhaust stream by collecting it on ceramic wall-flow filter elements. Some types of particle filters have reached the small scale technology level and is sold by several companies [Trafikministeriet & Færdselsstyrelsen 2001]. Apart from PM the emission of HC and CO is also reduced by some of these technologies. The filters reduce all sizes of PM. Some particle filter designs (catalytic particle filters) increase the emission of NO_2 around four times [Trafikministeriet & Færdselsstyrelsen 2001].
The fuel economy penalty by using particle filters is around 1-2% for some types and up to 2-4% for other types [Trafikministeriet & Færdselsstyrelsen 2001].

The reduction efficiencies of new particle filters are above 80% under practical operating conditions [Bradley et al. 2000; Trafikministeriet & Færdselsstyrelsen 2001], but Danish measurements indicate that the reduction performance of the particle filters is reduced already after one year of operation [Trafikministeriet & Færdselsstyrelsen 2001].

The development of particle filters have shown good progress in resent years, but further development is needed to achieve a reduction efficiency above 90% in real life duty cycles and improved durability.

8.4.2 Choice of fuel converter technologies for evaluation

The CI ICE, natural gas SI ICE, and the proton exchange membrane fuel cell are the fuel converter types included in this project. The NG SI ICE is included, because NG fuelled transit buses are very popular for the time being (see section 8.4.4). It is only evaluated in the short term.

The CI ICE or diesel engine is the engine type of choice in buses and trucks. It is a very mature technology with high reliability and low price. The performance of this engine type is the benchmark for other fuel converters used in heavy-duty applications.

Fuel cells are a very interesting technology with potentially high efficiency and low emissions. Fuel cells are still in the prototype stage, but a lot of effort is going into developing this technology with nearly all the large vehicle manufacturers involved in development programmes.

The SI ICEs using gasoline are used in most cars in the world, but very seldom used in heavy-duty applications like buses and trucks. Also the energy efficiency of SI ICEs are lower than the energy efficiency of CI ICEs. For these reasons SI ICEs using gasoline are not included in this work.

The same goes for gas turbines and sterling engines, i.e. the energy efficiencies of these fuel converters used in mobile applications are lower than the energy efficiency of CI ICEs. For this reason and to keep the technology analysis as small as possible gas turbines and sterling engines are not included in the analysis.

8.4.3 Compression ignition (diesel) engines

In a CI ICE the fuel is injected into the cylinders of the engine and mixed with compressed air. Further compression of the air-fuel mixture causes it to self-ignite due to the high pressure. The mixture between fuel and air is heterogen and uneven, which causes relatively large amount of particles in the exhaust gases compared to SI engines. The combustion temperature is high and the ratio between the amount of fuel and the amount of air in the air-fuel mixture is low relative to a SI ICE causing relatively large amounts of NO_X-emissions. The thermodynamic efficiency (η_T) is high, because of the high compression ratio and lean fuel-air mixture. The mechanical efficiency (η_M) (see section 5.5.2) is also high due to the use of air-fuel ratio (instead of throttling) for load control, thus avoiding the part-load pumping losses associated with throttled (SI) engines [Ross 1997; Bradley 2000].

Table 8-13 evaluates the present and future performance of the CI ICE technology. It is assumed that the performance of a CI ICE when used with RME with good approximation equals the performance when used with low-sulphur diesel.

	Units	Status	2005	2020
Engine ID		CI_1999	CI_2005	CI_2020
Technology level		Large scale		
Weight[178]				
- specific power	kW/kg	0.17	0.19	0.26
Energy efficiency[179]				
-Thermodyn. eff.		0.465	0.47	0.50
- f_{MEP}	kPa	180	180	153
Emissions				
Emission reduction equipment[180]		None	None	NO_X and PM emission reduction technology
Emission norm		Euro III	Euro III	Euro "V"[181]
- CO	g/kWh	5.45	5.45	4.0
- CH_4 (methane)	g/kWh	0.82	0.82	0.55
- NMHC	g/kWh	0.78	0.78	0.55
- NO_X	g/kWh	5.0	5.0	1.0
- PM	g/kWh	0.16	0.16	0.03
Durability				
- Operation hours	h	65000	65000	65000[182]
Economy				
- specific price power	$/kW	34	34	44[183]

Table 8-13 Compression ignition internal combustion engine technology [Weiss et al. 2000; Bradley et al. 2000; An et al. 2000].

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[178] Engine with associated cooling and exhaust system and including fluids. The status value is obtained from [Teknologisk Institut 1999]. A 50% improvement is assumed in 2020 due to the use of lightweight materials.

[179] [Weiss et al. 2000; Bradley et al. 2000]. The big challenge is to increase the thermal efficiency while at the same time reduce emission levels [Bradley et al. 2000].

[180] To achieve the Euro IV emission standard for PM for trucks and buses will require the use of particle filters [Trafikministeriet & Færdselsstyrelsen 2001]. The lower limit of engine-out NO_X emission for direct-injection diesels is estimated to 2.0 g/kWh [Bradley et al. 2000], i.e. further reductions in the NO_X emission require use of aftertreatment equipment.

[181] The only change from Euro IV to Euro V is a further reduction in NO_X (see Table 8-12). The emission levels of NO_X in the American emission standards are significantly lower than in the European emission standards. We therefore assume that the emission standard for heavy-duty diesel engines in 2020 will be equal to Euro V apart from a reduction of NO_X to 1.0 g/kWh.

[182] The emission standard of an engine decreases with time due to wear. Therefore for an engine to fulfil the Euro V standard during the whole of its lifetime, will be very difficult to achieve.

[183] [Weiss et al. 2000] estimate a retail price increment of 4.47 $/kW of emission control technology in 2020 for a car with a CI ICE. [Trafikministeriet & Færdselsstyrelsen 2001] estimate the OEM price of mass produced particle filters to 8000 DDK = 1143 $, i.e. around 6-8 $/kW for a bus engine of 150-200 kW maximum engine power. To this will come additional costs for the NO_X emission control. We assume an extra cost of 10 $/kW for measures to achieve the assumed emission levels in 2020, which include both emission control devices and changes in the engine design like exhaust gas recirculation.

8.4.4 Natural gas spark ignition internal combustion engines

The use of natural gas SI ICEs have become very popular in transit buses in USA, where NG is the most widely used alternative fuel with 22% of all transit buses built in 1998 powered by NG [Bradley et al. 2000]. The reason for the popularity is the low emissions of NO_X and PM relative to comparable diesel CI ICEs. Most buses have lean-burn engines (as opposed to stoichiometric[184] engines), because they offer the lowest NO_X emissions at the expense of higher HC and CO emissions relative to stoichiometric engines [NAVC 2000 A]. The lean-burn engine type is chosen as the NG engine type of choice in this project.

The average energy efficiency of a lean-burn NG SI ICE is around 10-20% lower than a comparable diesel CI ICE [Bradley et al. 2000; NAVC 2000 A], because both the thermal and mechanical efficiency are lower. The emission of methane is significantly higher than from a comparable diesel CI ICE, because some of the methane passes through the engine unburned [NAVC 2000 A].

[184] In a stoichiometric engine the amount of oxygen present in the air-fuel mixture is just enough to allow full combustion of the fuel. In a lean-burn engine there is a surplus amount of oxygen relative to fuel.

	Units	Status	2005	2020
Engine ID		SI_NG_1999	SI_NG_2005	SI_NG_2020
Technology level		Small scale		
Weight[185]				
- specific power	kW/kg	0.20	0.22	0.30
Energy efficiency[186]				
-Thermodyn. eff.		0.38	0.395	0.44
- f_{MEP}	kPa	165	155	124
Emissions[187]				
Emission reduction equipment		None	None	NO_X and PM emission reduction technology
Emission norm				Euro "V"[188]
- CO	g/kWh	8.0	8.0	4.0
- CH_4 (methane)	g/kWh	4	3	1
- NMHC	g/kWh	0.67	0.67	0.55
- NO_X	g/kWh	3.3	3.3	1.0
- PM	g/kWh	0.067	0.067	0.03
Durability				
- Operation hours	h	65000	65000	65000
Economy[189]				
- specific price power	$/kW	51	51	61
Future development				
- Technical problems				
- Market uncertainty				
- Time to market	Years	Already on the market		

Table 8-14 Natural gas lean-burn spark ignition internal combustion engine [Weiss et al. 2000; Bradley et al. 2000; NAVC 2000 A].

185 A spark ignition engine is lighter than a comparable compression ignition engine [Weiss et al. 2000].

186 [Weiss et al. 2000].

187 [Bradley et al. 2000; NAVC 2000 A].

188 The same emission target as for the CI ICE is assumed (see Table 8-13) except for a higher emission of methane.

189 A capital costs 50% higher than for a CI ICE is assumed, because of the small production volumes for NG engines.

8.4.5 Fuel cells

A fuel cell is an electrochemical device that produces electricity by the chemical reaction of a gaseous fuel, typically hydrogen, with oxygen. The design of a fuel cell resembles the design of a battery, because the basic components in a fuel cell like in a battery are two electrodes, a anode and a cathode, with a electrolyte in between. Like battery cells, single fuel cells can be connected in series and parallel to produce fuel cell stacks with suitable power outputs and voltage levels.

Fuel cells can be classified into different types after the type of electrolyte used in the fuel cell:

- Alkaline fuel cell (AFC).
- Direct methanol fuel cell (DMFC): it has been given this name because it can use methanol directly in the fuel cell without a need for a fuel reformer.
- Molten carbonate full cell (MCFC).
- Phosphoric acid fuel cell (PAFC).
- Proton exchange membrane fuel cell (PEMFC).
- Solid oxide fuel cell (SOFC).

Table 8-15 summarises some of the properties of the various fuel cell designs.

In a PEMFC both electrodes are porous electrodes covered with a platinum catalyst and with large catalytically active surface areas. A hydrogen rich gas is led to the anode, where the hydrogen is dissociated into hydrogen atoms and ionised to H^+ ions thereby releasing electrons. The electrons travel through the external circuit and to the cathode. Air is led to the cathode, where the oxygen present in the air dissociates and reacts with water and the electrons from the anode to form OH^- ions. The H^+ ions (protons) travel through the electrolyte and react with the OH^- ions on the surface of the cathode thereby producing water. The current in the external circuit continues to flow as long as hydrogen and oxygen are led to the electrodes.

The operating principles of other types of fuel cells are similar to the PEMFC outlined above, but other chemical reactions can be involved. SOFC and MCFC can use other gaseous fuels apart from hydrogen, because they have the ability to convert the fuels into a hydrogen rich gas inside the fuel cell. In a SOFC it is O^{2-} ions that travels through the electrolyte.

Apart from the fuel cell stack consisting of fuel cells stacked together in series via the use of separator plates, a fuel cell electrical engine consists of auxiliary equipment (e.g. for air, fuel and water management) and sensors and controls.

The storage of hydrogen on-board the vehicle takes up a lot of volume (see section 8.5), and the use of hydrogen as a vehicle fuel will require a new refuelling infrastructure to be established. Therefore considerable effort is investigated in developing fuel reformers that will enable liquid fuels to be used in connection with fuel cells. The function of the fuel reformer is to convert a liquid fuel consisting of hydrocarbons into a hydrogen rich gas consisting mainly of hydrogen and carbon dioxide and with a low content of gases that can poison the fuel cell like CO in the case of the PEMFC. The addition of a fuel reformer to the fuel cell electrical engine makes it considerable more complicated and degrade the performance with regard to start-up time, load-following capability, energy efficiency and price, but solves the problems with using hydrogen as a vehicle fuel.

Fuel cell type	AFC	DMFC	MCFC	PAFC	PEMFC	SOFC
Electrolyte type	Aqueous Alkaline	Proton exchange membrane	Molten carbonate	Phosphoric acid	Proton exchange membrane	Solid oxide
Electrode material	Nickel	Graphite etc., Platin	Nickel,, Lithiumoxide	Graphite etc., Platin	Graphite etc., Platin	Ceramics with nickel
Operating temp. [°C]	80-100	70-80	600-650	200-220	70-80	800-1000
Power density	High	Medium	Medium	Medium	High	High
Fuel	H2/O2	MeOH/Air	NG, H2/Air	H2/Air	H2/Air	CH4, CO, H2/Air
Fuel purity	high (no CO2)[190]		Low	Low	Medium (≤ 100 ppm CO)	Low
Other				Partial loads[191]		

Table 8-15 Characteristics of various fuel cell types today [Jung 1999; Nielsen 2001].

The advantages of a fuel cell relative to an ICE are high energy efficiency at part load, near zero emissions, and vibration free and low-noise operation because it has few moving parts. The disadvantages are the requirement for hydrogen being more difficult to handle and store both off-board and on-board the vehicle than liquid fossil fuels, and as with all new technologies the fuel cells need to improve performance especially with regard to costs, reliability and durability.

The important criteria when considering the usefulness of a fuel cell design for automotive applications are: high specific power and power density of the fuel cell, ability to change the power output fast (load-following capability), fuel flexibility, low sensitivity towards impurities in the fuel and air (oxygen) used in the fuel cell, high energy efficiency, high reliability and durability, and low costs.

[190] The AFC cannot tolerate even low concentrations of CO_2. It therefore requires very pure hydrogen and the use of a chemical scrubber to remove the CO_2 from the air, before being used in the fuel cell [Jung 1999].

[191] Some of the materials in the PAFC degrade when operated for longer periods at partial load.

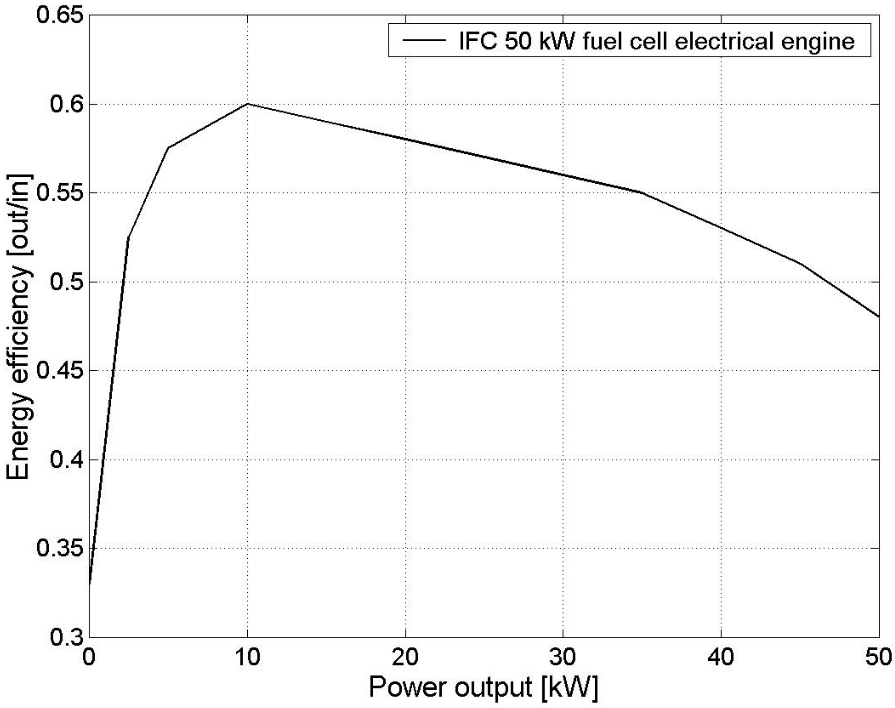

Figure 8-2 The efficiency of IFC's ambient-pressure 50 kW PEMFC electrical engine [NREL 2001].

As seen in Figure 8-2 the energy efficiency of a fuel cell is highest at part load. The efficiency of IFC's fuel cell electrical engine is very high, because it does not compress the air used in the fuel cell. Other fuel cell manufacturers, e.g. the leading company Ballard, use pressurised fuel cells where the air is compressed to 2-3 atmospheres, before being used in the fuel cell. This can led to lower overall efficiency, because the efficiencies of the compressors are low at the relatively low flow rates needed for fuel cell systems in the 50 kW range [Kalhammer et al. 1998]. The maximum efficiency of the 230 kW commercially available pressurised PEM fuel cell system P4/P5 (from *XCellsis*) is 55%, and the efficiency at maximum load is 40% [Niehues & Edwards 2000]. The average energy efficiency of the P4/P5 is at least 5% smaller than the average energy efficiency of the IFC 50 kW fuel cell system.

There is a trade-off between energy efficiency and power density in a fuel cell [Bradley et al. 2000]. As the volume constraints are not as severe in buses as in cars, this means that fuel cell electrical engines to buses can be made more efficient than fuel cell electrical engines to cars.

The energy efficiency of the fuel cell electrical engine is seriously degraded by the introduction of a fuel reformer in the system. Firstly the energy efficiency of the reformer itself affect the total energy efficiency. Secondly the fuel reformer produces a hydrogen-rich gas (a so-called reformate) with a hydrogen content of around 40% for gasoline reforming and around 75 % for methanol reforming [Ogden et al. 1999; Weiss et al. 2000]. The relatively low hydrogen content of the reformate decreases the energy efficiency of the fuel cell stack (as well as its peak power).

According to the opinions expressed by the major part of 44 fuel cell experts from different organisations and industries the PEMFC will be the predominant fuel cell technology for transportation applications at least in the near- to mid-term [NAVC 2000 B]. The reasons given are that the PEMFC is more developed technologically than other fuel cell technologies, its low temperature operation and quick cold temperature start-up time makes it the most appropriate technology for primary propulsion, and it has the potential to be produced very cost effectively. The SOFC is mentioned as having a good potential for being used as an auxiliary power unit in vehicles [NAVC 2000 B].

[Bradley 2000] mention the PEMFC, the SOFC and the AFC as candidates for use as prime power or auxiliary power units for vehicles.

We have chosen only to include the PEMFC in the evaluation of fuel cells in this project, but used with three types of fuel: hydrogen, methanol and gasoline. When hydrogen is used, there is no need for a fuel reformer, which gives the fuel cell electrical engine its best performance, but requires a hydrogen storage system on-board the vehicle.

Methanol is the easiest fuel to reform on-board a vehicle [NAVC 2000 B], which makes the fuel reformer more efficient than the fuel reformer used to gasoline. There are differing views about the safety problems connected with large-scale use of methanol in vehicles [NAVC 2000 B], because methanol is poisonous.

Finally gasoline is a well-known fuel with the refuelling infrastructure already established making it an attractive choice to fuel cells. The gasoline used in fuel cells will probably be of another quality than the one used in ICEs [Kalhammer et al. 1998]. It must have near-zero sulphur content, because sulphur will poison the fuel reformer and fuel cell, but do not need to meet ICE requirements like octane rating and boiling point range, implying that the gasoline additives used today can be left out [Kalhammer et al. 1998].

8.4.6 Evaluation of the proton exchange membrane fuel cell

Table 8-16, Table 8-17 and Table 8-18 summarises the performance of the PEMFC using hydrogen, methanol or gasoline as fuel. As before mentioned the addition of a fuel reformer reduces the energy efficiency and specific power of the fuel cell electrical engine and increases the price.

	Units	Status	2005	2020
Fuel cell ID		Fuelcell_H2_1999	Fuelcell_H2_2005	Fuelcell_H2_2020
Technology level		Short term		
Weight[192]				
- specific power	kW/kg	0.30	0.30	0.60
Energy efficiency[193]				
- Avg. eff.		0.56	0.56	0.56
Emissions[194]				
- CO	g/kWh	0	0	0
- CH_4 (methane)	g/kWh	0	0	0
- NMHC	g/kWh	0	0	0
- NO_X	g/kWh	0	0	0
- PM	g/kWh	0	0	0
Durability				
- Operating hours	h		4000[195]	65000
Economy				
- specific price power	$/kW		1000[196]	75[197]
Future development				
- Technical problems				
- Market uncertainty				
- Time to market	Years			

Table 8-16 Direct hydrogen proton exchange membrane fuel cell [Jørgensen & Schleisner 2001; Weiss et al. 2000; Ogden et al. 1999; Kalhammer et al. 1998; Åhman 1999; Gorman & Fuller 1997; Niehues & Edwards 2000].

192 The status value is the value for the IFC ambient-pressure 50 kW PEMFC electrical engine which weighs 141 kg all inclusive except a radiator[Gorman & Fuller 1997]. We assume a weight of 25 kg for the radiator and fluids.

193 The average energy efficiency of the IFC ambient-pressure 50 kW PEMFC electrical engine used in a fuel cell bus driving in Line5innercity_mod and Line5suburbs_mod is 0.56 according to ADVISOR simulations.

194 [National Research Council 2001].

195 Design goal for the Ballard "900" series PEMFC production stack [Kalhammer et al. 1998].

196 The price of the commercially available 230 kW PEM fuel cell system P4/P5 (from *XCellsis*) is expected to be around 300000 Euro in 2004 and fall below the 100000 Euro mark around year 2007, assuming a production volume of 100000 50 kW fuel cell stacks in 2004 has been achieved, and that a dedicated fleet of fuel cell buses of about 1000 vehicles is in place in 2007 [Niehues & Edwards 2000].

197 The price estimations available concern fuel cells to cars, i.e. with a factor 10 lower durability requirement. To increase the durability of a fuel cell to 50000 operating hours will be a major task, which may increase the price of a fuel cell to a bus relative to a car. On the other hand the start-up and volume requirements will be less restrictive for fuel cells to buses relative to cars.

	Units	Status	2005	2020
Fuel cell ID		Fuelcell_MeOH_1999	Fuelcell_MeOH_2005	Fuelcell_MeOH_2020
Technology level		Medium term		
Weight[198]				
- specific power	kW/kg	0.18	0.18	0.32
Energy efficiency[199]				
- Avg. eff.		0.36	0.36	0.39
Emissions[200]				
- CO	g/kWh	0	0	0
- CH_4 (methane)	g/kWh	0	0	0
- NMHC	g/kWh	0	0	0
- NO_X	g/kWh	0	0	0
- PM	g/kWh	0	0	0
Durability				
- Lifetime	Years		4000[201]	65000
Economy				
- specific price power	$/kW		1200	95[202]
Future development				
- Technical problems				
- Market uncertainty				
- Time to market	Years			

Table 8-17 Proton exchange membrane fuel cell with methanol steam reformer.

198 [Ogden et al. 1999] assumes a specific power of 0.57 kW/kg for a 50 kW fuel reformer. [Kalhammer et al. 1998] states values between 0.45-0.50 kW/kg. Here a value of 0.50 kW/kg is assumed for the status and 2005 value, and a value of 0.80 kW/kg is assumed for the 2020 value. Furthermore a 10% decrease in the peak power output of the fuel cell stack is assumed relative to a fuel cell stack being run on nearly 100% pure hydrogen.

199 A decrease of 35% in the energy efficiency is assumed in the short term, and a decrease of 30% in the long term. [Weiss et al. 2000] assumes a decrease in the efficiency of 37%. [Ogden et al. 1999] calculates a decrease in the energy efficiency of 35% for a methanol fuel cell car relative to a comparable but slightly lighter hydrogen fuel cell car.

200 The emissions connected with fuel reforming will be very small [Meyer et al. 1999; Jung 1999]. This is because the auxiliary combustion processes in the methanol reformer involve relatively small amounts of fuel and are carried out at rather low temperatures as well as under close control in catalytic burners [Jung 1999].

201 Design goal for the Ballard "900" series production stack [Kalhammer et al. 1998].

202 Assuming that the price of the reformer adds 20 $/kW to the total price of the fuel cell electrical engine [Ogden et al. 1999; Kalhammer 1998].

	Units	Status	2005	2020
Fuel cell ID		Fuelcell_Gas_1999	Fuelcell_Gas_2020	Fuelcell_Gas_2020
Technology level		Medium term		
Weight[203]				
- specific power	kW/kg	0.18	0.18	0.32
Energy efficiency[204]				
- Avg. eff.		0.34	0.34	0.36
Emissions[205]				
- CO	g/kWh	0	0	0
- CH_4 (methane)	g/kWh	0	0	0
- NMHC	g/kWh	0	0	0
- NO_X	g/kWh	0	0	0
- PM	g/kWh	0	0	0
Durability				
- Operating hours	h		4000[206]	65000
Economy				
- specific price power	$/kW		1200	95[207]
Future development				
- Technical problems				
- Market uncertainty				
- Time to market	Years			

Table 8-18 Proton exchange membrane fuel cell with partial-oxidation gasoline reformer.

[203] [Ogden et al. 1999] assumes a specific power of 0.57 kW/kg for a 50 kW fuel reformer. [Kalhammer et al. 1998] states values between 0.45-0.50 kW/kg. Here a value of 0.50 kW/kg is assumed for the status and 2005 value, and a value of 0.80 kW/kg is assumed for the 2020 value. Furthermore a 10% decrease in the peak power output of the fuel cell stack is assumed relative to a fuel cell stack being run on nearly 100% pure hydrogen.

[204] A decrease of 40% in the energy efficiency is assumed in the short term, and a decrease of 35% in the long term. [Weiss et al. 2000] assumes a decrease in the efficiency of 51%. [Ogden et al. 1999] calculates a decrease in the energy efficiency of 33% for a gasoline fuel cell car relative to a comparable but slightly lighter hydrogen fuel cell car.

[205] The CO and NO_X emissions will be very close to zero [NAVC 2000 B].

[206] Design goal for the Ballard "900" series production stack [Kalhammer et al. 1998].

[207] Assuming that the price of the reformer adds 20 $/kW to the total price of the fuel cell electrical engine [Ogden et al. 1999; Kalhammer et al. 1998].

8.5 Liquid and gaseous fuel storage systems

8.5.1 Description

The important evaluation parameters for liquid and gaseous fuel storage systems are the specific energy and energy density, the energy efficiency, the cost, security aspects and refuelling time. It is customary for hydrogen storage systems to use the "% hydrogen storage by weight"[208] as a parameter measuring the same as the specific energy. Another important parameter for hydrogen storage systems is how pure the hydrogen needs to be in order for the storage system to work. The cost is measured as the price per MJ storage capacity, and the specific energy and energy density are measured as MJ storage capacity divided by respectively the weight or volume of the storage system including the weight of the fuel.

The specific energy, energy density and price per MJ storage capacity of a fuel storage system depends both on the properties of the fuel storage system and on the mass density of the fuel measured at the storage pressure and storage temperature. For fuel storage systems using air as the storage medium, the mass of the storage vessel relative to the inner storage volume (designated with the symbol m_V), the outer storage volume relative to the inner storage volume (designated with the symbol v_V) and the cost of the storage vessel relative to the inner storage volume (designated with the symbol c_V) are the three parameters that determine the mass, volume and cost of a storage vessel of a given storage capacity. For storage vessels that can be used to store several different fuels, it is more straightforward to give the values of m_V, v_V and c_V. The specific energy, energy density and cost per MJ storage capacity can then be calculated with the following equations:

$$s_{FSTO} = \frac{\rho_F s_F}{m_V + \rho_F} \quad \text{and} \quad e_{FSTO} = \frac{\rho_F s_F}{v_V} \quad \text{and} \quad c_{FSTO} = \frac{c_V}{\rho_F s_F}$$

s_{FSTO}: the specific energy of the fuel storage system [MJ/kg].
s_F: the lower heating value of the fuel per mass [MJ/kg].
m_V: the mass of the storage vessel relative to the inner storage volume [kg/l].
ρ_F: the density of the fuel [kg/l].
e_{FSTO}: the energy density of the fuel storage system [MJ/l].
v_V: the outer storage volume of the storage vessel relative to the inner storage volume.
c_{FSTO}: the cost of the fuel storage system per storage capacity [$/MJ].
c_V: the cost of the storage vessel per inner storage volume [$/l]

The energy losses consist of the loss of fuel during refuelling and the loss of fuel from the vehicle storage system during driving and stand-by periods. Some studies, e.g. [Jørgensen & Schleisner 2001] include the consumption of additional energy (typically electric energy) to bring the fuel to the temperature and pressure levels needed during refuel-

[208] % H_2 storage by weight = weigt(H_2)/weight(tank + H_2)*100.

ling[209], but in this study the additional energy is included in the calculation of the fuel cycle efficiency. The total energy efficiency of the storage system is calculated as:

$$EF_{TOT} = \frac{E_{OUT,FUEl}}{E_{IN,FUEL}}$$

where EF_{TOT} is the total energy efficiency, $E_{OUT,\,FUEL}$ is the energy content of the fuel output from the storage system, $E_{IN,\,FUEL}$ is the energy content of the fuel input to the storage system.

For vehicles using liquid fuels, this technology bundle is not important for the overall performance of the vehicles. The situation is different for fuel cell vehicles (especially cars) where the volume constraints on the hydrogen storage systems so far put serious constraints on the travel range of the vehicles. According to an expert survey a breakthrough in hydrogen storage technology is critical to the successful commercialisation of pure hydrogen fuel cell cars in the passenger market [NAVC 2000 B]. For fuel cell buses the situation is less critical, because fuel cell buses can store compressed hydrogen on the roof of the vehicle, which is analogous to the way natural gas fuelled buses store the compressed natural gas.

LRVs and local trains have the same possibility for storage of hydrogen on the roof. A study of the possibilities for giving a LRV (the INCENTRO from Adtranz) fuel cell propulsion using a commercially available fuel cell system (the P4/P5 from *XCellsis*) and storage of compressed hydrogen in aluminium composite tanks, showed that it could be done, although only with considerable difficulty due to the volume requirements of the fuel cell system and hydrogen storage [Niehues & Edwards 2000]. The study points out that, because of restrictions in law concerning hydrogen-driven vehicles in closed buildings such as tunnels and underground stations, storage of hydrogen on-board the vehicle is not feasible, for vehicles used in such places. Instead use of hydrogen reformation from methanol or another liquid fuel may provide a solution.

Today the used technologies for storage of liquid and gaseous fuels onboard vehicles are almost entirely different kinds of tanks using air as the storage medium. The tanks can be classified according to the temperature and pressure levels they are designed for:

- Tanks for storage of liquid bio- and fossil fuels at ambient pressure and temperature. Such a tank usually made of steel is sitting in nearly all cars, buses and trucks today and must be considered a very mature technology having reached the mass-production technology level.
- Cryogenic tanks for storage of liquids at low temperature and low pressure[210], the most advanced being double-walled, super-insulated tanks for storage of liquid hydrogen at a temperature of –253 °C (20 K). These tanks are aluminium walled with a multilayer vacuum insulation.
- High pressure tanks for storage of gaseous natural gas or hydrogen at ambient temperature and high pressure (20-30 MPa). These tanks have an aluminium liner wrapped with carbon or glass fibre.

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[209] i.e. compression energy in the case of high pressure gas storage and cooling energy in the case of liquid hydrogen.

[210] Max. pressure 0.69 MPa [Berry & Aceves 1998].

Also tanks that store gases at low temperatures and high pressures have been suggested as superior to liquid hydrogen tanks [Berry & Aceves 1998].

Some promising hydrogen storage technologies under development are the following [Jung 1999]:

- Metal hydride storage where hydrogen is stored in the interatomic spaces of the metal. The storage vessel contains powdered metals (often alloys) that absorb hydrogen and at the same time release heat when the vessel is filled with hydrogen under pressure. By reducing the pressure and supplying heat the hydrogen is released. Normally the hydrides are divided into high temperature and low temperature hydrides depending on the temperature of the absorption/desorption [Pettersson & Hjortsberg 1999].
- Adsorption of hydrogen in nanofibres, nanotubes and catalyst-doped graphite. These storage technologies are still in the laboratory but have achieved outstanding results with reported storage densities of up to 70 % hydrogen by weight at 20 bar pressure and room temperature [Pettersson & Hjortsberg 1999].

The energy required to liquefy the hydrogen is around 30-40 % of the energy content of the hydrogen [Jørgensen & Schleisner 2001; Jung 1999]. This large energy loss combined with the possibility for using compressed hydrogen storage in the large vehicles used in public transport, has lead us to exclude liquid hydrogen storage in cryogenic tanks from the evaluation of the storage technologies.

The adsorption of hydrogen in different forms of nano carbon structures is still in a very early development stage [Jørgensen & Schleisner 2001]. There is therefore not many data available. For this reason this storage technology is left out of the evaluation.

8.6 The performance of the technologies

Table 8-19, Table 8-20 and Table 8-21 list the present and future values of the most important performance parameters for the storage systems. Apart from being the simplest and cheapest fuel storage technology the liquid fuel tank is also superior with regard to specific energy and energy density with a specific energy of 32 MJ/kg and energy density of 35 MJ/l when using diesel as fuel, and around half of these values when using methanol as fuel. In comparison the specific energy and energy density of a 25 MPa CNG fuel storage system are respectively 16 MJ/kg and 8 MJ/l, and the specific energy and energy density of a 25 MPa CH_2 fuel storage system are respectively 5 MJ/kg and 2 MJ/l.

A lot of development work has been and is going on with metalhydrides to be used in hydrogen storage vessels and in metalhydride batteries. Still the obtained results for the hydrogen storage systems are not promising in that the systems have very low specific energy and high costs. The big advantage of metalhydride systems compared to CH2 is the low pressures involved, that make metalhydrides very safe storage systems. The potential for improving the low specific energy seems small at this moment in time, and therefore metalhydride hydrogen storage systems are evaluated to be less suited for transportation purposes.

Especially the development of high pressure tanks is showing good progress for the time being [Mitlitsky et al. 1999] and a 7.5% hydrogen storage by weight high pressure tank has been made.

	Units	Status	2005	2020
Fuel storage ID		Liquid_1999	Liquid_2005	Liquid_2020
Technology level		Mass production		
Number of units prod.		Very many		
Technical parameters				
- Vessel material		Steel	Steel	Plast
- Storage medium		Air	Air	Air
- Max storage pressure	MPa	Ambient	Ambient	Ambient
- Storage temperature	K	Ambient	Ambient	Ambient
Energy density[211]				
Mass of storage vessel relative to inner storage volume	kg/l	0.25	0.25	0.12
Outer storage volume relative to inner storage volume	l/l	1.02[212]	1.02	1.02
Losses				
- in/out difference	%	0	0	0
- fuelling losses	%	0	0	0
- stationary losses	% /day	0	0	0
Total EF	%	100	100	100
Convenience				
Fuelling time	minutes	<5	<5	<5
Durability				
Lifetime	Years	20	20	20
Economy				
Cost per inner storage volume[213]	$/l	1	1	1
Future development				
Technical problems		None		
Market uncertainty		Very low		
Time to market	Years	Already on the market		

Table 8-19 Liquid fuel storage (diesel, gasoline, RME, methanol, ethanol).

[211] A 50 l steel tank for gasoline weighs 12 kg [Ogden et al. 1999; Åhman 1999] and a 300 l steel tank for diesel weighs 82 kg [Teknologisk Institut 1999]. It is assumed that a shift in vessel material from steel to plast will give a weight reduction of 50%.

[212] Example of a rectangular box with inner dimensions 0.2×0.5×1.0 m^3 and 0.003 m thick steel walls.

[213] [Ogden et al. 1999] assumes that a 50 l steel tank costs 100 $. The cost of larger storage tanks used in buses are cheaper when measured relative to inner storage volume, because less material is used per l of storage volume.

	Units	Status	2005	2020
Fuel storage ID		25MPa_1999	25MPa_2005	34MPa_2020
Technology level		Small scale[214]		
Technical parameters				
Vessel material		Al liner wrapped with fibreglass or carbon fibre	Al liner wrapped with fibreglass or carbon fibre	Plastic liner wrapped with carbon fibre
Storage medium		Air	Air	Air
Max storage pressure	MPa	25	25	30-50
Storage temperature	K	Ambient	Ambient	Ambient
Energy density[215]				
Mass of storage vessel relative to inner storage volume	kg/l	0.40	0.40	0.19
Outer storage volume relative to inner storage volume	l/l	1.22	1.22	1.1
Losses		NG/H_2	NG/H_2	NG/H_2
- fuelling losses	%	1/ 4	1/4	0.5/2
- stationary losses	%/day	0/0	0/0	0/0
Total EF	%	99/96	99/96	99.5/98
Convenience				
- Fuelling time	minutes	3-5	3-5	3-5
Durability				
- Lifetime	Years	20	20	20
Economy				
Cost per inner storage volume	$/l	18[216]	14	4.6±1.2[217]
Future development				
- Technical problems		Small		
- Market uncertainty		High[218]		

Table 8-20 High pressure vessels – onboard storage of hydrogen or natural gas.

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[214] A relatively small number of storage tanks are produced to natural gas vehicles.

[215] At 21 °C and 25 MPa (3600 psi). Status values calculated using the specifications of a commercial available tank from Dynetek with a inner volume of 320 l, outer volume of 394 l and weight of 108 kg [Dynetek 2001]. The additional mounting equipment was assumed to weigh 19 kg, which was added to the weight of the storage cylinder [Niehues & Edwards 2000]. The 2020 values corresponds to a 34.4 MPa (5000 Psi) fuel storage system with a inner volume of 216 l, outer volume of 237 l and storage vessel mass of 32 kg [Berry & Aceves 1998]. The additional mounting equipment was assumed to weigh 10 kg.

[216] The present price of a 25 MPa CNG storage system used in the DaimlerChrysler Dodge Charger concept car and storing the equivalent of 45 l (12 gallons) gasoline is 2500 $ [Office of Transportation Technologies 1999].

[217] [Berry & Aceves 1998] estimate a price of 100-200 $/kg hydrogen stored assuming high-volume production of storage cylinders corresponding to 0.8-1.6 $/MJ storage capacity. [Ogden et al. 1999] estimate a cost of 133-266 $/kg hydrogen stored for mass produced 34.4 MPa hydrogen storage cylinders storing 7.5% hydrogen per weight. We assume a value of 200 ± 50 $/kg hydrogen stored for 34.4 MPa storage cylinders storing 10.6% hydrogen per weight.

[218] The future market for high pressure vessels depends on the evolution of fuel cells and reformers and the choice of fuel infrastructure for the fuel cell vehicles and is therefore highly uncertain.

	Units	Status	2005	2020
Fuel storage ID		MeHyd_1999	MeHyd_2005	MeHyd_2020
Technology level		Short term		
Number of units prod.		Few prototypes		
Technical parameters[219]				
Vessel material		Steel	Steel	Plastic/ composites
Storage medium		Metal hydride	Metal hydride	Metal hydride
Absorption pressure	MPa	3-6	3-6	3-6
Desorption pressure	Bar	0.1-1	0.1-1	0.1-1
Desorption temperature	C	150-300/20-90[220]	150-300/20-90	150-300/20-90
Energy density[221]				
- per mass	MJ/kg	2	2	3
- per volume	MJ/l	3	3	7
Losses				
- in/out difference	%	1	1	1
- fuelling losses	%	0	0	0
- stationary losses	% H2/day	0	0	0
Total EF	% of H2 in	99	99	99
Convenience				
Fuelling time	minutes	<30	<30	15
Demands for hydrogen purity		Moderate	Moderate	Moderate
Economy				
Lifetime	Years			
Capital cost	$/MJ	7[222]	7	6[223]
Future development				
Technical problems		High		
Market uncertainty		High		
Time to market	Years			

Table 8-21 Metal hydrides – onboard storage of hydrogen.

[219] [Pettersson & Hjortsberg 1999].
[220] The desorption temperature is in the interval 150-300 °C for high temperature metalhydrides and in the interval 20-90 °C for low temperature metalhydrides.
[221] [Pettersson & Hjortsberg 1999; Jørgensen & Schleisner 2001]. A wide range of different metalhydrides exist with very different cost, specific energy and energy density.
[222] The price estimations done in the literature varies between 4-70 $/MJ [Jørgensen & Schleisner 2001].
[223] [Jørgensen & Schleisner 2001].

8.7 Transmissions

The evaluation parameters for a transmission are the costs, energy efficiency and weight of the transmission.

The types of transmission evaluated are the 4-speed automatic used in buses today, the 5-speed automatically-shifting clutched transmission to be used in future conventional buses, which have higher efficiency than the 4-speed automatic, and finally the 1-speed transmission used by EVs and SHEVs. The 1-speed transmissions used in wheel-hub motors and in the motors situated right next to the wheels in LRVs and trains are more efficient and cheaper, than the 1-speed transmissions used to transmit power from a centrally placed motor, because the mechanical power is transmitted over a considerably shorter distance in the former case. Therefore we divide the evaluation of 1-speed transmissions into two: one for wheel-hub motors and the like and one for centrally placed motors. Table 8-22 evaluates the transmission technologies

	4-speed automatic	5-speed automatic clutched	1-speed (used with centrally placed motor)	1-speed (used with wheel-hub motor)
Transmission ID	4_aut	5_clutched	1_central	1train/1_hub
Technology level	Large scale	Short term	Large scale	Large scale
Peak efficiency	0.90	0.93	0.96	0.98
Avg. energy efficiency	0.72/0.75[224]	0.88	0.94	0.98[225]
Specific power [kW/kg]	0.4	0.6	1.2	1.0[226]/1.2
Specific price [$/kW] [227]	30	30	5	3

Table 8-22 Evaluation of transmission technologies [Weiss et al. 2000; An et al. 2000]. The same values are assumed in 2020 as today.

224 An average energy efficiency of 0.72 in Line5city and Line5city_mod, and of 0.75 in Line5suburbs and Line5suburbs_mod is assumed.

225 In LRVs and local trains the electric motor is placed right beside the wheels and the reduction geartrain is an integral part of the motorhousing leading to high efficiency.

226 The specific power of the one-speed transmission used in the S-train is 1.0 kW/kg.

227 The price of the 5-speed automatically shifted clutched transmission is assumed equal to the price of the 4-speed automatic transmission. The price of the 4-speed automatic and the 1-speed transmission is taken from [An et al. 2000].

9. Technology analysis vehicle loads

In this chapter the technological possibilities for reducing the vehicle loads are analysed. The parameters determining the size of the vehicle loads are: the total mass of the vehicle, the coefficients of rolling resistance, the frontal area and the coefficient of drag, and the average power demand of accessories.

Of these parameters the mass of the vehicle has the biggest influence on the energy consumption of urban public transport modes with a 10% reduction in the curb mass of a vehicle leading to an energy saving of 4.9-6.9% (see Table 5-10). The influence of the coefficients of rolling resistance is smaller with a 10% reduction leading to a reduction of 1.5-2.3% depending on the vehicle and driving cycle investigated (see Table 5-10). Air resistance, i.e. the frontal area and the coefficient of drag, only has a minor influence (below 1.0% reduction in the energy consumption for a 10% reduction in the size of the product AC_D) in driving cycles for buses and LRVs with low maximum speeds. For the S-train with maximum speeds of 100 km/h, the importance of the air resistance equals the importance of the rolling resistance (see Table 5-10).

Finally the importance of the power consumption of accessories is minor for all vehicles considered except the LRV, where the power demand of accessories exercise the same influence on the energy consumption as the rolling resistance. This situation is very much different for public transport modes using air condition (see section 9.4).

9.1 Coefficients of rolling resistance

Rolling resistance is caused by (see section 5.3.3):

- Deformation of the wheel/tyre in the contact area, so called hysteresis.
- Deformation of the track/road surface.
- Frictional losses in the contact patch, i.e. energy dissipation because of the driving wheels/tyres slipping and sliding relative to the track/road surface. For rail wheels there are also frictional losses between the flange of the wheel and the rail especially in curves.
- Bearing resistance caused by the frictional losses in wheel-bearings.
- Energy dissipated in the suspension system of the vehicle.
- Frictional losses due to the brake shoes touching the brake disc or brake drum.
- Air drag on the inside and outside of the tire.

Improvements in the coefficients of rolling resistance must always be balanced against the development in other key performance parameters for tyres/wheels like traction, braking behaviour, behaviour on wet surface, durability, wear on the ground and cost. For example increasing the pressure of a tyre is a method to reduce the coefficients of rolling resistance of the tyre, but can lead to increased wear on the roads.

For tyres used in heavy-duty vehicles a typical distribution of the losses are [Bradley 2000]: 80-90% hysteresis, 5-10% tyre/road friction, 3-5% aerodynamic losses, below 1% tyre/wheel friction. As can be seen the main part of the rolling resistance is caused by hysteresis. The hysteresis is very low for steel rail wheels because of their high elasticity module causing small deformations. This explains why the size of the first coefficient of rolling resistance for the S-train is 4 times smaller than the value used for the buses (see Table 5-9).

The frictional losses between the wheels and the rail for rail-bound vehicles can be reduced by techniques that align the wheels with the rail also in curves [Andersson & Berg 1999]. The potentials for improvement of the coefficients of rolling resistance for rail-bound vehicles using steel wheels with an aligning technique must be considered small. This is the case for the coefficients of rolling resistance used to model the rolling resistance of the S-train and the LRV in this project. We therefore do not assume any improvement in the coefficients of rolling resistance used in the rail-bound modes from now to 2020.

For road-bound modes (buses) a C_{R1}-value of 0.009 has been used as the status value. The presently best value for tyres used in large trucks is around 0.006[228], which is expected to be reduced to around 0.004-0.005 in 2010 [Bradley 2000]. [Bradley 2000] assume a C_{R1}-value of 0.0065 in 2010 for a transit bus. We assume a C_{R1}-value of 0.0075 in 2005 and 0.005 in 2020, i.e. a reduction of 44% between now and 2020. The reduction will be caused by the use of lower-hysteresis rubber compounds in the tyre, optimised tread design and increasing the tyre pressure [Bradley 2000].

The performance of tyres with regard to rolling resistance, lifetime, noise and braking performance have been gradually increasing in the past without increased costs [Weiss et al. 2000]. We assume that this development will continue, such that the improvement in rolling resistance will come about without increased costs.

9.2 Coefficient of drag and frontal area

Assuming that the future propulsion systems of public transport modes will not be significantly smaller in volume than the existing propulsion systems, a reduction in the frontal area of a public transport mode will decrease the available passenger space. This option is therefore not considered feasible in this project, which leaves reduction in the size of the coefficient of drag as the only means to reduce the air resistance of a vehicle.

The potential for reducing the C_D-value of urban buses must be considered large, because the present shape of these buses is very box-like, which is not a very optimal aerodynamic shape. On the other hand as we have seen the influence on the energy consumption of a reduction in the air resistance is very small for urban buses, which makes it hard for any improvements in the aerodynamic shape of the vehicle to be cost-effective. The present C_D-value for buses is 0.8, and we assume a modest improvement to 0.6 in 2020. This can be compared with the C_D-value for large trucks, which already toady is around 0.6 [Bradley 2000; Muster 2000].

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[228] This value is used as the default value in the vehicle simulation programme SEEK [Teknologisk Institut 2000].

The influence of the air resistance on the energy consumption for the local train (S-train) is larger than for the bus and LRV, so the motivation for improving the C_D-value of the local train is stronger. The potential for improvement is smaller, because the present shape of the S-train is already optimised to achieve low air resistance with a smooth body with no protruding elements except the pantographs, and no gaps between the individual cars in the train. The shapes of the front and end of the train are not very aerodynamic, because they are shaped to enable the formation of longer trains by connecting individual train sets. All in all the potential for improvement must be considered small, and we assume a 10% reduction in the C_D-value from now to 2020, i.e. a C_D-value of 0.77 in 2020. The same assumption is done for the LRV.

As the assumed improvements are very modest, we assume that they will be realised without incurring extra costs.

9.3 Weight savings

Weight reductions of a public transport mode is a good thing not only with regard to the energy consumption of the mode, but also with regard to the wear on the vehicle infrastructure (roads or tracks). Furthermore weight reductions of buses and trams are beneficial for the safety, in that it reduces the impacts, these vehicle types have on other users of the traffic system (see appendix A).

The mass of vehicles belonging to the same vehicle concept and of the same size can be compared directly. To compare the masses of vehicles belonging to different vehicle concepts, the curb mass of the vehicle divided by the seat capacity (from now on called the mass per seat) is often used as a bench mark figure. The mass per seat do, apart from the curb mass of a vehicle, depend on the chosen seat configuration in the vehicle. Often there is a trade-off between having many seats in a public transport mode versus having space for many standees. This has to be taken into consideration when comparing the mass per seat of vehicles belonging to different vehicle concepts. Table 9-1 gives the mass per seat and mass per total passenger capacity of the baseline vehicles. It can be seen that the bus is the lightest of the three vehicles. The S-train is lighter than the Combino LRV when measured according to the weight per seat, but the opposite is true when measured according to the weight per total passenger capacity. This illustrates the importance of different seat configurations, where the Combino LRV has relatively more space reserved to standees than the S-train.

	HT bus 12 m	S-train new	Combino LRV
Mass per seat [kg]	314	354	433
Mass per total passenger capacity [kg]	126	198	173

Table 9-1 The mass per seat and the mass per total passenger capacity of the baseline vehicles.

The curb mass of a vehicle is the sum of the masses of all the components in the vehicle, so reducing the masses of different components in the vehicle will lead to a reduction in the curb mass. Designing a vehicle is a recursive process as the weight reduction of one component or subsystem of the vehicle e.g. batteries allows weight reductions in other parts e.g. the motor and the load carrying components (chassis, wheels, suspension system). This is because the vehicle load gets smaller and the weight that the chassis shall carry is reduced enabling a lighter chassis. The derived weight reductions in a car are around 50%, i.e. a weight reduction of one kg in one place enables further weight reductions of 0.5 kg [Moore and Lovins 1995]. A study by Mitsubishi gave a derived weight reduction of 23% without engine down scaling and 47% with engine down scaling [Koto and Shiroi 1992].

The model used to determine the masses of the different subsystems in the propulsion system (see section 5.8) take the derived weight reductions into consideration, because the peak tractive power required of the propulsion system is proportional to the curb mass of the vehicle and the mass of the support structures is increased or decreased proportional to the difference in curb masses between the vehicle under consideration and a comparable reference vehicle. If the curb mass is reduced the peak tractive power will be reduced, which enable reductions in the peak performance and weight of the subsystems in the propulsion system, and the weight of the support structures will be reduced. In other words the model take both the engine (or more general propulsion system) down scaling and the reduction in the weight of the load carrying components (chassis, wheels, suspension system) due to weight reductions of the vehicle into consideration.

The mass of a component is reduced by optimising the design of the component including using lighter materials in the component. In some cases a change in the materials used enable a so-called parts consolidation, such that a component previously made up of several assembled parts, now can be produced as one part. Therefore the price of more expensive materials can partially be offset by the reduced price of assembling the vehicle due to a simpler construction. For example researchers in a American joint industry and government project team has designed a carbon fiber and aluminium intensive car body-in-white that is 68% lighter and reduce the number of parts in the body-in-white from more than 200 to only 13, thereby reducing assembly costs greatly [USCAR 2000].

The dominant material in public transport modes today is steel (see Table 9-2) although aluminium is increasingly used, because of the weight reduction possible with the use of aluminium compared to steel.

Apart from aluminium other materials with a weight-reducing potential compared to steel and used in the vehicle industry are [Jørgensen 2000]:

- Composites[229].
- Plast[230].

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229 A composite material consists of fibres or particles embedded in a matrix. The matrix is the material gluing the fibres together. Both fibres and the matrix can be made of a wide range of materials, e.g. the fibres include inorganic, cheramic and natural fibres, and the matrices include metallic, cheramic and polymeric matrices. Common composite materials are carbon or glas fibres embedded in epoxy matrices. Composites are complicated materials with complex, anisotropic properties. The properties of composites are dependent on the choice of fibre material and structural geometry of the fibres, i.e. length, mean diameter, wall thickness, the choice of matrix material and the laminate design, i.e. the orientation of the fibres in the matrix.

– High strength steel.
– Magnesium.
– Titanium.

Group of materials	12 m bus Share of curb mass	S-train Share of curb mass
Steel	47.7	> 31
Aluminium and aluminium alloys	23.0	22
Wood	5.4	
Glass	5.2	2
Plast/Rubber	5.1	
Other	13.6	
Total	100	

Table 9-2 The curb weight of a 12 m bus and a S-train distributed on different group of materials [Teknologisk Institut 1999; Pedersen 2001].

The choice of material depends on the properties of the material, which will be explained in more detail in the next section.

9.3.1 Choice of materials

The following parameters and conditions have an influence on the choice of materials:

- Price of the material.
- Production considerations:
  - production flexibility.
  - tooling and assembly operations.
  - working environment.
- Safety considerations: crashworthiness, fire resistance.
- Stiffness of the material.
- Design considerations: mouldability, surface structure, colouring.
- Weight.
- Durability: fatigue, creep, corrosion and degradation.
- Disposal, recycling.

9.3.1.1 Crashworthy capability

As explained in appendix A, the crashworthy capability of a material depends on the materials capability to absorb energy when strained. The crashworthy capability depends on the crush mode investigated, e.g. there is difference between how the materials crush under an axial load and under a crush mode mainly associated with bending. Also how fast the crush load is applied (the crushing speed) has importance for the energy absorption capability [Mamalis et al. 1997].

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[230] Plast consist of long chain-like molecules [Crawford 1992]. Common types of plastic in cars are Polyurethane, Polypropylene and PVC.

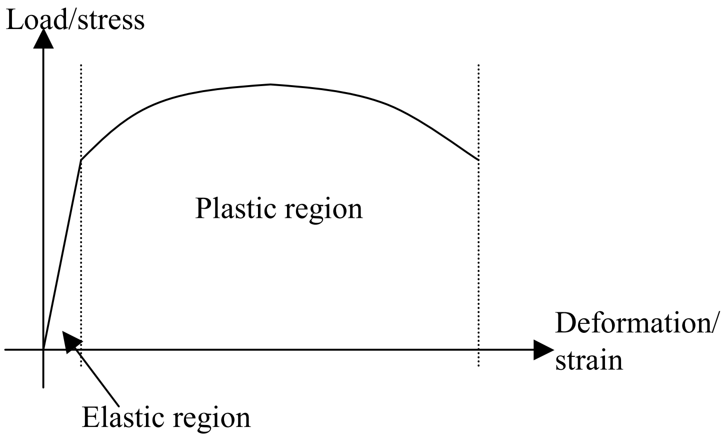

Figure 9-1 The relationship between load and deformation in a quasi-static tensile test of a ductile material. In the elastic region the deformation and load are proportional, and the constant of proportionality is called Youngs modulus, E. For strains in the elastic region the material will return to its original shape, when the load is removed. Moving into the plastic region plastic (permanent) deformations take place.

Usually the energy absorbing capability of a material is investigated in two types of test:

- Compression or tensile tests.
- Bending tests.

In Figure 9-1 is shown the load-displacement curve for a ductile material in a quasi-static tensile test. The material is ductile because it can be stretched a lot before breaking, around 30% of the original length in case of metals and much more for plastics. Brittle materials on the other hand can only be stretched a little before braking, e.g. around 10% of the original length in the case of metals. The energy absorbed is given by the area beneath the curve, and consists of elastic strain energy and plastic strain energy. For a ductile material the plastic strain energy is much larger than the elastic strain energy.

For materials used in applications where weight is important, it is the specific energy absorption that is of interest. It can be defined as [Mamalis et al. 1997]:

$$e_A = \frac{E_A}{V_c \rho}$$

e_A is the specific energy absorption [J/kg].
E_A is the total energy absorbed by the crushed/deformed material [J].
V_c is the volume of the crushed/deformed material [m^3].
ρ is the density of the material [kg/m^3].

It is important, that the materials used in the crush zones in vehicles have a predictable failure mechanism, i.e. that the way they crush under different external loads and the energy absorbed in the different crush strokes can be predicted. As composites are complex anisotropic materials a lot of effort is going into developing good models of the failure of the materials under different conditions [Mamalis et al. 1997].

9.3.1.2 Stiffness of a component

The **stiffness** of a component subjected to a constant load is the capability of the component to carry the load only undergoing small elastic deformations. The larger the stiffness of a component the smaller the deformation for a given load. This capability is important in structures and components governed by deflection limitations like the chassis of a vehicle. The stiffness depends on the type of load the component is subjected to, the geometrical shape of the component, and the properties of the material used in the component. Assuming a given (fixed) design value for the stiffness of a component, it can be shown [Hearn 1985; Crawford 1992] that the mass of the component subjected to tension or compression is proportional to ρ/E. If the component is a beam subjected to bending the mass will be proportional to $\rho/\sqrt{E}$, and if the component is a plate subjected to bending, i.e. uniformly loaded plates or centrally concentrated load on plates, the mass is proportional to $\rho/E^{1/3}$. E is Youngs modulus of the material, and ρ is the density of the material.

Material	Density [kg/m3]	E-module [GN/m2]	Energy absorption [kJ/kg]	Mass of component relatively to the same component made out of mild steel		
				Compression/ tension $(\rho/E)/(\rho/E)_{steel}$	Bending of beam $(\rho/E^{1/2})/(\rho/E^{1/2})_{steel}$	Bending of plate $(\rho/E^{1/3})/(\rho/E^{1/3})_{steel}$
Medium strength mild steel	7840	200	33	1.00	1.00	1.00
Medium strength aluminium alloy	2800	70	72-90	1.02	0.60	0.51
Magnesium alloy	1800	45		1.02	0.48	0.38
Carbon fibre/epoxy	1550	55	46-99	0.72	0.38	0.30
Glass fibre/epoxy	1920	21	30-53	2.33	0.76	0.52

Table 9-3 Crashworthy capability and stiffness properties of selected materials [Case et al. 1993; Mamalis 1997, Bak 2000 B]. For the composite materials the properties depends strongly on the orientation of the fibres (the ply orientation) and the shape of the fibres. Therefore the values quoted are only given as an example.

From Table 9-3 it can be seen that a beam in aluminium with the same stiffness as one in steel will be 40% lighter, and a aluminium plate with the same stiffness as a steel plate will be 49% lighter. The corresponding values for a beam or plate made in a carbon composite consisting of carbon fibre and epoxy are 62% and 70% respectively. It can be seen that significant weight savings can be achieved by using other materials than steel in the vehicles.

9.3.2 Possible weight reductions

The model used to determine the size of the subsystems in the propulsion system divide the curb mass of a vehicle into the glider mass (the mass of the vehicle exclusive the propulsion system) plus the masses of the subsystems in the propulsion system (see section 5.8). The masses of the subsystems in the propulsion systems are calculated in the model with the use of specific power or specific energy values estimated in chapter 8, so the subject of interest in this section is the possible weight reductions in the glider mass.

Vehicle	12 m bus	S-train
Glider mass [kg]	9100	103600
Propulsion system mass [kg]	1850[231]	15400[232]

Table 9-4 The estimated glider mass and propulsion system mass of different vehicles [Teknologisk Institut 1999; Pedersen 2001].

Table 9-4 shows the propulsion system mass of the baseline vehicles and the glider mass of the baseline vehicles calculated as the difference between the curb mass of the vehicles and the propulsion system mass. As can be seen the glider mass constitutes 83% of the curb mass for the bus and 87% of the curb mass for the S-train.

A few examples of carbon composite buses exist. Neoplan has produced and sold a 10.6 m. bus (the Metroliner N8012) with a passenger capacity of 77 total and 33 seats. The curb mass of the Metroliner is 6100 kg corresponding to a curb mass of around 7.0 (12/10.6*6.1) tons for a 12 m bus. The weight reduction achieved is around 3.7 tons (around 35%) with the main part coming from the use of a self-carrying body made of carbon reinforced glasfiber weighing 989 kg, which substitutes a ordinary body plus chassis weighing around 3.7 tons in a ordinary 12 m bus [Bak 2000 B]. The Metroliner is equipped with a 169 kW engine, which also can be found in ordinary low-floor buses, i.e. only little use has been made of engine down-scaling. The Metroliner shows that a weight reduction of around 3 tons in the glider mass of a 12 m bus can be achieved, i.e. a 33% reduction in glider mass. The body of the Metroliner is made in one piece and experience with adapting the design of the composite body of the Metroliner to the individual wishes of customers (length, number of doors, engine) has revealed that changes are expensive, because they require changes in the large mould used to make the body [Bak 2000 B]. This has lead to the Metroliner only being produced in a few standard designs, and modifications are only undertaken within large orders above 300 buses.

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[231] Mass of engine including motor oil, cooling system and exhaust system, mass of transmission (gearbox, gearoil, cardan axle), mass of starter battery, mass of fuel storage including fuel.
[232] Mass of electrical motors, transmission and power electronics.

A small 7.5 m bus made of composites is in production toady by the company Omni-Nova. The bus with 18 seats and a total passenger capacity of at least 30 (depending on the configuration) weighs 3500 kg [Omninova 2001]. Assuming as a rough estimate that the curb weight of the bus can be scaled with the area of the bus, a comparable 12 m bus would weigh (12 m × 2.5 m)/(7.5 m × 2.13[233] m)*3.5 tons = 6.6 tons.

A weight reduction of 30% in the curb mass has been achieved with a 9.1 m. hybrid bus with a one-piece composite body and chassis [Electric Vehicle Progress 2000].

It can be seen that very large reductions in the glider mass of buses can be achieved, but these reductions can be partially off-set by the inclusion of new and heavy equipment in the buses for example air condition. On the basis of the above considerations we estimate that a 40% reduction in the glider mass of a 12 m bus can be achieved in 2020 by a optimised design and the use of composites. A 33% reduction has already been achieved with the Metroliner. In [Bradley 2000] a mass reduction of 23% in the curb mass of a 12 m transit bus is suggested as a reasonable goal in 2010. We assume a 10% reduction in the glider mass in 2005.

The mass per seat of the S-train has been reduced from 542 kg per seat for the second generation of S-trains to 354[234] kg per seat for the new (fourth) generation of S-trains, i.e. a 34% reduction [DSB 2001 B; Pedersen 2001]. This substantial reduction has been achieved by the optimisation of the ratio between weight and strength of the load carrying elements of the train with the use of the "finite element method", the use of a wider train set enabling more seats per length of the train, the use of fewer (a reduction from 16 axles to 10 for comparable train sets [Pedersen 2001]) bogies and the use of aluminium in the body, brake disks, axle bearings and transmission [DSB 2001 B].

The weight of the bodyshell of the COMBINO LRV has been reduced around 30% compared to an all-steel body construction by the use of aluminium in the underframe, sidewalls and roof of the body and a fiberglass-reinforced plastic foam sandwich for the front [Siemens 2000 B]. This corresponds to a 10% reduction in the curb mass.

Further reduction of the curb mass of the S-train and LRV could be achieved by the use of composites and more widespread use of aluminium. The specific powers of the electric motors and power electronics used in the S-train or LRV are much lower than the values found for electric motors and power electronics used in buses (see Table 8-1 and Table 8-3), so there is also a significant potential for weight reductions of the propulsion system.

Composites should not only be used to reduce the weight of the body, because if the sprung mass of the vehicle gets to small compared to the unsprung mass, the train will experience vibration problems [Pedersen 2001]. Therefore weight reductions of the bogies are also necessary.

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[233] The width of the 7.5 m bus.

[234] According to the source [DSB 2001 B] the mass per seat of the fourth generation of S-trains is 373 kg per seat corresponding to a curb mass of 125.3 tons, but newer information from [Pedersen 2001] has established the curb mass of the most recently delivered units of the fourth generation of S-train to be 119 tons.

We assume a 20% reduction in the glider mass in 2020 for local trains and LRVs and a 5% reduction in 2005. The weight reduction is only half the value assumed for buses, because we assume that the penetration of new weight-reducing materials and technologies into the local trains and LRVs will be slower. This is founded in the lifetime of local trains and LRVs being considerably longer (30 years compared to 12 years for buses) than the lifetime of buses, and the number of local trains and LRVs produced each year is far smaller than the yearly production of transit buses. Furthermore the technology transfer from the weight reductions of cars will be easier to buses than to rail-bound vehicles, because a bus and a car has a more similar design than a car and a rail-bound vehicle.

9.3.3 Cost of weight reductions

The costs connected with the weight reductions of the glider mass are very difficult to estimate. No estimates of the extra costs connected with the present use of aluminium and composites in buses, LRVs and local trains have been found, but it seems reasonable to assume that the price penalties are small and outweighed by the advantages connected with the use of these materials. If this were not the case these vehicles would be difficult to sell and would probably not be produced.

The extra price of the Metroliner was 400000 DDK in 1990 [Bak 2000 B], which translates into around 18 $ per kg saved[235]. Studies of the costs connected with weight reductions using composites have been done for cars [Das 2001; Mascarin et al. 1996]. [Das 2001] refers to a study giving a costs of 8$ per kg weight saved for a carbon-reinforced thermoplastic body-in-white compared to a steel body-in white not including the derived weight reductions.

The use of fibre-reinforced plastics in the automotive industry is still in its infancy, especially the use of composites as structural elements in vehicles, so there is still room for large cost reductions. Both in Europe and United States development projects are going on with the aim to lower the barriers connected with the use of composites by lowering the costs of composites and increase the experiences with the use of these materials. The material costs of the above mentioned carbon-reinforced thermoplastic body-in-white were 60% of the total production costs with the price of the carbon fibre constituting the main part of the material costs [Das 2001]. The price of carbon-fibre is around 17 $/kg at present for large customers [Advanced Materials and Composites News 2001], where as the price in 1990 (when the above mentioned Metroliner was bought) where around 44 $/kg [Berner 2000], i.e. a cost reduction of around 60% in 10 years. The biggest manufacturer, Zoltek, did make a price-forecast of 11 $/kg already in year 2000 but has not reached that price target yet [Advanced Materials and Composites News 2001]. If the production volumes of carbon-fibre go up due to an increased demand for this fibre in different production sectors, the cost of the carbon fibre will probably continued to decrease.

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[235] Using the US Consumer Price Index to convert the 400000 DDK to 1999 DDK, using an exchange rate of 7.0 DDK/$ and a total weight saving of 4000 kg.

The cost of weight reductions in cars achieved by the use of high-strength steel instead of mild steel is estimated to be largely cost-neutral [Weiss et al. 2000].

Adding to the costs of weight reductions is the fact that plastics, composites and aluminium already to a certain extent are used in the vehicles, indicating that the most obvious and cost effective weight reductions have already been carried out.

As a very rough estimate of the costs connected with the assumed weight reductions in the glider mass an increase in the OEM price of the vehicle of 8 $ per kg saved in 2005 and 4 $ per kg saved in 2020 is assumed. Sensitivity analysis of this cost parameter will be carried out using a variation in the price of weight reductions of ± 4$ per kg saved.

9.4 Accessory loads

There seem to be no precise definition of what constitutes the accessory loads in a vehicle. Some sources include all auxiliary systems driven by the engine, i.e. pumps, compressors, alternators and fans [Bradley 2000], thereby including for example the oil pump, the energy consumption of which alternatively could be included in the assessment of the overall efficiency of the engine. Other sources concentrate only on the equipment not involved in the propulsion of the vehicle [Moore & Lovins 1995], i.e. the equipment used to heat, cool and ventilate the passenger compartment, door openers, lights, power steering, power brakes, entertainment equipment, communication system and computer system.

Vehicle	12 m conv. bus	12 m SHEV bus	12 m conv. bus	Future (2010) 12 m SHEV bus
Average accessory load [kW]	3 mechanical	6 electrical	16.5 electrical, 7.5 mechanical, total load on engine 39.0	6.5 electrical Total load on engine 8.1
Comments	No air condition, value used in SEEK model	Value used in modelling study	Air condition on, value used in modelling study	Air condition on, value used in modelling study
Source	Bak 2000 A	Bavard & Gayed 2000	Bradley 2000	Bradley 2000

Table 9-5 The average accessory loads for 12 m buses used in different modelling studies. The mechanical load is delivered directly from the engine, whereas the electrical load is delivered from a power bus getting power either directly from a generator (alternator) or from a battery, which in turn is charged by the generator.

The accessory loads present in a vehicle depend to a certain extent on the vehicle concept and propulsion system of the vehicle. For example power steering is only present in road-bound vehicles, where as the heating of the passenger compartment do not use any extra energy in conventional vehicles, because they can use the large amount of waste heat from the engine to heat the passenger compartment, which is not an option for EVs.

Table 9-5 shows values for the average accessory load for 12 m buses taken from different sources. As can be seen the values vary considerably, for example for conventional buses the value used in the SEEK model is 3 kW and the value used by [Bradley 2000] is 39 kW. A large part of this difference can be explained by the energy consumption of air condition included in the 39 kW value but not in the 3 kW value. Air condition is the largest auxiliary load in a vehicle by an order of magnitude [Farrington et al. 1999], and the air-conditioning compressor power requirements are around 18 kW in urban buses [Bradley 2000].

The potentials for reductions of the accessory loads in buses are very large. The engine-driven alternator used in conventional propulsion systems to produce electricity has an average efficiency of around 45% on average [Miller et al. 1999], where as the generator and power bus used in a SHEV have an average total efficiency of 80-85% [Miller et al. 1999]. The accessories driven directly by the engine in conventional propulsion system must be able to operate adequately at all operating speeds of the engine. The systems have remained essentially unchanged for several decades, and some of them (air compressors and refrigerant compressors) are heavy and large with poor noise and vibration characteristics [Bradley 2000]. The hydraulic systems used to power steering and power brakes are generally inefficient [Bradley 2000].

In EVs and HEVs it is possible to make all accessories electrically driven. Electric drive provides the capability to operate the accessories independently of the engine in a demand-responsive mode, which saves considerable energy. Electrical drive also provides flexibility to mount and package the accessory systems away from the engine in less hostile environments and in locations providing easy access to maintenance. As an example replacing the constant-operating power-steering pump with an electric-assist demand-responsive unit would give a power saving in excess of 0.90 kW, when the unit is not used, i.e. the vehicle is driving straight or idling. [Bradley 2000] estimate that a 80% decrease in the accessory loads of a 12 m bus can be achieved by changing from a conventional propulsion system to a SHEV propulsion system (see Table 9-5).

The potentials for reduction of the accessory loads in local trains and LRVs are substantially smaller, because in these EVs the accessories are already electrically driven. As for buses it is very important for the size of the accessory loads if the vehicle has air condition or not.

The cooling load in a vehicle can be substantially reduced by the use of spectrally selective glass or coated plastics, which allows the visible light to go through the windows but reflects the infrared radiation, thereby reducing the amount of sun energy absorbed in the vehicle [Farrington et al. 1999; Moore & Lovins 1995]. The heating load can be reduced by the use of insulation and double-glazed windows.

Vehicle	Status	2005	2020
Conventional 12 m bus	3[236] mech.	3 mech.	3 mech.
SHEV, EV or fuel cell 12 m bus		1.5[237] elec.	1.5 elec.
Local train	27[238] elec.	27 elec.	27 elec.
LRV	11[239] elec.	11 elec.	11 elec.

Table 9-6 The values assumed for the average accessory loads. Only accessory loads not directly involved in the propulsion of the vehicle are included, i.e. fuel, oil and water pumps are not included in the values, but assumed to be included in the values for the engine efficiency. The energy consumption of air condition is not included in the values.

Table 9-6 summarises the values used for the average accessory loads in this project. Due to lack of information especially with regard to the accessory loads of LRVs and local trains the values are very uncertain. Part of the costs connected with the reduction of the accessory load in buses are covered by the costs connected with the change to a more advanced propulsion system, so no extra costs are attributed to the reduction in the accessory loads in buses.

[236] [Bak 2000 A].

[237] Assuming all accessory loads being electrically driven and getting power from the power bus. The average power demands of the accessories are reduced to 1.5 kW electrical by the introduction of demand-responsive electrical units.

[238] Assuming an average heating load of 17 kW as explained in Table 5-9, and an average load to ventilation, doors, lights, communications, computer of 10 kW.

[239] Assuming a value equal to 42% of the value used for the S-train, because the total passenger capacity of the LRV is 42% of the total passenger capacity of the S-train.

10. Vehicle level analysis

This chapter contains the analysis of integrated technology packages at the vehicle level. The technology data for fuel cycles, propulsion systems and vehicles presented in chapter 7, 8 and 9 are used in the energy consumption model and propulsion system design model developed in chapter 5. The energy consumption, emission of greenhouse gases and emission of regulated air pollutants are calculated and compared for different transport modes.

Results for two time frames are presented: 2005 representing the short-term possibilities, and 2020 representing the mid/long term possibilities for improvement of the vehicles. First, results using different propulsion systems in a given vehicle concept are presented, where four different vehicle concepts are investigated. Secondly, different vehicle concepts are compared in different driving cycles.

For each vehicle concept and time frame a baseline vehicle is defined representing the incremental improvements in the vehicle concept happening continuously and more or less "by-it-self" as a result of the competition in the market. The other vehicles in the vehicle concept should be compared to the baseline vehicle, such that the advantages of new propulsion systems are not over-estimated.

The increase in retail price of the vehicles relative to the baseline vehicles and the net present value of the fuel savings, reductions of the emission of GHG and reductions in the emissions of regulated air pollutants obtained relative to the baseline vehicles are calculated.

Sensitivity analysis of the energy consumption and emission results obtained is carried out by calculating the results under best and worst case assumptions. In the worst case the parameters are varied according to the following:

- The vehicle load parameters (glider mass, coefficients of rolling resistance and air drag) are increased by 10%.
- The thermal efficiency of the engine and the peak and average efficiencies of electric motor, generator, power electronics and transmission is decreased by 2%, and the frictional mean effective pressure of the engine is increased by 2%.
- The efficiency of the electricity storage is decreased by 5%, and the efficiency of the fuel cell is decreased by 10%.
- The highest value of fuel cycle process energy and fuel cycle GHG emissions are used.

In the best case all of the above assumptions are reversed, e.g. the vehicle loads are decreased by 10% etc. The 10% variation of the vehicle load parameters are chosen as a reasonable estimation of the possible variation between different vehicle designs (glider mass and coefficient of drag) and between the coefficients of rolling resistance of different tyres and wheels. The variations chosen for the efficiency parameters of the propulsion subsystems reflect that the uncertainties in the determination of the efficiencies of electric motors, generators, power electronics, transmissions and engines are considered rather small. For electricity storages and especially fuel cells larger uncertainties are in our opinion connected with the determination of the efficiencies. This is reflected in the choice of larger variations of the efficiency parameters of these systems.

All parameter changes in the two cases influence the results in the same direction, which is the reason for designating the above changes in the parameter values as best and worst cases. The results obtained by using the unchanged parameter values found in the technology analysis is designated the neutral case.

The sensitivity of the results found in this way indicates the absolute sensitivity in the energy consumption and emission of GHG for a single vehicle design. When comparing the energy consumption and emission of GHG of two vehicle designs, the sensitivity in the results will be much smaller, because most of the changes in the parameter values will influence the energy consumption and emission of GHG of each vehicle design in the same way. The more propulsion subsystems the two vehicle designs have in common, the smaller the uncertainty in the results obtained when comparing the two vehicle designs.

10.1 Calculation of net present value

The net present value of investing in an advanced public transport mode (i.e. one using a hybrid electric, electric or fuel cell propulsion system or one with large reductions in the curb mass) compared to investing in the comparable baseline transport mode is calculated using the following equation [Finansministeriet 1999]:

$$NPV = \sum_{t=0}^{T} \frac{B_{A,t} - B_{B,t} - C_{A,t} + C_{B,t}}{(1+r)^t}$$

NPV: net present value of investing in an advanced public transport mode compared to investing in the comparable baseline vehicle [$].
T: the economical lifetime of the vehicle [years].
$B_{A,t}$: the benefits of the advanced vehicle in the year t [$].
$B_{B,t}$: the benefits of the baseline vehicle in the year t [$].
$C_{A,t}$: the costs of the advanced vehicle in the year t [$].
$C_{B,t}$: the costs of the baseline vehicle in the year t [$].
r: the discount rate, where 6% is used as recommended in [Finansministeriet 1999].

The benefits of the advanced and the baseline vehicle (providing transportation to some people) are assumed to be the same for the two vehicles, because they belong to the same vehicle concept and transportation mode i.e. they provide the same transport service. The costs included in the calculation of the net present value are the capital cost of a vehicle, the electricity storage replacement costs, the fuel costs, the costs of the emission of GHG and the costs of the emission of regulated air pollutants.

The inclusion of the costs of emission of GHG and local emissions in the calculation of the net present value implies that the calculation is done from the viewpoint of society. The reason for choosing the viewpoint of society instead of the viewpoint of the operators of the transport modes, is that public transport is subsidised by society [PLS 2000], thus if it is advantageous to introduce advanced public transport modes from the viewpoint of society, there are good possibilities for changing the subsidy in a direction that favours the advanced public transport modes.

The capital cost (retail price) of a vehicle is calculated as the sum of the retail price of the propulsion system and the retail price of the vehicle exclusive the propulsion system. The retail price of the propulsion system is the sum of the costs to the original equipment manufacturer (OEM) for each subsystem[240] multiplied by an overhead factor covering sales and marketing, administration, depreciation, research and development and a profit for the OEM. An overhead factor of 1.3 is used taken from [An et al. 2000]. The retail price of the vehicle exclusive the propulsion system is assumed to be equal to the present price of a comparable vehicle exclusive the propulsion system plus the costs connected with mass savings (see section 9.3.3). Taking the difference between the retail price of the advanced and the baseline vehicle the present retail price of a comparable vehicle exclusive propulsion system disappears from the calculation, so this value does not influence the results. In other words the difference in retail price between the advanced and the baseline vehicle is assumed to be a result of the difference in propulsion system prices and the extra costs associated with mass savings larger than the ones assumed for the baseline vehicle.

The lifetime of a given type of electricity storage is assumed to be equal to the calendar life of the electricity storage. For year 2005 vehicles the replacement cost is calculated from the equation:

$$P_E(2005+t) = P_E(2005) + \frac{P_E(2020) - P_E(2005)}{2020-2005}t$$

For year 2020 vehicles the replacement cost is equal to the retail price of the electricity storage in year 2020, i.e. no further price reduction of the electricity storage is assumed after year 2020. A scrap value proportional to the years of useable life left in the electricity storage when the vehicle is discarded is assigned to electricity storages.

The yearly fuel cost, the yearly costs of the emission of GHG and the yearly costs of the emission of regulated air pollutants are calculated using equations of the following form:

$$P_{i,Y} = E_i p_i D_Y \qquad \text{where} \qquad i = fuel, GHG, NO_X, CO, Particles, HC$$

$P_{i,y}$: the yearly cost of fuel or the yearly cost of greenhouse gas emission or the yearly costs of emission of either NO_X, CO, particles or NMHC [$].
E_i: the energy consumption per vehicle km or the emission of GHG per vehicle km or the emission of either NO_X, CO, particles or NMHC per vehicle km [GJ/km or kg/km].
p_i: the price of fuel per GJ, or the costs connected with the emission of GHG or the costs connected with the emission of either NO_X, CO, particles or NMHC [$/GJ or $/kg].

240 It is the OEM (original equipment manufacturer) costs that are given in the technology analysis tables in chapter 8.

D_Y: the yearly driven distance of the vehicle [km]. It is calculated by assuming that the vehicle is used 4750 hours a year[241], which is multiplied with the average speed of the vehicle driving in a given driving cycle.

The assumed costs connected with the emission of GHG and emission of regulated air pollutants are given in Table 10-1.

GHG [$/kg CO_2 eqv.]	NO_X [$/kg]	CO [$/kg]	Particles [$/kg]	HC [$/kg]
0.032	14.3	0.71	14.3	4.0

Table 10-1 Socio-economic costs connected to emission of GHG and air pollutants [Finansministeriet 1999].

The costs not included in the calculation of the net present value are the costs connected with noise, maintenance and repair costs and the cost of vehicle infrastructure. The maintenance and repair effort required and the reliability and availability of public transport modes are very important for the operators of public transport modes. According to [Siemens 2000 C] the maintenance costs including investment costs for standby rolling stock (availability) of rail-bound mass transit vehicles are of the same size as the investment costs of the rolling stock. As can be seen the maintenance and repair costs are an important part of the total cost picture of public transport modes, but unfortunately the estimation of these costs is difficult due to a lack of data about these issues for technologies, which are not yet on the market. An important part of the learning process for new technologies from the first prototypes to a market-ready product is to increase the availability and reliability to a level comparable to the level achieved by the mature technologies already on the market.

The capital cost and maintenance and repair cost of the vehicle infrastructure are also left out of the calculation of the net present value. For the comparison of public transport modes assumed to be using already established vehicle infrastructure (already existing roads or tracks), it is correct to leave out the capital cost of the vehicle infrastructure. The wear on the vehicle infrastructure is strongly dependent on the axle pressure of the vehicles[242], which means that weight savings of the vehicles would be more profitable if maintenance and repair costs where included in the calculation of the net present value.

All in all the omission of the above mentioned costs combined with the uncertainty in the estimations of the cost and durability of future propulsion subsystems imply that the results obtained from the net present value calculations should not be over-interpreted.

Sensitivity analysis of the economical results are carried out by varying the parameters of the electric motor, power bus, generator, electricity storage and fuel cell according to the best and worst case parameter assumptions. The propulsion system cost of the advanced vehicles are varied by ± 25%, and the costs of weight savings are changed by ± 4 $/(kg saved). The neutral case energy consumption, emissions, fuel cost and vehicle retail price values of the baseline vehicle are used in the calculation of the net present val-

[241] Assuming a daily use of 14 hours a day, 339 days a year, i.e. the vehicle is take out of operation around 4 weeks a year due to maintenance requirements.

[242] The wear on a road increases with the fourth power of the axle pressure [Bak 2000 B].

ues. The fuel costs of fuels other than diesel[243] and gasoline are varied by using the highest or lowest value of the fuel costs. The vehicle load parameters and the parameters of the transmissions and engines are kept constant at the neutral case values, because changes in these parameters influence the energy consumption and emissions results for the advanced vehicles in the same direction as the baseline vehicle.

10.2 12 meter buses in 2005

Nine different vehicle designs have been defined for 12 meter buses in 2005, three using a conventional propulsion system, four series hybrid buses using different types of electricity storage systems, and two electric buses using different types of batteries. The vehicle designs are specified in Table 10-2, which contains identification names for each subsystem used in the propulsion system, vehicle load parameters and the sizes of the subsystems used in the propulsion system. The subsystem identification names can be used in the relevant tables in chapter 7and 8 to find the parameter values used for a given subsystem in the calculations. For example if the electricity storage ID is PbAcid_HEV_2005 the data used for the electricity storage is given in Table 8-6, column 4. The values of the average efficiency of electric motors (Table 8-1 and Table 8-2) depend on the choice of driving cycle. It is assumed that the motor efficiencies in LineA and Line LRV are the same, and the motor efficiencies in Line5_mod and Line5suburbs_mod are the same.

Compared to the values used for the present conventional buses, the baseline bus in 2005 has reduced rolling resistance and an improved compression ignition engine while the rest of the vehicle parameters are unchanged. The improved conventional bus in 2005 is equal to the baseline bus in 2005 except for a 10% reduction in the glider mass.

[243] As the baseline vehicle uses diesel varying the cost of diesel will only provide little change in the net present value results for the advanced vehicles using diesel, and the changes in the net present values of vehicles using other fuels than diesel will be underestimated if the diesel cost is varied in the same direction as the costs of the other fuels. The fuel cost of gasoline is also kept constant because the gasoline cost is assumed to vary in the same way as diesel.

Vehicle name	1999 CI diesel conv.	Baseline 2005 CI diesel conv.	2005 CI diesel conv.	2005 SI NG conv.	2005 SHEV PbAcid	2005 SHEV NiMH	2005 SHEV Ultra/PbAcid	2005 SHEV Ultra/NiMH	2005 EV PbAcid	2005 EV NiMH
Propulsion system type	Conv	Conv	Conv	Conv	SHEV	SHEV	SHEV	SHEV	EV bat	EV bat
Fuel cycle ID	Diesel_1999	Diesel_2005	Diesel_2005 /RME_2005	CNG_2005	Diesel_2005	Diesel_2005	Diesel_2005	Diesel_2005	EL_NG_2005	EL_NG_2005
Fuel storage ID	Liquid_1999	Liquid_2005	Liquid_2005	25MPa_2005	Liquid_2005	Liquid_2005	Liquid_2005	Liquid_2005		
Engine ID	CI_1999	CI_2005	CI_2005	SI_NG_2005	CI_2005	CI_2005	CI_2005	CI_2005		
Generator ID					PM_2005	PM_2005	PM_2005	PM_2005		
Power bus ID					PB_2005	PB_2005	PB_2005	PB_2005	PB_2005	PB_2005
Electricity storage ID					PbAcid_HEV_2005	NiMH_HEV_2005	Ultra_2005/ PbAcid_EV_2005	Ultra_2005/ NiMH_EV_2005	PbAcid_EV_2005	NiMH_EV_2005
Motor ID					IM_2005	IM_2005	IM_2005	IM_2005	IM_2005	IM_2005
Transmission ID	4_aut_2000	4_aut_2000	4_aut_2000	4_aut_2000	1_central	1_central	1_central	1_central	1_central	1_central
Vehicle load parameters										
Curb mass [kg]	10938	10736	9751	9987	9859	9859	9637	9516	12747	10702
Frontal area (A) [m^2]	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75
Drag coefficient (C_D)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
1. Rolling resistance coeff. (C_{R1})	0.009	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075
Auxiliary power (P_{AUX}) [kW]	3	3	3	3	1.5	1.5	1.5	1.5	1.5	1.5
Sizing of subystems										
Engine power [kW]	171	169	160	162	72	72	72	71		
Engine displacement [liters]	9.02	8.92	8.40	8.53	3.79	3.79	3.77	3.75		
Generator power [kW]					76	76	76	75		
Power bus power [kW]					159	159	157	155	187	167
Motor power [kW]					148	148	146	145	175	156
Transmission power [kW]	168	166	157	159	148	148	146	145	175	156
Electricity storage efficiency					0.85	0.85	0.90	0.90		
Electricity storage power [kW]					98	98	105	105	1414	558
Electricity storage energy [kWh]					12.5	25.5	10.5	10.5	124	112

Table 10-2 Specification of vehicle designs for 12 meter buses in 2005. An EV-range of 5 km is used in the determination of the electricity storage size of SHEVs. The values of the power output of electricity storages given the table are measured at the specified electricity storage efficiencies for SHEVs and at the matched impedance condition for EVs. The size of the electricity storages for EVs is determined by requiring that the electric buses can operate 4 hours between recharges on a discharge from 100% SOC to 20% SOC.

In two of the series hybrid buses electricity storages using a combination of ultracapacitors and batteries are defined to investigate if a combination of these electricity storage technologies can be superior in terms of performance and price relative to battery storages consisting of one type of batteries. The masses of ultracapacitors and batteries were determined by the following equations:

$$\begin{aligned} E_E &= s_{UC} M_{UC} + s_{BAT} M_{BAT} \\ P_E &= q_{UC} M_{UC} + q_{BAT} M_{BAT} \end{aligned} \qquad (10\text{-}1)$$

E_E : the energy storage capacity of the electricity storage [Wh].
P_E: the power output of the electricity storage at 0.90 average efficiency[244] [W].
s_{UC}: the specific energy of the ultracapacitors [Wh/kg].
s_{BAT}: the specific energy of the batteries [Wh/kg].
q_{UC}: the specific power of the ultracapacitors [W/kg].
q_{BAT}: the specific power of the batteries at an average efficiency of 0.85 [W/kg].
M_{UC}: the mass of the ultracapacitors [kg].
M_{BAT}: the mass of the batteries [kg].

The equation system 10-1 is solved for M_{UC} and M_{BAT}, and the total weight of the electricity storage is the sum of the masses of the ultracapacitors and batteries. We have assumed that the series hybrid buses should have an EV-range of at least 5 km. Using this assumption model calculations have shown that P_E equal to 100 kW and E_E equal to 10 kWh are reasonable values for SHEV buses in 2005, and these values have been used to determine M_{UC} and M_{BAT}.

Using ultracapacitors in combination with batteries will increase the specific power of the combined system and decrease the specific energy relative to a system using only batteries. The ultracapacitors are very suitable to provide large power outputs in short time intervals, and will therefore relieve the power requirements on the batteries.

Figure 10-1 and Figure 10-2 show respectively the energy consumption and emission of GHG of the buses relative to the baseline bus. The markers show the results using the values found in the neutral case (using the parameter values found in the technology analysis). The lengths of the bars show the variation in the results between the worst and best case parameter assumptions. The variations are large being plus 18-21% for the worst case and minus 16-18% for the best case relative to the neutral case for the energy consumption of conventional buses, plus 41-43% and minus 30-32% for the energy consumption of series hybrid buses, and plus 37% minus 29% for the energy consumption of electric buses. The variations are not symmetrical around the neutral case results, which is due to the expressions used in the calculations being non-linear in some of the parameters changed.

The baseline bus reduces the energy consumption with 5% relatively to a conventional diesel bus today, and the improved conventional bus reduces the energy consumption with 6% relatively to the baseline bus. Using series hybrid buses a 50% reduction in the

[244] The average efficiency of the ultracapacitors are 0.92 and the specific power of the batteries is scaled with the use of equation 8-4 assuming average battery efficiency of 0.85. The resulting average efficiency of the electricity storage is assumed to be 0.90.

energy consumption relatively to the baseline bus can by achieved. A reduction of approximately 53% can be achieved by using electric buses relatively to the baseline bus, assuming the electricity is produced by combined cycle natural gas power plants without district heating. The electric buses have approximately four hours of operation time between recharges, so the operation of these buses during a whole day requires a fast recharging station situated somewhere along the route of the electric buses.

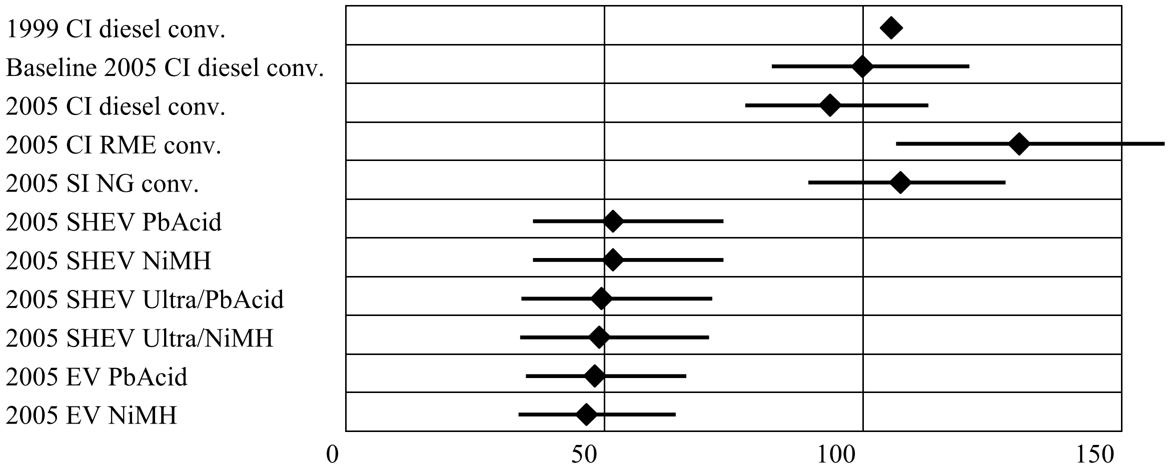

Figure 10-1 The energy consumption of 12 m buses in 2005 driving in Line5_mod including the fuel cycle process energy relative to the baseline bus. The series hybrid buses use a compression ignition engine with diesel as fuel. The reference energy consumption (equal to 100 in the figure) of the baseline bus is 20.2 MJ/km. The value of f_R is 0.85 for all vehicles. For the series hybrid buses α=0.25 and T_{FC}=1652 s.

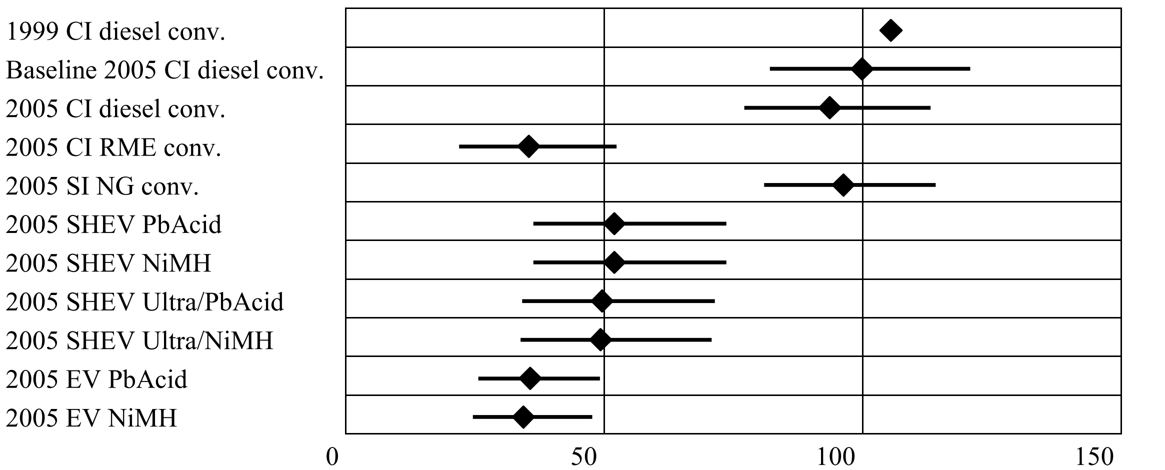

Figure 10-2 The emission of GHG of 12 m buses in 2005 driving in Line5_mod including the fuel cycle emissions relative to the baseline bus. The reference emission of GHG (equal to 100 in the figure) of the baseline bus is 1.60 kg CO_2 eqv./km. The series hybrid buses use a compression ignition engine with diesel as fuel. The value of f_R is 0.85 for all vehicles. For the series hybrid buses α=0.25 and T_{FC}=1652 s.

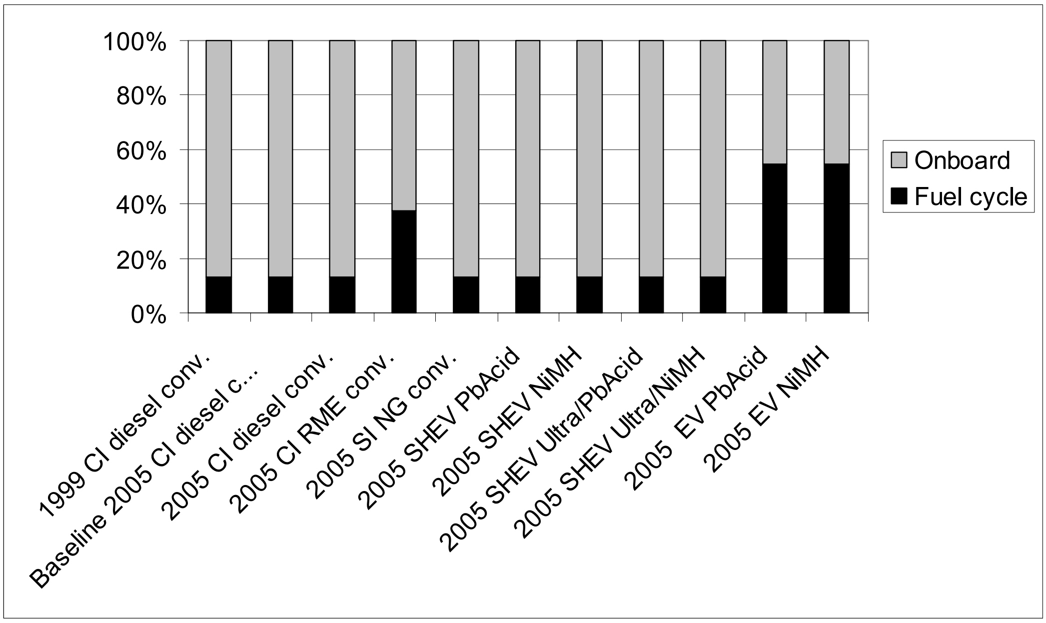

Figure 10-3 The distribution of the energy consumption between energy used by the vehicle and energy used in the production and distribution of the fuel.

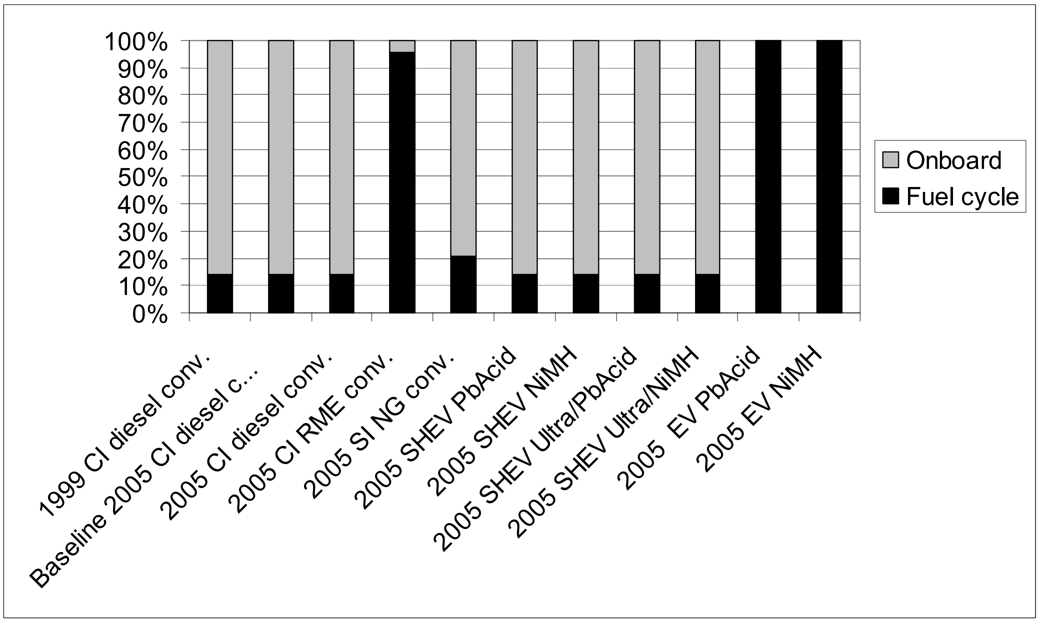

Figure 10-4 The distribution of the emission of GHG between emissions from the vehicle and emissions in connection with the production and distribution of the fuel.

The emission of GHG can be reduced by approximately 50% by using series hybrid buses relatively to the baseline bus, by approximately 65% using RME as fuel instead of diesel in conventional buses, and by approximately 65 % using electricity buses relatively to the baseline bus.

The reductions in the energy consumption and emission of GHG of the series hybrid bus using a combination of ultracapacitors and NiMH-batteries relative to the series hybrid bus using PbAcid-batteries are approximately 6%. This is due to the assumed 6% higher average efficiency of the ultracapacitors/NiMH-batteries electricity storage relative to the PbAcid electricity storage (see Table 10-2), and due to the 343 kg total weight reduction (equal to a weight reduction of 4%) achieved with the use of an electricity storage with higher specific power and specific energy relative to the PbAcid batteries[245]. For electric buses the use of NiMH batteries instead of PbAcid batteries gives a curb mass reduction of 2045 kg, but because the average energy efficiency of the NiMH batteries are 9% lower than the average efficiency of PbAcid batteries, the resulting reduction in the energy consumption and emission of GHG is only 4%.

Figure 10-3 and Figure 10-4 show the distribution of the energy consumption and emission of GHG between the vehicle and the fuel cycle.

	RP + battery replacement	Fuel savings	GHG reductions	Reductions regulated emissions	NPV	Variation NPV
2005 CI diesel conv.	-6417	5245	2291	5613	6731	± 7000
2005 CI RME conv.	-6417	-37659	23349	5613	-15114	± 32000
2005 SI NG conv.	-29703	-26392	1177	28381	-26536	± 25000
2005 SHEV PbAcid	-20538	39912	17323	27127	63823	± 25000
2005 SHEV NiMH	-44658	39912	17323	27127	39704	± 27500
2005 SHEV Ultra/PbAcid	-23195	41760	18136	29965	66666	± 28000
2005 SHEV Ultra/NiMH	-25342	42079	18276	30430	65444	± 28000
2005 EV PbAcid	-55144	25496	23246	84588	78186	± 21000
2005 EV NiMH	-89680	27456	23688	84588	46053	± 39000

Table 10-3 The retail price difference plus the discounted battery replacement costs, the discounted value of fuel savings during the lifetime of the bus, the discounted value of reductions in emission of GHG during the lifetime of the bus, the discounted value of reductions in emissions of regulated air pollutants during the lifetime of the bus, the net present value of the bus relative to the baseline vehicle in 2005, and the variation in the net present value when the parameters are changed as explained in section 10.1. The lifetime of the bus is assumed to be 12 years, the discount rate is 6%, the yearly driven distance is 83900 km, and the buses are driving in Line5_mod. All values in US $.

Table 10-3 shows the economical results. All the defined vehicles are more expensive than the baseline with the retail price increment plus the battery replacement costs varying between approximately 6000 $ for the conventional bus to 90000 $ for the electric bus with NiMH-batteries. The retail price difference between actual natural gas buses compared to diesel buses is around 38000 $ [West et al. 1998], where the model result for 2005 is 29703-6417=23286 $.

All the vehicles achieve savings in the fuel cost except the conventional bus using RME and the natural gas bus, the reason being that the costs of one GJ of RME and natural gas

[245] The specific power and specific energy of the ultracapacitor/NiMH-battery electricity storage are respectively 353 W/kg and 35 Wh/kg whereas the same figures for the PbAcid battery are 173 W/kg and 22 Wh/kg.

including the costs of the fuel infrastructure are respectively 55% and 22% higher than the cost of diesel, and in the case of the natural gas bus that it uses approximately 7% more energy per vehicle kilometre than the baseline bus.

The net present values are positive for all vehicles except the conventional bus using RME and the natural gas bus with the most favourably option being an electric bus with PbAcid batteries. This is worth noting since the most popular bus type for use in urban areas after the conventional diesel bus is natural gas buses [Bradley et al. 2000]. The model results indicate that series hybrid buses could become a very attractive alternative to the use of natural gas buses assuming that the maintenance costs of series buses will be comparable in size to the maintenance costs of natural gas buses. The net present values of series hybrid buses using different electricity storages are within uncertainty the same except for the series hybrid bus using NiMH-batteries, which has a net present value approximately 40% lower than the other series hybrid buses.

As the calculation of the emission of regulated air pollutants in the model is oversimplified and therefore very uncertain, it is interesting to look at the net present values excluding the value of the reductions in regulated air pollutants. This is done by subtracting column 5 from column 6 in Table 10-3. Doing this the series hybrid buses (except the option with NiMH-batteries) become the most attractive vehicles to invest in from the viewpoint of socio-economics.

10.3 Buses in 2020

Results from 12 different designs of 12 m buses in 2020 are presented. The vehicle designs are given in Table 10-4. The baseline bus has reduced rolling resistance, a conventional propulsion system using a 5 speed clutched automatic transmission, an improved compression ignition engine using diesel with emissions reductions equipment, and a 15% reduction in the glider mass of the vehicle relative to the glider mass of 12 m buses today.

Series hybrid buses using PbAcid-battery, NiMH-battery, LiIon-battery, LiPolymer-battery, flywheel, ultracapacitors/PbAcid-battery and ultracapacitors/LiPolymer-battery were designed in the model[246]. The PbAcid-battery, ultracapacitors/PbAcid-battery and ultracapacitors/LiPolymer-battery turned out to be the most advantageous with regard to price versus performance. No price estimation has been found for the flywheel, but it compares favourably with the ultracapacitors/PbAcid-battery and ultracapacitors/LiPolymer-battery if the OEM price of the flywheel can be brought below 600 $/kWh.

[246] We have assumed that the series hybrid buses should have an EV-range of at least 5 km. Using this assumption model calculations have shown that P_E equal to 80 kW and E_E equal to 6 kWh are reasonable values for SHEV buses in 2020, and these values have been used to determine M_{UC} and M_{BAT}. The power of the batteries have been determined assuming an average efficiency of 0.90, and the efficiency of the ultracapacitor is 0.94. Therefore an average efficiency of the combined system of 0.92 is assumed.

Electric buses using PbAcid, NiMH, LiIon and LiPolymer batteries have been designed in the model assuming that the buses should be able to operate 16 hours between recharges on a discharge from 100% SOC to 20% SOC. The LiPolymer-battery turned out to be the best with regard to price versus performance with the weight of the PbAcid electricity storage being 14.3 tons, the weight of the NiMH-battery being 4.4 tons, the weight of the LiIon-battery being 2.6 tons and the weight of the LiPolymer-battery being 2.4 tons. The results for the mass of the vehicles (see Table 10-4) show that it will be possible in 2020 to make an electric bus with the ability to operate a whole day between recharges without the mass of the vehicle getting excessively large.

Figure 10-5 and Figure 10-6 show the energy consumption and emission of GHG of the advanced buses in 2020 relatively to the baseline vehicle. The markers show the results using the values found in the neutral case (using the parameter values found in the technology analysis). The lengths of the bars show the variation in the results between the worst and best case parameter assumptions.

The baseline vehicle itself reduces the energy consumption and emission of GHG by approximately 40% relatively to a conventional bus today. The reduction of the glider mass of the conventional bus with 25% relatively to the glider mass of the baseline bus enables an 18% reduction of the energy consumption and emission of GHG of the conventional bus relatively to the baseline bus. This 18% reduction is a result of an 18% reduction in the vehicle loads following from the weight savings[247], and a 16% reduction in the engine friction following from the engine downsizing made possible by the weight savings.

The series hybrid buses reduces the energy consumption and emission of GHG by approximately 60% relatively to the baseline bus, i.e. a factor of four reduction of the energy consumption and emission of GHG relatively to a conventional bus today. Using an induction motor instead of a permanent magnet motor in the propulsion system of series hybrid vehicles increases the energy consumption by 8%. The net present value of the series hybrid bus using an induction motor is 6% lower than the net present value of the equivalent bus using an permanent magnet motor (see Table 10-5) indicating that it is profitable to use permanent magnet motors instead of induction motors in series hybrid buses from the viewpoint of socio-economics.

[247] A 27% reduction of the curb mass of the conventional bus relatively to the baseline bus is achieved (see Table 10-4), because the 25% reduction in the glider mass enables a smaller propulsion system to be used.

Vehicle name	Baseline 2020 CI diesel conv.	2020 CI diesel conv.	2020 SHEV PbAcid	2020 SHEV Ultra/LiPo	2020 SHEV Ultra/LiPo IM motor	2020 fuel cell CH2	2020 fuel cell MeOH	2020 fuel cell Gasoline	2020 EV LiIon	2020 EV LiPo	2020 EV LiPo IM motor
Propulsion system type	Conv	Conv	SHEV ICE	SHEV ICE	SHEV ICE	SHEV FC	SHEV FC	SHEV FC	EV bat	EV bat	EV bat
Fuel cycle ID	Diesel_2020	Diesel_2020	Diesel_2020	Diesel_2020	Diesel_2020	CH2_NG_2020/ CH2_Wind_2020	MeOH_NG_2020/ MeOH_Wood_2020	Gasoline_2020	EL_NG_2020/ EL_Wind_2020	EL_NG_2020/ EL_Wind_2020	EL_NG_2020/ EL_Wind_2020
Fuel storage ID	Liquid_2020	Liquid_2020	Liquid_2020	Liquid_2020	Liquid_2020	34MPa_2020	Liquid_2020	Liquid_2020			
Fuel converter ID	CI_2020	CI_2020	CI_2020	CI_2020	CI_2020	FC_H2_2020	FC_MeOH_2020	FC_Gasoline_2020			
Generator ID			PM_2020	PM_2020	PM_2020						
Motor ID			PM_2020	PM_2020	IM_2020	PM_2020	PM_2020	PM_2020	PM_2020	PM_2020	IM_2020
Transmission ID	5_clutched	5_clutched	1_central	1_central	1_central	1_central	1_central	1_central	1_central	1_central	1_central
Electricity storage ID			PbA-cid_HEV_2020	Ultra/LiPo_EV_2020	Ultra/LiPo_EV_2020	PbA-cid_HEV_2020	PbAcid_HEV_2020	PbAcid_HEV_2020	LiIon_EV_2020	LiPo_EV_2020	LiPo_EV_2020
Vehicle load parameters											
Curb mass [kg]	8773	6387	6401	6021	6040	6304	6401	6309	8705	8443	8704
Frontal area (A) [m^2]	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75
Drag coefficient (C_D)	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
1. Rolling resistance coeff. (C_{R1})	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Auxiliary power (P_{AUX}) [kW]	3	3	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Sizing of subsystems											
Engine power [kW]	145	122	44	44	45	43	44	43			
Engine displacement [liters]	7.64	6.44	2.34	2.31	2.36						
Generator power [kW]			48	47	48						
Power bus power [kW]			120	116	119	119	120	119	141	139	144
Motor power [kW]			116	112	112	115	116	115	137	135	137
Transmission power [kW]	142	119	116	112	112	115	116	115	137	135	137
Electricity storage efficiency			0.90	0.92	0.92	0.9	0.9	0.9			
Electricity storage power [kW]			81	85	85	80	81	80	2350	957	1039
Electricity storage energy [kWh]			10.4	6.4	6.4	10.3	10.4	10.3	287	287	312

Table 10-4 Specification of vehicle designs for 12 meter buses in 2020. An EV-range of 5 km is used in the determination of the electricity storage size of SHEVs. The values of the power output of electricity storages given the table are measured at the specified electricity storage efficiencies for SHEVs and at the matched impedance condition for EVs. The size of the electricity storages for EVs is determined by requiring that the electric buses can operate 16 hours between recharges. The power bus ID is PB_2020.

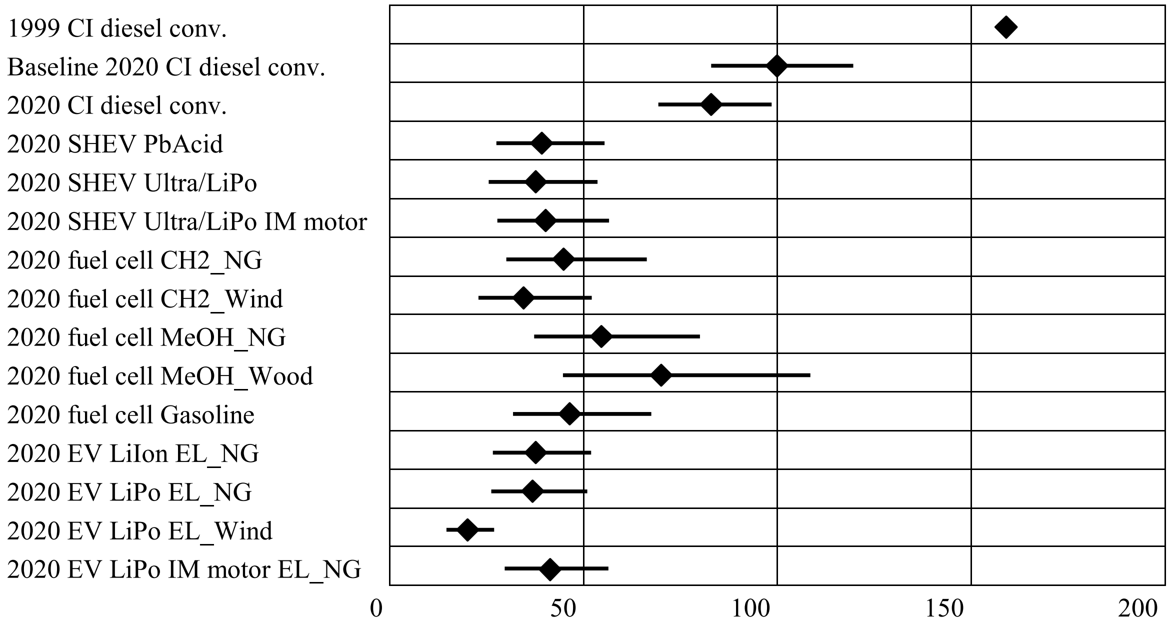

Figure 10-5 The energy consumption of 12 m buses in 2020 driving in Line5_mod including the fuel cycle process energy relative to the baseline bus. The series hybrid buses use a compression ignition engine with diesel as fuel. The series hybrid buses, fuel cell buses and electric buses use permanent magnet motors unless otherwise is indicated in the figure (row 6 and 15). The reference energy consumption (equal to 100 in the figure) of the baseline bus is 13.3 MJ/km. The value of f_R is 0.85 for all vehicles. For the series hybrid buses with PM motor α=0.15 and T_{FC}=1652 s, for the series hybrid buses with IM motor α=0.21 and T_{FC}=1652 s, for the fuel cell buses α=0.10.

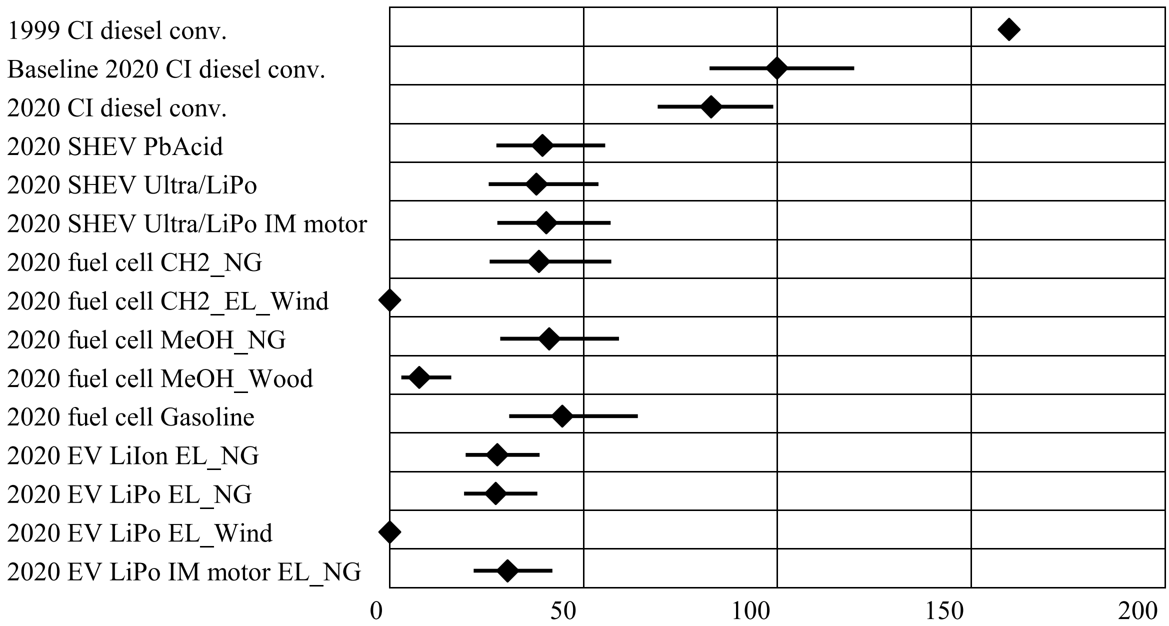

Figure 10-6 The emission of GHG of 12 m buses in 2020 driving in Line5_mod including the fuel cycle emissions relative to the baseline bus. The reference emission of GHG (equal to 100 in the figure) of the baseline bus is 1.06 kg CO_2 eqv./km. See the caption of Figure 10-5 for values of f_R, α and T_{FC} and information about the vehicle designs.

There is a large variation in the results obtained for the different designs of fuel cell buses. Both with regard to energy consumption and emissions of greenhouses gases the fuel cell bus with compressed hydrogen storage and using hydrogen produced by electrolysis using electricity from wind power is the best among the fuel cell buses, the energy consumption and emission of GHG being respectively 35% and 0% of the values found for the baseline bus. Unfortunately the net present value of this fuel cell bus is significantly lower than the net present value of the other fuel cell buses due to the high cost of the hydrogen produced from wind power (see Table 10-5).

The energy consumption of the fuel cell bus using methanol produced from wood is the highest among the fuel cell buses being 70% of the value for the baseline bus, but the emission of GHG are very low being 8% of the value found for the baseline bus. Looking at the fuel cell buses using fossil fuels the bus using compressed hydrogen comes out best with the energy consumption and emission of GHG being respectively 22% and 7% higher for the fuel cell bus using methanol from natural gas, and respectively 3% and 16% higher for the fuel cell bus using gasoline.

The electric bus with LiPolymer-batteries and a permanent magnet motor using electricity produced from wind power achieve the lowest energy consumption and emission of GHG[248] of all the bus designs in this work being respectively 20% and 0% of the values found for the baseline bus. When the electricity is produced from natural gas the performance of electric buses are not as impressive but still very good with the energy consumption being approximately 37% of the baseline value and the emission of GHG being approximately 27% of the baseline value. The electric buses have lower GHG emissions than fuel cell, series hybrid and conventional buses when fossil fuels are used, although this conclusion is not robust towards a fuel change from natural gas to coal in the power plants[249]. Using combined heat and power plants in the model instead of condensing power plants would improve the results obtained for the electric buses, because the energy efficiency of a combined heat and power plant is significantly higher than the energy efficiency of a pure power plant.

Although the energy efficiency of an induction motor in Line5_mod is only 4% smaller than the energy efficiency of a permanent magnet motor, the energy consumption is increased by 12% when using an induction motor in an electric bus with LiPolymer-batteries instead of a permanent magnet motor. This is because the lower energy efficiency of the electric motor necessitates the use of a larger battery, which in turn increases the weight of the vehicle, thereby requiring more powerful propulsion system components. This result underlines the many feedback loops involved in the design of vehicles, and the benefits connected with the use of high efficiency components, which are not only efficient in themselves, but also allows other components in the propulsion system to be made smaller[250].

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[248] Together with the fuel cell bus using hydrogen from wind power.

[249] Such a change would increase the emission of GHG connected with the production of the electricity with approximately 60%, because the CO_2 emission when burning one GJ of coal is 95 kg compared to 60 kg for natural gas.

[250] In our vehicle design model each subsystem in the propulsion system can obtain whatever size is needed, e.g. a change in the motor size from 100 kW to 97.5 kW is no problem in the model. In the real world a subsystem like a motor can only be bought in given standard sizes, i.e. the optimum size of a subsystem will not always be available if the subsystem is not designed specially to a given vehi-

	RP + battery replacement	Fuel savings	GHG reductions	Reduction regulated emissions	NPV	Variation NPV
2020 CI diesel conv.	-12337	9437	4100	2580	3780	± 18000
2020 SHEV PbAcid	-12907	33132	14352	6700	41276	± 22000
2020 SHEV Ultra/LiPo	-14849	34036	14747	7055	40989	± 24000
2020 SHEV Ultra/LiPo IM motor	-14622	32351	14011	6392	38131	± 24000
2020 fuel cell CH2_NG	-16971	18074	14552	14218	29873	± 40000
2020 fuel cell CH2_EL_Wind	-16971	-27680	23744	14218	-6689	± 57000
2020 fuel cell MeOH_NG	-14695	30494	13894	14218	43910	± 31000
2020 fuel cell MeOH_Wood	-14695	-8266	21934	14218	13190	± 50000
2020 fuel cell Gasoline	-14516	25127	13135	14218	37964	± 25000
2020 EV LiIon EL_NG	-182528	25387	17143	14218	-125781	± 61000
2020 EV LiPo EL_NG	-134658	25928	17265	14218	-77247	± 51000
2020 EV LiPo IM motor EL_NG	-145244	22547	16503	14218	-91977	± 54000
2020 EV LiPo EL_Wind	-134658	25928	23744	14218	-70768	± 48000

Table 10-5 The retail price difference plus the discounted battery replacement costs, the discounted value of fuel savings during the lifetime of the bus, the discounted value of reductions in emission of GHG during the lifetime of the bus, the discounted value of reductions in emissions of regulated air pollutants during the lifetime of the bus, the net present value of the bus relative to the baseline vehicle in 2020, and the variation in the net present value when the parameters are changed as explained in section 10.1. The lifetime of the bus is assumed to be 12 years, the discount rate is 6%, the yearly driven distance is 83900 km, and the buses are driving in Line5_mod. All values in US $.

The baseline bus in 2020 has significantly reduced the emission of regulated air pollutants relatively to the baseline bus in 2005. As a consequence, the values of the reductions in regulated air pollutants of the advanced buses in 2020 are much smaller than the values obtained in 2005[251], meaning that the net present value results in 2020 are in general not as favourable as the results obtained for buses in 2005.

The series hybrid and fuel cell buses using fossil fuels have net present values of around 30000-45000 $ while the fuel cell buses using renewable fuels have considerably lower net present values. The net present values of electric buses are around –70000 to –125000 $, which can be entirely attributed to the costs of the large batteries needed to achieve 16 hours operating time between recharges.

Comparing the retail price increments including the battery replacement costs shown in the second column of Table 10-5, it can be seen that the increase in the propulsion sys-

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cle application, which will either increase costs or require high production volumes. Therefore the model probably has a tendency to optimise the vehicle design to a degree, which is not always possible in the real world.

[251] For example the value of the reduction of regulated air pollutants for electric buses is 84588 $ in 2005 and 14218 $ in 2020.

tem costs including battery replacement is only 400-2000 $ for the series hybrid buses and 2000-4000 $ for the fuel cell buses relatively to the conventional bus. This result is highly uncertain for the fuel cell buses where the costs and especially durability of the fuel cells in 2020 can only be determined with high uncertainty. The results for the series hybrid buses are more certain, i.e. the retail price of a series hybrid bus will probably be comparable to a conventional bus in 2020.

10.4 Rail bound vehicles

Two different vehicle concepts are investigated in this section: the local train where the vehicle parameters of the newest generation of S-trains operating in Greater Copenhagen are taken as the starting point, and the light rail vehicle or tram where the vehicle parameters of the Combino product platform from Siemens are taken as the starting point. The propulsion system of choice for these vehicle concepts is the electric with contact line, which has the highest efficiency[252] of all the propulsion systems investigated and results in no emissions from the vehicles. If the vehicle infrastructure (contact lines, converter stations, etc.) is in place on a given route, it is difficult to suggest a propulsion system that can compete with the electric with contact line in terms of local pollution and energy consumption. On routes where the vehicle infrastructure is not in place yet, other propulsion systems, which do not require a contact line, can be considered due to the lower vehicle infrastructure costs connected with using these propulsion systems. As an alternative to using the electric with contact line in local trains and light rail vehicles, we investigate the use of fuel cells in these vehicles.

All in all we end up with 6 vehicle designs for local trains and 6 for light rail vehicles, which are shown in Table 10-6. No baseline vehicles have been defined, but the present vehicles are used as the reference point to which the improved vehicles are compared.

[252] The propulsion system electric with contact line is more efficient than the propulsion system electric with electricity storage, because the average efficiency of the contact line is around 0.95, which is higher than the average efficiency of the electricity storage being around 0.70-0.85. As seen in Figure 10-1 and Figure 10-5 the propulsion system electric with electricity storage is more efficient than the propulsion systems series hybrid with internal combustion engine, series hybrid with fuel cell and conventional.

Vehicle name	1999 Local train EV con.	2005 Local train EV con.	2020 Local train EV con.	1999 LRV EV con.	2005 LRV EV con.	2020 LRV EV con.	2020 Local train fuel cell CH2	2020 Local train fuel cell MeOH	2020 Local train fuel cell Gasoline	2020 LRV fuel cell CH2	2020 LRV fuel cell MeOH	2020 LRV fuel cell Gasoline
Propulsion system type	EV con	EV con	EV con	EV con	EV con	EV con	SHEV FC	SHEV FC	SHEV FC	SHEV FC	SHEV FC	SHEV FC
Fuel cycle ID	EL_NG_1999	EL_NG_2005	EL_NG_2020/ EL_Wind_2020	EL_NG_1999	EL_NG_2005	EL_NG_2020/ EL_Wind_2020	CH2_NG_2020/ CH2_Wind_2020	MeOH_NG_2020/ MeOH_Wood_2020	Gasoline_2020	CH2_NG_2020/ CH2_Wind_2020	MeOH_NG_2020/ MeOH_Wood_2020	Gasoline_2020
Fuel storage ID							34MPa_2020	Liquid_2020	Liquid_2020	34MPa_2020	Liquid_2020	Liquid_2020
Fuel converter ID							FC_H2_2020	FC_MeOH_2020	FC_Gasoline_2020	FC_H2_2020	FC_MeOH_2020	FC_Gasoline_2020
Power bus ID	PB_2000_train	PB_2005	PB_2020	PB_2000_lrv	PB_2005	PB_2020	PB_2020	PB_2020	PB_2020	PB_2020	PB_2020	PB_2020
Motor ID	IM_1999_train	IM_2005	PM_2020	IM_1999_train	IM_2005	PM_2020	PM_2020	PM_2020	PM_2020	PM_2020	PM_2020	PM_2020
Transmission ID	1_train	1_hub	1_hub	1_train	1_hub	1_hub	1_hub	1_hub	1_hub	1_hub	1_hub	1_hub
Electricity storage ID							PbAcid_HEV_2020	PbAcid_HEV_2020	PbAcid_HEV_2020	PbAcid_HEV_2020	PbAcid_HEV_2020	PbAcid_HEV_2020
Vehicle load parame.												
Curb mass [kg]	119033	103538	85795	43681	38819	32082	97636	98980	96856	36745	37132	36664
Frontal area (A) [m^2]	11.55	11.55	11.55	7.59	7.59	7.59	11.55	11.55	11.55	7.59	7.59	7.59
Drag coefficient (C_D)	0.86	0.86	0.77	0.86	0.86	0.77	0.77	0.77	0.77	0.77	0.77	0.77
1. Rolling res. coeff.	0.00205	0.00205	0.00205	0.00205	0.00205	0.00205	0.00205	0.00205	0.00205	0.00205	0.00205	0.00205
2. Rol. res. coeff. [sm^{-1}]	2.6E-05	2.6E-05	2.6E-05	2.6E-05	2.57E-05	0.0000257	0.0000257	0.0000257	0.0000257	0.0000257	0.0000257	0.0000257
Aux. power (P_{AUX}) [kW]	27	27	27	11	11	11	27	27	27	11	11	11
Sizing of subsystems												
Fuel conv. power [kW]							520	522	519	165	165	165
PB power [kW]	1897	1717	1451	816	753	637	1583	1598	1574	696	701	695
Motor power [kW]	1758	1589	1395	757	697	614	1525	1539	1516	671	676	670
Trans. power [kW]	1758	1589	1395	757	697	614	1525	1539	1516	671	676	670
Electricity storage eff.							0.9	0.9	0.9	0.9	0.9	0.9
Elec. sto. power [kW]							1128	1142	1120	560	565	559
Elec. sto. energy [kWh]							144.8	146.6	143.8	71.9	72.6	71.8

Table 10-6 Specification of vehicle designs for local trains and light rail vehicles. The values of the power output of electricity storages given in the table are measured at the specified electricity storage efficiencies for SHEVs.

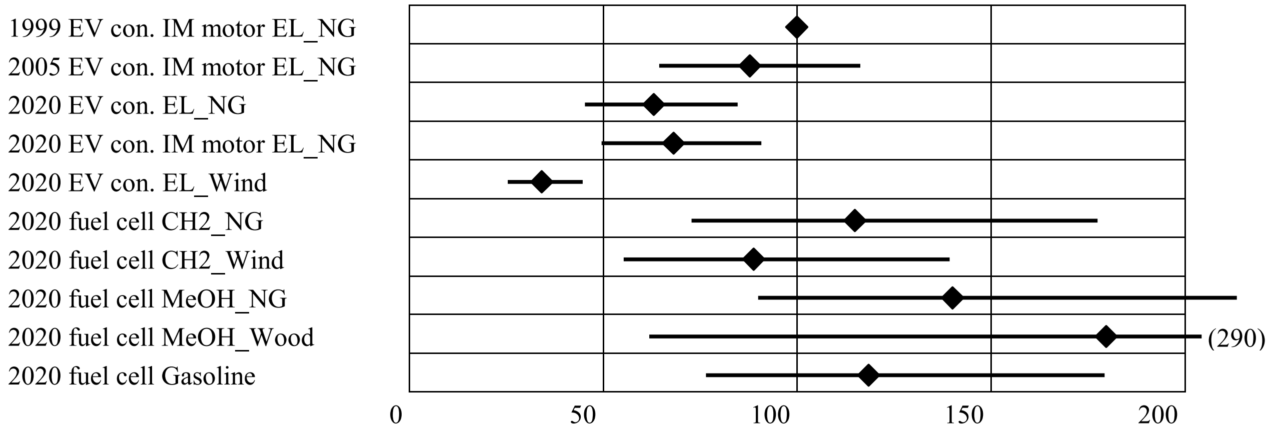

Figure 10-7 Energy consumption of local trains driving in LineA including the fuel cycle process energy relative to the energy consumption of the local train today. The vehicles use permanent magnet motors unless otherwise are indicated in the figure (row 1, 2 and 4). The reference energy consumption (equal to 100 in the figure) of the local train is 40.1 MJ/km. The value of f_R is 0.85 for all vehicles. For the fuel cell trains α=0.29.

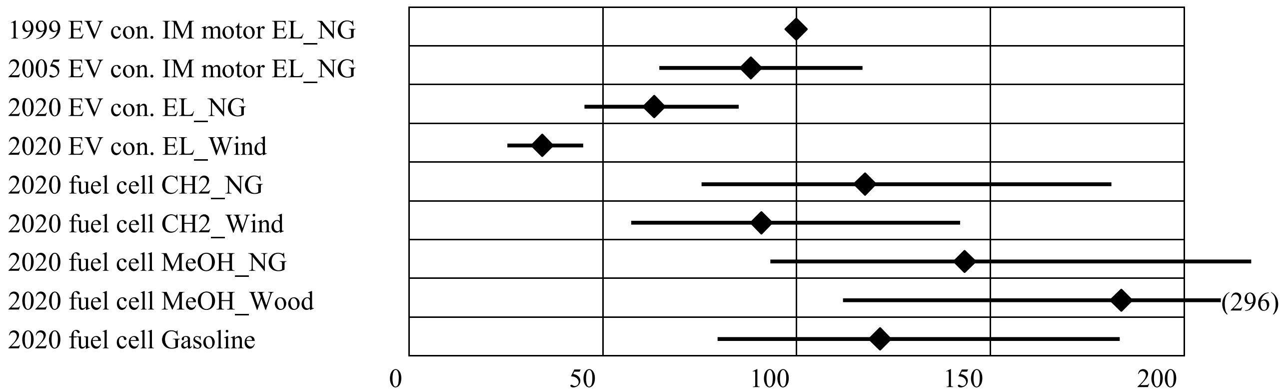

Figure 10-8 The energy consumption of light rail vehicles driving in LineLRV including the fuel cycle process energy relative to the energy consumption of the light rail vehicle today. The vehicles use permanent magnet motors unless otherwise are indicated in the figure (row 1 and 2). The reference energy consumption (equal to 100 in the figure) of the light rail vehicle is 18.3 MJ/km. The value of f_R is 0.85 for all vehicles. For the fuel cell light rail vehicles α=0.29.

Figure 10-7 shows the energy consumption of local trains driving in LineA including the fuel cycle energy consumption relative to the energy consumption value of the local train today, and Figure 10-8 shows the same for a light rail vehicle driving in LineLRV. The markers show the results using the values found in the neutral case (using the parameter values found in the technology analysis). The lengths of the bars show the variation in the results between the worst and best case parameter assumptions.

Comparing the two figures it can be seen that the relative variation in the results for different local train designs is very similar to the relative variation in the results for different light rail vehicle designs. This is because the propulsion subsystems used in the local train designs and light rail vehicle designs use the same size-independent parameter values (specific powers, specific energies, average energy efficiencies)[253].

The results depicted in Figure 10-7 and Figure 10-8 show that the improvement potentials in the future of local trains and light rail vehicles are a 37% reduction in the energy consumption and emission of GHG from now to 2020 assuming the electricity is produced at combined cycle natural gas power plants both today and in 2020, and a 65% reduction in the energy consumption and 100% reduction in the emission of GHG assuming the electricity in 2020 is produced by wind turbines. For comparison the reduction in the energy consumption of series hybrid buses using diesel are 75% in 2020 relative to a conventional diesel bus today, and the reduction in the energy consumption of a electric bus in 2020 getting electricity from wind turbines was 88% relative to a conventional diesel bus today.

As can be seen the improvement potentials of local trains and light rail vehicles are significantly smaller than those found for buses. This is due to the propulsion system electric with contact line already today having very high energy efficiency with the only significant efficiency improvement potentials being a shift from induction motors to permanent magnet motors. A model calculation shows that this reduces the energy consumption of local trains in 2020 by 7%. Another reason for the smaller improvement potentials is the lower weight reduction potential assumed for the local trains and light rail vehicles with a 20% reduction in the glider mass assumed in 2020, and a 40% reduction in the glider mass assumed for buses.

Depending on the fuel cell type and fuel cycle the use of fuel cells in local trains and light rail vehicles in 2020 increases the energy consumption by between 40%-190% relatively to local trains and light rail vehicles in 2020 using the electric with contact line propulsion system and getting electricity from natural gas power plants. The increases in the emission of GHG are between 110%-150% for fuel cell local trains and fuel cell light rail vehicles using fossil fuels (see Figure 10-9 and Figure 10-10). The use of hydrogen produced with the use of wind turbine electricity makes the fuel cell vehicles to zero-emission vehicles, and the use of methanol from wood in the fuel cell vehicles reduces the emission of GHG by 60% relatively to the electric with contact line vehicles in 2020 getting electricity from natural gas power plants.

[253] Except for the specific power values for the power bus used in 1999, where the S-train uses a value of 0.32 kW/kg and the light rail vehicle uses a value of 0.75 kW/kg.

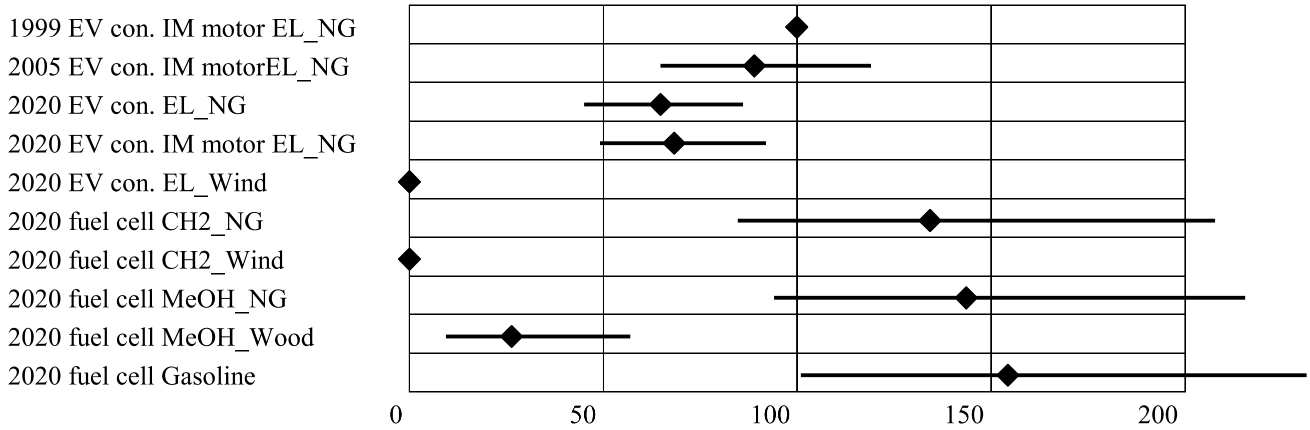

Figure 10-9 Emission of GHG of local trains driving in LineA including the fuel cycle process energy relative to the emission of GHG of the local train today. The vehicles use permanent magnet motors unless otherwise are indicated in the figure (row 1, 2 and 4). The reference emission of GHG (equal to 100 in the figure) of the local train is 2.3 kg CO_2 eqv./km. The value of f_R is 0.85 for all vehicles. For the fuel cell trains α=0.29.

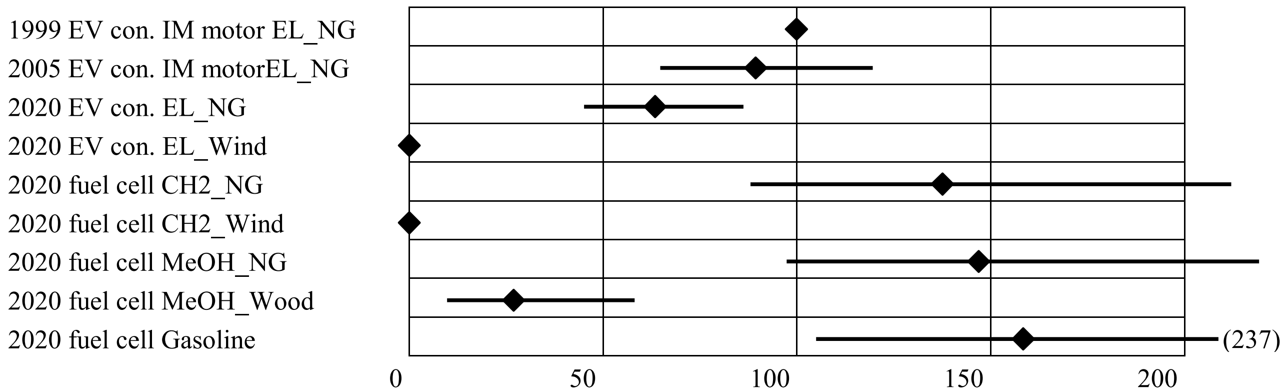

Figure 10-10 Emission of GHG of light rail vehicles driving in LineLRV including the fuel cycle emissions relative to the emission of GHG of the light rail vehicle today. The vehicles use permanent magnet motors unless otherwise are indicated in the figure (row 1 and 2). The reference emission of GHG (equal to 100 in the figure) of the light rail vehicle is 1.1 kg CO_2 eqv./km. The value of f_R is 0.85 for all vehicles. For the fuel cell light rail vehicles α=0.29.

The use of fuel cells increases the curb masses of local trains and light rail vehicles considerably. The curb mass of the local train in 2020 is increased by 13-15% and the curb mass of the light rail vehicle in 2020 is increased by 14-16% depending on the fuel cell type used (see Table 10-6). This mass increase explains part of the increase in the energy consumption when going from an electric with contact line propulsion system to a series hybrid with fuel cell propulsion system. Another reason is that the total well-to-wheel energy efficiency is higher for electric with contact line vehicles than for fuel cell vehicles (see Table 10-7).

Vehicle design	Fuel cycle ID	Propulsion system eff.	Fuel cycle eff.	Total well-to-wheel eff.
1999 Local train EV con.	EL_NG_1999	1.41	0.43	0.61
2005 Local train EV con.	EL_NG_2005	1.39	0.45	0.63
2020 Local train EV con.	EL_NG_2020	1.59	0.48	0.76
2020 Local train EV con.	EL_Wind_2020	1.59	0.88	1.40
2020 Local train fuel cell	CH2_NG_2020	0.84	0.54	0.45
2020 Local train fuel cell	CH2_Wind_2020	0.84	0.70	0.59
2020 Local train fuel cell	MeOH_NG_2020	0.59	0.64	0.38
2020 Local train fuel cell	MeOH_Wood_2020	0.59	0.50	0.29
2020 Local train fuel cell	Gasoline_2020	0.54	0.81	0.44
1999 LRV EV con.	EL_NG_1999	1.48	0.43	0.64
2005 LRV EV con.	EL_NG_2005	1.46	0.45	0.67
2020 LRV EV con.	EL_NG_2020	1.68	0.48	0.80
2020 LRV EV con.	EL_Wind_2020	1.68	0.88	1.47
2020 LRV fuel cell	CH2_NG_2020	0.88	0.54	0.48
2020 LRV fuel cell	CH2_Wind_2020	0.88	0.70	0.62
2020 LRV fuel cell	MeOH_NG_2020	0.61	0.64	0.39
2020 LRV fuel cell	MeOH_Wood_2020	0.61	0.50	0.31
2020 LRV fuel cell	Gasoline_2020	0.57	0.81	0.46

Table 10-7 The propulsion system, fuel cycle and total well-to-wheel efficiencies of different combinations of vehicle designs and fuel cycles.

10.5 Comparison of different vehicle concepts

In this section the energy consumption and emission of GHG of different vehicle concepts are compared. As mentioned in section 5.1 the most common indicator for the energy consumption of public transport modes is MJ per person kilometre (pkm), i.e. the average energy consumption for transporting one person one kilometre. We have not developed a framework enabling us to estimate the passenger load of a transport mode in different demand situations, so our approach will be to calculate the energy consumption and emission of GHG of the vehicles per seatkm[254]. The energy consumption/emissions per person kilometre is given by the energy consumption/emissions per seatkm divided by the degree of utilisation of the vehicle measured as the average number of passengers in the vehicle divided by the number of seats:

$$\frac{X}{D\cdot\# pas} = \frac{X}{D\cdot\# seats}\frac{\# seats}{\# pas}$$

#pas: the average number of passengers on the vehicle in a given demand situation.
#seats: the number of seats in the vehicle.
X: the energy consumption of the vehicle in a given driving cycle [MJ] or the emission of GHG or local air pollutants of the vehicle in a given driving cycle [kg CO_2 eqv]. or [kg] of a given air pollutant.

[254] The energy consumption per seatkm is the energy consumption of a vehicle per km divided by the number of seats in the vehicle.

D: the length of the driving cycle [km].

Having calculated the energy consumption/emissions per seatkm of different vehicle concepts, the degree of utilisation needed for a given vehicle concept to have the same energy consumption/emissions per passengerkm as another vehicle concept can be estimated.

The comparisons of different vehicle concepts are done using technology analysis results of two time frames 2005 and 2020. In 2005 all the buses investigated are assumed to use a series hybrid electric propulsion system with a compression ignition diesel engine. In 2020 all buses use a series hybrid electric propulsion system with a fuel cell using compressed hydrogen produced via electrolysis using electricity from wind turbines. The light rail vehicles and local train use an electric with contact line propulsion system getting electricity from wind turbines.

Three comparisons are made. First, in demand situations with low passenger loads it is relevant to discuss if smaller bus sizes would be more optimal to use. Therefore a 7.2 m bus, a 9 m bus and a 12 m bus all driving in Line5_mod are compared. Secondly, in demand situations with larger passenger loads a choice between large buses or light rail vehicles often exists. Therefore a 12 m bus, an 18 m bus, a 24 m bus (bi-articulated), and a light rail vehicle all driving in LineLRV are compared. Finally for completeness an 18 m bus, a 24 m bus and the local train driving in LineA are compared.

Table 10-8 and Table 10-9 show the vehicle designs used in the comparisons with the seat and total passenger capacity of the vehicles shown in the last row. Existing 7.2 m and 9 m buses from Mercedes have been used as the starting point for the modelling of 7.2 m and 9m buses [Mercedes 2001]. The number of seats in a vehicle can vary a lot. For example, the Vario 7.2 m bus from Mercedes has 20 seats and room for 15 standing, whereas the Cito 8.9 m bus from Mercedes only has 16 seats but room for 40 standing. To ensure a reasonably fair comparison between the buses, the ratio between seat and total passenger capacity of the 7.2 m, 9 m, 18 m, and 24 m buses have been modified in accordance with the ratio between the seat and total passenger capacity of the 12 m bus.

The tractive power at the wheels per mass of the 12 m, 18 m and 24 m buses driving in LineLRV and LineA has been increased to the same as the light rail vehicle (12 kW/tons) to ensure that the vehicles can follow the driving cycles. The tractive power at the wheels of the 7.2 m bus has been set to 12 kW/tons in accordance with the value for present Mercedes Vario buses, and the tractive power at the wheels of the 9 m bus has been set to 11 kW/tons. Both the 7.2 m and 9 m bus will therefore have higher tractive power per mass and therefore be able to accelerate faster than the comparable 12 m buses.

Vehicle name	2005 SHEV 7.2 m bus PbAcid	2005 SHEV 9m bus PbAcid	2005 SHEV 12 m bus PbAcid	2005 SHEV 12m bus PbA-cid LRV	2005 SHEV 18m bus PbA-cid LRV	2005 SHEV 24m bus PbA-cid LRV	2005 SHEV 18m bus PbA-cid train	2005 SHEV 24m bus PbA-cid train	Combino_2005	Strain_2005
Vehicle concept	7.2 m bus	9 m bus	12 m bus	12 m bus	18 m bus	24 m bus	18 m bus	24 m bus	LRV	Local train
Propulsion system type	SHEV	SHEV	SHEV	SHEV	SHEV	SHEV	SHEV	SHEV	EV con	EV con
Fuel cycle ID	Diesel_2005	Diesel_2005	Diesel_2005	Diesel_2005	Diesel_2005	Diesel_2005	Diesel_2005	Diesel_2005	EL_NG_2005	EL_NG_2005
Fuel storage ID	Liquid_2005	Liquid_2005	Liquid_2005	Liquid_2005	Liquid_2005	Liquid_2005	Liquid_2005	Liquid_2005		
Fuel converter ID	CI_2005	CI_2005	CI_2005	CI_2005	CI_2005	CI_2005	CI_2005	CI_2005		
Generator ID	PM_2005	PM_2005	PM_2005	PM_2005	PM_2005	PM_2005	PM_2005	PM_2005		
Power bus ID	PB_2005	PB_2005	PB_2005	PB_2005	PB_2005	PB_2005	PB_2005	PB_2005	PB_2005	PB_2005
Motor ID	IM_2005	IM_2005	IM_2005	IM_2005	IM_2005	IM_2005	IM_2005	IM_2005	IM_2005	IM_2005
Transmission ID	1_central	1_central	1_central	1_central	1_central	1_central	1_central	1_central	1_hub	1_hub
Curb mass [kg]	4527	7138	9859	10668	16988	22307	17700	23170	38819	103538
Frontal area (A) [m^2]	5.83	6.35	6.75	6.75	6.75	6.75	6.75	6.75	7.59	11.55
Drag coefficient (C_D)	0.8	0.8	0.8	0.8	0.8	0.9	0.8	0.9	0.86	0.86
1. Rolling res. coeff.	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.00205	0.00205
2. Rol. res. coeff. [sm^{-1}]									0.0000257	0.0000257
Aux. power (P_{AUX}) [kW]	1	1	1.5	1.5	2	2	2	2	11	27
Fuel conv. power [kW]	53	63	72	74	114	135	174	206		
Engine displacement [l]	2.80	3.29	3.79	3.89	5.98	7.12	9.18	10.82		
Generator power [kW]	56	66	76	78	120	143	184	217		
PB power [kW]	98	132	159	224	353	468	362	480	753	1717
Motor power [kW]	91	123	148	209	330	438	339	449	697	1589
Trans. power [kW]	91	123	148	209	330	438	339	449	697	1589
Electricity storage eff.	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85		
Elec. sto. power [kW]	52	79	98	165	262	363	214	307		
Elec. sto. energy [kWh]	6.6	10.1	12.5	21.1	33.4	46.2	27.2	39.2		
Driving cycle name	Line5_mod	Line5_mod	Line5_mod	LineLRV	LineLRV	LineLRV	LineA	LineA	LineLRV	LineA
α	0.10	0.10	0.25	0.29	0.30	0.36	0.20	0.20		
Braking constant K	0.83	0.83	0.83	0.84	0.84	0.84	0.86	0.87	0.87	0.82
Seat capacity/Total passenger capacity	16/39	21/52	35/87	35/87	54/134	73/182	54/134	73/182	101/252	336/600

Table 10-8 The 2005 vehicle designs used to compare different vehicle concepts. f_R = 0.85 for all vehicles. The electricity storage type used by the series hybrid vehicles is PbAcid_HEV_2005.

Vehicle name	2020 bus 7.2 m fuelcell CH2	2020 bus 9 m fuelcell CH2	2020 bus 12 m fuelcell CH2	2020 bus 12 m fuelcell CH2 LRV	2020 bus 18 m fuelcell CH2 LRV	2020 bus 24 m fuelcell CH2 LRV	2020 bus 18 m fuelcell CH2 train	2020 bus 24 m fuelcell CH2 train	Combino_2020	Strain_2020
Vehicle concept	7.2 m bus	9 m bus	12 m bus	12 m bus	18 m bus	24 m bus	18 m bus	24 m bus	LRV	Local train
Propulsion system type	SHEV FC	SHEV FC	SHEV FC	SHEV FC	SHEV FC	SHEV FC	SHEV FC	SHEV FC	EV con	EV con
Fuel cycle ID	CH2_Wind_2020	CH2_Wind_2020	CH2_Wind_2020	CH2_Wind_2020	CH2_Wind_2020	CH2_Wind_2020	CH2_Wind_2020	CH2_Wind_2020	EL_Wind_2020	EL_Wind_2020
Fuel storage ID	34MPa_2020	34MPa_2020	34MPa_2020	34MPa_2020	34MPa_2020	34MPa_2020	34MPa_2020	34MPa_2020		
Fuel converter ID	FC_H2_2020	FC_H2_2020	FC_H2_2020	FC_H2_2020	FC_H2_2020	FC_H2_2020	FC_H2_2020	FC_H2_2020		
Power bus ID	PB_2020	PB_2020	PB_2020	PB_2020	PB_2020	PB_2020	PB_2020	PB_2020	PB_2020	PB_2020
Motor ID	PM_2020	PM_2020	PM_2020	PM_2020	PM_2020	PM_2020	PM_2020	PM_2020	PM_2020	PM_2020
Transmission ID	1_central	1_central	1_central	1_central	1_central	1_central	1_central	1_central	1_hub	1-hub
Curb mass [kg]	2736	4418	6304	6740	10846	14298	11109	14660	32082	85795
Frontal area (A) [m^2]	5.83	6.345	6.75	6.75	6.75	6.75	6.75	6.75	7.59	11.55
Drag coefficient (C_D)	0.6	0.6	0.6	0.6	0.6	0.7	0.6	0.7	0.77	0.77
1. Rolling resistance. coefficient	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.00205	0.00205
2. Rolling resistance coefficient [sm^{-1}]									0.0000257	0.0000257
Aux. power (P_{AUX}) [kW]	1	1	1.5	1.5	2	2	2	2	11	27
Fuel converter power [kW]	49	55	43	62	69	83	156	185		
Power bus power [kW]	71	95	119	165	260	347	263	351	637	1451
Motor power [kW]	68	92	115	160	253	338	256	343	614	1395
Transmission power [kW]	68	92	115	160	253	338	256	343	614	1395
Electricity storage efficiency	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9		
Electricity storage power [kW]	25	44	80	110	202	279	119	181		
Electricity storage energy [kWh]	3.2	5.7	10.3	14.1	25.9	35.8	15.2	23.3		
Driving cycle name	Line5_mod	Line5_mod	Line5_mod	LineLRV	LineLRV	LineLRV	LineA	LineA	LineLRV	LineA
α	0.10	0.10	0.10	0.01	0.10	0.20	0.10	0.10		
Braking constant *K*	0.83	0.83	0.83	0.84	0.84	0.84	0.86	0.87	0.87	0.82
Seat capacity/Total passenger capacity	16/39	21/52	35/87	35/87	54/134	73/182	54/134	73/182	101/252	336/600

Table 10-9 The 2020 vehicle designs used to compare different vehicle concepts. f_R = 0.85 for all vehicles. The electricity storage type used by the series hybrid vehicles is PbAcid_HEV_2020.

	2005 vehicles				**2020 vehicles**			
Vehicle name	2005 SHEV 7.2 m bus PbAcid	2005 SHEV 9m bus PbAcid	2005 SHEV 12 m bus PbAcid		2020 bus 7.2 m fuelcell CH2	2020 bus 9 m fu-elcell CH2	2020 bus 12 m fuelcell CH2	
Energy consump. per seatkm [MJ/seatkm]	**0.360 (100%)**	**0.353 (98%)**	**0.292 (81%)**		**0.159 (100%)**	**0.153 (96%)**	**0.129 (81%)**	
Vehicle name	2005 SHEV 12m bus PbAcid LRV	2005 SHEV 18m bus PbAcid LRV	2005 SHEV 24m bus PbAcid LRV	2005 Combino	2020 bus 12 m fuelcell CH2 LRV	2020 bus 18 m fuelcell CH2 LRV	2020 bus 24 m fuelcell CH2 LRV	2020 Combino
Energy consump. per seatkm [MJ/seatkm]	**0.297 (100%)**	**0.291 (98%)**	**0.271 (91%)**	**0.159 (54%)**	**0.129 (100%)**	**0.124 (96%)**	**0.116 (90%)**	**0.062 (48%)**
Vehicle name	2005 SHEV 18m bus PbAcid train	2005 SHEV 24m bus PbAcid train	2005 Strain		2020 bus 18 m fuelcell CH2 train	2020 bus 24 m fuelcell CH2 train	2020 Strain	
Energy consump. per seatkm [MJ/seatkm]	**0.335 (100%)**	**0.302 (90%)**	**0.105 (31%)**		**0.155 (100%)**	**0.141 (91%)**	**0.041 (26%)**	

Table 10-10 The energy consumption per seatkm at half seated load for different vehicle concepts. Vehicles in the second row are driving in Line5_mod. Vehicles in the third row are driving in LineLRV, and vehicles in the fourth row are driving in LineA. The numbers in parenthesis are the energy consumption per seatkm of the vehicles relative to the highest energy consumption per seatkm calculated for each driving cycle and time frame.

Table 10-10 shows the energy consumption per seatkm of the different vehicles. As can be seen for both time frames the energy consumption per seatkm of a 12 m bus driving in Line5_mod is only 19% smaller than the energy consumption per seatkm of a 7.2 m bus driving in Line5_mod. The same result is obtained for the emission of GHG in 2005 because both vehicles use diesel. In 2020 both vehicles have zero emission of GHG because they use compressed hydrogen produced via electrolysis using wind power. Therefore, if it is plausible that the average degree of utilisation of 7.2 m buses on a given route will be at least 23% higher than the average degree of utilisation of 12 m buses used on the same route, it will be a more optimal choice to use 7.2 m buses with regard to energy consumption and emission of GHG[255].

[255] This can of course be a bad idea according to other criteria. For example as the passenger load on a given route both can vary along the route and over the time of day, the exclusive use of 7.2 m buses can have as a consequence that on certain places on the route at certain times the passenger capacity of

The energy consumption per seatkm of the light rail vehicle is considerably smaller (40%-50 % depending on the size of the bus) than the energy consumption per seatkm of the 12 m, 18 m and 24 m buses both in short and long term. The same but even more pronounced goes for the local train with an energy consumption per seatkm being around 65%-75 % smaller than 12, 18 and 24 m buses. Looking at the emission of GHG in 2005 the results are even more in favour of the light rail vehicle and local train, because they are assumed to be powered by natural gas power plants, and natural gas emits less GHG than diesel relative to the energy content of the fuels. The emission of GHG per seatkm of the light rail vehicle in 2005 is 57%-60 % smaller than the emission per seatkm of 12, 18 and 24 m buses, and the corresponding figures for the local train are 74%-77% reductions compared to 12, 18 and 24 m buses.

The results indicate that on a given route the degree of utilisation of large buses need to be between 100-150 % higher than the degree of utilisation of light rail vehicles to make a bus solution a more optimal choice than a light rail solution based on energy consumption and GHG criteria. Again it has to be emphasised that the energy consumption and GHG criteria constitute only a small part of the criteria used to select public transport solutions.

10.6 Summary of the results

The main results are the following:

- In the long term (2020) the combination of reduced vehicle loads, an improved transmission system and an improved diesel engine can reduce the energy consumption and emission of GHG of conventional 12 m buses driving in Line5_mod with approximately 50% relatively to a conventional diesel bus today.
- A shift from a conventional propulsion system using a diesel engine to a series hybrid propulsion system using a diesel engine enables a further 50% reduction of the energy consumption and emission of GHG, such that the energy consumption and emission of GHG of 12 m series hybrid diesel buses in 2020 driving in Line5_mod are approximately 25% of the values for a conventional diesel bus today. The retail price difference between conventional diesel buses and comparable series hybrid diesel buses in the long term will be very small (below 5000 $).
- Already in the short term (2005) an approximately 50% reduction of the energy consumption and emission of GHG can be achieved by the use of series hybrid diesel buses relatively to a conventional diesel bus today.
- In the long term an electric 12 m bus using Lithium Polymer batteries can be designed with the ability to operate 16 hours in Line5_mod between recharges while keeping the curb mass at approximately 8.5 tons. Using electricity produced from renewable energy sources like wind power such a bus will have zero or near-zero greenhouse gas emission and the energy consumption will be approximately 13% relatively to a conventional diesel bus today. Using electricity produced by natural gas combined cycle power plants without district heating the greenhouse gas emis-

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the 7.2 m buses is too small and passengers are forced to wait for the next bus. A very frustrating situation for the passengers, that should be avoided if possible.

sion connected with the use of the electric bus will be approximately 17% relatively to a conventional diesel bus today, and the energy consumption will be 23% relatively to a conventional diesel bus today. The emission of air pollutants on the street-level from the bus will be zero. The retail price including the battery replacement costs will be approximately 120000 $ higher for the electric bus compared to a comparable conventional diesel bus.

- Series hybrid fuel cell buses will be an interesting option in the long term, the main reason being that they have zero or near-zero street-level emission of air pollutants, while having the potential to become significantly cheaper than the electric buses and achieve a retail price comparable with conventional diesel buses[256]. Zero or very low GHG emissions can be achieved with the use of hydrogen produced via electrolysis using electricity from renewable energy sources or with the use of methanol produced from biomass[257]. Looking at the fuel cell buses using fossil fuels the bus using compressed hydrogen produced from natural gas comes out best with the energy consumption and emission of GHG being respectively 22% and 7% higher for the fuel cell bus using methanol from natural gas, and respectively 3% and 16% higher for the fuel cell bus using gasoline. The energy consumption and GHG emissions of the fuel cell bus using compressed hydrogen from natural gas are respectively 28% and 24% of the values for a conventional diesel bus today.
- The energy consumption and GHG emissions reduction potentials of local trains and light rail vehicles in the short and long term are significantly smaller than those found for buses. This is explained with the already high efficiency of the electric with contact line propulsion system, and with the smaller weight reductions assumed for the local trains and light rail vehicles compared to buses. The energy consumption and emission of GHG of local trains and light rail vehicles can be reduced with approximately 37% from now to 2020 assuming that the electricity is produced by natural gas combined cycle power plants.
- In the long term using fuel cells in the local trains and light rail vehicles instead of getting power from a contact line will increase the energy consumption between 40%-190% depending on the fuel cell type and fuel cycle, and increase the GHG emissions with 110%-150% for fuel cell local trains and light rail vehicles using fossil fuels. The use of fuel cells in these vehicles types in 2020 will increase the curb mass of the vehicles with approximately 15%.
- In the short term the energy consumption and GHG emissions per seatkm of a 12 m series hybrid diesel bus driving in Line5_mod are only 19% smaller than the energy consumption per seatkm of a 7.2 m series hybrid diesel bus driving in Line5_mod. The same result applies in the long term for 7.2 m and 12 m fuel cell buses using compressed hydrogen. Therefore reductions in the energy consumption and GHG emissions can be achieved on routes with low passenger loads by using smaller sizes of buses.
- Even very large buses (18 m and 24 m) can not compete with light rail vehicles and local trains, when it comes to the energy consumption and GHG emissions per seatkm. In the driving cycle LineLRV the energy consumption per seatkm of the

[256] This conclusion depends heavily on the assumption that fuel cells will be durable enough to last the lifetime of a bus (around 60000 operating hours), and that their price come down to approximately 75 $/kW for the fuel cell and 20 $/kW for the reformer.

[257] The GHG emissions connected with the use of a 12 m fuel cell bus using methanol produced from wood are approximately 5% of the GHG emissions of a conventional 12 m diesel bus today.

light rail vehicle is considerably smaller (40-50 % depending on the size of the bus) both in the short and long term than the energy consumption per seatkm of the 12 m, 18 m and 24 m buses[258]. The same but even more pronounced goes for the local train with an energy consumption per seatkm being around 65-75 % smaller than 12, 18 and 24 m buses, all vehicles driving in LineA. Looking at the emission of GHG in 2005 the results are even more in favour of the light rail vehicle and local train, because they are assumed to be powered by natural gas power plants, and natural gas emits less GHG than diesel relative to the energy content of the fuels.

[258] In the short term the buses are series hybrid diesel buses and in the long term fuel cell buses using compressed hydrogen.

11. Discussion

Results achieved, assumptions and uncertainty

This study has focused on analysing the energy consumption, GHG emissions, propulsion system cost and fuel cost of urban public transport modes, specifically buses, light rail vehicles and local trains. It has been shown that the combinations of large reductions in the vehicle loads and the use of advanced propulsion systems[259] enable very large reductions in both the energy consumption and GHG emissions connected with the use of buses. Only buses using renewable fuels obtain zero or near-zero emission of GHG[260]. Smaller but still significant reductions in the energy consumption and GHG emissions connected with the use of light rail vehicles and local trains can be achieved by weight reductions and the use of permanent magnet motors in the propulsion systems.

The analysis undertaken has included the energy consumption and emission of GHG of the vehicles when driving and the energy consumption and emission of GHG connected with the production of vehicle fuels. These two phases cover around 80-95% of the life-cycle energy consumption and GHG emissions of transport modes.

Maintenance of vehicles and vehicle infrastructure, the production of vehicles and vehicle infrastructure, and the disposal of vehicles and vehicle infrastructure are excluded from the life cycle analysis. As discussed in section 5.1.1 the omission of the production and maintenance of vehicle infrastructure puts road-bound vehicles in a relatively better light compared to rail-bound vehicles. The omission of the maintenance of the vehicle infrastructure from the net present value calculations means that weight reductions appear less profitable, because the wear on the vehicle infrastructure from vehicles is strongly dependant on the axle pressure.

The question of market penetration of new technologies has not been treated in this work. New technologies have been evaluated under the assumption that they will gain large enough shares of the market either in the short or the long term to be able to go down the learning curve and improve their performance to levels which apply to large scale production of the technologies.

In our vehicle design model each subsystem in the propulsion system can obtain whatever size is needed. In the real world a subsystem like a motor can only be bought in given standard sizes, i.e. the optimum size of a subsystem will not always be available if the subsystem is not designed specially to a given vehicle application, which will either increase costs or require high production volumes. Therefore the model probably has a

[259] Series hybrid with an ICE, series hybrid with a fuel cell, or electric with electricity storage propulsion systems.

[260] There exist methods for storing the CO_2 produced when producing hydrogen from natural gas for many hundred years in depleted natural gas fields, aquifers or in the oceans [Sørensen et al 1999]. So for a substantial price increase the GHG emissions connected with the use of compressed hydrogen produced from natural gas can also be made near to zero. This possibility has not been analysed in the project.

tendency to optimise the vehicle design to a degree, which is not always possible in the real world.

A number of assumptions have been made to arrive at the results, some of them on a rather uncertain basis due to lack of information. For example, the cost of weight reductions has been difficult to estimate. Due to this and due to the unavoidable uncertainty connected with the evaluation of the possible future performance of new technologies, the results achieved are connected with considerable uncertainty. Sensitivity analysis of the results has been carried out to illustrate this.

Emission performance of advanced propulsion systems to buses

When evaluating the environmental performance of the propulsion system technologies used in buses, the emission of air pollutants from the vehicles are the most important environmental problem for the time being. Especially the emission of ultrafine particles is considered a serious health problem. Therefore it is interesting to discuss how the propulsion systems technologies perform in this area as a complement to the energy consumption and GHG emissions calculations.

If zero or near-zero tailpipe emission vehicles are required, the three types of fuel cell buses will be the foremost candidates in the long term. They all have a potential for becoming significantly cheaper than electric buses, because the electricity storage requirements are smaller. Our results do not indicate a clear winner among the three choices of fuels to fuel cells investigated in this project: compressed hydrogen, methanol and gasoline, but compressed hydrogen and methanol have the advantage that they can be produced from renewable energy sources. Using compressed hydrogen in the fuel cell simplifies the propulsion system, but at the expense of a more complicated refuelling structure. The problem with the on-board storage of hydrogen due to volume constraints is not so serious for the larger buses (12 m and above) that can have the storage cylinders on the roof.

For electric buses our results show that with large glider mass reductions and the development of Lithium Polymer batteries the travel range problem of existing electric buses can be solved. However the advanced batteries will be expensive with the large energy storage capacities needed to achieve the desired travel range.

Finally, as explained in section 8.4.1 there is still possibilities for substantial reductions of the emission of regulated air pollutants from diesel engines by using a combination of improved fuels with lower sulphur content, engine design improvements and aftertreatment technologies. For example a particle filter will probably be able to reduce the particle emissions by 90% over the whole range of particle sizes. However the requirement that the very low emission levels must apply to the CI ICEs during the whole lifetime of the engines, instead of as today only for new engines, will be hard to achieve, and possibly lead to more frequent maintenance or lower durability of the engines.

Danish reduction targets for GHG

Denmark has a national CO_2 emission reduction target of 20% reduction from 1988 to 2005 [Miljø- og Energiministeriet 2001]. As part of the Kyoto agreement Denmark has a obligation toward the European Union of a 21% reduction of six greenhouse gases among which are CO_2, CH_4 and N_2O from 1990[261] to 2008-2012 [Miljø- og Energiministeriet 2001]. The introduction of advanced buses or light rail vehicles which significantly reduce GHG emissions relatively to the present conventional diesel buses in urban areas can contribute to the achievement of these reduction targets, but the contribution will be relatively small. This is firstly because the emission of GHG connected with transportation of persons with route-bound buses in Denmark only constitute a fraction (below 1%) of the total GHG emissions in Denmark[262]. Secondly, because the market penetration of the advanced buses takes time, so only a small part of the buses in Denmark in 2012 will be advanced buses.

The success of advanced buses in urban public transport may be significant also from a GHG emissions reduction perspective, because they can pave the way for the market introduction of advanced propulsion systems in cars. This applies especially to fuel cells used in urban buses, where the barriers for use are smaller and the benefits achieved are larger than for fuel cells in cars. Having fuel cell buses on the streets will enable the vehicle producers and bus operators to achieve day-to-day experience with the use of fuel cells in transport applications, and furthermore allow the public to get acquainted with this type of vehicle.

Importance of fuel consumption and vehicle retail price for operators of public bus transport

An operator of bus services in Greater Copenhagen get paid around 55 $ per bus hour provided by the operator [PLS 2000]. The price of diesel constitutes around 5% of the 55 $[263], and the deprecation of the vehicle around 20% of the 55 $[264]. Labour expenses constitute the main part of the price of a bus hour. This leads to two conclusions. First, that fuel savings are not very important for the bus operators. Secondly considering that the price premium of advanced buses in the long term will be below 50% of the retail price of a conventional diesel bus[265], the use of these buses can be paid for by the buyers of

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[261] From 1995 in the case of the industrial GHG.

[262] The CO_2 emissions from the transport sector in 1999 was 27% of the total CO_2 emission [Energistyrelsen 2000 A] of which approximately 5% came from bus transport (both route-bound and other forms of bus transport) [Cowi 2000].

[263] Assuming a diesel price of 0.29 $/litre and a fuel consumption of 10 litre per hour giving a fuel cost per operation hour of 2.9 $.

[264] Assuming the following: The retail price of a low-floor 12 m diesel bus is 250000 $ [West et al 1998]. The economical lifetime of the bus from the viewpoint of the operator is 6 years [Overgaard 2001]. The investment must yield a profit of 16% per year, which corresponds to a profit of 6% per year if there instead had been invested in a non-depreciating asset, and finally that the number of bus hours per year are 5000. These assumptions give a depreciation cost per bus hour of 12 $.

[265] Assuming a retail price of 250000 $ of a low-floor diesel bus and a maximum retail price increment inclusive battery replacement costs of 120000 $ for electric buses (see section 10.3). For series

bus services for a price increase of less than 10%. Here it is assumed that the maintenance costs of the advanced buses equals the maintenance costs of conventional diesel buses, a subject that has not been analysed in this project. Considering the potential large reductions in both GHG emissions and emission of local air pollutants by using the advanced bus technologies, the price increase of maximum 10% in the case of electric buses and a much smaller price increase in the case of series hybrid buses with internal combustion engines seem small in the opinion of the author.

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hybrid buses using CI ICEs the retail price increment will be much lower, which probably also will be the case for series hybrid buses using fuel cells in the long term.

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A. Safety of vehicles

In this section the safety considerations, that the vehicle designers have to take into account, is described. The link between the demand for safety and important vehicle design parameters like choice of materials and vehicle mass is analysed.

When analysing the safety of a certain vehicle, it is not only the safety of the persons inside the vehicle that are of importance. Also the safety of the persons in the surrounding traffic system has to be taken into account, e.g. persons in other vehicles, pedestrians, bicyclists. Unfortunately as will be explained, there is a conflict between the safety designs for the persons inside the vehicle and the persons in the surrounding traffic system.

A.1 Active and passive safety measures

The measures to improve the safety of vehicles can be divided into two groups: active safety measures, and passive safety measures.

The goal of active safety is to avoid crashing the vehicle into other objects. This means having a vehicle with good braking performance, and the ability to change direction suddenly without loosing control over the vehicle (skidding and rollover). Below is listed the vehicle properties of importance for the active safety:

- Braking performance: important parameters: tire-road friction (depends on the condition of the road surface, vehicle velocity, vehicle load), ABS (anti-lock braking system).
- Ability to avoid obstacles: stability to sudden changes in the vehicle direction, steering properties (centre of mass, width between the wheel pairs, tire-road friction, vehicle suspension systems, EPS (electronic position stabiliser)).
- Trains: ability to stay on the tracks: (vehicle suspension systems).
- Active safety equipment: warning systems when other vehicles are getting close, automatic kept safety distance, automatic systems that react to the warning signals for trains.

The goal of passive safety design is to minimise the damage happening to persons involved in an accident. This involves the following sub goals:

- Keeping the accelerations and decelerations of the different parts of the bodies of the persons below damage levels.
- Prevent impacts between vehicle parts and persons, especially pointed and sharp vehicle parts, like the steering column if the steering wheel brakes. For the persons inside a vehicle this can be expressed as keeping a survival space between the persons and the collapsing vehicle in the case of a collision.
- Prevent fire in the vehicle and the development of poisonous gases.

When looking at private cars the passive safety has been improving in resent years [Mamalis et al. 1997]. The efforts of the car designers have been focused on improving the vehicle structures such that the material surrounding the passenger compartment will absorb the maximum amount of energy during deformation, thus protecting the people inside.

The following vehicle properties are of importance for the passive safety:

- Mass.
- Crashworthiness: Choice of materials and construction of crush zones.
- Passive safety equipment: seat belts, air bags, neck rests.
- Fire resistance and development of poisonous gases: location of fuel tank, choice of materials, containment of potentially dangerous substances like fuel, battery liquids.

A.2 Standards for passive and active vehicle safety

Standards for passive vehicle safety

Before sending a new car on the streets, it has to pass a number of prescribed crash tests [Dyrelund 2000]. In the European Union these tests encompass a head-on collision with a deformable barrier with 56 km/h speed and a side collision into a deformable barrier with a speed of 50 km/h. In the head-on collision test the offset is 40 % meaning that the car hits the barrier with 40 % of its width. In each test the accelerations and forces on the different parts of the crash test dummies inside the vehicles must be below limiting values to pass the tests. There must not be developed leaks in the hoses carrying fuel. There is also a crash test with a collision of the vehicle from behind, where the purpose is to test the durability of the fuel tank.

For buses no such crash tests are required before approval of the vehicles.

There are rules for the collision performance of the windows in cars, buses and trucks. For tourist and long-distance buses there are standards for the strength of the superstructure. It must not collapse in case of a rollover, where the bus ends on top with the weight on the superstructure [Dyrelund 2000].

Apart from this there are no standards for the strength and durability of the components used in cars and buses.

There are no standards regarding the passive safety of the car in collisions with pedestrians or cyclists. A standard involving the design of the front of the car has been under negotiation for the last 15 years, but as it will affect the appearance of the cars, no agreement has been achieved.

For locomotives, wagons or train sets there are strength conditions that the different components like the bogies and wheel sets have to meet. There are demands on the forces that the wagon body must be able to absorb in the longitudinal direction without deformation of the body. There are demands on the fire resistance of the materials used. The different demands on the strength and fire resistance of components depend on the use of the trains. If the train is going to be used on tracks, also used by heavy freight locomotives, the demands are higher, than for light rail driving on their on track. In the case of the metro in Copenhagen currently under construction, the standard adopted for the strength of the construction was a German standard for trams.

In Europe the international union of railways (UIC) has a set of demands, that are often used, when the operators specify their demands to the new train material, especially for material used across borders. It is also possible for the operators to specify their own set of demands, which subsequently has to be approved by the relevant public railway institution.

Standards for active vehicle safety

Cars, buses and trains have to fulfil standards for braking performance expressed as deceleration performance in different situations.

A.3 The dynamics of a vehicle collision

A.3.1 Head on collision with a stationary object

When a vehicle collides head-on into a stationary object, e.g. a big tree at the roadside, the vehicle velocity changes from v to zero during a short time interval. The vehicle experiences a large force from the stationary object opposing the vehicles motion and as a result experiences large decelerations. The initial kinetic energy of the vehicle is dissipated into other forms of energy, a lot of it being absorbed by the vehicle structures, as they are crushed. The phase where the vehicle is crushed is called the crush stroke. The energy absorbing mechanisms are diverse and entail elastic strain energy, plastic strain energy, fracture, friction, light and sound. The challenge of the passive safety designers is to ensure that the available crush stroke is long enough to absorb the kinetic energy of the vehicle (including payload) at a rate survivable for the occupants.

This can be illustrated by a simple calculation:

We analyse a vehicle in a head-on collision with a fixed wall (see Figure A-1). The rate of change of the kinetic energy of the vehicle during the crash is given by:

$$E_k(t) = ½(m_c + m_p)v(t)^2 \Rightarrow P_k(t) = \frac{dE_k(t)}{dt} = (m_c + m_p)v(t)a(t)$$

$E_k(t)$: kinetic energy of vehicle at the time t [J].
$P_k(t)$: rate of change of the kinetic energy of the vehicle [W].
m_c: curb mass of the vehicle [kg].
m_p: payload of the vehicle [kg].
$v(t)$: velocity of the centre of mass of the vehicle [ms^{-1}] in the x-direction.
$a(t)$: acceleration of the centre of mass of the vehicle [ms^{-2}] in the x-direction.

If we make the simplifying assumption, that the cross section of the crushed section of the vehicle, i.e. the front of the vehicle, has a constant area during the crush, the crushed volume of the vehicle are given by $V(t) = A_c(B-x(t))$ (see Figure A-1), where B is the fixed distance between the centre of mass and the front of the non-deformed vehicle, and $x(t)$ is the distance between the centre of mass and the front of the vehicle during deformation. The energy absorbed by the deforming vehicle structures during the crush stroke can then be expressed as:

$$E_c(x(t)) = \int_B^{x(t)} -e_c(x(t))A_c dx \Leftrightarrow E_c(t) = \int_0^t e_c(t)A_c v(t)dt$$

$E_c(x(t))$: the energy dissipated in the crushed volume $A_c x(t)$ [J].
$e_c(x(t))$: the specific energy absorption per volume[266] of the crushed material at the place $x(t)$ [J/m3].
A_c: the cross sectional area of the crushed section of the vehicle [m2].

Notice that according to the definition of $x(t)$: $dx(t)/dt = -v(t)$.

The rate of energy absorption during the crush stroke is then given by:

$$P_c(x(t)) = \frac{dE_c(x(t))}{dt} = A_c v(t) e_c(x(t))$$

$P_c(x(t))$: the rate of energy absorption at the place x(t) [W].

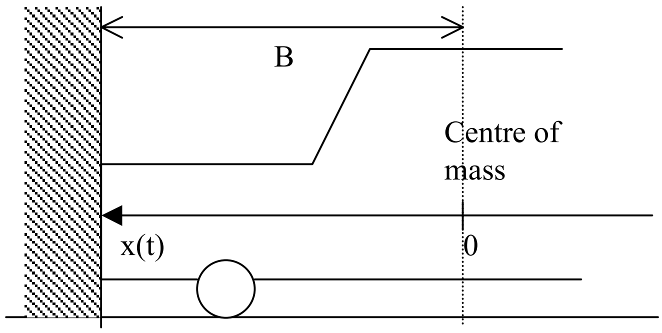

Figure A-1 Sketch of the vehicle just before it makes a head-on collision with a stationary wall.

It is assumed that no deformation of the wall takes place. Also with good approximation it can be assumed that the head-on collision is nearly entirely inelastic [Vibe-Petersen 1993]. Under these assumptions it is reasonably to assume, that the vehicles kinetic energy is entirely absorbed by the crushed vehicle structures:

$$P_k(t) = -P_c(x(t)) \Leftrightarrow a(t) = -A_c \frac{e_c(x(t))}{m_c + m_p} \Rightarrow \bar{a} = -A_c \frac{\bar{e}_c}{m_c + m_p}$$

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266 As there is a lot of different components with different geometry's and materials in the front of the vehicle, $e_c(x(t))$ is understood as the average specific energy absorption at the place x(t).

where $\overline{a}$ and $\overline{e}_c$ is the average of the deceleration and the specific energy absorption during the crush stroke.

From this equation the following observations can be made:

- During the crush stroke the deceleration is inversely proportional to the total mass.
- The average deceleration during the crush is proportional to the average specific energy absorption of the crushed volume.

Now the average deceleration is given by: $\overline{a} = {-v_0}/{\tau}$, where v_0 is the initial velocity before the collision, and τ is the duration of the crush stroke. The length of the crush stroke, l_c is given by:

$$l_c = \overline{v}\tau = \frac{-\overline{v}v_0}{\overline{a}} = \frac{\overline{v}v_0(m_c + m_p)}{A_c\overline{e}_c} \qquad \text{(A.1)}$$

where $\overline{v}$ is the average velocity of the centre of mass during the crush stroke.

It can be seen from equation (A.1, that if the curb mass of the vehicle is reduced, and the allowable length of the crush stroke is unchanged[267], the average value of the energy absorbing capability of the vehicle can be reduced. This reduces the demands on the materials going into and the construction of the front of the vehicle.

A.3.2 Head-on collision between two vehicles

Let two vehicles with the total masses m_1 and m_2 collide head-on, and assume that all movement before, during and after the crash take place in the direction going through the centre of masses of the two vehicles. The velocities of the vehicles just before the collision are called v_1 and v_2, and the velocities of the vehicles after the crush stroke are called V_1 and V_2.

During the crush stroke some of the kinetic energy of the vehicles is taken up by the deforming vehicle structures. A simple way to express this is to introduce a coefficient of restitution, *e,* defined by [Brach 1991]:

$$e = \frac{-(V_2 - V_1)}{v_2 - v_1} \qquad \text{(A.2)}$$

e is defined as the ratio of the relative velocities of rebound and approach. During the crush the two vehicles interact without external forces coming into play (neglecting tire/ground friction), meaning that there will be conservation of the linear momentums:

$$m_1v_1 + m_2v_2 = m_1V_1 + m_2V_2 \qquad \text{(A.3)}$$

By combining equation (A.2 and (A.3 the velocities after the collision can be expressed as a function of the velocities before the collision:

[267] because the size of the vehicle is unchanged.

$$V_1 = v_1 + \frac{m_2}{m_1 + m_2}(1+e)(v_2 - v_1) \quad \text{(A.4)}$$

$$V_2 = v_2 - \frac{m_1}{m_1 + m_2}(1+e)(v_2 - v_1) \quad \text{(A.5)}$$

The energy absorbed by the vehicle structures during the collision, E_A, equals the difference between the kinetic energies of the vehicles before and after the collision. By using the expression for the kinetic energies and equation (A.4 and (A.5, the energy absorption, $E_{A,}$ can be elegantly expressed as:

$$E_A = \frac{m_1 m_2}{m_1 + m_2}(1-e^2)(v_2 - v_1)^2 \quad \text{(A.6)}$$

As can be seen from equation (A.6, the collision is entirely elastic when $e = 1$, and the largest energy absorption occurs for $e = 0$.

Now with the basic framework at place, we can investigate the safety consequences of a given difference in mass between two vehicles involved in a head-on collision.

First we look at the velocity changes each vehicle experiences. This gives an estimate of the average accelerations the passengers in the vehicles experience during the crash.

Let $m_1 = km_2$, $v_1 = -v_2$, i.e. the vehicles have equal but opposite velocities and vehicle one is k times heavier than vehicle two:

$$\Delta V_1 = V_1 - v_1 = -\frac{m_2}{km_2 + m_2}(1+e)(-v_1 - v_1) = \frac{2v_1(1+e)}{k+1}$$

$$\Delta V_2 = V_2 - v_2 = \frac{km_2}{m_1 + km_2}(1+e)(-v_1 - v_1) = \frac{-2kv_1(1+e)}{k+1}$$

$$\frac{\Delta V_2}{\Delta V_1} = -k$$

The occupants in the light vehicle are experiencing a velocity change k times bigger, i.e. equal to the difference in mass, than the occupants in the heavy vehicle. In other words it is much safer to be in a relatively heavier vehicle in a collision between vehicles all other parameters being equal.

To investigate the importance of the mass difference for the energy absorption of each vehicle, it is informative to relate the energy absorption in the collision between the vehicles, with the energy absorption in a head-on collision with a stationary wall at the same velocity. This is because the standards for passive safety in cars all consist in collisions with stationary objects, so the passive safety design goals will be aimed at managing collision with stationary objects.

Equation (A.6 gives the total energy absorbed in the crash between to vehicles. How the total absorbed energy is divided between the vehicles depends on the energy absorbing capabilities of the two vehicles, and can not be estimated in a simple way. Therefore it is assumed, that the energy absorption in the collision between the two vehicles is equally divided between the two vehicles. Also it is assumed that both the collision between two vehicles and the collisions between a vehicle and a stationary wall are almost inelastic, i.e. $e^2 \approx 0$ for both types of collisions. This assumption is supported by experimental evidence for head-on collisions [Vibe-Petersen 1993; Brach 1991].

Let S_1 be the ratio between the energy absorbed by vehicle one in the collision with vehicle two and the energy absorbed by vehicle one in a collision with a stationary wall at the same vehicle speed. Let $v_1 = -v_2$ and $m_1 = km_2$.

$$S_1 = \frac{½E_A}{E_{K1}} = \frac{½\frac{m_1 m_2}{m_1+m_2}(v_2-v_1)^2}{½m_1 v_1^2} = \frac{m_2}{m_1+m_2}\frac{(v_2-v_1)^2}{v_1^2} = \frac{4}{k+1}$$

$$S_2 = \frac{½E_A}{E_{K2}} = \frac{½\frac{m_1 m_2}{m_1+m_2}(v_2-v_1)^2}{½m_2 v_2^2} = \frac{m_1}{m_1+m_2}\frac{(v_2-v_1)^2}{v_2^2} = \frac{4k}{k+1}$$

$$\frac{S_1}{S_2} = \frac{m_2}{m_1}\frac{v_2^2}{v_1^2} = \frac{m_2}{m_1} = \frac{1}{k}$$

It can be seen, that S_2 is k times bigger than S_1. Assuming that the vehicles are designed to absorb their own kinetic energy in a collision with a stationary object, the light vehicle must absorb much more energy in the collision with a heavier moving vehicle (e.g. $k=2 \Rightarrow S_2 = 8/3$), and therefore will experience large deformations.

A.3.3 Conclusions from the analysis of the dynamics of vehicle collisions

When considering the safety consequences of reducing the mass of a vehicle two different collision situations have to be distinguished; collision between a vehicle and a stationary object and collision between two moving vehicles.

With regard to a collision with a stationary object, it can be seen from equation (A.1, that if the curb mass of the vehicle is reduced without reducing the allowable length of the crush stroke, the average value of the energy absorbing capability of the vehicle can be reduced. This reduces the demands on the materials going into and the construction of the front of the vehicle. For all other types of collisions with stationary objects the same considerations are valid, i.e. mass reductions are beneficial for the passive safety.

On the other hand when the curb mass of a vehicle is reduced, the payload makes a bigger contribution to the total mass. Therefore the total mass can vary significantly dependent on the size of the payload, e.g. up to a factor of two for a weight reduced urban bus with a passenger capacity of 87 persons. This makes it more difficult to design the energy absorbing zones in the vehicles, because they shall be able to absorb a wider range of kinetic energies.

With regard to collisions between two vehicles, we have shown that the mass difference between the vehicles makes the passive safety design of lighter vehicles very challenging.

The answer to these challenges is to build a number of successively stiffer crush stages into the vehicle. The outermost of these stages can be very soft to protect pedestrians and cyclists in collisions, and the innermost must be very stiff to prevent intrusion into the passenger compartment.

A.4 The connections between designing for safety and designing for low energy consumption

The driving cycles of both urban buses and trams are characterised by low speeds, and the curb masses of these vehicle types are significantly heavier than most other moving objects on the streets, e.g. pedestrians, cyclists and cars. Therefore in collisions with other vehicles, it is not so much the safety of the occupants of the buses and trams that are at stake, but more the safety of the other part involved in the collision. Mass reductions of buses and trams are therefore a good thing for the safety, in that it reduces the impact, these vehicle types have on other road users.

Local trains have their own track isolated from the rest of the traffic system, so collisions are normally with stationary objects or with other local trains. In some cases they achieve quite high speeds around 100 km/h.

For all vehicle types colliding with stationary objects it has been shown, that mass reductions loosens the passive safety demands, in that the total kinetic energy of the vehicles are reduced. The problem with the variation in the kinetic energies due to variation in payload gets bigger. This is mainly a problem for buses, because the ratio between payload and curb mass is smaller for trams and trains than for buses.

B. Marginal versus average considerations

When considering the consequences of a change in travel habits and transport technology, it is important to clarify whether the consequences are calculated from marginal or average values of the impacts. When using marginal considerations, it is the marginal changes in the surroundings resulting from the proposed initiative that are taken into account, and they are all ascribed to the proposed initiative. In the average consideration, average values for the impacts in the surroundings are ascribed to the proposed initiative. The average consideration means that the initiative is seen as an integrated part of the surroundings, and the impacts on the surroundings are divided equally between both existing and new actors.

An example is given by the environmental impacts from moving one passenger from a private car to a public bus. Assuming that no extra buses are put into operation, the changes in the environmental impacts from the bus are close to zero, if a marginal consideration is used. On the other hand if average values of the environmental impacts per passenger from a bus with an average load factor are used, the change in the environmental impact from the bus is no longer close to zero.

Another relevant example is given by the calculation of the environmental loads connected with the power consumption in an electric vehicle. Again should the environmental loads connected with producing an extra amount of power be used or the average environmental impacts of the power production?

The argument in favour of the marginal consideration goes as follows: The proposed initiative causes some impacts on the surroundings. It is therefore logical to attribute these impacts fully to the initiative.

This is a reasonable argument, but there are problems with using the marginal consideration. First of all it can be quite complicated to calculate the exact changes following from the implementation of a specific measure. Taking the marginal power production as an example, the way this power is produced varies both over the day and the year. To take this into consideration demands an intimate knowledge of the load dispatching strategy of the relevant power sector not only today, but also over the lifetime of the measure. To use average values of the power production today and in the future is much easier.

Secondly the marginal impacts depend on both the proposed measure and the existing system. In some cases it can be argued that it is the existing elements in the system that needs to be changed to give room for the implementation of the measure [Anderson & Berg 1999]. This will not be done if only a marginal consideration is used. An example is the extra power consumption following from the introduction of EVs compared with the existing use of power for heating houses. According to environmental criteria it will often be a better idea to use the power in EVs and find other ways to heat the houses.

In conclusion it is hard to state a priori whether a marginal or an average consideration should be used. In each specific case it has to be deliberated. In theory, the **right** way to calculate impacts is to make a model of the surroundings influenced by the proposed measure, and compare the total calculated impacts from the model with and without the measure implemented, i.e. a comparison at the system level. In many cases this will not be done because of the large work effort involved.

In the case of large proposed changes in a system, it can be problematic to use values for the existing system in the analyses. Instead the scenario technique should be used.