Feasibility study for an ultra-compact hybrid driveline

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E. Wijn s0508988

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Coach at TU/e: dr.ir.Alex Serrarens
Coach at DTI: dr.ir.Roël van Druten
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Eindhoven University of Technology
Department of Mechanical Engineering
Automotive Engineering Science

Abstract

This report describes the feasibility study of an ultra compact hybrid driveline, called the SLZ-driveline. The SLZ-driveline is to be designed specifically for the Cito Dual Mode (CDM) vehicle which is developed by SAM. It should also be a concept that could be marketed independently. This report presents the study which is carried out in order to determine the technical feasibility of the concept. A stepwise approach is adopted starting with a market research this first step leads to a set of requirements for the SLZ-driveline. After that an overview of the state-of-the-art in (hybrid) driveline technology is given. Different technologies that fulfil a similar function are described and compared. Several possible driveline topologies are analysed in a qualitative way.

A short list of the most potent driveline topologies is put up and a set of criteria on which to compare the different concepts is constructed. The shortlist consists of a series hybrid, a parallel hybrid and a power split hybrid configuration. In order to judge the different concepts some numerical simulations, with the Cito vehicle as a basis, are carried out. The quantitative results and some qualitative judgements are weighed in a Multi Criteria Analysis which returns the most attractive concept. Finally, it is examined which driveline concept is most suitable for a number of other (niche-market) applications.

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Chapter 1

Introduction

1.1 Cito Dual Mode concept

SAM and Drive Train Innovations (DTI) [1] jointly work on a concept development for a compact city car, named Cito. An integral part of the development is the so called Cito Dual Mode (CDM) concept. The aim of this concept is to reduce traffic jams, improve the quality of life and economics. The concept wants to demonstrate these improvements by offering a compact vehicle and an associated smart interurban infrastructure. The infrastructure will be placed alongside the highly congested highways in between cities. On this infrastructure the vehicle is guided automatically. In this way, the vehicle capacity can be higher than with contemporary infrastructure. Also the driver influence, which is a major factor in causing traffic jams, is eliminated. In urban areas the driver takes control again and is able to drive the vehicle like an ordinary one. This assures the reachability of destinations to be similar as any other car. See [2] for more information about the CDM concept and its probable acceptance by society.

1.2 SLZ-Driveline

For the development of the driveline for the Cito, first a feasibility subsidy is granted by SenterNovem. The driveline is named an SLZ-driveline, which stands for:

- 'Stil' or silent: Which refers to the low noise emissions of the driveline.
- 'Laag vermogen' or low power: The driveline is suitable for small and light vehicles
- 'Zuinig' or fuel economical: Fuel consumption should lie between 3 to 4 liter/100km

In order to comply with these characteristics, a hybrid driveline is presumable. The Cito will have to reach a top speed of 100 km/h on the interurban infrastructure and a maximum of 70 km/h in urban areas. In the city a sportive driving character is desired in order to keep up with other vehicles. This means that a good acceleration is mandatory. In the automatic mode (at higher velocities), accelerating performance is less important.

Another important demand is that the vehicle must be attractively priced. This in turn implies that the driveline must be low cost. In this driveline feasibility study a production cost target of €1700,- is set. Another point which is important as of societal acceptance is that the Cito must comply to the present fueling infrastructure. i.e. It has to run on either petrol, diesel or LPG. On the other hand the design should also be flexible and must be able to run on alternative fuels (e.g. bio-fuels or even hydrogen) in the future, without the need for radical modifications to the driveline or the vehicle.

1.3 Problem statement

Since no compact hybrid driveline that complies with the SLZ-driveline requirements is currently commercially available, the need for a new design is inevitable. The design of a hybrid driveline depends on a lot of parameters. A lot of different technologies exist or are being developed at the moment. And the design of a hybrid driveline is strongly dependent on the vehicle parameters. This feasibility study should give insight in what is the best concept for a SLZ-driveline. The problem statement becomes:

Determine the optimal topology for an SLZ-driveline that fits the Cito vehicle and can also be flexibly scaled for implementation in other applications.

1.4 Research questions

The problem statement will be divided into several, more concrete research questions. Solving these questions will subsequently provide the answer to the problem statement.

- Analyse what light (hybrid) drivelines and/or vehicles are available on the market, and find out what the requirements for such a driveline are.
- Analyse what the requirements for the SLZ-driveline should be, when implemented in a Cito vehicle operating in CDM modes.
- Create a carefully deliberated shortlist which presents the driveline concepts that are most likely to form the basis for the SLZ drive line.
- By means of a more in depth analysis determine which of the concepts is best suited to form the basis for the SLZ-driveline.
- Research the scalability and applicability of the driveline concept in other (niche) markets.

1.5 Approach

To answer the problem statement it is necessary to find out what products are currently available on the market and what products are currently being developed. This is presented in Chapter 2. This chapter will also focus on implementing the SLZ-driveline the Cito vehicle. The specifications of the driveline will be determined by a road load analysis. In Chapter 3 an overview of the available technologies that can be used in the SLZ-driveline is given and a pre-selection of certain technologies wil be made. With the specifications of the driveline, the boundary conditions put by SAM and the technological boundaries researched in Chapter 3, a short list of driveline concepts will be made. These concepts will be presented in Chapter 4. Chapter 5 gives insight in numerically modeling the concepts. Based on the numerical results of these simulations and some qualitative observations the best concept will be chosen in Chapter 6. Chapter 7 examines if the chosen concept complies with market demands and presents the idea of modular driveline design. Finally some conclusions are drawn and recommendations for future work are given in Chapter 8.

Chapter 2

Requirements

Before the SLZ-driveline can be developed it is important that the boundary conditions that the driveline has to satisfy are put up correctly. The requirements are mainly determined by the applications in which the driveline will be used. The Cito vehicle is the primary application and therefore defines most of the requirements. Since the SLZ-driveline is a stand alone concept, which will be marketed as a product itself, it is important to get an idea of what the potential customers expect of this product. This will be done by interviewing several potential customers and process their wishes into the SLZ-driveline requirements. Further on this chapter will present some basic calculations in order to determine the required power and energy specifications for the SLZ-driveline. These calculations will be made on the basis of the resistances that the vehicle has to overcome whilst driving. A drive-cycle that represents the typical loads that a CDM-vehicle will encounter is first constructed. Also some extra computations are carried out to check if the calculated required power on the drive-cycle suffices to drive at certain road inclination angles.

2.1 Interviews

In order to get an overview of the requirements that potential customers have for an SLZ-driveline, a market research is carried out. A list of potential customers is put up representing a large variety of mobile applications. The actual interview and an overview of the results can be found in Appendix C.

The interviews showed that there is a large interest for an SLZ-driveline. A lot of companies are also working on projects to make their products more environmentally friendly and an SLZ-driveline can probably fill in some of the demands. An important fact that appeared out of the interviews is that an SLZ-driveline has to be very flexible in placement and application. It has to be able to drive a large range of vehicles, ranging from small and light passenger cars to heavy duty industrial applications. The interviews also showed that low costs of the driveline will be very important for succes. At this field a division can be made between commercial and private applications. For private applications the initial purchase costs are most important, whereas for commercial use running and maintenance costs are most important. This division and the fact that a large variety of applications must be supported already at this point leads to the idea of a flexible driveline concept. A low cost basic version with performance that should already satisfy a large group of customers must be extendable with several different component packages that could satisfy the niche markets. One could think of for instance a sport-package for more attractive driving sensation in recreational or personal vehicles and a power-package for more heavy industrial applications.

2.2 Requirements Cito

This section gives some basic information about the Cito vehicle. However, the data given in this section is not definite, since the development of the Cito vehicle goes in parallel with this project. Possibly leading to adaptations in the vehicle specifications.

Figure 2.1: The Cito vehicle dimensions

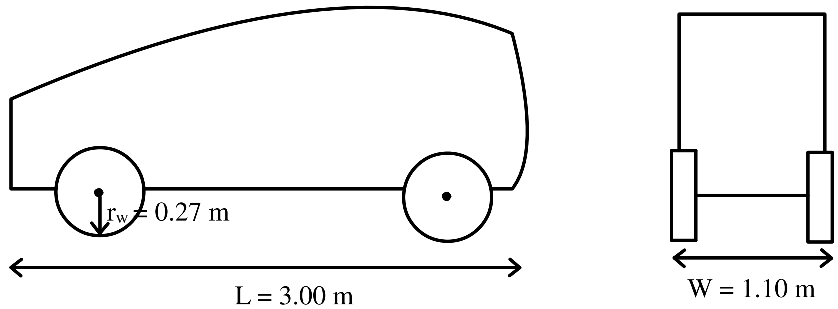
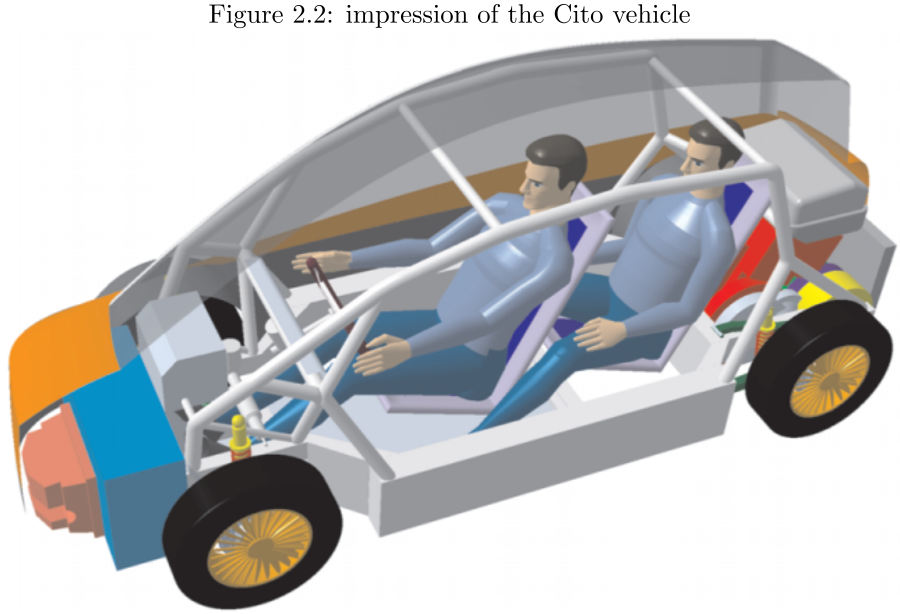


Table 2.1: Cito data

M_v	empty mass	600	[kg]
M	laden mass	750	[kg]
r_w	wheel radius	0.27	[m]
l	vehicle length	3.00	[m]
w	vehicle width	1.10	[m]
c_w	drag coefficient	0.3	[-]
A	frontal area	1.3	[m^2]
f_r	rolling resistance coefficient	0.01	[-]
μ_h	static friction coefficient	0.7	[-]
v_{max}	maximum velocity	100	[km/h]

Figure 2.2: impression of the Cito vehicle



2.3 Requirements SLZ-driveline

Combining the requirements for the Cito vehicle and the requirements that roll out of the market research provides the requirements that the SLZ-driveline has to meet. A detailed set list of requirements for the SLZ-driveline is given below. Noise emission should be minimized, but no exact figures are provided by SAM. This is why it is not incorporated in the list of requirements.

Table 2.2: SLZ driveline list of requirements

Performance indicators		
maximum velocity in city	70	$[km/h]$
maximum velocity on interurban infrastructure	100	$[km/h]$
maximum acceleration (in city)	2.8	$[m/s^2]$
0-60 acceleration (in city)	6	[s]
acceleration requirement on interurban infrastructure is lower		
minimum speed at 6 % inclination angle	80	$[km/h]$
minimum range	70	$[km]$
Environment		
fuel economy (if IC is used)	3-4	$[liter/100km]$
	1:25-33	$[liter : km]$
emission standard	Euro V (see Appendix A)	
Comfort indicators		
driveline should be silent	-	-
accessoires power	300	[W]
Cost indicators		
consumer costs total driveline	5000,-	[€]
manufacturing costs total driveline	1700,-	[€]
Implementation indicators		
maximum driveline weight	120	[kg]

2.4 Drive-cycle

In order to make the road load computations and determine what the minimum power and energy capacity of the SLZ-driveline should be, it is useful to use a representative drive-cycle. This is a drive-cycle that represents the everyday use of a CDM-vehicle.

Already a lot of drive-cycles exist for different purposes. But none of the available drive-cycles represents the Dual Mode usage accurately. That is why a new CDM drive-cycle is designed. In [2] a description of the typical use of a CDM-vehicle is given. The potential user is a commuter that travels 3-5 days a week, 10 to 50 kilometers a day. A certain part of this distance will be urban and a part interurban. The percentage of urban and interurban use depends on the overall distance traveled. The percentage of urban travel decreases as the overall distance traveled increases. For very short trips (0-10 km), the urban percentage is 95-100%. For journeys of 50-60 km this percentage lowers to about 50%. For constructing a CDM drive-cycle a typical trip is chosen, which covers a distance of 50 kilometers. At this distance 56% of the trip (28 km) will be driven in urban areas. The remaining 22 kilometers will be driven on the interurban infrastructure. The velocity on this infrastructure will be 100 km/h, in automatic cruisecontrol mode. No drive-cycle yet exists for such driving modes. A lot of urban drive-cycles already exist. The drive-cycle that was chosen as a basis for the urban part of the CDM drive-cycle is the ECE drive-cycle which

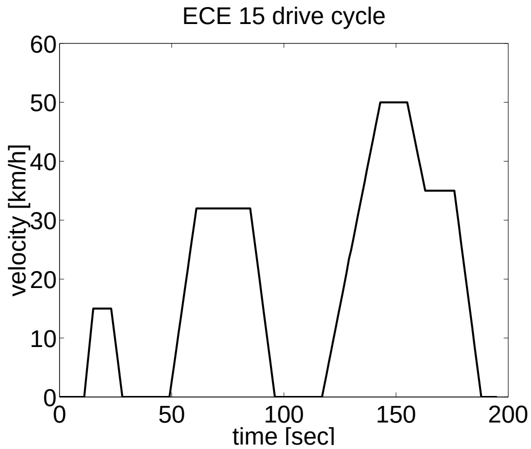


Figure 2.3: ECE urban drive-cycle

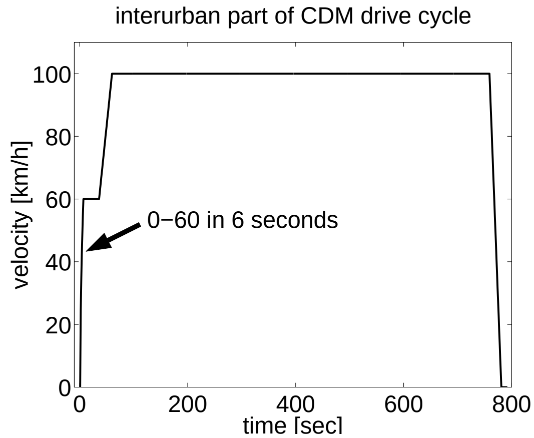


Figure 2.4: interurban drive-cycle

is depicted in Figure 2.3. A series of 28 ECE cycles in combination with a newly designed, 22 kilometer long interurban cycle will form the CDM drive-cycle. The interurban part of the drive-cycle is shown in Figure 2.4. It also incorporates the toughest acceleration requirement (0-60 km/h in 6 seconds) this occurs at the point where the CDM-vehicle merges into the interurban infrastructure.

The resulting drive-cycle now is a reflection of a typical CDM journey. But it is not a practical cycle for testing purposes, because of its length of over an hour. Making use of a scaling factor it is possible to make the drive-cycle more compact, but maintain the typical CDM characteristics. If a scaling factor of 3/28=0.107 is used, the number of ECE cycles is reduced to exactly three and the length of the interurban part is reduced to 2.2 km. The result is shown in Figure 2.5. To validate the short cycle the results of the road load calculations (for details see following sections) for both the short and the long cycle are compared. In Table 2.3 the results are displayed. It appears that the required power to drive both cycles is equal and that the required energy is scaled down with the same scaling factor as the distance was scaled with. This behaviour is expected and confirms that the CDM short drive-cycle is representative for CDM driving.

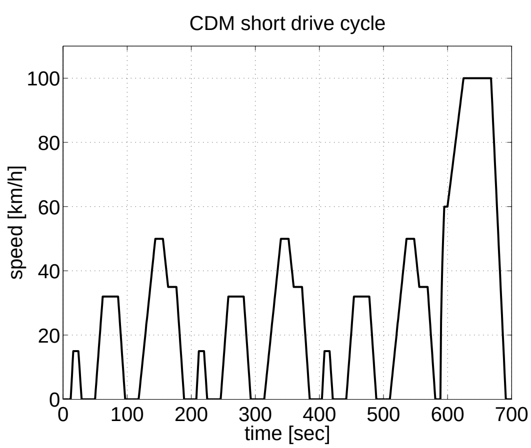


Figure 2.5: the CDM short drive-cycle

2.5 Road load analysis

The power required to drive a vehicle can be calculated using the driving resistances. These are:

- wheel resistance: $F_r = f_r Mgcos\alpha_{st}$
- air resistance: $F_l = \frac{1}{2}\rho_l c_w A v^2$
- gradient resistance: $F_{st} = Mgsin\alpha_{st}$
- acceleration resistance: $F_a = \lambda Ma$

The total resistance is the sum of the separate elements:

$$F_{tot} = F_r + F_l + Fst + F_a = f_r Mgcos\alpha_{st} + \frac{1}{2}\rho_l c_w A v^2 + Mgsin\alpha_{st} + \lambda Ma \quad (2.1)$$

with:
v vehicle speed in [m/s]
α_{st} road inclination angle [°]
$\rho_l = 1.199$ $[kg/m^3]$ at 20°C
$g = 9.81$ $[m/s^2]$ gravitational acceleration
$M = 750$ [kg] vehicle mass
λ the rotational inertia coefficient [-]
This coefficient expresses the proportion of the total mass that is rotary.

The required power can then be calculated with:

$$P_{req} = F_{tot} v \quad (2.2)$$

The rotational inertia coefficient λ highly depends on the type of engine and driveline. Since the configuration of the drive line has yet to be determined, λ is not known. However the effect of λ at the total required power is low, and since we are making an estimation it is set equal to 1.
The required power on the CDM short drive-cycle as function of time is given in figure 2.6 and 2.7. The maximum required peak power is approximately 35 [kW]. This is needed when the vehicle accelerates from 0 to 60 [km/h] in 6 seconds. This amount of power is only required for a very short time. The continuously required power for driving at 100 km/h equals 7 [kW]. Furthermore, it is obvious that urban driving requires less power than interurban driving. This is mainly due to air resistance at higher interurban velocities. Note that when the vehicle is decelerating naturally a negative power occurs. This energy can be reused or stored, otherwise it is lost and transformed into heat by the vehicles (disc)brakes. Section 2.6 will discuss this issue further.

2.5.1 extreme situations

The previous calculations using the CDM drive-cycle do not account for a road inclination angle. Some extra calculations are made in order to check whether the required power reaches a maximum when a road inclination other than zero is chosen. For these calculations the forward velocity of the vehicle is chosen as a constant. The following two situations are evaluated:

Table 2.3: Characteristics of both CDM drive-cycles

	unit	**CDM long cycle**	**CDM short cycle**
duration	[sec]	6280	700
distance	[km]	49.2	5.2
average velocity	[km/h]	28.2	26.7
maximum velocity	[km/h]	100	100

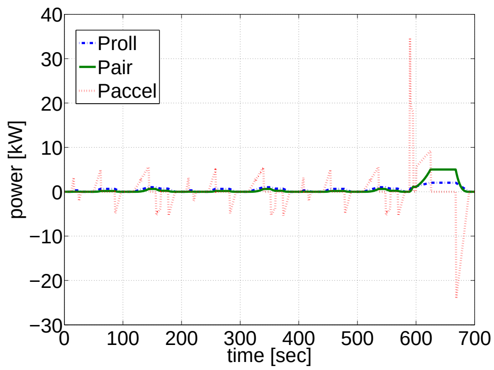


Figure 2.6: contribution of different resistances

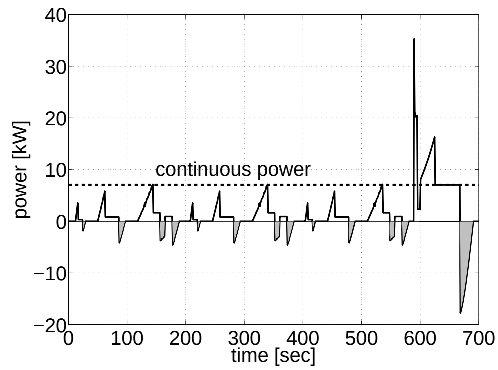


Figure 2.7: total required power on CDM short drive-cycle

1. Automated driving uphill: 80 $[km/h]$ at 6% road inclination angle
2. Extreme inclination angle: 10 $[km/h]$ at 30% road inclination angle

The required power follows from equation (2.2). Because of the steady state motion the inertia term drops out. The results of these calculations are given in Table 2.4. It shows that the extreme road inclination angle of 30% requires a relatively low power output. The 6% road inclination angle at 80 km/h requires much more power. Actually, this situation requires twice the power than the continuous power calculated in the previous section.

Table 2.4: required power in extreme situations

situation	speed [km/h]	inclination angle [%]	P_{req} [kW]
1	80	6	14.0
2	10	30	6.9

2.6 Energy requirement

Now that the required power is known, the required energy at the wheels can be calculated. This amount of energy is needed to determine the energy capacity of the primary energy source. The Cito requirement states that the vehicle should have a range of, at least, 70 kilometers. If we assume that these kilometers are built up in the same way as the average trip, it is possible to use the CDM short drive-cycle as a reference. The amount of energy required to drive 70 kilometers can than be determined by calculating the energy consumption of 14 CDM short drive-cycles (14 * 5.2 [km] = 72.8 [km]). First, the amount of energy is calculated for one CDM short drive-cycle. It is equal to the surface underneath the power curve shown in Figure 2.7. The required energy for a CDM short drive-cycle also depends on the (in)ability to recover brake energy, the so called Brake Energy Recuperation method. If BER is not possible, no energy can flow back from the vehicle to the energy source. In other words: all negative power in Figure 2.7 is lost and transformed into heat.

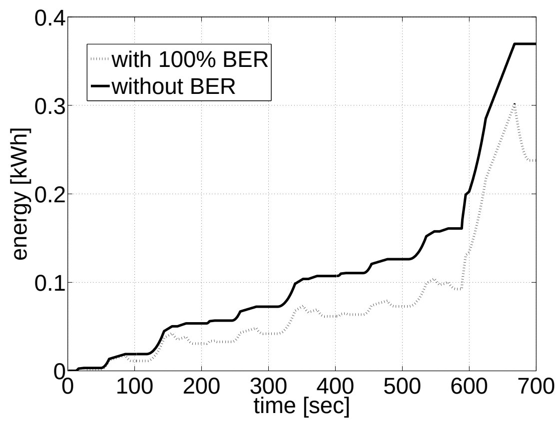
Integrating over the entire drive-cycle gives the results as shown in Figure 2.8. It also shows that a BER capable vehicle requires less energy to complete the drive-cycle than a non-BER vehicle requires. Note that in this case a 100% efficient BER system is assumed, which is not very realistic. Table 2.5 gives a overview of the required energy.

Table 2.5: required energy at the wheels

	1*CDM cycle		14*CDM cycles	
vehicle	[kJ]	[kWh]	[kJ]	[kWh]
BER	856	0.24	11990	3.4
non-BER	1330	0.37	18631	5.2

This means that the SLZ-driveline (without BER) needs approximately 5.2 [kWh] delivered at its wheels in order to cover the required range. However, the total required primary energy storage in the vehicle will be significantly larger, since a lot of energy is lost in the driveline itself. The total required primary energy storage thus highly depends on the type of implemented driveline, its tank-to-wheel and brake-to-storage efficiency.

Figure 2.8: energy consumption on CDM short drive-cycle



2.7 Summary on road load

Finally we can conclude this chapter with a short overview of the obtained results. Keep in mind that the power and the required energy calculated in this chapter are net power and net energy delivered at the wheels. To obtain the energy and power that has to be delivered by the engine/motor the quantities have to be divided by the load dependant driveline efficiency.

Table 2.6: summary of road load analysis

required continuous power	15 [kW]
required peak power	35 [kW]
required energy without BER	5.2 [kWh]

Chapter 3

Component Technologies

In order to determine a suitable topology and size for an SLZ-driveline, a schematic representation of a driveline is presented. The driveline will be split into groups of components that fulfil a certain function. The optimal topology of a hybrid vehicle strongly depends on the technologies available. Nowadays a lot of research is carried out into the optimization of existing technologies and the development of new technologies. This chapter will give an overview of what the current state of the art is for several technologies applicable when designing a hybrid vehicle. A division will be made between primary and secondary source applications. A hybrid drivetrain often contains electric machines (motors and generators). And since a lot of technologies are available in this field, a short overview is given at the end of this chapter.

3.1 Hybrid driveline characterization

3.1.1 schematic driveline representation

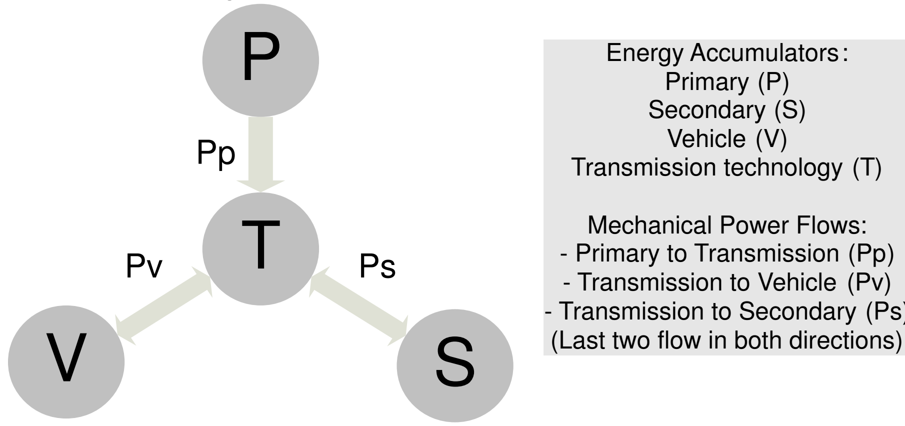
Various schematic hybrid driveline descriptions are already available. The description which is used here is taken from [3]. This model is built up out of four energy accumulators, namely:

- Primary source (P)
- Secondary source (S)
- Vehicle (V)
- Transmission technology (T)

These energy accumulators are connected with each other via 3 mechanical links. This is displayed in Figure 3.1. In a conventional drive line for instance, (P) is the fuel tank and engine and (T) will be either a manual or automatic transmission. No secondary source is present. In case of hybridization, a secondary source (S) is added to the primary source (P) in order to improve the driving functions. These driving functions can comprise fuel consumption, emissions, comfort, driveability (performance) and safety. (S) can for instance be an electric motor/generator and a battery.

The four functions have different characteristics that are of importance. For the primary source (P) this is the energy capacity. The vehicle must carry enough energy to travel the desired distance. The secondary source (S) is primarily installed to improve the driving functions as described above. Therefor, its main characteristic is the ability to deliver peak power when it is requested by the vehicle. Also the energy capacity is of importance. Some important parameters for the vehicle (V) are the wheel radius, the maximum velocity the vehicle has to reach and, of course, the mass of the vehicle. The main task of the transmission (T) is to conduct the power between the primary

Figure 3.1: schematic driveline representation



and/or secondary source and the wheels. To do this it has to be able to match the rotational velocities of the wheels and power source(s).

3.1.2 morphological list

The energy accumulators (P), (S) and (T) can be realized in a large number of different technologies. Some technologies are already fully developed and have been used in cars for years. Other technologies are newer and are still being developed. Figure 3.2 gives an overview of some potential technologies for the different applications. In the rows of the matrix are several technical implementations of the specific functions (P), (S), and (T). The driveline concept needs an technique from each row/function. The Toyota Prius for example has the combination of an ICE, a battery with generator and motor and an infinitely variable transmission (1A-2A-3D). It is however not always possible or smart to match every given technology. For example, combining a fuel cell with a compressed air vessel and a stepped transmission (1B-2C-3B), will not be very successful. The following 2 sections wil describe the primary and secondary source technologies in more detail. Their advantages, disadvantages and suitability for the SLZ-driveline are discussed.

Figure 3.2: morphological list

Functions		Technologies				
		A	B	C	D	E
1	Primary power source (P)	**ICE** running on Diesel/petrol/ CNG/LPG/Bio Diesel/hydrogen	**Fuel Cell** running on Hydrogen, combined with Electric Motor	**Fuel Cell** with reformer on alternative H_2 source, combined with Electric Motor	**Electric Motor** on battery	**Compressed air engine** with or without compressor
2	Secondary power source (S)	**Battery** with Generator and Electric Motor	**Capacitor** with Generator and Electric Motor	**Flywheel**	**Compressed air** vessel with compressor	
3	Transmission Technology (T)	**Fixed ratio**	**Stepped** (automatic) transmission	**Continuously variable** transmission	**Infinitely Variable** transmission	**Electric** transmission (Electric Motor and Generator)

3.2 Primary source technologies

3.2.1 internal combustion engine

ENGINES

The basic design of the internal combustion engine has not changed fundamentally in over a century of development and production. Nowadays, the internal combustion engine (ICE) is still the primary source with the highest power density. Furthermore, fossil fuels have a very high energy density. However, the internal combustion engine also has its drawbacks. Its very poor overall efficiency in combination with harmful emissions lead to developments aiming at the replacement of the ICE by an alternative primary source. Today, no serious contender for the ICE is available yet. Instead, technological progress has constantly upgraded and improved the ICE. Nowadays, the ICE is controlled by an electronic computing unit (ECU) and contains advanced technologies, for instance variable valve timing, ultra high pressure fuel injection and exhaustgas after treatment systems. These technologies have dramatically reduced fuel consumption and the exhaust of harmful emissions throughout the years. For more information about these technologies, see [4]

If the Cito vehicle will have an ICE as primary source, it will be a very small engine. This is because the required power for the Cito is rather small, that is 15 [kW] continuous power and 35 [kW] peak power. We could choose for an engine of 15 [kW] and an electric assist motor of 20 [kW]. The peak power of 35 [kW] could then be produced by adding both powers (hybridize). However, the disadvantage of using a 15 [kW] engine is that the technology of those engines is quite underdeveloped. Another disadvantage is that a 15 [kW] engine will have to run at its maximum power, which is detrimental to the lifespan of the engine and unwanted acoustics. These problems can be overcome by selecting a larger high quality engine available from massproduction. In Table 3.1 the smallest engines that are available from the major car manufacturers typically having a 1 liter displacement and a maximum power output of 30 to 50 [kW] are shown. Besides the lower costs the advantage of using a larger engine is that at normal operating conditions the engine runs at low speeds. This improves acoustics, comfortable riding and average combustion efficiency. The latter is realized since the engine can be operated near the sweet spot (operating point with highest efficiency) which lies around 1/3 of its maximum power. Besides this, when more power is needed, the engine can also deliver this at any moment, improving vehicle performance.

A short overview of some currently available low power ICEs that might serve as a primary source for the Cito-vehicle is given in Table 3.1.

FUELS

An ICE is an energy convertor. It converts caloric energy in the fuel into mechanical energy. The most commonly used fuels are fossil fuels in the from of petrol, diesel, LPG. The major disadvantage of using fossil fuels is that they exist in finite sources and that they pollute the environment. This is the reason that all over the world alternative fuels are developed. These fuels can be produced from renewable sources. Furthermore they reduce harmful pollutants and exhaust emissions. Especially biofuels, produced from plants and crops, enable the neutralization of CO_2 after it is exhausted by the ICE. The information on the following alternative fuels is taken from the Alternative Fuels Data Center. See [7]

ethanol Ethanol is an alcohol-based alternative fuel produced by fermenting and distilling starch crops that have been converted into simple sugars. Feedstocks for this fuel include corn, barley, and wheat. Ethanol can also be produced from 'cellulosic biomass' such as trees and grasses and is called bio-ethanol. Ethanol is most commonly used to increase octane and improve the emissions quality of gasoline. Ethanol can be blended with gasoline to create E85, a blend of 85% ethanol and 15% gasoline. E85 fueling equipment is slightly different and of similar cost to equipment used to store and dispense petroleum fuels. Saab recently presented 2.0 liter turbo engine that runs on petrol and E85 in any mixture, see [8].

Table 3.1: Currently available low power internal combustion engines

manufacturer	**fuel**	**displ.** [cm^3]	**power** [kW]	**emission standard**	**avail-ability**	**info**
Daihatsu	petrol	1000	43	euro 4	+	Cuore
Daihatsu	petrol	600	48	euro 3	+	turbo, Carver
Daimler Chrysler	diesel	800	30	NA	-	Smart fortwo
Fiat	petrol	1100	40	euro 4	-	Panda
Honda	petrol	1200	58	euro 4	-	Jazz
Lombardini	petrol	500	15	NA	++	generatorset
Mitsubishi	petrol	1100	55	euro 4	-	Colt
Nissan	petrol	1000	40	euro 3	-	Micra
Peugeot	petrol	1000	50	euro 4	-	107
Toyota	petrol	1000	48	euro 4	-	Yaris
Toyota	petrol	1200	55	euro 4	-	Yaris
Volkswagen	petrol	1000	37	euro 4	-	Lupo
Volkswagen	diesel	1200	45	euro 4	-	Lupo
Volkswagen	diesel	1200	40	euro 4	-	Polo

sources: [5], [6]

natural gas Natural gas is domestically produced and readily available to end-users through the utility infrastructure. It is also clean burning and produces significantly fewer harmful emissions than gasoline or diesel when used in natural gas vehicles. In addition, commercially available medium- and heavy-duty natural gas engines have demonstrated over 90% reductions of carbon monoxide (CO) and particulate matter and more than 50% reduction in nitrogen oxides (NO_x) relative to commercial diesel engines. Natural gas can either be stored onboard a vehicle as compressed natural gas (CNG) at 200 to 250 [bar] or as liquefied natural gas (LNG) at typically 1.5 to 10 bar. Natural gas can also be blended with hydrogen.

propane Propane or liquefied petroleum gas (LPG) is a popular alternative fuel choice for vehicles because there is already an infrastructure of pipelines, processing facilities, and storage for its efficient distribution. Besides being readily available to the general public, LPG produces fewer vehicle emissions than reformulated gasoline. Propane is produced as a by-product of natural gas processing and crude oil refining.

hydrogen Hydrogen (H_2) will play an important role in developing sustainable transportation, because in the future it may be produced in virtually unlimited quantities using renewable resources. Hydrogen has been used effectively in a number of internal combustion engine vehicles as pure hydrogen mixed with natural gas. Another application for H_2 is as fuel in a fuel cell. This technology will be discussed further on in this Chapter. Hydrogen is not a natural source, it has to be generated. It can be generated by Electrolysis of water or reforming of fossil fuels. These processes consume large amounts of energy. Nowadays, this energy comes from the regular electricity grid. In the future the required energy might be generated using solely renewable energy sources.

biodiesel Biodiesel is a domestically produced, renewable fuel that can be manufactured from vegetable oils, animal fats, or recycled restaurant greases. Biodiesel is safe, biodegradable, and reduces serious air pollutants such as particulates, carbon monoxide, hydrocarbons, and air toxics. Blends of 20% biodiesel with 80% petroleum diesel this (B20) can generally be used in unmodified diesel engines. Biodiesel can also be used in its pure form (B100), but this may require certain engine modifications to avoid maintenance and performance problems. An advantage of biodiesel is that it can be distributed using the traditional petrol/diesel infrastructure. Several biodiesel projects have been launched worldwide. For more information on projects in the USA, see [9]. For more information on projects in the EU see [10].

CITO PRIMARY SOURCE?

In spite of its serious drawbacks such as limited efficiency and harmful emissions, the internal combustion engine is still the number one primary source in the automotive world. Until no other technology is able to achieve comparable power and energy density at acceptable cost, it will be further exploited and developed. Even when using hydrogen on a large scale, a technically modified ICE may remain the most attractive primary source. BMW has good experience with direct combustion of hydrogen in an ICE. They are marketing the second generation of their bi-fuel powered 7 series, see [11] and Figure 3.3. Also for the Cito the ICE is an obvious possibility. Especially the low production cost and existing infrastructure are strong points. The drawbacks of the low efficiency and harmful emissions are partly compensated by the efficient CDM mobility concept itself (low traffic congestion) and partly by using more environmentally friendly fuels and hybrid technology.

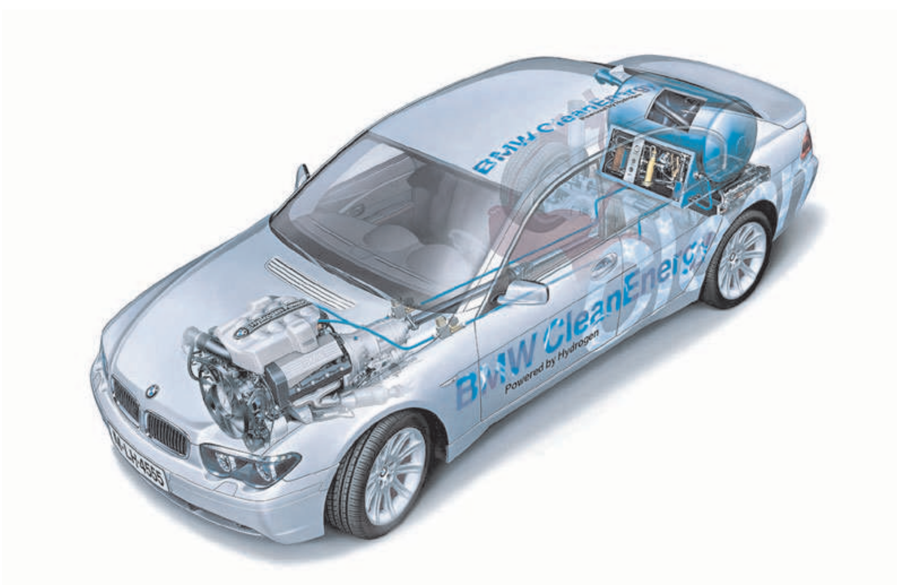


Figure 3.3: BMW 745h bi-fuel vehicle

3.2.2 battery

Information from this section is taken from the nrel website. See [9].

A conventional vehicle uses a lead acid battery to start the engine and power auxiliary loads (lighting, electronics, etc.). Hybrid electric, electric, and fuel cell vehicles (HEVs, EVs, and FCVs) have conventional lead acid batteries, but also have propulsion batteries, which are constructed quite differently. They are built for high power, high energy, and long cycle lives. Some low-voltage hybrid vehicles use advanced lead acid batteries, known as valve regulated lead acid (VRLA) batteries. Most propulsion batteries for full hybrid vehicles are made of nickel-metal hydride (NiMH), rather than lead-based. A NiMH battery can hold twice as much energy as a lead-acid battery, has a longer life cycle (factor 2 to 3). Its materials are less toxic than those in a regular car battery. A few production hybrids with advanced batteries have been introduced in the market. For instance the Honda civic IMA, Honda Insight a number of vehicles that incorporate

Toyota's Hybrid System (THS see [12]). All these vehicles make use of NiMH Batteries, see Appendix B. However, technical challenges remain for demonstrating battery technology that has an acceptable combination of powerdensity, energydensity and efficiency, and lifespan especially for the high-volume production vehicles. A short overview of different battery technologies is given below. Table 3.3 gives an overview of the characteristic values of the discussed battery types and also the long term goals by the United States Advanced Battery Consortium (USABC).

TYPES OF BATTERIES

Lead-Acid Batteries Lead-acid batteries can be designed to be high power, low cost, safe, and reliable. A recycling infrastructure is available, which reduces environmental load. But low specific energy, poor cold temperature performance, and short calendar and cycle life are still impediments to their use. Advanced high-power lead-acid batteries are being developed for HEV applications. These are also known as valve regulated lead acid (VRLA) batteries.

Nickel-Metal Hydride Batteries Nickel-metal hydride batteries, used routinely in computer and medical equipment, offer reasonable specific energy and specific power capabilities. Their components are recyclable, but a recycling structure is not yet in place. Nickel-metal hydride batteries have a much longer life cycle than lead acid batteries and are safe and abuse-tolerant. These batteries have been used successfully in production electric vehicles and recently in low-volume production HEVs. The main challenges using nickel-metal hydride batteries are their high cost, high self-discharge and heat generation at high temperatures, the need to control losses of hydrogen, and their low efficiency.

Lithium Ion Batteries The lithium ion batteries are rapidly penetrating into laptop and cell-phone markets because of their high specific energy. They also have high specific power, high-energy efficiency, good high-temperature performance, and low self-discharge. Components of lithium ion batteries could also be recycled. These characteristics make lithium ion batteries suitable for HEV applications. However, to make them commercially viable for HEVs, further development is needed including improvement in calendar and cycle life, higher degree of cell and battery safety, abuse tolerance, and acceptable cost.
Recently a new type of Lithium-Ion battery was presented by Toshiba. They claim very short recharge time (80% of it's capacity in 60 seconds) and a high energy density. It should also have a long cycle life and a very low temperature dependency. All this is made possible by the use of nano-particles on the negative electrode. This battery type is still in development, see also [13]

Lithium Ion Polymer Batteries Lithium ion polymer batteries with high specific energy, initially developed for cell phone applications, also have the potential to provide high specific power for HEV applications. The other key characteristics of the lithium polymer are safety, and good cycle life. The battery could be commercially viable if the cost is lowered and higher specific power batteries are developed.

Nickel-Cadmium Batteries Although nickel-cadmium batteries, used in many electronic consumer products, have higher specific energy and better life cycle than lead-acid batteries, they do not deliver sufficient power and are not being considered for HEV applications. Cadmium is a heavy metal that is toxic, which increases recycling costs when using in hybrid applications.

Sodium Chloride Batteries Sodium Chloride batteries exist in two different types, the positive electrode can be either a nickel chloride or a ferrous chloride material. Although metal is cheaper than nickel, the latter is more attractive as the iron component because of fewer complications and a wider operating temperature range. The Sodium/Nickel Chloride battery is also known under the name ZEBRA battery. It is a high energy battery which operates at high temperatures of approximately 300^oC. The ZEBRA high energy battery, based on the electrochemical couple

Sodium/nickel chloride, is produced on a commercial scale in Switzerland by MES-DEA. The high specific energy of this battery (120 Wh/kg) makes it particulary suitable for EV purposes. The ZEBRA battery is, for instance, used in the TH!NK City cars several busses in Italy and some military vehicles.

CITO PRIMARY SOURCE?

The main problem with Battery Electric Vehicles (BEV's) is the large battery (and accompanying weight) that is needed to provide the vehicle with the required minimum range. If we use the road load data from Chapter 2 and assume that a copy of the NiMH battery from the Toyota Prius (See Table 3.2) is used, we can estimate the required size, weight and cost of the battery.
Chapter 2 showed that the Cito needs 5.2 [kWh] of energy and 15 [kW] continuous power. Since a battery cannot be used over its full charge, an assumption is made that the battery will function between 10 and 90 % State Of Charge (SOC). This means that the battery has to be 25 % oversized in order to deliver the required energy output. The energy demand leads to a battery of

$$5.2 * 10^3[Wh]/29.6[Wh/kg] * 1.25 \approx 220[kg]. \tag{3.1}$$

The power output places a smaller demand on the battery with a weight of,

$$35 * 10^3[W]/467[W/kg] \approx 75[kg]. \tag{3.2}$$

A battery of about 220 kilograms is needed to power the Cito vehicle. The weight calculated out of the energy demand can be lowered by usage of Brake Energy Recuperation (BER). The cost of such a battery can be estimated on basis of the characteristic cost given in Table 3.3,

$$5.2 * 1.25[kWh] * 240[EUR/kWh] \approx 1560, -EUR. \tag{3.3}$$

This is already a great deal of the €1700,- goal for the entire driveline. A bigger problem is however the weight of the battery, which is already almost double of the maximum total weight of the driveline. Another major disadvantage of a pure BEV is that it needs to be recharged when the battery at its minimum state of charge. This means that the vehicle has to be recharged and plugged into the electric power grid for some hours, before it can be used again. This problem is only increased by the absence of an BEV equipped infrastructure. The problems are worsened by the fact that battery performance is highly dependant on operating conditions like temperature and charging strategy. A major advantage of a pure electric drive train over an drive train with mechanical links is that the flexibility in placement of the electric components is much larger. The disadvantages however (literally) outweigh the advantages and it is clear that a pure electric drive is not an option for the SLZ-driveline.

3.2.3 fuel cell

The fuel cell works on the principle that hydrogen and oxygen can be combined to produce water and an electric current. This principle was already discovered in 1839 by Sir William Robert Grove. In the 1950s NASA scientists used fuel cell technology to produce drinking water in space and to power space exploration vehicles. Nowadays, extensive research is carried out on fuel cells all over

Table 3.2: Toyota Prius NiMH battery properties

energy	6.6 [Ah] @ 201.6 [V]=1.33 [kWh]
power	21 [kW]
weight	45 [kg]
specific energy	29.6 [Wh/kg]
specific power	467 [W/kg]

Table 3.3: Battery types and characteristics

type	**Specific Energy** [Wh/kg]	**Specific Power** [W/kg]	**Energy Density** [Wh/L]	**Cycle life** [# cycles]	**Cost** [€/kWh]
VRLA	35-50	150-400	60-100	400-600	100
NiMH	25-70	180-600	100-140	1000-2000	240
Li-Ion	80-130	200-1400	240-280	1200	210
Li-Po	150-200	315	220	600-1000	120
NiCd	30-50	150-350	80-100	1000-2000	300
Zebra	90-120	130-160	NA	1000	200-300
Toshiba	NA	NA	150-250	>1000	NA
USA BC	200	400	300	1000	80

sources: [14], [15], [16]

the world. Applications range from cellular phones to submarines, but especially the automotive industry might benefit from the advantages of the fuel cell. This chapter will give an overview of the current state of the art in (automotive) fuel cell (FC) technology. First the different types of fuel cells are discussed. Safety is discussed and finally a conclusion is drawn with respect to the SLZ-driveline and the Cito vehicle.

TYPES OF FUEL CELLS

Information from this section is taken from the Fuel Cells 2000 website. ([17])

Phosphoric Acid Fuel Cell (PAFC) This type of fuel cell is commercially available today. The cell is primarily used for stationary power generation. For instance in hospitals, office buildings, schools and airport terminals. PAFCs generate electricity at more than 40% efficiency and operating temperatures range from 150 to 200 $°C$. Existing PAFCs have outputs ranging from 200 kW up to 1 MW. The main advantage of the PAFC is that it is the most mature fuel cell technology. Another advantage is that the fuel cell can use impure hydrogen as fuel. PAFCs can tolerate a CO concentration of about 1.5 percent, which broadens the choice of fuels they can use. Disadvantages include the expensive platinum which is used as a catalyst, the low current and power output when compared to other types of fuel cells and the large size and weight of the fuel cell. This combined with the high operating temperatures makes this type of FC unsuited for automotive applications.

Proton Exchange Membrane fuel cell (PEM) The PEM fuel cell is the main candidate for light duty vehicles, most prototype vehicles are equipped with this type of FC. These cells operate at relatively low temperatures of 80 $°C$ have a high power density and have a quick startup. Besides these, another advantage of the PEM is that it can quickly vary its output to meet shifts in power demand. The electrolyte used is organic polymer polyperflourosulfonic acid, which is a solid state electrolyte. This is an advantage because it reduces corrosion and management problems. A drawback of the PEM fuel cell is that it is sensitive to fuel impurities. Power output generally ranges from 50 to 250 kW.

Molten Carbonate Fuel Cell (MCFC) These fuel cells use a liquid solution of lithium, sodium and/or potassium carbonates, soaked in a matrix for an electrolyte. They operate at high temperatures of about 650 $°C$, which is good for efficiency (up to 60 % in electricity generation). It also increases flexibility to use different fuels and makes it possible to use inexpensive catalysts. Disadvantages are that a high temperature enhances corrosion and breakdown of cell components.

MCFCs have been tested with outputs of 10 kW up to 2 MW. The high temperature makes this FC unsuited for automotive applications.

Solid Oxide Fuel Cell (SOFC) A fuel cell primarily used for big, high power applications including industrial and large-scale electricity generating stations. A SOFC usually uses a hard ceramic material of solid zirconium oxide and a small amount of ytrria, instead of a liquid electrolyte. This makes it possible to operate at high temperatures of up to 1000 $°C$. Power generating efficiencies could reach 60 % and 85 % with cogeneration. The SOFC is still in development, Japan is testing two 25 kW units and in Europe a 100 kW unit is being tested.

Direct Methanol Fuel Cell (DMFC) These cells are similar to the PEM fuel cell in that they both use a polymer membrane as the electrolyte. However, in the DMFC, the anode catalyst itself draws the hydrogen from the liquid methanol, eliminating the need for a fuel reformer. Efficiencies typically are 40 % but could be higher if a higher operating temperature is used. The relative low operating temperature (50 to 100 $°C$) however makes this FC ideally suited for tiny to mid sized applications, such as cellular phones and laptops. A major problem however is fuel crossing over from the anode to the cathode without producing electricity. A number of companies, however, claim that they have solved this problem.

Zinc-Air Fuel Cell (ZAFC) The proces in a ZAFC is very similar to a PEM FC, but the refueling is very different and shares characteristics with batteries. In the ZAFC electricity is created as zinc and oxygen are mixed in the presence of an electrolyte, creating zinc oxide. Once fuel is used up, the system is connected to the grid and the proces is reversed, creating pure zinc fuel pellets. The key is that this reversing proces takes only about 5 minutes to complete, so the battery recharging time hang up is not an issue. The main advantage zinc-air technology has over other battery technologies is its specific energy. Zinc-air fuel cells have a potential wide range of applications, ranging from EVs, consumer electronics to military.

Protonic Ceramic Fuel Cell (PCFC) This new type of fuel cell is based on a ceramic electrolyte material that exhibits high protonic conductivity at higher temperatures. These higher operating temperatures (about 700 $°C$) give it the same advantages as with MCFCs and SOFCs. These are high electric efficiency and the ability to extract hydrogen from the fuel directly to the anode. Which eliminates the need for a fuel reformer. Additionally PCFCs have a solid electrolyte so the membrane cannot dry out as with PEM fuel cells, or liquid can leak out as with PAFCs.

INFRASTRUCTURE

Nowadays, fuel cells are already commercially available and numerous concept vehicles and a few production vehicles have been developed. (See [18] and Appendix B) Also a lot of ideas have been conceived about how how to produce and distribute the required hydrogen and deliver it to the fuel cell vehicles (FCVs). The ideas can be grouped into:

- **Centralized production and delivery** Hydrogen production and delivery services - including a limited pipeline system - already serve the needs of today's industrial demands.
- **On-site production** The energy station of the future might produce hydrogen on demand from natural gas, other compounds or even water.
- **Solar Power** The ultimate solution might be solar powered hydrogen filling stations, where electricity is generated by the sun (or wind power) is used to extract hydrogen from water.

All around the world prototype hydrogen refuel stations are build and operated on basis of research projects. No real standardized or full scale projects are planned at this time. The technologies are still too new and a lot of research still has to be carried out.

CITO PRIMARY SOURCE?

A fuel cell hybrid vehicle wil be a serial hybrid. Instead of an engine these vehicles use a fuel cell unit. The leading technology for automotive fuel cell units is the Proton Exchange Membrane (PEM). The potential advantages of a fuel cell as primary source for the Cito vehicle will be:

- Zero pollution if fuel cell is run directly on hydrogen
- Systems with onboard reformer still reduce smog forming by up to 90% compared to traditional combustion engines, depending on the choice of fuel
- A reduced dependency on fossil fuels
- High efficiency compared to ICE (A fuel cell has no moving parts and thus no engine losses due to friction)
- Fuel flexibility
- Packaging flexibility

There are however also some serious problems, which will take some time to overcome. The main problems are:

- There is still no suitable or efficient method for the production and onboard storage of hydrogen. Therefore FCEVs will depend on onboard fuel reformers resulting in CO2 emissions from the vehicle and reducing its efficiency. [19]
- Fuel cell systems require the use of pumps, compressors and expanders to manage the fluids flowing through the systems. This equipment consumes energy (parasitic power) reducing the overall efficiency of the system [19]
- Current fuel cell plants are still under development. Because of their size and mass fuel cells are still not suitable for automotive application. Downsizing a fuel cell system will reduce its overall efficiency [19]
- Fuel cells are still very expensive: currently 1500$/kW compared to a 50$/kW for ICE technology. There is a lot of variation in prognoses for the cost of fuel cells. It is difficult to say what a fuel cell will cost in about ten years. This depends heavily on technological developments and commerce. However, it is expected that fuel cell cost will stabilize around 50 to 100$/kW. Exactly when this will happen is unclear.

These problems, combined with the boundary conditions put by SAM (cost, weight, availability, infrastructure), make it obvious that the fuel cell, at this moment, is not capable of meeting the requirements for the primary source for the Cito vehicle. However, care is taken that the design of the SLZ-driveline will be flexible towards future implementation of fuel cell technology. This will of course only be the case if a full electric or serial hybrid lay-out is chosen.

3.2.4 compressed air engine

sources [20], [21]

The compressed air engine is currently being developed by the French company MDI cars. The air-powered car consists of a two-cylinder, compressed-air engine. The basic concept behind the engine is unique, it can run either on compressed air alone or act as an internal combustion engine. Compressed air is stored in carbon or glass fiber tanks at a pressure of 300 [Bar]. This air is fed through an air injector to the engine and flows into a small chamber, which expands the air. The air pushing down on the pistons moves the crankshaft, which gives the vehicle power. Air tanks fixed to the underside of a car can hold 300 [liter] of air. This compressed air can fuel the air-powered car for up to 200 [km] at a top speed of 110 [km/h]. The car is fitted with a compressor and, using a household electrical source, it takes about four hours to refill the compressed air tanks. However, a rapid three-minute recharge is possible, using a high-pressure air pump. Although there are no service stations equipped with the compressed air machines yet. The company is currently looking for investors and trying to get production started. The main target group is the urban motorist.

A major advantage of the compressed air engine is that it has no local emissions other than air. Which is ideal for the smog covered metropolises all over the world. A disadvantage is that the energy needed to compress the air is coming from the power grid, which makes this vehicle currently not as environmentally friendly as it seems. The fact that the technology is currently still not in production and the absence of an appropriate infrastructure together with uncertainty of the actual performance of the technology make that the compressed air engine is not a potential primary source for the SLZ-drivetrain.

3.2.5 Well to Wheel analysis

sources: [22], [23], [24]

A well to wheel analysis is needed to examine the environmental pressure which a certain vehicle concept has. A well to wheel analysis (WtW) is the rigorous examination of the entire proces of creating and using fuels to provide power to the wheels of a vehicle, resulting in an assessment of requisite energy consumption and corresponding greenhouse gas (GHG) emissions. The WtW analysis can be split up into:

- Well to Tank (WtT) analysis (Fuel): Accounting of energy consumption and GHG emissions over the entire fuel pathway, from feedstock to fuel dispenser nozzle.

- Tank to Wheel (TtW) analysis (Vehicle): Accounting of energy consumption and GHG emissions resulting from moving the vehicle through its drive-cycle.

Conducting an entire WtW analysis is far beyond the scope of this study, but a study into the results of several WtW analysis led to the following observations.

QUALITATIVE OBSERVATIONS

Diesel and Petrol

- Diesel engines typically have a better WtW efficiency than petrol engines but higher NOx emissions

- Over the time span 2005-2010 conventional Petrol and CNG fueled engines will show more improvement than diesel fueled engines.

- Hybridization of the above mentioned engines always leads to an improved efficiency and reduced GHG emissions.

Compressed Natural Gas

- At this moment the WtW emissions of CNG are situated between those of diesel and petrol

- In the future CNG emissions will score slightly better than diesel emissions

- The WtW efficiency of CNG will always be better than that of diesel and petrol

Hydrogen

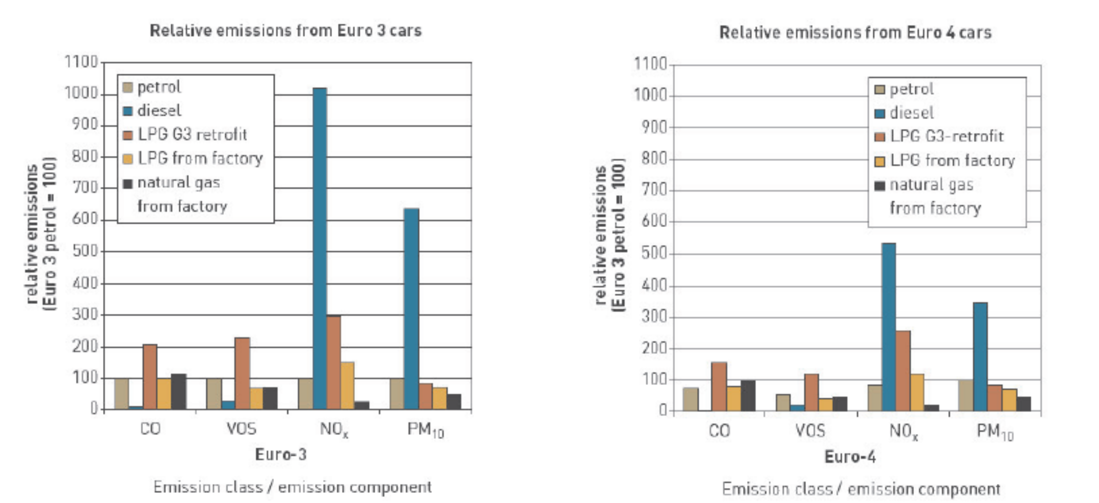
- CNG is in short-term the only suitable and cheapest source for creating hydrogen.
- Only if hydrogen is used in combination with a fuel cell will it lead to improvements in WtW emissions. Hydrogen in combination with an ICE does not lead to WtW emission improvement
- Renewable sources for hydrogen are limited in their potential and are very expensive at the moment.
- The use of renewable sources works more cost effective if they deliver power directly to the electricity grid instead of being used as fuel in hydrogen powered vehicles.

Bio fuels like ethanol, FAME (Fatty Acid Methyl Ether), DME (Di-Methyl-Ether), Biomass-to-liquid (BTL) and Gas-to-Liquid (GTL) fuels are not being discussed in this WtW analysis because they are still in the development phase.

QUANTITATIVE OBSERVATIONS

The following figures give the TtW and WtW emissions and GHG emissions for several regular fuels relative to a Euro-3 petrol engine. The figures are taken from [24].

Figure 1. Tank-to-wheel emissions from petrol, diesel, LPG (retrofit and OEM) and natural gas (OEM)



Relevant conclusions that can be made from this data are:

- TtW NOx emissions of Euro-3 diesel vehicles are still 10 times as high as those of petrol vehicles.
- TtW The NOx emissions of a Euro-4 diesel engine are 7 times higher than those of a Euro-4 petrol engine
- A big difference in environmental performance between diesel and petrol powered engines will remain to exist at least until the introduction of the Euro-5 standard, which will make the application of a NOx filter inevitable.
- The difference in WtW NOx emissions between diesel and petrol is much smaller but still a factor 5.
- For CNG vehicles, all emissions excluding CO and VOS (Volatile Organic Compounds) will be significantly smaller than for diesel and petrol vehicles.

Figure 2. Well-to-wheel emissions from petrol, diesel, LPG (retrofit and OEM) and natural gas (OEM)

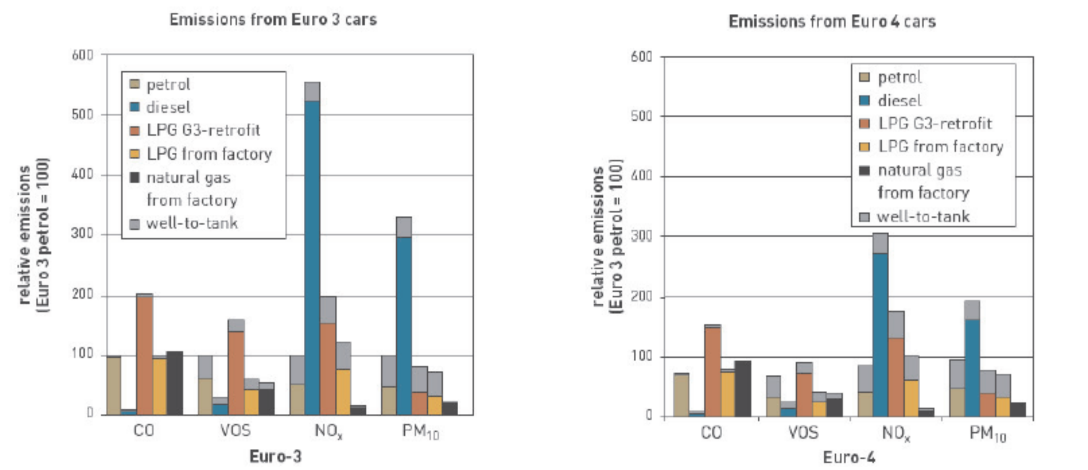
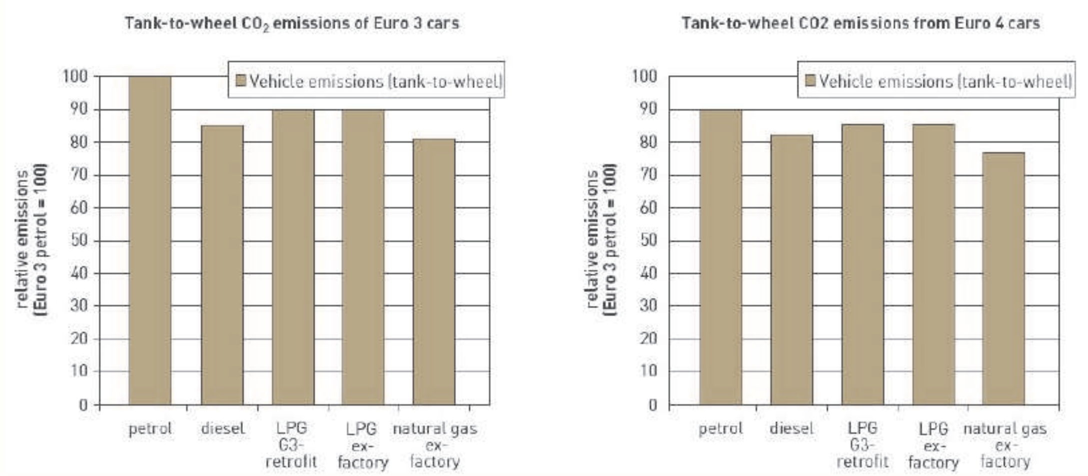


Figure 3. Tank-to-wheel CO_2 emissions from petrol, diesel, LPG (retrofit and OEM) and natural gas (OEM)



- CO emissions of a Euro-3 diesel engine is 15 % less than that of a Euro-3 petrol engine
- CO emissions of a Euro-3 CNG engine is 19 % less than that of a Euro-3 petrol engine
- Euro-4 petrol engines will be have 10% fuel savings relative to Euro-3 petrol engines. This also leads to 10% less CO emissions.
- CO emissions of a Euro-4 diesel engine are just 8% better than those of a Euro-4 petrol engine
- Because progress in diesel engines improvement is smaller than that of petrol engines the difference in CO emissions will only become smaller, while all other emissions are better for the petrol engine. In WtW perspective this percentage rises to 10 %.

RECOMMENDATIONS FOR THE SLZ-PROJECT

The previous observations conclude to the following recommendations:

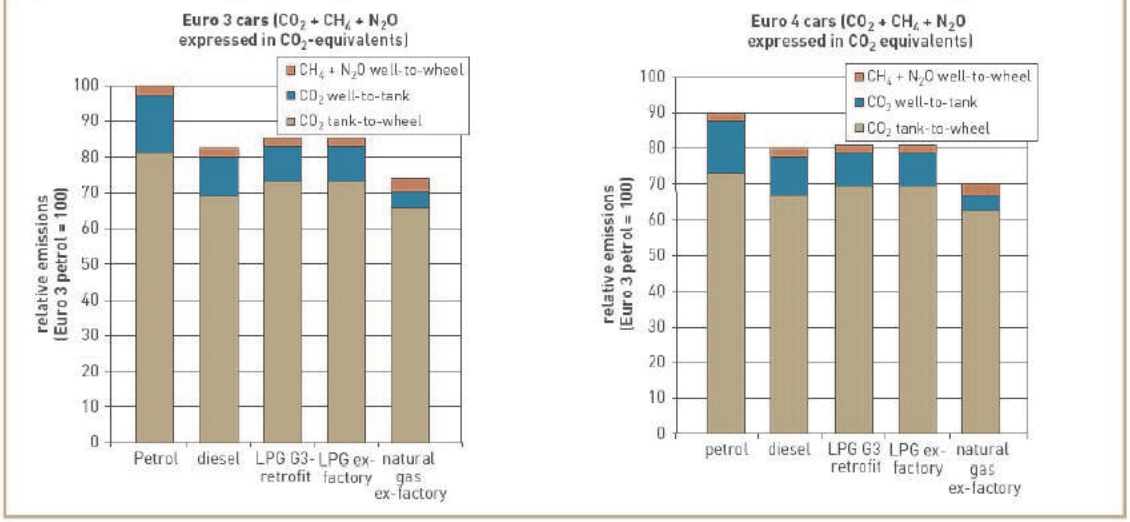


Figure 4. Well-to-wheel greenhouse gas emissions from petrol, diesel, LPG (retrofit and OEM) and natural gas (OEM)

- On the short term a Euro-4 ICE is the best compromise between minimal emissions, fuel consumption and GHG emissions.
- The convincing WtW performance of CNG fueled engines makes it recommendable to look at the possibilities for a CNG fueled engine.
- The use of CNG as a source for hydrogen is important for the near future. Important in this case is that the hydrogen is used in a fuel cell and not in an ICE.
- If, in the longer future, more progress is made in the production development of hydrogen from renewable energy than in the development of fuel cells, than the use of an hydrogen fueled ICE may become more attractive in a cost point-of-view.

3.3 Secondary source technologies

The secondary source in a hybrid drivetrain is included to improve the driving functions described earlier. Its main purpose is to deliver peak power and store energy which is recuperated when braking a vehicle. The most important characteristic for a secondary source is its specific power.

3.3.1 battery

The different types of batteries and their characteristics are already discussed in Section 3.2 and Table 3.3. The application of batteries as a secondary source take away some of their main drawbacks. The specific energy of batteries, which was a problem in the primary source application, poses no problem in the secondary source application because the required energy capacity in secondary source application is much lower than in the primary source application. The overal size and cost of a battery as secondary source are lower than in the primary source application. A difference in operating strategy between batteries used in primary source and secondary source applications is that the first usually uses a deep cycle strategy. In this strategy the battery is used over a large part of its SOC range (between 10% and 90%). This in contrast to a battery which is used in a secondary application, which uses only a very small SOC window.

3.3.2 capacitor

sources: [15], [25]

Capacitors are devices that are able to store energy by the separation of equal positive and negative electrostatic charges. They are widely used in all kinds of electric circuits. Super and Ultra capacitors are derived from conventional capacitors. The difference between them is that energy density is increased at the expense of power density so the device function more like a battery. Compared to batteries ultra and super capacitors have a much lower energy density, but the advantage of the capacitor is that it has a much faster (dis)charge rate than the battery and the capacitors have a much higher power density. Also cycle life is much longer.
The difference between super and ultra capacitors is that the ultra capacitor has electrochemical systems to store energy compared to the electrostatic storage system of a super capacitor. The table below gives some characteristics that were estimated by on basis of the BCAP0010 boost cap from Maxwell. In this data a operating range of 50 % is incorporated.

capacitor info	
type	Maxwell BCAP
capacity	2600 [F]
volume	0.42 [liter]
mass	0.525 [kg]
cost	€72,22 @ min. 1000 pieces

characteristics	
specific power	1062 [W/kg]
specific energy	3.22 [Wh/kg]
specific volume	1.329 [kW/liter]
specific cost	128 [€/kW]
	43000 [€/kWh]

Figure 3.4: maxwell supercapacitor

3.3.3 flywheel

sources: [26], [14] and [15].

Flywheels have several technical applications, one of those applications is energy storage. Typically, a difference can be made between sub- and super-critical flywheels. The first term relates to a flywheel that operates in speed regions beneath it's first eigen mode. The super-critical flywheel operates in a speed region between the first eigen mode and its maximum speed (imposed by material properties). The high operating speeds of the supercritical flywheel demand for operation in vacuum. It typically has an electrical output. The sub-critical variant does not need a vacuum to operate and typically has a mechanical outputshaft.
An advantage of a flywheel system is its high specific power (2-5 kW/kg). Other advantages of the flywheel come along with its mechanical nature. It is not affected by temperature or humidity extremes and there are also no problems with disposal of waste materials. The service lifetime of a flywheel is many times that of a battery, with little maintenance required. Furthermore, it has the ability to absorb or release a high amount of power in a short time which is ideal for brake energy recovery.
Besides these advantages, there are also some major disadvantages to the flywheel system. The first is that the flywheel system requires a lot of extra equipment to operate. Especially the super critical flywheel, which needs a vacuum chamber, pump and magnetic bearings. Also safety is a concern, and demands a safety containment vessel. But the biggest drawback of the flywheel is its cost. Typically a (sub- or super-critical)flywheel cost about 300 [€/kW]. This makes the flywheel concept to expensive to be incorporated into the SLZ-driveline design.

3.3.4 electric machine technology

ELECTRIC MACHINE BASICS

An electric machine is a device that converts electric energy to mechanical energy and vice versa. When electric energy is converted to mechanical energy the electric machine is called a 'motor'. When mechanical energy is converted into electric energy the machine is called a 'generator'. Different electric machine technologies exist, but a main division can be made between DC and AC machines. DC motors were used quite extensively in the past, especially in automotive applications because of the present 12 Volt DC supply. However, the size and maintenance (brushes!) requirements of DC motors are major drawbacks. Nowadays more and more use is made from AC motors. The control of AC motors is more difficult than that of DC motors. However, with the current advances in computer technology and processors this poses no restrictions anymore. AC machines include induction motors and permanent magnet (PM) motors. In induction machines a magnetic field is created electrically while the PM motors use permanent magnets to do so. The advantage of the PM machine over the induction machine is that it can be smaller in size and has a higher power density and efficiency. The disadvantage of the PM machine is that the use of high density magnets that give it its high power density also make the machine more costly than the induction type. However, especially in HEV development the advantages of the PM machine seem to be large and make the higher cost acceptable, this is why the trend is to use PM machines.
An advantage of electric machines in general is that they can deliver short term peak power that is 200-300 % higher than their continuous power. [15]

WHEEL MOTORS

A lot of manufacturers are currently experimenting with wheel motors. A wheel motor is a self propelled electrically powered wheel. It consists of a integration of a wheel and an electric motor. A lot of different wheel motor implementations exist, but they can be subdivided into three groups:

- **in-wheel motors**
  This type of wheel motor is most similar to a conventional electric drive. The difference is

that every wheel has its own motor and the driveline is very compact. Normally an electric driveline consists of a motor connected to two wheels via an axle, whereas in the wheel motor concept the motor and axle are compactly integrated with the wheel. A recent example of this technology is the MIEV-driveline by Mitsubishi. See Figure 3.5. For more information see [27] and [28].

Figure 3.5: Mitsubishi's MIEV in-wheel motor design

- **wheel hub motors**
  In this type of wheel motors the wheel hub itself is an integral part of the electric machine. The motor is built into the wheel and the rim is the rotor of the electric machine. A typical example is 'TheWheel' from a company called e-traction [29]. The concept is shown in Figure 3.6. Usually the center of an electro motor spins around and the housing remains stationary. In the case of TheWheel this is reversed. The exterior of the motor, the rotor, fixed with permanent magnets on the inside spins around. The stator, which contains the electromagnets, remains stationary. The tire is mounted directly to the exterior of the direct drive motor. A disadvantage of this system is that the available torque depends on the size of the wheel. So for applications with small wheels this system may be underpowered.

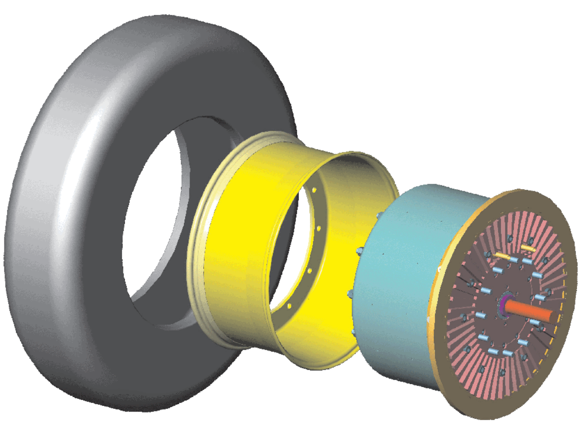


Figure 3.6: wheel hub motor

Figure 3.7: internal reduction motor

- **internal reduction motors**
  The third concept consists of a motor combined with a reduction gear that are both mounted in the wheel. The advantage of this system is that the motor can be much smaller in size since it can be operated at much more efficient higher velocities. Michelin [30] recently developed the Hy-Light concept car which incorporated internal reduction wheel motors. A picture of this system is shown in Figure 3.7. Note that this concept also includes active suspension, the equipment to do this is also included in the wheel which is shown in this figure.

Wheel engines have some considerable advantages over normal shaft driven wheels. The main advantage is that these systems are fully integrated into the wheels and that there are no mechanical connections between the wheels and the primary source. This gives a packaging and design advantage. Other advantages come from the fact that all wheels can be controlled independently, both for traction, braking and even steering.
Disadvantages of wheel motors include the higher unsprung mass of the wheel, which is bad for vehicle dynamics and the necessity for a cooling system which has to be onboard. Especially internal reduction wheel motors require a lot of cooling since they operate at very high speeds.

Chapter 4

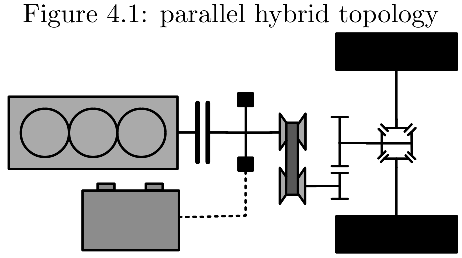
Three Hybrid Concepts

In general a car needs a transmission to couple the energy source(s) to the wheels. This transmission must be able to conduct the requested torque and it must also be able to connect the different rotational velocities of the wheels and motor. Three general concepts will be sketched in this chapter. These concepts are all based on an ICE primary source and an electric machine (motor/generator) as secondary source. In this chapter the three basic concepts, namely the parallel hybrid, power split hybrid and series hybrid are presented. Further on in this report the three concepts will be modeled in Matlab and profound calculations will be made in order to choose the best suiting concept for our application. This choice will be made using a multi criteria analysis. The criteria for this analysis are presented in this chapter.

4.1 Parallel hybrid

The parallel hybrid is the driveline topology resembling most with conventional drivelines. It consists of an ICE as primary energy source and a mechanical transmission. This transmission can be either a discrete transmission ((Automated) Manual or Automatic) or a Continuously Variable Transmission (CVT). Nowadays in most passenger cars, an electric motor and battery are used only to start the engine. The function of this starter motor can however be expanded. If a larger motor and battery are used the setup actually becomes a parallel-hybrid topology. In this way the motor and battery are the secondary energy source and can for instance be used as a Starter Alternator (SA) system (see [19] for a detailed description). The secondary storage displayed in Figure 4.1 can be substituted by batteries or supercapacitors.

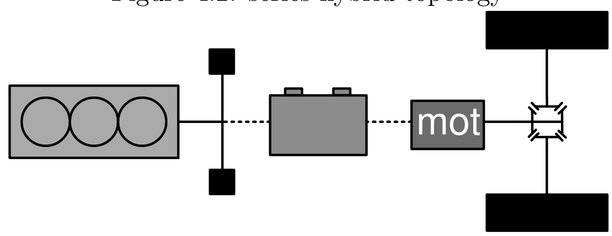
Figure 4.1: parallel hybrid topology



4.2 Series hybrid

In a series hybrid, the engine drives a generator that generates electricity. Another electric machine uses this energy to drive the wheels. A battery can be placed between the generator and motor as a buffer, but this is not a necessity. The advantage of a series hybrid driveline in combination with a buffering battery is that the ICE can be a relative small, low power engine that steadily runs in an efficient operating region. Because the battery functions as a buffer, it can be much smaller than in the BEV case. A disadvantage of a series hybrid is that two equally sized (large) motors are needed to charge the battery during braking and drive the wheels otherwise. Another disadvantage is the relatively low efficiency compared to the parallel and power split transmission. This is due to the conversions between mechanical and electrical energy, vice versa

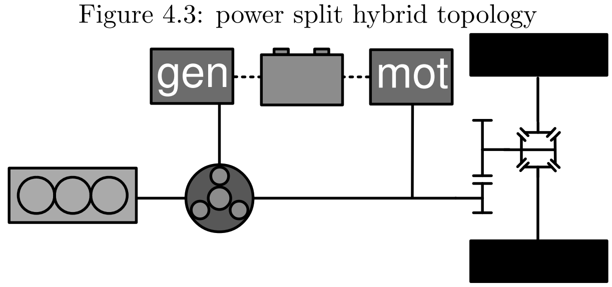
Figure 4.2: series hybrid topology



4.3 Power split hybrid

A power split hybrid is in fact a combination of a series and a parallel hybrid and it benefits from the advantages of both configurations. Depending on the driving conditions the wheels are driven either by the electric motor, the engine, or a combination of the engine and the electric motor. The power coming from the engine is split by a power split device. One part of the power flows via a mechanical path to the wheels, the other part via an electrical path. The power split unit as displayed in Figure 4.3 is a planetary gear set. Together with the electric motor and generator a transmission is formed that is called an infinite variable transmission (IVT). The transmission ratio is changed by varying the rotational velocities of the engine, motor and generator. The power split method is being commercially produced by Toyota in the the form of the Toyota Hybrid System THS II (see [12]). An advantage compared to the series hybrid is that the 2 electric machines do not have to be equally sized. They can be smaller since not all engine power follows the electrical path. The power split transmission is in fact a combined mechanical and electric transmission.

Figure 4.3: power split hybrid topology



4.4 Criteria

The three hybrid concepts are modeled in Matlab and some additional qualitative characteristics are determined. This is described in Chapter 5. All this data will be compared in a multi criteria analysis in Chapter 6. The characteristics that will be investigated are listed in Table 4.1. The criteria under "performance" and "environment" will be calculated with the help of the models described in the following chapters. The other criteria are either calculated with characteristic values or estimated otherwise. The results of the analysis are presented in Chapter 6.

Table 4.1: Criteria on which the hybrid concepts will be judged

Criteria	Unit	
performance		
0-60 km/h acceleration	[sec]	acceleration simulation
60-100 km/h acceleration	[sec]	acceleration simulation
environment		
driveline efficiency	[%]	efficiency simulation
emissions	[gram/kWh]	efficiency simulation
fuel consumption	[km/liter]	efficiency simulation
cost & complexity		
driveline cost	[€]	
number of components	[#]	
packaging		
volume	[liter]	
weight	[kg]	
flexibility in placement	1-3 scale	
flexibility		
flexibility towards future developments	1-3 scale	
flexibility towards other automotive applications	1-3 scale	

Chapter 5

Modeling Hybrid Drivelines

Chapter 4 presents three basic drive train concepts and a set of criteria on which to evaluate each of these concepts. This chapter will cover the modeling of each of the concepts in order to obtain realistic results on which a fair judgement can be made. The first section covers the basic modeling assumptions and the calculation method. The rest of the chapter covers the modeling of the three concepts. The topologies are explained and the components are defined. Some additional modeling assumptions are also made.

5.1 Modeling assumptions

5.1.1 method

For each of the three concepts, two different simulations are modeled in Matlab. The first type is a simulation which determines the driveline efficiency, fuel consumption and emissions over a given drive-cycle. The inputs to this calculation are the required power and vehicle velocity that both follow from vehicle parameters and a certified drive-cycle. From this input the corresponding operating points and efficiencies of the driveline components are calculated via an iterative approach. The second type provides information about the maximum vehicle acceleration in the form of a 0-100 km/h acceleration. In these simulations the maximum power output to the wheels for each condition is calculated. This power output is bounded by the boundary conditions that are placed by the different driveline components, e.g. maximum [RPM] or Power.

5.1.2 efficiency simulation

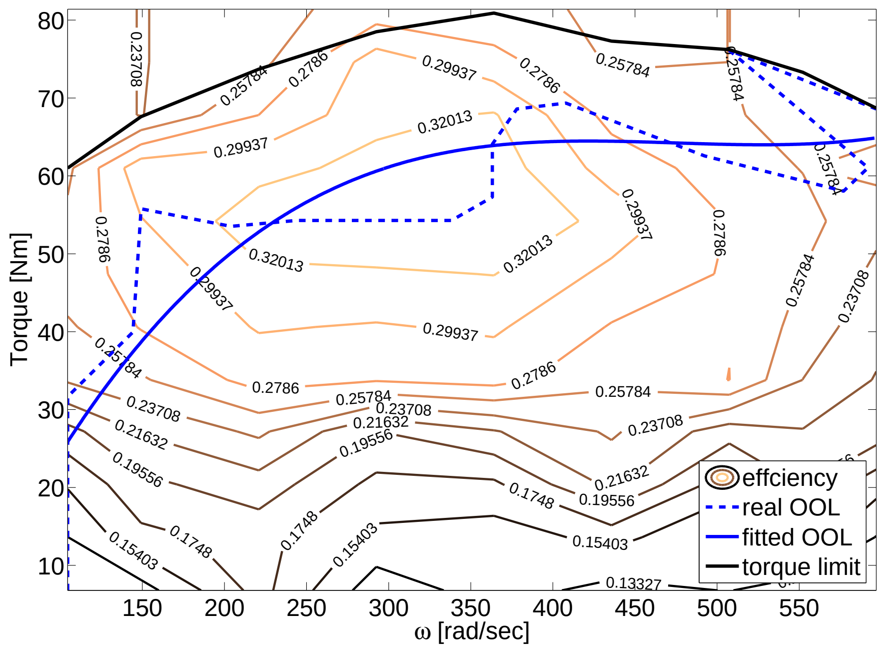
DRIVE-CYCLE

The drive-cycle which is used in the simulations is the CDM short drive-cycle. This drive-cycle is derived specifically for the Cito Dual Mode application and is explained in detail in Chapter 2.

ENGINE OPERATION

The engine which is used in the simulations is a 1 liter petrol engine. The data of this engine is taken from the ADVISOR simulation program from the National Renewable Energy Laboratory (NREL, see [9]). The engine is a 1991 Geo Metro 1.0L SI engine with a maximum power of 41 [kW] at 5700 [RPM] and a peak torque of 81 Nm at 3477 rpm. Figure 5.1 gives the efficiency map of the engine. In order to keep fuel consumption and emissions at a minimum, the goal is to operate the engine on its Optimum Operating Line (OOL) as much as possible. The OOL is the ensemble of operating points with the highest efficiency for each power output. The precise OOL and a fit, which is used in the calculations, are also shown in Figure 5.1. With this assumption, the operating point for the engine (angular velocity and torque) is fixed for each power output. The

Figure 5.1: efficiency map and optimum operating line of ICE



fuel consumption and emissions of the engine are calculated for every time step in the simulation. When the vehicle is idling, the fuel consumption and emissions are set to an idling consumption and idling emissions. And when the engine decelerates quickly, a fuel cut off rule is implemented which sets both consumption and emissions to zero. This is displayed in Figure 5.2.

BATTERY OPERATION

Energy management of a hybrid driveline incorporating a battery is often complicated. It is not the purpose of this study to optimize battery strategies for the 3 proposed hybrid concepts. However, some modeling of battery operation is desired, since this is a essential part of the hybridized topologies. In the efficiency simulations the influence of a battery which feeds an electric motor is incorporated. Two fuel and emissions saving principles incorporated:

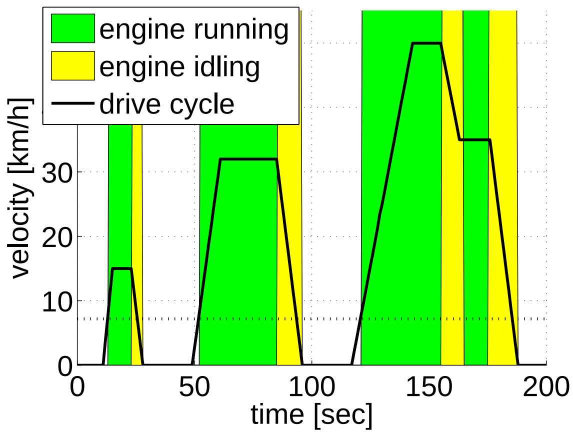
- **Electric Drive Off** With this strategy the first 7 km/h from stand still will be fully electrically driven on energy taken from the battery. In reality the battery will be recharged by regenerative braking. However, for simulation purposes an infinite battery capacity is supposed and regenerative braking is not modeled.

- **Stop-Go** This system halts the engine during full vehicle stops and restarts the engine when desired. In this case the engine will be started when the vehicle is traveling faster than 7 km/h.

The two principles are also graphically displayed in Figure 5.2. Engine operation is plotted together with vehicle velocity as a function of time. The colored patches show when the engine is idling or delivering power to the wheels. The white areas represent that the engine is halted.
Fuel savings and emission reductions obtained from the simulation are very similar for all three hybrid concepts. This is because the concepts make use of the same vehicle parameters and drive-cycle. In this simulation the Electric Drive Off and Stop-Go principles are modeled only in the

parallel hybrid topology simulation. The results from the simulations of the other two concepts are adapted with fuel savings and emission reductions from the parallel hybrid concept.

Figure 5.2: Engine operation with Electric Drive Off and Stop-Go on NEDC



CALCULATIONS

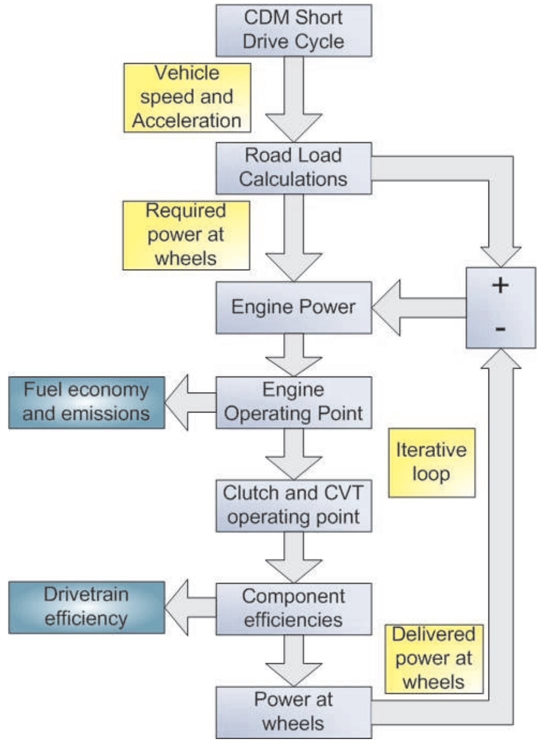
The basic calculation scheme is displayed in Figure 5.3. The scheme starts with the definition of the drive-cycle over which the simulation is run. This drive-cycle provides information on vehicle speed and acceleration. Next, the total resistance of the vehicle along the drive-cycle is calculated. From this, the power that is required at the wheels to actually drive the vehicle over the cycle is determined. For the first iteration run, the driveline efficiency is assumed to be 100%. For each required power output an engine operating point is determined using the OOL definition. This in turn delivers data on fuel consumption and emissions. Now that the angular velocity of the engine and the wheels are known, it is also possible to compute the transmission ratio, corresponding operating points and efficiencies of the driveline components. Using the efficiencies, the power that is actually delivered to the wheels can be computed. Since this delivered power is generally lower than required to drive the cycle, an iteration loop is started. In this iteration loop the engine power is updated with the difference between required power at the wheels and delivered power at the wheels. This iteration proces continuous until the power delivered at the wheels equals the power required at the wheels, within a certain tolerance (1 [kW]). The scheme is run for every time step in the drive-cycle definition.

5.1.3 acceleration simulation

In contrast to the efficiency calculation, the acceleration simulation is a strictly time-forward calculation. At each time step the maximum power which can be transmitted to the wheels is computed. This maximum power is restricted by the engine and by restrictions of the drive line components, such as fixed ratio bounds and efficiencies. Also care has to be taken that the torque output at the wheels does not exceed the traction limit. The maximum force and torque that can be transmitted via the wheels to the road is determined by the friction between the road and the tyre surface. If the maximum traction force is exceeded, wheelslip occurs. in the acceleration simulation, driveline power-output is limited if the traction limit is reached. The maximum torque that can be transmitted to the road is determined by the vehicles mass, wheel radius and the static friction coefficient. With the parameters taken from Table 2.1 the maximum traction torque becomes:

$$T_{max} = r_w \mu_h M g = 1391[Nm]. \tag{5.1}$$

Figure 5.3: Calculation sequence



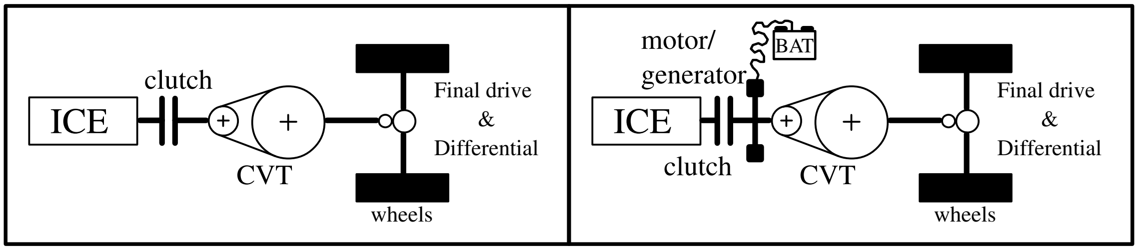
5.2 Parallel hybrid/conventional modeling

5.2.1 efficiency simulation

TOPOLOGY

The layouts of the modeled parallel hybrid and conventional drivetrains are shown in Figure 5.4. Both drivetrains consists of an internal combustion engine (ICE), a clutch, a Continuously Variable Transmission (CVT), a final drive and differential. The only difference is that the parallel hybrid driveline incorporates a battery and a motor. As explained in the previous chapter the conventional drivetrain topology will be the reference topology. And the parallel hybrid topology simulation will be the only simulation Electric Drive Off and Stop-Go systems are with incorporated, see Section 5.1.2. The clutch is needed because the CVT has a limited ratio-coverage and the engine has a minimal idling speed. So below a certain vehicle speed a gradual (dis)engagement of the clutch is needed to prevent the engine from stalling.

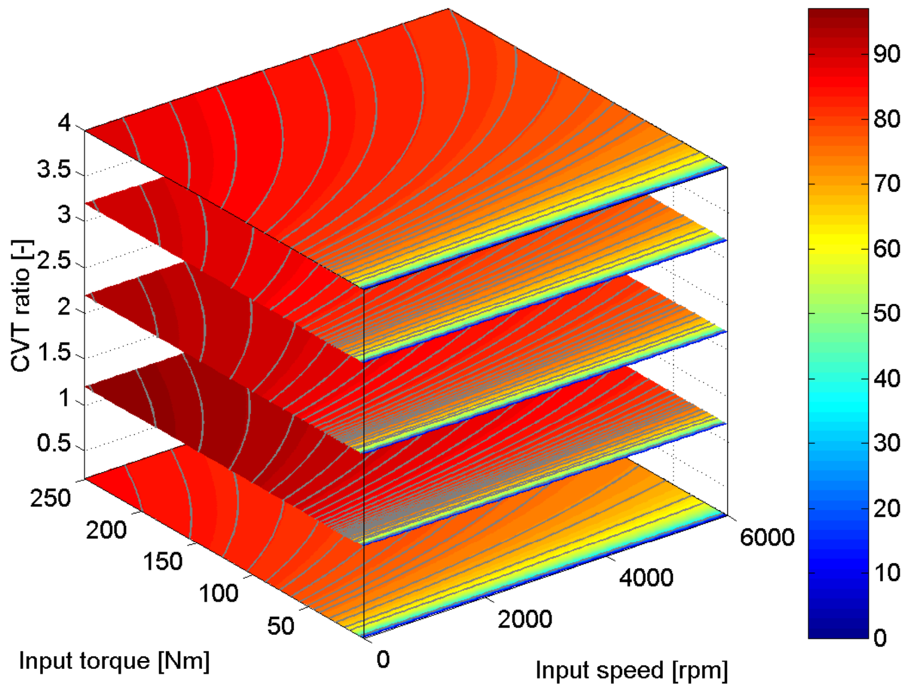
Figure 5.4: The conventional and parallel hybrid model



MODELING ASSUMPTIONS

transmission and final drive/differential The CVT efficiency map which is used in the simulation is coming from polynomial fit on measurements of a Van Doorne Transmissies CVT. The efficiency of a CVT depends on the torque and angular velocity at the primary pulley and the transmission ratio. The efficiency data shown in Figure 5.5 represents the efficiency with which power is transmitted through the CVT. The final drive and differential efficiency is assumed constant and set to 97 %.

Figure 5.5: CVT efficiency



clutch The clutch model consists of two different modes. In the first mode the efficiency is proportional to the difference in angular velocity between the engine and primary pulley. The second mode simulates a closed clutch with an efficiency of 100%. The switching point between these two modes is determined by the velocity at which the engine runs at its minimum rpm. This speed is determined as follows:

$$V_{limit} = \frac{\omega_{enginelimit}}{r_{underdrive} * r_{finaldrive}} * R_{wheel} * 3.6[km/h] \tag{5.2}$$

In this simulation $V_{limit} \approx 7[km/h]$. The clutch efficiency below this vehicle speed increases linearly from 0% to 100% with the angular speed difference.

5.2.2 acceleration simulation

The strategy which is used to control the CVT is of great influence on the accelerating performance. In this simulation the CVT is kept in the underdrive ratio as long as possible. Only at the moment that the engine reaches maximum engine speed (6000 [RPM]) the CVT starts gearing up to a higher ratio in order to prevent the engine from overrevving. Furthermore, it is assured that maximum engine power is transferred to the wheels at all time. To prevent wheelspin, the maximum torque at the wheels may never exceed the maximum traction torque that the tyres can put on the road.

5.3 Power split hybrid modeling

5.3.1 efficiency simulation

The power split technology is based on splitting the power flow from the engine to the wheels into a mechanical and an electric power flow. This is done by using a power split device, which is in this case a planetary gear set. The transmission ratio of the driveline is determined by the ratio of mechanical power versus electrical power. The power split drive train consists of an engine, a planetary gear set, a final drive and differential and an electrical path containing a generator, a motor and power electronics. In this simulation the battery is left out, but the the influence of the battery model within the parallel hybrid topology will be post-processed in the results. All the components are connected as is shown in Figure 5.6.

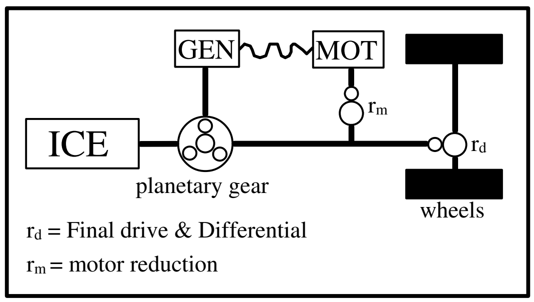


Figure 5.6: The powersplit hybrid model

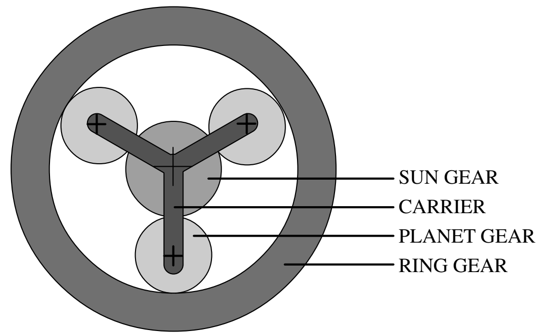


Figure 5.7: planetary gear

PLANETARY GEAR BASICS

The basic planetary gear consists of a sun gear, a ring gear and a number of planet gears connected to each other by a carrier. See Figure 5.7. The principle equations of the planetary gear set are:

$$\omega_{sun} = (z+1)\omega_{carrier} - z\omega_{ring} \tag{5.3}$$

$$T_{ring} = zT_{sun} \tag{5.4}$$

$$T_{carrier} = (z+1)T_{sun} \tag{5.5}$$

with:
ω_i is the angular velocity of component i,
T_i is the torque working on component i,
$z = radius_{ring}/radius_{sun}$.

Using these equations it is possible to calculate the torques on all three components if one torque is known. If two angular velocities are known, the third can be determined. In the power split transmission the following connections are made:

- the sun-gear is connected to the generator
- the ring-gear is connected to the wheels via the final drive ratio r_d
- the carrier is connected to the engine
- the motor is connected to the wheels via the motor reduction r_m and the final drive ratio r_d.

When these connections are substituted into equations (5.3) to (5.5) the following results are obtained:

$$\omega_{gen} = (z+1)\omega_{eng} - z r_d \omega_{wheel} \quad (5.6)$$

$$\omega_{motor} = r_d r_m \omega_{wheel} \quad (5.7)$$

$$T_{ring} = z T_{gen} \quad (5.8)$$

$$T_{motor} = T_{gen} * \omega_{gen} / \omega_{motor} \quad (5.9)$$

$$T_{eng} = (z+1) T_{gen} \quad (5.10)$$

$$T_{wheel} = r_d (T_{ring} + r_m T_{motor}) \quad (5.11)$$

The power split hybrid transmission is an Infinite Variable Transmission (IVT). This also means that the drive train does not need any form of clutch or torque-convertor for driving off, it is a so called geared neutral transmission. The transmission ratio is determined by the power split ratio, which is the ratio between electric and mechanical power, and is controlled by changing the amount of generator torque withdrawn from the planetary gear set.

MODELING ASSUMPTIONS

drive-cycle and engine The drive-cycle which is used in the simulation is the CDM short drive-cycle. This drive-cycle was already presented in Chapter 2. The engine is again the 1991 Geo Metro 1.0L SI engine from the ADVISOR software package. A more detailed description of this engine is given in Section 5.2. Again the engine is tracking the OOL in order to obtain the highest engine efficiency.

electric machine efficiencies The power split transmission contains two electric machines, one primarily functions as a motor and the other as a generator. The efficiency of an electric machine is a function of its angular velocity and torque. The efficiency maps which are used in this model are taken from ADVISOR. They originate from the first model Toyota Prius, but the torque is scaled down with a factor 0.5. The resulting efficiency map for the generator is displayed in four quadrants of operation in Figure 5.9. The efficiency map for the motor is displayed in two quadrants of operation in Figure 5.8. Both maps include a power electronics efficiency of 95 %.

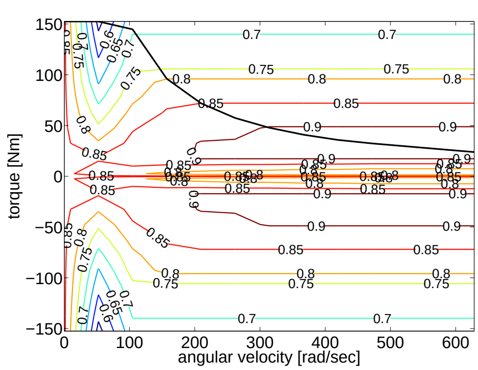


Figure 5.8: motor efficiency map

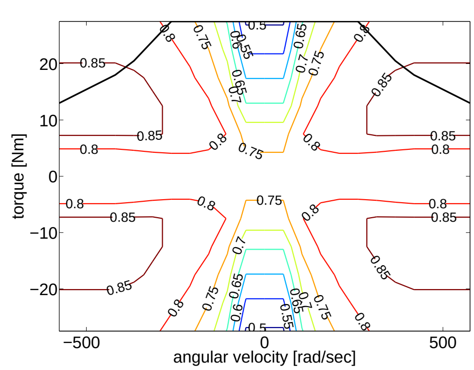


Figure 5.9: generator efficiency map

remaining component efficiencies The remaining component efficiencies are assumed to be constant. Based on experience from DTI, they are set to:

planetary gear set	98 %	
final drive and differential	97 %	
motor reduction	98 %	
power electronics	95 %	(included in electric machine efficiency)

PARAMETERS

The power split transmission model includes 3 parameters that have to be chosen before simulating. The motor reduction r_m is chosen equal to one. This is done because the motor and generator used in the simulation are designed for the Toyota Prius, in which they are optimized to work with a motor reduction of 1. So choosing r_m equal to 1 ensures that the electric machinery is working in its optimum operation area.

The other two parameters that still have to be chosen are the planetary gear parameter z and the final drive ratio r_d. The final drive ratio is particularly important for accelerating performance while the planetary gear set parameter determines the power split ratio. The idea is to choose both parameters in such a way that if the vehicle is traveling at 100 [km/h] all the power travels through the mechanical path. Mechanical efficiency is generally higher than electric efficiency and in this way the efficiency is optimal at the point where the highest power is required. This in turn means that the power loss, the fuel economy and emissions are minimized. The relation between r_d, z and driveline efficiency at a velocity of 100 km/h is given in Figure 5.10. It can be seen that if one of the two parameters is set, the other can also be determined by choosing the value at which efficiency is highest. A typical value of z = 3 is chosen. Figure 5.11 shows a slice of Figure 5.10 for z = 3. From this figure the optimum r_d of 2.1 can be determined. Of course care has to be taken that the chosen set of parameters also satisfies the other functions, e.g. acceleration. In Chapter 6, some feedback on this choice will be given.

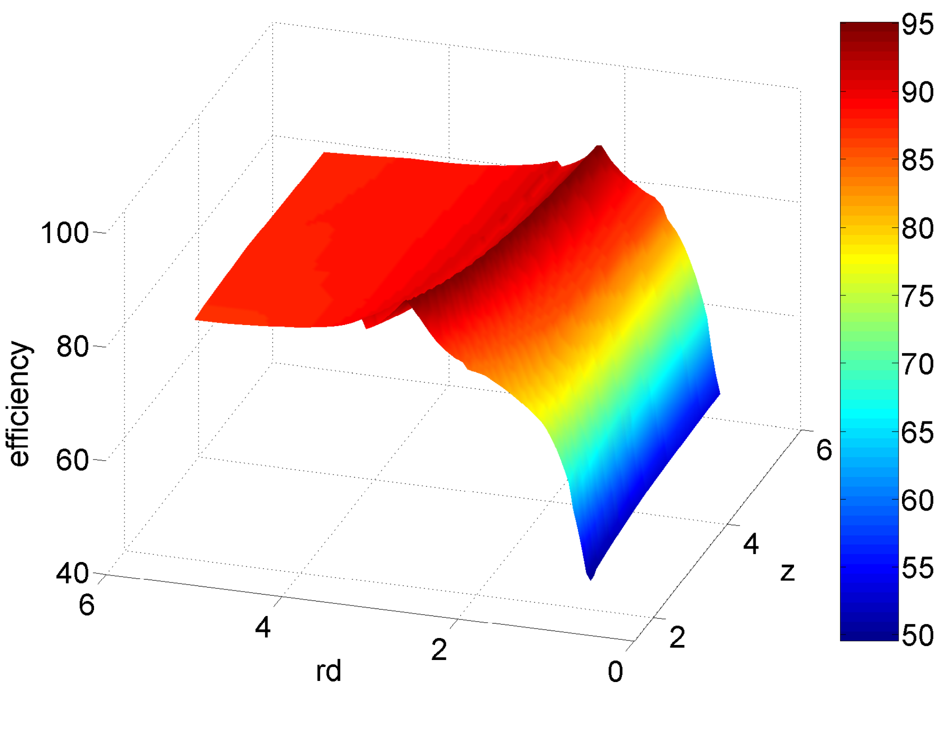


Figure 5.10: Overall efficiency as function of z and r_d, 100 km/h

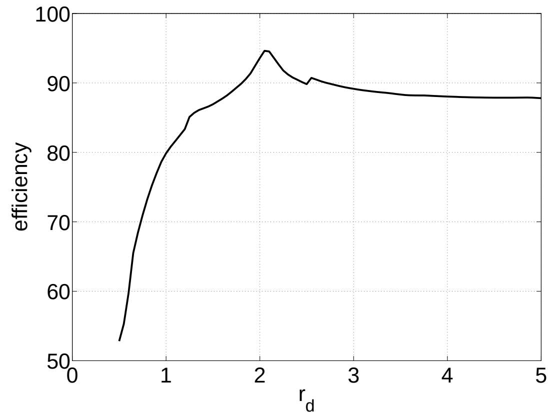


Figure 5.11: Overall efficiency as function of r_d for z = 3 at 100 km/h

5.3.2 acceleration simulation

The maximum acceleration is primarily limited by the generator and motor maximum power. The absence of a battery implies that the generator cannot generate more power than the motor delivers. For maximum acceleration the traction torque at the wheels needs to be as large as possible. Equation (5.11) shows that this is the case if T_{ring} and T_{motor} are as large as possible. Equations (5.8) and (5.9) then show that the torques are large if T_{gen} is maximized. So to get maximum acceleration the generator torque has to be maximized at all time. Furthermore, the calculation has a number of boundary conditions in the from of the mechanical limitations of the drive train components. (i.e Torque and angular velocity)

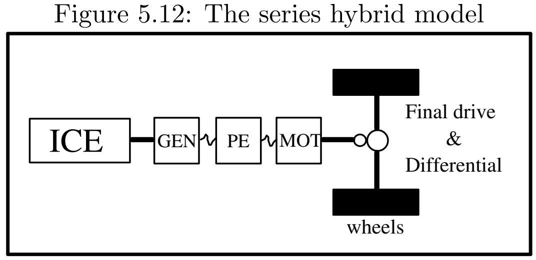
5.4 Series hybrid modeling

5.4.1 efficiency simulation modeling

TOPOLOGY

The series hybrid topology model consists of the 1 liter engine, a generator, a motor, power electronics and a final reduction gear/differential. In this simulation the battery is left out, but the the influence of the battery model within the parallel hybrid topology will be post-processed in the results. The absence of a battery implies that the power that is required at the wheels is approximately the same as the power that has to be delivered by the motor. And it is thus also approximately equal to the power that the engine has to deliver. The lay-out is displayed in Figure 5.12. The transmission in this topology is purely electric and is controlled by the power electronics.

Figure 5.12: The series hybrid model



MODELING ASSUMPTIONS

The modeling assumptions of all the components used in the series hybrid are already covered in the power split hybrid. A brief summation of the efficiency is given in Table 5.1. The simulations are carried out with a final reduction of 1:5.5.

Table 5.1: series hybrid component efficiencies

electric motor	scaled down prius. see Figure 5.8
generator	scaled down prius. see Figure 5.9
final drive and differential	97 %
power electronics	95 % (included in EM efficiency)

5.4.2 acceleration simulation modeling

The maximum acceleration of the series hybrid vehicle is closely related to the maximum speed of the vehicle and the motor characteristics. The maximum vehicle velocity in combination with the maximum allowable generator angular velocity determines the final drive reduction r_d. If a high top speed is desired, a low final drive reduction is chosen. This however has a negative influence on acceleration performance, since torque amplification by the final drive is reduced.

Chapter 6

Hybrid Concept Comparison

In this chapter the three hybrid drivetrain concepts are compared on basis of the criteria already introduced in Table 4.1 and relative to the reference conventional drive train. On some of the criteria a quantitative score can be determined by either simulation or use of characteristic values. Other criteria are qualitative and will be marked with a 1 to 10 score. This chapter will first discuss the results for each individual criterion and finally use a weighted multi criteria analysis to find out which topology is best suited to form the basis of the SLZ drivetrain.

6.1 Comparison on criteria

6.1.1 performance

The performance topic contains two criteria. The first criteria is a full power sprint from stand still to 60 km/h. The time it takes to complete this sprint is a measure for the sportiness of the drivetrain in urban driving situations. The second criteria is the sprint from 60 km/h to 100 km/h. In case of the Cito operating in a CDM mode, the vehicle generally performs this acceleration when it enters the interurban infrastructure. Both criteria have been tested for all three hybrid drivetrain concepts in the accelerating simulations. Figures 6.1 and 6.2 show the accelerating results of the three concepts as a function of time.

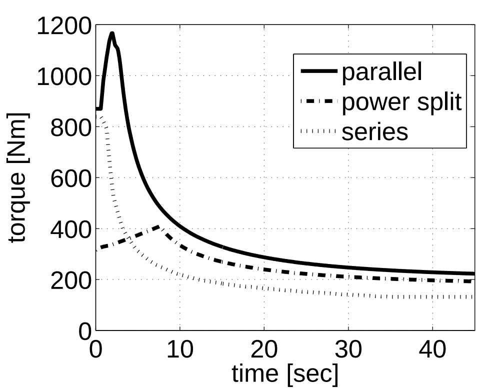


Figure 6.1: comparison of traction torque of the 3 concepts

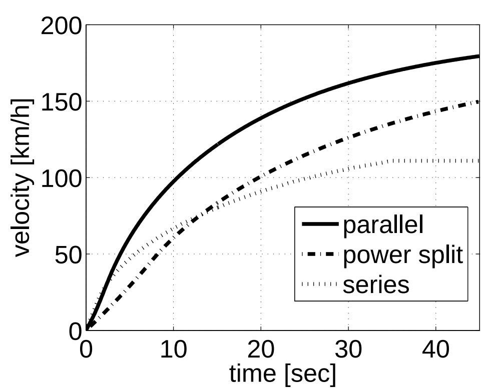


Figure 6.2: comparison of acceleration of the 3 concepts

It can be seen that the vehicle can only achieve the 0-60 km/h in 6 seconds requirement if the parallel hybrid or conventional lay out is chosen. Both the power split hybrid and the series hybrid are limited in their acceleration by the size of the motor.

Figure 6.3: acceleration results with different electrical configurations

#	Topology	Motor	Generator	Bat./Cap.	Acc. time 0-60	Acc. time 60-100
1	Powersplit	15 kW	15 kW	0 kW	9.90 sec	9.90 sec
2	Powersplit	27 kW	27 kW	0 kW	5.91 sec	7.02 sec
2a	Powersplit Z=2,rd=3	10kW nom. 20 kW peak	10kW nom. 20 kW peak	0 kW	5.73 sec	7.17 sec
3	Powersplit	15kW nom. 27kW peak	15 kW nom.	12 kW	5.36 sec	6.03 sec
3a	Powersplit	10kW nom 27kW peak	6 kW nom. 15 kW peak	12 kW	5.36 sec	6.03 sec
4	Series	15 kW	15 kW	0 kW	8.04 sec	17.46 sec
5	Series	10kW nom. 20kW peak	10kW nom 20 kW peak	0 kW	5.89 sec	11.76 sec
6	Series	9 kW 20 kW peak	6 kW nom. 15 kW peak	5 kW	5.89 sec	11.76 sec
7	Parallel	0 kW	0 kW	0 kW	4.91 sec	5.55 sec

In order to check the influence of the size of the electric machines in these topologies, several different configuration are being tested. Figure 6.3 displays the various changes in motor, generator and battery configuration. The parallel hybrid and conventional topologies were not further examined because they already comply with the acceleration requirements without a battery and motor assist. The standard configuration consisted of two 15 [kW] electric machines which are called topology 1 and 4 in Figure 6.3. Using larger electric machines results in a better acceleration. It is shown with configuration 2 that using two 27 [kW] electric machines also delivers an acceleration that complies with the requirements. The big disadvantage is that the machines and power electronics are much heavier and more expensive. To overcome this problem use is made of the ability to temporarily overcharge the electric machines. Configurations 3 and 5 make use of overcharging the electric machines. By overcharging with a peak power of 2 to 3 times the nominal power output, it is possible to down scale the electric machines, this is done in configurations 3a and 6. It is assumed that overcharging is possible during the entire 0-100 km/h acceleration. For configurations 3 and 6 an energy buffer of at least the following capacities is necessary:

configuration 3, 3a: $12 * (5.36 + 6.03)/3600 = 38[Wh]$
configuration 6: $5 * (5.89 + 11.76)/3600 = 25[Wh]$

Table 6.1: buffer specifications, based on Prius battery and Maxwell Super-Cap data

	NiMH weight	**Capacitor weight**	**NiMH cost**	**Capacitor cost**
power split 3, 3a	26 kg	11.8 kg	€185,-	€1650,-
series 6	11 kg	7.8 kg	€80,-	€1100,-

This analysis shows that the series configuration has the lowest buffer cost and weight. However, as stated in Section 5.3 the power split hybrid transmission is configured in such a way that it optimizes efficiency. The accompanying final drive reduction and planetary gear set reduction are not optimized for accelerating performance. Larger electric machines and energy buffer are needed in order to comply with the acceleration requirements.
For this reason an alternative configuration is proposed where z and r_d are optimized for acceleration. This configuration is referred to with 2a in Figure 6.3. With this configuration the ICE runs at 1900 [RPM] at a vehicle velocity of 100 km/h. This means that the engine stays in the high efficiency area in Figure 5.1. Also the generator speed stays close to zero at 100 km/h, which

leads to a high efficiency.
Conclusion of this analysis is that the power split hybrid configuration 2a and series hybrid configuration 5 have equal electrical systems, but the power split hybrid has better accelerating performance, fuel consumption and emissions. Also there is the possibility to clamp the sun branch (generator) when driving 100 km/h so that a fixed ratio purely mechanic connection between the wheels and engine is established. This will allow the vehicle to accelerate to higher velocities because the engine can already deliver enough torque at 1900 [RPM].

6.1.2 environment

The environmental topic consists of three criteria. Namely, driveline efficiency, fuel consumption and emissions. Numerical results for all three criteria follow from the efficiency simulations. Driveline efficiency is defined as:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{wheel}}{P_{engine}} [-] \tag{6.1}$$

This efficiency changes as a function of the operating conditions of the driveline and is calculated for every time step in the efficiency simulation. An overall efficiency is calculated by taking the average of all the efficiencies for a driving vehicle. This means that the efficiency for standstill ($\eta = 0$, since no power is required at the wheels) is left out in the results. The resulting overall efficiencies for all three hybrid concepts are given in Table 6.2. Note that battery operation as described in Section 5.1.2 is taken into account in these results. The average driveline efficiencies are not that high. On the other hand they relate strongly on the operating conditions. Especially when high power outputs are required, for instance at 100 km/h continuous speed, high efficiency is important. This can be made comprehensible when one looks at the power loss in the driveline. The goal is, of course, to have as little power loss as possible.

$$P_{loss} = P_{engine} - P_{wheel} = (1 - \eta) P_{engine} \tag{6.2}$$

This equation shows that P_{loss} is dependant of both η and P_{engine}. Especially at higher engine power requirements it is important to optimize efficiency. This is exactly what is done in the power split transmission. By choosing the final reduction r_d and the planetary gear parameter z such that at 100 km/h all power flows through the (highly efficient) mechanical path. This also comes forward in the fuel consumption and emission results, which are graphically displayed in Figure 6.4. Care must be taken in interpreting these results since the effect of increased emissions after a restart of the engine are not simulated. On three out of four criteria the power split hybrid driveline outperforms the other three drivelines. The series hybrid driveline scores worst compared two the other two hybrid concepts on all criteria. But it stil scores better than the conventional drivetrain.
In the multi criteria analysis input will be fuel and emission savings. The conventional driveline is taken as a reference and the relative improvement is calculated for the remaining three drivetrain concepts. Table 6.3 gives an overview of these relative improvements. The CO emissions show a different distribution than the other emissions. Engine combustion technology always has to make a trade off between optimizing NO_x and CO emissions.
The European emission standards are defined over the New European Drive-Cycle (NEDC) and are thus not comparable with the results obtained with the CDM drive-cycle. An additional simulation over the NEDC delivered the results as depicted in Table 6.4. The calculated emissions do not meet the requirements for the Euro emission standards (see Appendix A), not even Euro I. An explanation for these results can be found in the fact that the engine data which is used is from a very obsolete engine (1991 make, thus before Euro I) which indeed does not comply with the Euro standards. Incorporation of engine data from newer engines will provide more representative results.

Table 6.2: average efficiencies on CDM drive-cycle

	parallel	**power split**	**series**
urban	74.3%	74.7%	60.5%
inter urban	81.3%	87.5%	64.6%
total CDM short cycle	75.8%	77.4%	61.4%

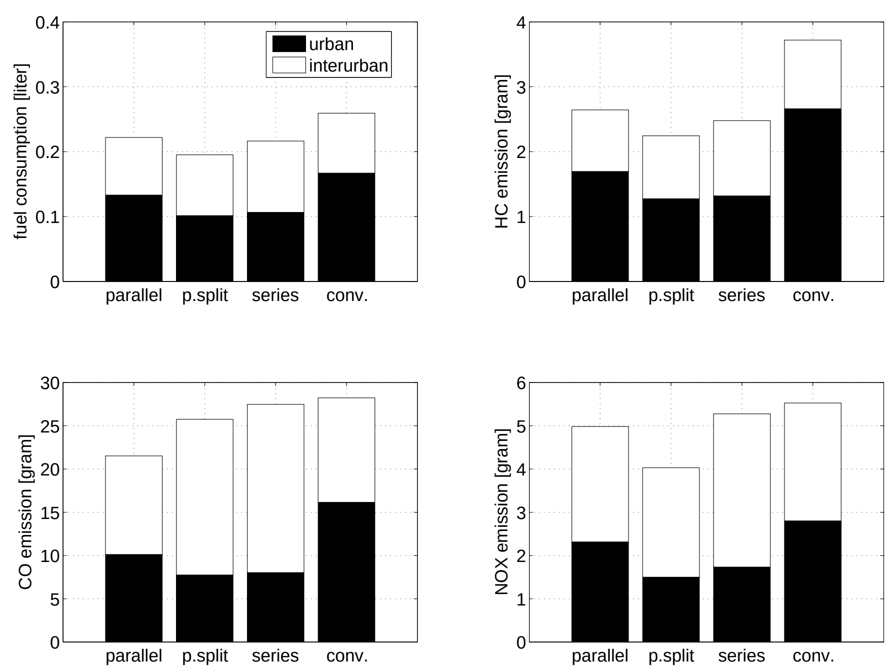
Table 6.3: relative improvements with conventional drivetrain as a reference

	parallel	**power split**	**series**
fuel savings	14.42%	24.72%	16.54%
HC savings	28.91%	39.65%	33.35%
CO savings	23.78%	8.75%	2.68%
NO_x savings	9.81%	27.07%	4.53%

Table 6.4: Emissions on New European Drive-Cycle (NEDC) in [gram/km]

	parallel	**power split**	**series**	**conventional**
HC	0.46	0.39	0.43	0.60
CO	2.82	2.41	2.79	3.70
NOx	0.90	0.69	0.92	0.97

Figure 6.4: fuel consumption and emissions on CDM short drive-cycle



6.1.3 cost and complexity

Cost and complexity are often closely related to each other. Complexity of a concept will be expressed in the number of components that are required. The cost of the driveline will be determined by summing up the cost of single components. Most component cost are being determined by means of characteristic values or are estimated on basis of experience. Table 6.5 gives the characteristic values or estimated cost of several components. The table also gives characteristic values and estimates for volume and weight, which will be used for the packaging criteria. The data used for the electric machines is taken from [14]. The chosen machines are the permanent magnet type because of their lower volume and weight compared to other electric machines. The actual cost, weight and volume of the driveline concepts are given in Tables 6.6 to 6.8. The electric machines of the power split hybrid are set to the values obtained with the acceleration simulation (see Table 6.3). The electric machines of the series hybrid are not determined by the acceleration requirements, but by the continuous power demand of 15 [kW], as was calculated in Chapter 2. The acceleration simulations showed that the parallel hybrid topology requires no secondary source to fulfil the acceleration requirements. In the comparison however, the parallel hybrid is fitted with a small battery, motor/generator and power control unit. This is equipment is necessary to perform Stop-Go actions. This is exactly what the Honda Civic IMA (Integrated Motor Assist) parallel hybrid does. A 6 [kW] machine is chosen. Both for series and the parallel hybrid a battery 10 [kW] is fitted. This is necessary to perform brake energy recovery and electric drive off. The power split hybrid requires a slightly larger battery in order to comply with the acceleration requirement, see Table 6.3.

Table 6.5: component characteristic values

component	**weight**	**volume**	**cost**
engine + acc.	85 [kg][1]	70 [liter][1]	10 [€/kg][2] = €850
electric machines	taken from [14]	taken from [14]	18 [€/kW][3]
power electronics	12 [kg/kW][4]	12 [liter/kW][4]	5 [€/kW][4]
battery (NiMH)	467 [W/kg][5]	120 [Wh/liter][5]	240 [€/kWh][5]
CVT	60 [kg][3]	36 [liter][3]	10 [€/kg][3] = €600
other metal components	-	-	10 [€/kg][2]

[1] data taken from a 1000 cc daihatsu cuore engine
[2] estimate of DTI on basis of market interviews
[3] taken from report [14]
[4] data taken from NREL Advanced Power Electronics [9]
[5] Table 3.2 and Table 3.3

Table 6.6: component data **parallel hybrid**

component	**characteristic**	**weight** [kg]	**volume** [liter]	**cost** [€]
engine+acc.	45 [kW]	85	70	850
motor/gen	6 [kW]	18	8	180
power elec.	10 [kW]	0.8	0.8	50
battery	10 [kW]	21.4	5.3	152.1
CVT		60	36	600
clutch		3	0.5	30
reduction		3	0.5	30
differential		5	1.5	50
total		190.2	121.6	1870.1

Table 6.7: component data **power split hybrid**

component	characteristic	weight [kg]	volume [liter]	cost [€]
engine+acc.	45 [kW]	85	70	850
generator	6 [kW]	12	7	108
motor	10 [kW]	17	8	180
power elec.	27 [kW]	2.3	2.3	135
battery	12 [kW]	25.7	6.3	182.5
chaindrive		15	8	150
planet. gear		3	0.5	30
reduction		3	0.5	30
differential		5	1.5	50
total		167.9	104.6	1715.5

Table 6.8: component data **series hybrid**

component	characteristic	weight [kg]	volume [liter]	cost [€]
engine+acc.	45 [kW]	85	70	850
generator	15 [kW]	25	9	270
motor	15 [kW]	25	9	270
power elec.	20 [kW]	1.7	1.7	100
battery	10 [kW]	21.4	5.3	152.1
reduction		3	0.5	30
differential		5	1.5	50
total		166.1	96.9	1722

6.1.4 packaging

The packaging topic consists of two quantitative, weight and volume, and one qualitative criterion, flexibility in placement. Weight and volume of a driveline have to be as low as possible in order to give the vehicle good dynamic performance and as much passenger space as possible. The target for driveline weight is 120 kg. The quantitative criteria have been incorporated in tables 6.6 to 6.8. The final packaging criteria is flexibility in placement. This is a qualitative criteria that is marked on a 1 to 10 scale. A driveline that is very flexible in placing its components scores close to 10 points, while a driveline where the components are not so free to position score lower. Flexibility in placement of components is especially important in applications where there is very little room for the driveline, which is the case in the Cito vehicle. Incorporating a driveline which is very flexible in placement is preferred because the available space can be used more efficient than when certain components have to be placed in fixed positions.

The three drive train concepts can basically be divided in a pure mechanical transmission (parallel hybrid), a electric/mechanical transmission (power split hybrid), and a pure electric transmission (the series hybrid). The series hybrid has a large advantage in this criteria because the components can be very flexibly placed, only electric wiring connects them. Especially when wheel motors are used the flexibility is optimal. Downside of the series hybrid is the large size of the electric machines needed to deliver the required power. Especially in heavy duty applications this might cause packaging problems. The other two transmissions need a mechanical connection between the engine and the wheels, which restricts placement of components. The parallel hybrid drivetrain uses a CVT, which is a very bulky component with in and output axles on fixed spatial positions. However, the spatial restrictions on the power split transmission are similar to those on the parallel hybrid. This gives the following judgement for the three drivetrain concepts:

Table 6.9: qualitative assessment: flexibility criteria

flexibility towards:	**parallel hybrid**	**power split hybrid**	**series hybrid**
placement	6	6	7
future	6	6	8
applications	7	7	8

6.1.5 flexibility

The flexibility topic contains two criteria: flexibility towards future developments and flexibility towards other applications. The first criteria focusses on the ability to replace components of the drivetrain with different components that fulfil a similar function but with future technologies. One can for instance think of the replacement of the internal combustion engine with a fuel cell, when this technology has reached the point that it is financially more attractive and a more extensive hydrogen infrastructure is available. At this point the series hybrid topology is again the most flexible of the three concepts. The fact that it has no mechanical connection between its components is advantageous. The parallel and power split topologies have a similar degree of flexibility towards future developments, which is lower than that of the series hybrid.

The second criteria in the flexibility topic is flexibility towards other applications. Other applications can be all kinds of non-automotive applications. One can think of marine applications or stationary generator applications. Again, the series hybrid driveline is the most flexible of the three concepts. It's full electric transmission can easily be adapted for a variety of output speeds and torques. The power split topology can also be adapted over a large area but does have constraints in that it is mechanically connected to the engine via the planetary gear set. The parallel hybrid drivetrain has got most constraints because of the limited operating conditions and ratios of the CVT transmission. The resulting qualitative factors for the flexibility criteria are shown in Table 6.9.

6.2 Multi criteria analysis

Now that all criteria are discussed and corresponding values have been determined, the multi criteria analysis (MCA) can be carried out. MCA techniques have the advantage that they can assess a variety of options according to a variety of criteria that have different units. This is a significant advantage over traditional decision aiding methods (for example cost-benefit analysis) where all criteria need to be converted to the same unit. Another significant advantage of the MCA technique is that it has the capacity to analyse both quantitative as well as qualitative evaluation criteria. The MCA consists of the following three components:

- A given set of alternatives (in this case the three hybrid drivetrain concepts)
- A set of criteria for comparing the alternatives (see Table 4.1 and previous Section)
- A method for ranking the alternatives based on how well they satisfy the criteria.

The three concepts are ranked on basis of the criteria which are determined above. In order to do this properly and to make a distinction between the importance of the different criteria, weighing factors are defined. These weighing factors are determined by using a questionaire amongst several participants in this project. The average weighing factors of these questionaires are used as weighing factor in the MCA. For scaling purpose, the results of every criteria are made relative to each reference criterion in order to assure that every criteria is judged with the right importance. Finally, all criteria are multiplied with their accompanying (relative)weighing factor and summed for each concept to form a total score. This score is again made relative. The entire MCA ranking is displayed in Figure 6.6 and the input is displayed in Figure 6.5.

Figure 6.5: data input for MCA

	powersplit	series	parallel	conventional	target	UNIT
performance						
0-60 km/h acceleration	5,7	5,9	4,9	4.9	6	seconds
60-100 km/h acceleration	7.2	11,8	4.5	4.5	10	seconds
environment						
driveline efficiency	77,4	61,4	75,8	75,8	--	%
CO emission savings (compared with conv.)	8,75	2,68	23,78	0	--	%
HC emission savings (compared with conv.)	39,65	33,35	28,91	0	--	%
NOx emission savings (compared with conv.)	27,07	4,53	9,81	0	--	%
fuel consumption	26,6	24	23,4	20	25-30	km/liter
cost & complexity						
driveline cost	1716	1722	1870	1560	1700	€
number of components	9	7	8	5	--	#
packaging						
volume	105	97	122	109	--	liter
weight	168	166	190	156	120	kg
flexibility in placement	6	7	6	6	10	1 to 10
flexibility						
flexibility towards future developments	6	8	6	6	10	1 to 10
flexibility towards other applications	7	8	7	6	10	1 to 10

Figure 6.6: MCA weighing and results

CRITERIA	CONCEPT			WEIGH FACTOR	
	powersplit	series	parallel	absolute	relative
performance					
0-60 km/h acceleration	35%	36%	30%	-3,75	-7,8%
60-100 km/h acceleration	31%	50%	19%	-2,5	-5,2%
environment					
driveline efficiency	36%	29%	35%	4,25	8,8%
CO emission savings	32%	31%	37%	4	8,3%
HC emission savings	35%	33%	32%	4	8,3%
NOx emission savings	37%	31%	32%	4	8,3%
fuel consumption	36%	32%	32%	4,75	9,8%
cost & complexity					
driveline cost	32%	32%	35%	-3,75	-7,8%
number of components	38%	29%	33%	-3,5	-7,3%
packaging					
volume	32%	30%	38%	-4,25	-8,8%
weight	32%	32%	36%	-3,75	-7,8%
flexibility in placement	32%	37%	32%	3,75	7,8%
flexibility					
flexibility towards future developments	30%	40%	30%	3,25	6,7%
flexibility towards other applications	32%	36%	32%	3	6,2%
TOTAL RESULT	7,0%	6,2%	6,5%	48,25	100,0%
	35,45%	31,68%	32,87%		

6.3 Conclusions of MCA

The absolute results from the simulations performed in this chapter do not give a 100 percent justified image of the real life performance of the hybrid drive train concepts. The MCA shows that there is not much absolute difference in the three concepts. Nevertheless, there are some conclusions that can be drawn, especially in a relative way.

- the power split hybrid transmission has the best result in the MCA. It is less flexible than the series hybrid and equally flexible as the parallel hybrid. It has the best efficiency, fuel consumption and emission results. To judge the power split hybrid effectively a further study into the optimization of the power split parameters is required.
- The parallel hybrid scores best on the performance criteria. It is the most expensive and bulkiest lay-out. On the environment criteria, the parallel holds the middle between the series and the power split hybrid.
- The series hybrid comes thirds. It is the most flexible drivetrain of the three. It is the smallest and lightest variant. On the downside it does have the poorest score on efficiency, fuel consumption and emissions.

Chapter 7

Market Applications

7.1 Market demand

A market research was conducted by an extended questionaire taken from 6 manufacturers of niche application vehicles. The market research was carefully planned in such a way that the group of interviewed manufacturers produce vehicles over a wide range. The market research showed that the requirements for a SLZ driveline differ quite a lot. Determinative for the best suitable driveline setup is the large variation in vehicle characteristics, i.e.:

- **vehicle weight** determines (in combination with acceleration) the amount of power that is required to operate the vehicle. The larger the vehicle weight, the larger the acceleration forces required. It also has influence on the rolling and inclination resistance.

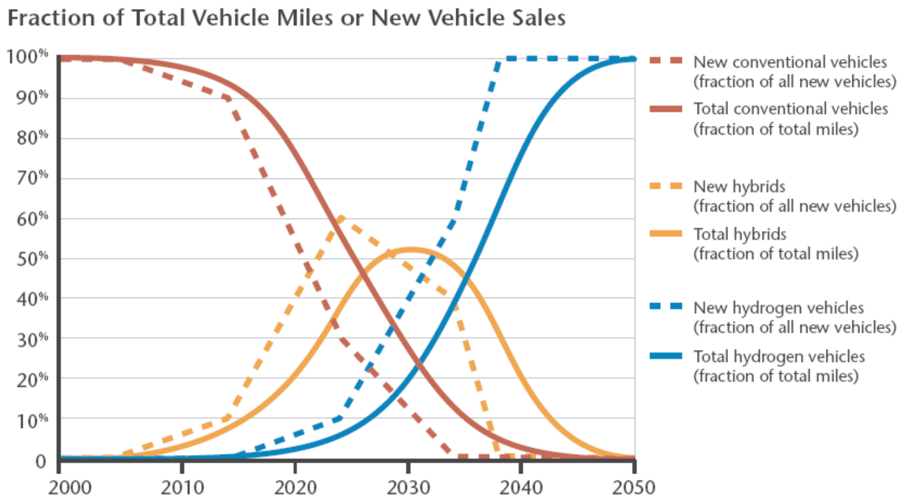
- **acceleration** requirements (in combination with vehicle weight) have great influence on the amount of peak power that has to be delivered.

- **top speed** mainly determines the amount of maximal sustaining power that is required. In case of an electric motor with a fixed reduction, generally a compromise has to be made between top speed and good acceleration.

- **range** of a vehicle determines how much energy has to be carried on board. For shorter ranges a battery as primary energy source suffices, for more extended ranges ICE's, optionally mated to a hybrid driveline, are still the preferred choice because of their energy density.

Currently a slight shift from using fossil fuels as a primary energy source to renewable energy sources as primary source can be observed. This shift requires a radical change in drivetrain technologies which will consist of two phases. The first phase has just started and covers the conversion from pure ICE drive trains to more efficient ICE powered hybrid vehicles. The gain in fuel savings and reduction of emissions is mainly achieved by adding a secondary power source. This second power source enables to install a smaller engine that uses less fossil fuels to power the same car, though has the same performance. Although considerable reduction in fuel consumption and emissions can be achieved by hybridization, the main fuel that provides the energy will still be fossil. This will for a large part be accompanied by bio-fuels, but the most promising fuel of the future is hydrogen. The second phase of the shift in drive train development will be the change over from fossil fuels to hydrogen powered vehicles. Hydrogen powered fuel cells will slowly replace the ICE powered hybrid vehicles. The final important step is made in the production of hydrogen. At first hydrogen will be extracted out of fossil fuels, but the final goal is to create hydrogen using only renewable energy sources. The shift from conventional to hybrid to hydrogen powered vehicles is also shown in Figure 7.1. This figure is taken from [31].

Figure 7.1: shift in drivetrain development



7.2 Possibilities with hybrid concepts

The following sections will give a range of possibilities with the three hybrid concepts that have been proposed in this report.

7.2.1 parallel hybrid concept

The parallel hybrid concept is the concept that is most similar to current conventional drive trains. The main advantage is that the components that are used, are already produced in large quantities. This lowers component cost and requires no dramatic changes in production facilities. The parallel hybrid drivetrain scores very good on the performance criteria. This might make it an interesting concept for recreational vehicles. A drawback of the parallel hybrid drive train is the required CVT. This is a very bulky and costly component.

7.2.2 series hybrid concept

The major advantages of the series hybrid concept is the flexibility of the concept. Flexibility in component placement ensures that a large variety of vehicles or other non-automotive applications can be driven by this driveline. Also, the fact that that it has a good flexibility towards future developments is an advantage. If, for instance, after some years the ICE is replaced by the fuel cell, it just a matter of exchanging, since all components are only connected electrically. An advantage of the series hybrid over the BEV concept, which shares the same amount of flexibility, is that the battery does not need to be recharged, leading to large advantages in the vehicles range. Directly opposed to this is the fact that the series hybrid is by far the least efficient drivetrain of the three hybrid concepts. Typical automotive applications of the series hybrid are vehicles that do not have a very high top speed but, on the other hand, have good acceleration performance or the ability to drive very heavy loads. Other applications are those where packaging problems arise when using conventional mechanical drive lines. For instance low loaders or busses that have a floor at streetlevel, so there is no place for a mechanical connection between the wheels and the drivetrain.

7.2.3 power split hybrid concept

The power split hybrid concept combines the advantages of a mechanical drivetrain, high efficiency, with the advantages of an electric drivetrain, energy recuperation and boosting function. The power split hybrid is not as flexible in placement as a series hybrid, since it still needs a mechanical connection between the wheels and the driveline. Another disadvantage is the slightly more complex construction of the drivetrain. All drivetrains have to be tuned to a specific vehicle. A typical example of this is the Cito application. Since this vehicle drives at constant high velocities (100 [km/h]) for prolonged times, it can be tuned to drive purely mechanical at these speeds. This results in high savings in fuel consumption and emissions compared to a pure electrical drive. Typical applications for this concept are Cito-like vehicles, such as the Van den Brink Carver.

7.3 Modular design

As became clear in the previous Chapters, both electrically driven and mechanically driven concepts have their advantages. The final MCA-scores are very similar. Which of the concepts is preferred, strongly depends on the type of application it is used in. An idea is to manufacture the SLZ-driveline in a modular design. In this way the drive line can be composed by a customer in such a way that it meets his requirements best. Basically, the transmission is a black box connecting the engine to the differential, see Figure 7.2. The customer can fill this black box with the transmission technology that suites him best. There will be a basic driveline which can be extended with several different modules. For instance, there is a basic driveline in the form of a series hybrid which can be extended with a power split module that converts the series hybrid into a power split hybrid.
Another option to adapt the power split hybrid in such a way that the power split device (planetary gear) can be locked. In this way the driveline can actively switch between a power split hybrid or series hybrid whilst driving. Locking and coupling of the planetary gear set can be done by adding two clutches. The topologies and power flows for the three operating cases are shown in Figure 7.3. This option is included in the table of possible topologies, which will be presented in the next section. This table also includes a more extended version of the power split hybrid topology. By adding a second planetary gear set there is an extra variable gearing in the system which can for instance be used to operate the motor in a more efficient point, so that it can be down scaled. Also for this version there is the possibility to switch between power split, pure mechanical and pure series operation.

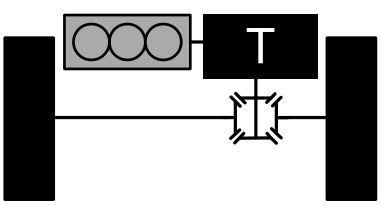


Figure 7.2: transmission black box

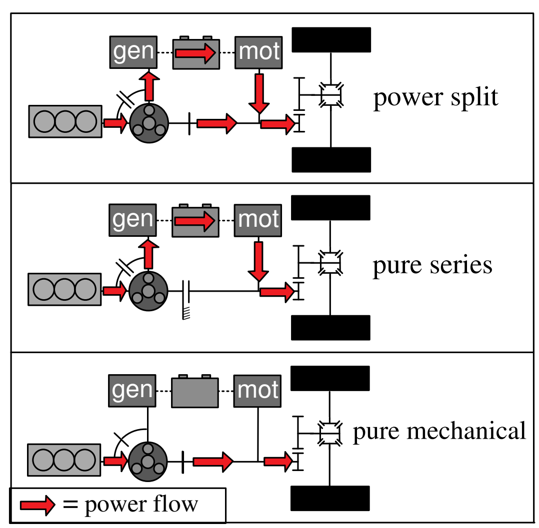


Figure 7.3: active switching between power split hybrid and series hybrid

Another option can be the addition of extra driven wheels. Since the hybrid vehicles already have the battery and power electronics to control a motor, it is a small step to expand the driveline with with some extra motors. Especially wheel motors are suited to fulfil this task since they require a minimum of structural changes and do not need a lot space to be built in. In this way all kinds of advantages can be conceived like all wheel drive and all wheel steering.

7.4 Overview

This section presents a table that gives an overview of what type of drivetrain suites a particular automotive application. The graphical presentations in Figure 7.5 do not include the four wheel drive variants of the drive trains. However, in most cases four wheel drive can easily be incorporated in the design by adding extra wheel motors to the undriven wheels.

Figure 7.4: legend application overview

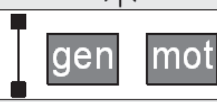
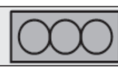
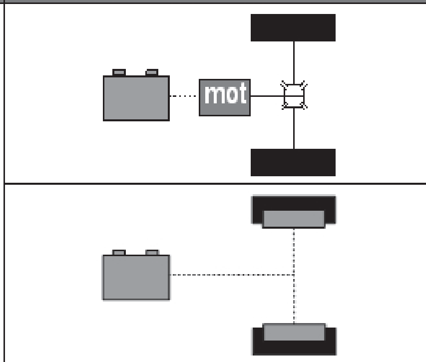
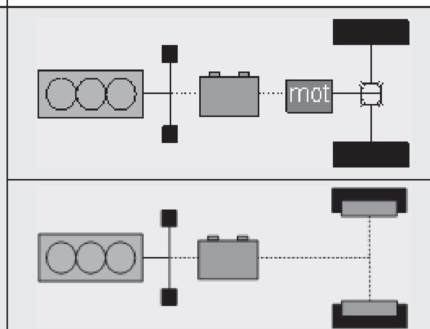
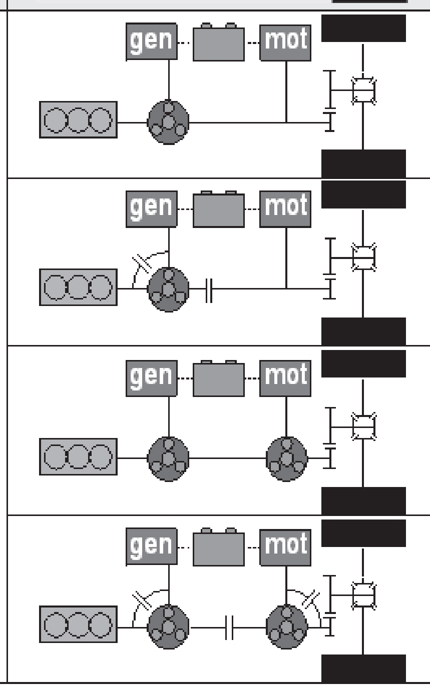
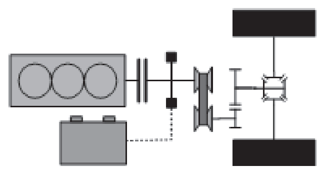
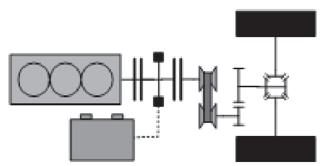
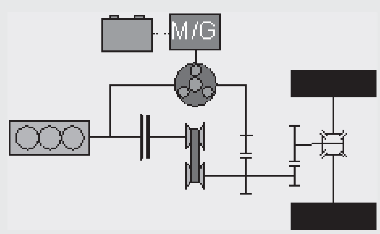
Image	component
	battery
	clutch
	CVT
	differential
	electric machines
	engine
	gears
	planetary gear set
	wheel
	wheel with wheel motor

Figure 7.5: application overview

	application	graphical presentation	characteristics / market
BATTERY ELECTRIC VEHICLE	disabled person vehicle recreational vehicle (light) warehousing (urban) distribution		**characteristics** short range low top speed flexible placement **market** Spykstaal Freewiel Canta Trigger
SERIES HYBRID	distribution recreational vehicle urban bus warehousing vehicle		**characteristics** extended range low top speed good acceleration or heavy load capability flexible placement **market** Spykstaal Trigger Gemco Freewiel
POWER SPLIT HYBRID	distribution recreational/sportive bus commuter		**characteristics** extended range high top speed good acceleration high efficiency also possible in combination with wheel motors **market** Cito Spykstaal Carver

	application	graphical presentation	characteristics
PARALLEL HYBRID	distribution recreational/sportive commuter bus	 	extended range high top speed good acceleration **market** Carver Cito Spijkstaal also possible in combination with wheel motors
PARALLEL/POWER SPLIT	distribution recreational/sportive commuter bus		**characteristics** Combination of power split and parallel hybrid **market** Carver Cito Spijkstaal

Chapter 8

Conclusions

In order to find the optimal topology for the SLZ-driveline first a market research has been carried out. Based partially on the requirements that came out of this research and partially on the requirements posed by SAM, three hybrid concepts are proposed and simulated. The parallel hybrid, power split hybrid and series hybrid are examined and judged on the basis of some quantitative and qualitative criteria. Also an overview of the current state of the art in drivetrain component technologies is given.

8.1 Market research

The market research revealed that the requirements for an SLZ drivetrain depend heavily on the type of the target application. Applications differ greatly in weight, acceleration, top speed and range. In the field of maintenance and cost a division can be made between commercial and private applications. Commercial vehicles are allowed to be more expensive at purchase, but must be inexpensive at maintenance, while for private vehicles this is, in moste cases, the other way around. Also flexibility in placements of components plays an important role in a driveline concept. There is an overall trend towards more environmentally friendly drivetrains.

8.2 Technology overview

The division has been made into primary source and secondary source technologies. Today and in the near future the internal combustion engine is still the primary source par excellence. In combination with fossil fuels it is unrivaled in its power and energy density and price. The BEV is no competitor since the battery pack will become to bulky. This may change in the future since battery development enables increasing power and energy density and decreasing recharge times. These new technologies are however still in development phases and very expensive. The fuel cell development is in full progress, but the absence of a suitable infrastructure and production quantities make that currently the fuel cell is no serious competitor.
Batteries used as secondary source technologies (HEV) overcome the biggest drawbacks of batteries in primary source applications (BEV). No recharge is needed and since they only buffer energy, they do not have to be as bulky as in primary applications. Another option for secondary source technology is the supercapacitor, which has a smaller energy density, but a higher power density and longer cycle life than a battery. Depending on the application the choice between battery or supercapacitor can be made. Even smart combination packages can be adopted. Flywheels have a lot of advantages, such as power density and its mechanical nature. But since it has to be combined with a rather expensive CVT, currently the cost is to high to incorporate this technology into the SLZ-driveline.
Well to Wheel analysis show that the best choice for a primary source in a vehicle is a Euro-4 (or better) petrol engine. It is the best compromise between minimal emissions, fuel consumption and

GHG emissions. CNG has the best results in the WtW analysis, both as a fuel for ICEs and as source for hydrogen production. It is essential that hydrogen -if produced from fossil fuels (CNG)- is used in a fuel cell and not used to fuel an ICE.
In the field of motor technology the trend in the hybrid drivetrain world is to use permanent magnet motors. These are more expensive than induction motors, but have higher power density and can as such be smaller and lighter. Special attention should be given to the development of wheel motors. In some applications, they offer packaging advantages and offer the possibility to create all wheel drive vehicles without having to change a lot in the lay out of the driveline.

8.3 Concept comparison

A number of criteria to which the the 3 proposed concepts and a conventional reference drivetrain were tested were proposed. It consists of the topics: performance, environment, cost and complexity, packaging and flexibility. The criteria in each field were filled in for each drivetrain either by simulation, the use of characteristic values or a qualitative approach. The following conclusions are drawn for each field:

- **performance**
  The conventional drivetrain and parallel hybrid topology score best at this field. The series hybrid is limited by the relation between top speed and acceleration due to the fixed motor reduction and the operating boundaries of the motor. The accelerating performance of the power split hybrid is strongly dependent on the choice of the planetary gear reduction. Which also influences the power split and with it, driveline efficiency.

- **environment**
  From an environmental perspective it can be concluded that hybridization gives improvements on efficiency, fuel consumption and emissions. On these criteria the power split hybrid has the best results. The series hybrid and parallel hybrid have comparable results on fuel consumption and emissions.

- **cost and complexity**
  Driveline complexity and cost are closely related to each other. Due to its CVT, the parallel hybrid is the most expensive concept. The series hybrid and power split hybrid concepts cost about the same. In the series hybrid, the electric machines are most expensive. In the power split hybrid, the electric machines are smaller and less expensive, but the transmission contains more mechanical components.

- **packaging**
  The series hybrid is the most ideal concept from a packaging point of view. It is the least complex drivetrain and has no mechanical connections between the engine and the wheels. Second is the power split hybrid, which has a more boundary conditions to its placement since it has mechanical links between the engine and wheels. The power split hybrid and series hybrid have a lower weight and smaller volume than the parallel hybrid.

- **flexibility**
  Also in the flexibility field the series hybrid is the most ideal concept. Again the fact that it has no mechanical connection between the engine and the wheels plays an important role here. The power split hybrid and parallel hybrid have similar scores in the flexibility topic.

8.4 Modular design

The scores in the MCA for the three concepts are quite similar, but the different concepts score in different topics. A possibility to combine the best features of the transmissions is proposed. Also, by applying a modular design the SLZ-driveline can be configured as wished by the customer. The idea is to create a basic package that can be extended with separate modules, for specific driveline improvements. One can, for instance, think of an efficiency module, a performance module or an flexibility module. In this way the customer can choose whether he prefers the flexibility of the series hybrid and compromises on lower environmental performance or chooses for higher efficiency and is willing to sacrifice a bit of flexibility.

8.5 Future work

After this report there is still some work that has to be done before a definitive choice for a topology for the SLZ-driveline can be made.

Simulations More extensive simulations might give more information about the different topologies. With the incorporation of more up to date data for the ICE and other components, the application of a battery/supercapacitors and suitable control strategy, the absolute results are probably more realistic. Also, research has to be done on ways to optimize the choice of parameters and size of components in hybrid transmissions.

Technical implementation Some more in depth research has to be carried out into the different types of configurations that can be designed. What are the technical consequences of a certain configuration and do the advantages weigh up to those consequences. Is it technically (and economically) feasible to create the modular drivetrain?

Well to Wheel analysis A more extensive research into the the well to tank and tank to wheel efficiency and emissions has to be conducted. This research must give conclusions on what the optimal primary source will be in the near future. The SLZ-driveline can than be prepared for a future implementation of this primary source.

Market feedback The potential customers must be asked for their opinion about idea for a modular design. Are they interested in such a driveline? What modules would they be interested in?

Appendix A

Emissions Standards

EU emission standards for passenger cars and Source: dieselnet [32]

EU Emission Standards for Passenger Cars (Category M_1*), g/km

Tier	Date	CO	HC	HC+NOx	NOx	PM
Diesel						
Euro 1†	1992.07	2.72 (3.16)	-	0.97 (1.13)	-	0.14 (0.18)
Euro 2, IDI	1996.01	1.0	-	0.7	-	0.08
Euro 2, DI	1996.01[a]	1.0	-	0.9	-	0.10
Euro 3	2000.01	0.64	-	0.56	0.50	0.05
Euro 4	2005.01	0.50	-	0.30	0.25	0.025
Petrol (Gasoline)						
Euro 1†	1992.07	2.72 (3.16)	-	0.97 (1.13)	-	-
Euro 2	1996.01	2.2	-	0.5	-	-
Euro 3	2000.01	2.30	0.20	-	0.15	-
Euro 4	2005.01	1.0	0.10	-	0.08	-

* Excluding cars over 2,500 kg, which meet N_1 Category standards
† Values in brackets are conformity of production (COP) limits.
a - until 1999.09.30 (after that date DI engines must meet the IDI limits)

The euro 5 standard (2008) is not determined yet, but a proposal by the German Environment Agency (UBA) states the following:

CO	HC	NOx	PM
-	0.05	0.08	0.0025

Appendix B

Overview of HEV's

The following pages give an overview of some of the currently existing low powered vehicles and technologie demonstrators.

ELECTRIC AND HYBRID VEHICLE OVERVIEW

PRODUCTION VEHICLES 3
Trigger 50 3
Canta 3
Spijkstaal elektrowagens 4
Chrysler TEVan 4
Th!nk City 4
Jetcar sport II (Jetcar 2.5) 5
GM EV1 5
Spijkstaal ZEUS 6
Ford Explorer hybrid 6
Lexus RX400h 7
Toyota Prius II 7
Honda Civic Ima 8
Honda Insight 8

CONCEPT VEHICLES 10
Greenpeace SmILE 10
Renault Zoom 10
Nissan Hypermini 11
Esoro E301 11
Horlacher Blue Angel 11
Citroen Berlingo dynavolt 12
GM Zafira 12
Necar5 13
Spijkstaal Zeus 13
MDI Aircar Mini CAT 14

PRODUCTION VEHICLES	
Naam	type
Trigger 60	IC petrol
Canta	IC petrol
JetCar	IC petrol and diesel
Spijkstaal elektro wagens	EV
Chrysler TEVan	EV
Th!nk City	EV
GM ev1	EV
Spijkstaal Zeus	EV
Ford Explorer hybrid	Gas/electric hybrid
Lexus RX400h	Gas/electric hybrid
Toyota Prius II	Petrol/electric hybrid
Honda Civic Ima	Petrol/electric hybrid
Honda Insight	Petrol/electric hybrid
CONCEPT VEHICLES	
Greenpeace Smile	Supercharged petrol IC
Renault Zoom	EV
Nissan Hypermini	EV
Esoro E301	EV
Horlacher Blue Angel	CNG/electric hybrid
Citroen Berlingo dynavolt	LPG/electric hybrid
GM Zafira	FCEV
Necar5	FCEV
Spijkstaal Zeus	FCEV
MDI Aircar	Compressed air engine

PRODUCTION VEHICLES

Trigger 50

Small 3 wheeled recreational vehicle with 1 cylinder 2 stroke engine and variomatic. Mix between scooter and car.	
L*B*H:	2.38*1.30*1.24 [m^3]
Weight:	175 [kg]
Propulsion:	1 cylinder 2 stroke IC 49cc
Power:	3 [kW] @ 6500 rpm
Gear:	Variomatic
Top speed:	45 [km/h]
Range:	120 [km]
Fuel economy:	4.5 [l/100km]
Consumer price:	€ 5000,-
Info:	http://www.triggers.nl/

Canta

4 wheel disabled persons vehicle. 4 stroke petrol engine combined with CVT	
Weight:	Aprox. 200 [kg]
Propulsion:	Honda 160 cc 4 stroke petrol IC
Power:	4 [kW]
Gear:	CVT
Top speed:	45 [km/h]
Acceleration:	0-45 km/h in 20 seconds
Range:	400 [km]
Fuel economy:	5 [l/100km]
Consumer price:	€ 7000,-
Info:	http://www.waaijenberg.com/

Spijkstaal elektrowagens

Commercial EV's with simple modular design and simple electric driveline	
L*B*H:	2*.75*.78 [m³] – 4*1.58*2 [m³]
Weight:	570-2260 [kg]
Propulsion:	EM
Power:	2-8.75 [kW]
Gear:	Fixed ratio
Top speed:	12-28 [km/h]
Fuel economy:	432 [kJ/km]
Consumer price:	€ 5000,-
Info:	http://www.spijkstaal.nl/


Chrysler TEVan

Commercial EV on basis of a standard Dodge Caravan. 56 were produced in 1993	
Propulsion:	General electric DC motor and controller (68 kg)
Battery:	SAFT STM5-200 NiCad
Power:	52 [kW] @ 8000 rpm
Gear:	Automatic transmission
Top speed:	117 [km/h]
Range:	240 [km]
Info:	Alternative cars in the 21th century; Robert Q Riley 1994

Th!nk City

Launched to much acclaim in the autumn of 1998 at the Electric Vehicle Symposium in Brussels, 1.005 TH!NK city's were produced between November 11th, 1999 and March 22nd, 2002.	
Weight:	940 [kg]
Propulsion:	3 phase asynchronous induction motor
Battery:	Water cooled NiCad (250 kg) 11 [kWh], 100 Ah
Full charge:	6-8 hours from 10-16 A 220 V supply

Power:	27 [kW]
Gear:	Fixed reduction gear set
Top speed:	90 [km/h]
Acceleration:	0-50 [km/h] in 7 seconds
Range:	80 [km]
Consumer price:	€ 20.000,-
Info:	http://www.think.no/

Jetcar sport II (Jetcar 2.5)

Tandem seat, small engine car. Available as 3 cylinder petrol engine (3 cylinder commenrail diesel)	
Weight:	660 [kg] (660 [kg])
Engine:	698cc petrol 60[kW] 110[Nm] (799cc diesel 30[kW] 100[Nm])
Gear:	6 speed AMT (6 speed AMT)
Top speed:	185 [km/h] (160 [km/h])
Fuel consumption:	5.3 liter/100 km (2.5 liter/100 km)
Consumer price:	€ 34.000,- to € 45.000,-
Info:	http://www.jetcar.de/

GM EV1

Until October, 1997 the EV1 held the land speed record for EVs at 296 [km/h]. GM wanted this car to be a head-turner that contradicts everything people believe about electric cars	
Propulsion:	3-phase AC induction motor
Battery:	NiMH battery pack supplied by GM/Ovonics
Charging:	Up to 80% in 15 min using 50 [kW] charger
Power:	100 [kW]
Gear:	Fixed ration dual reduction gear set
Top speed:	130 [km/h] regulated
Acceleration:	0-96 [km/h] in 8.5 [sec]

Range:	130 [km]
Info:	http://www.evworld.com/archives/testdrives/gmev1.html

Spijkstaal ZEUS

Zero Emission Urban System. 32 passenger EV Bus	
Propulsion:	3-phase AC induction motor
Battery:	1450 [kg] Lead Acid Battery
Power:	18 [kW] nominal, 40 [kW] peak
Gear:	Fixed ration tripple reduction gear set
Top speed:	35 [km/h] regulated
Acceleration:	< 1 [m/s^2]
Range:	80 [km]
Consumer price	€ 120.000,-
Info:	http://www.spijkstaal.nl/

Ford Explorer hybrid

4wd truck. Full gas engine/electric hybrid.	
Engine:	2.3 SI Gas powered
Motor:	70 [kW] electric motor
Battery:	250-D cell
Power:	Combined 115 [kW]
Gear:	CVT
Consumer price	In US $ 26.970,-
Info:	http://4wheeldrive.about.com/

Lexus RX400h

4wd SUV. Full gas engine/electric hybrid. Built around the Toyota Hybrid system 2 (THSII)	
Engine:	3.3 SI V6
Motor:	50 [kW] AC synchronous permanent magnets
Battery:	NiMH
Power:	Combined 195 [kW]
Gear:	CVT
Acceleration:	0-100 [km/h] in 8 seconds
Info:	http://en.lexus-hybrid.com/

Toyota Prius II

Second version of Toyota Hybrid System (THSII). This system is based on the powersplit principle. The powersplit device is a planetary gear set.	
Weight:	1250 [kg]
Engine:	1.5 liter Atkinson cycle petrol engine, 57 [kW] 115 [Nm]
Motor:	50 [kW] AC synchronous permanent magnets
Battery:	NiMH 201.6 V 45 [kg]
Gear:	ECVT
Top speed:	170 [km/h]
Acceleration:	0-100 [km/h] in 10.9 seconds
Fuel economy:	4.3 liter/100km
Consumer Cost:	€ 25.250,-
Info:	www.toyota.co.jp http://home.hccnet.nl/jc.visbeen

Honda Civic Ima

ICE electric hybrid based on the existing Honda Civic. Extended with the Integrated Motor Assist (IMA) concept. Available with manual and CVT.	
Weight:	850 [kg]
Engine:	1339 cc, 62.5 [kW] 87 [Nm] SOHC VTEC petrol
Motor:	DC 60 mm thick
Battery:	NiMH
Gear:	Manual or CVT
Top speed:	177 [km/h]
Acceleration:	0-100 [km/h] in 12.9 seconds
Fuel economy:	4.9 liter/100 km
Consumer Cost:	€ 22.000
Info:	http://automobiles.honda.com/models

Honda Insight

Presented in 1999 and commercially available in 2001. The insight is a parallel hybrid vehicle built around the Integrated Motor Assist (IMA) system	
Weight:	850 [kg]
Engine:	995 cc, 50 [kW] 91 [Nm] SOHC VTEC petrol
Motor:	DC 60 mm thick
Battery:	NiMH 20 kg 144 V
Gear:	Manual or CVT
Top speed:	180 [km/h]
Acceleration:	0-100 [km/h] in 12.0 seconds
Fuel economy:	3.4 liter/100 km
Consumer Cost:	US $ 19.330
Info:	http://www.verdaat.nl/honda/showroom/insight.htm http://automobiles.honda.com/models


insight

CONCEPT VEHICLES

Greenpeace SmILE

The SmILE is a modified Renault Twingo, which is almost 50% more efficient than its conventional counterpart and other cars of similar size	
Weight:	650 [kg]
Engine:	358 cc 2-cylinder flat engine, four-stroke Otto, Pressure-wave supercharger 2.6 [bar]
Max torque	75 [Nm] at 2.900 rpm
Power:	40 [kW] at 5.500 rpm
Gear:	5 MT
Top speed:	150 [km/h]
Acceleration:	0-100 [km/h] Approx. 14 sec.
Fuel economy:	3.3 [liter/100km]
Info:	http://archive.greenpeace.org/climate/smile

© Greenpeace / Klapsch

Renault Zoom

Zoom was an urban and suburban concept car born of common research by Renault and Matra into modern electric vehicles	
Weight:	800 [kg]
Motor:	Self-synchronous AC
Battery:	NiCad (350 [kg])
Power:	25 [kW]
Gear:	Fixed ratio
Top speed:	120 [km/h]
Acceleration:	0-60 [km/h] in 6 seconds
Range:	260 [km]
Info:	Alternative cars in the 21st century; Robert Q Riley 1994

Nissan Hypermini

An ultra-compact electric vehicle designed for short commutes and is built around the philosophy of maximizing and conserving finite resources	
Motor:	neodymium magnet synchronous electric motor
Battery:	lithium-ion
Power:	20 kW at 15,000 rpm
Gear:	Fixed ratio
Top speed:	100 [km/h]
Range:	130 [km]
Info:	http://www.evworld.com/archives/testdrives/hypermini.html

Esoro E301

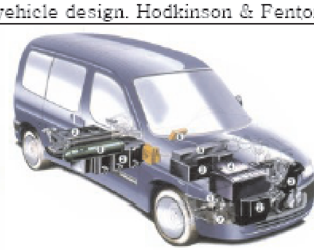
Safety, efficiency and comfort were combined for the first time with lightweight construction, a modular body shell concept and an open system for three different drive concepts - electric, hybrid and small IC-engine.	
Weight:	620 [kg]
Motor:	Asynchronous motor
Battery:	NiCad (260 [kg])
Power:	21 kW
Gear:	Fixed reduction ratio (10:1)
Top speed:	120 [km/h]
Acceleration:	0-50 [km/h] in 7.5 seconds
Energy demand:	9 kW/100km
Info:	http://www.esoro.ch/

Horlacher Blue Angel

CNG IC/electric hybrid concept car from 1992	
Weight:	640 [kg]
Engine:	2 cylinder, 4-stroke, 360 cc
Motor:	gt-20 AC-motor
Battery:	6 lead acid batteries, 60 Ah

Power:	Engine: 9 [kW] Motor: 21 [kW]
Gear:	?
Top speed:	110 [km/h]
Acceleration:	0 – 50 km/h: 10 seconds
Range:	Pure electric: 50 [km]; combined 500 [km]
Info:	http://www.horlacher.com
	

Citroen Berlingo dynavolt

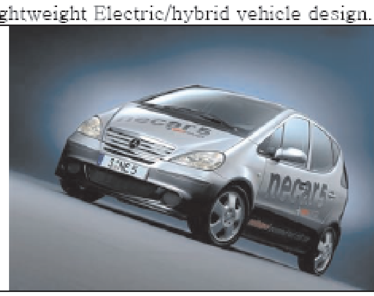
EV with range extender in the from of an IC. Not a classic hybrid	
Engine:	Lombardini two cylinder 500 cc LPG
Motor:	Dynalto–style
Battery:	NiCad
Power:	Engine: 12 [kW] Motor: 8 [kW]
Gear:	?
Range:	Pure electric: 80 [km], Combined: 260 [km]
Info:	Lightweight Electric/hybrid vehicle design. Hodkinson & Fenton
	

GM Zafira

Compact fuel cell driven vehicle on basis of the conventional GM zafira	
FC:	Liquid hydrogen FC
Motor:	3 phase synchronous traction motor
Battery:	?
Power:	55 [kW]
Gear:	Fixed gear reduction
Top speed:	140 [km/h]
Acceleration:	0–100 [km/h] in 16 seconds
Range:	400 [km]
Info:	Lightweight Electric/hybrid vehicle design. Hodkinson & Fenton

Necar5

FCEV based on Mercedes A-class vehicle. Entire driveline based in vehicle floor.	
Weight:	1450 [kg]
FC:	Ballard PEM Methanol fuelled FC with reformer
Motor:	Asynchronous motor
Battery:	?
Power:	75 [kW]
Gear:	?
Top speed:	150 [km/h]
Info:	Lightweight Electric/hybrid vehicle design. Hodkinson & Fenton



Spijkstaal Zeus

Prototype on basis of the ZEUS EV bus	
FC:	Liquid hydrogen FC
Motor:	3-phase AC induction motor
Battery:	12 [kW] NiMh 100 Ah
Gear:	Fixed ratio reduction gear
Range:	280 [km]
Info:	Contact spijkstaal

MDI Aircar Mini CAT

The Mini Cat is in the preproduction phase. It is a small 3 seat citycar which is powered by a compressed air engine. Recharging can be done with an onboard electric compressor (4 hours) or in a recharge station (3 minutes). It includes BER. Lot's of criticism can be found on the internet. The aircar wouldn't live up to it's expectance.	
Weight:	750 [kg]
Engine:	Compressed air engine
Power:	6 [kW]
Gear:	AMT
Top speed:	110 [km/h]
Range:	200-300 [km]
Consumer price:	Expected around $ 10.000,-
Info:	http://www.theaircar.com/ http://www.wired.com/news/autotech/0,2554,60427,00.html

Appendix C

Results Interviews

C.1 Interview

On the following pages the questionnaire which was used to interview several manufacturers is shown.

Marktonderzoek SLZ-aandrijving

Inleiding

Modesi en DriveTrain Innovations (DTI) werken gezamenlijk aan de conceptontwikkeling van een compact stadsvoertuig, Cito genaamd. Voor de ontwikkeling van de aandrijving van dit voertuig is een subsidie toegekend door SenterNovem.

Concreet gaat het hier om de zogenaamde SLZ-aandrijving. SLZ staat daarbij voor:

- Stil: zeer lage geluidsproductie;
- Laag vermogen: aandrijving is geschikt voor compacte, lichte voertuigen;
- Zuinig: het verbruik zal lager zijn dan 5l/100km.

Om aan de bovenstaande kenmerken te kunnen voldoen zal er waarschijnlijk een hybride aandrijving worden ontwikkeld. Met behulp van een hybride aandrijving kunnen de nadelen van elektrische aandrijving en een conventionele verbrandingsmotor opgeheven worden. Compacte hybride aandrijving zijn nog niet op de markt verkrijgbaar.

Basis voor de ontwikkeling van het Programma van Eisen voor de SLZ-aandrijving is de toepasbaarheid in de Cito. De Cito heeft als kenmerk een topsnelheid van 70 km/h in de stad waarbij een sportieve acceleratie mogelijk moet zijn. Tussen steden rijdt de Cito volledig automatisch. Dit gebeurd op een kruissnelheid van 100km/u, in de automatische mode is het acceleratievermogen van minder belang.

Uw betrokkenheid

Voordat er met de concrete ontwikkeling van SLZ-aandrijving begonnen wordt, willen wij middels dit marktonderzoek inventariseren of er nog meer partijen interesse hebben in de SLZ-aandrijving. Uw betrokkenheid via het invullen van bijgesloten vragenlijst wordt dan ook op prijs gesteld.

De bijgesloten vragenlijst geeft ons een beeld van de activiteiten van het bedrijf en de producten die uw onderneming levert. Daarnaast krijgen wij een helder beeld van de interesse, eisen en wensen die u heeft ten aanzien van een SLZ-aandrijving.

Op basis van de eisen en wensen van de meerdere partijen zullen wij een programma van eisen opstellen waarmee een zo breed mogelijke doelgroep kan worden bediend. Dit programma van eisen zullen wij u eind maart 2005 toesturen. Een reactie hierop stellen wij op prijs.

Bij voorbaad dank voor uw medewerking.

Vragenlijst SLZ-Motor

Bedrijfsnaam: ………………………………………………………………………………………..

Adres:………………………………………………………………………………………..……..

Contact persoon: ……………………………………………………………………………..…..

Emailadres: ……………………………………………………………………………………

Datum: ………………………………………………………………………………………….

---

1. Wat is de *core bussiness* van uw bedrijf en waar liggen de markt(en) van uw product(en)?

1.1. Wat zijn de huidige doelgroep(en)?

…………………………………………………………………………………………………

1.2. Wat voor een type voertuigen worden er geproduceerd?

…………………………………………………………………………………………………

1.3. Wat is het productieaantal per jaar en wat zijn de toekomst verwachtingen?

…………………………………………………………………………………………………

1.4. Wat zijn de kostprijzen van uw huidige geleverde voertuigen?

…………………………………………………………………………………………………

1.5. Worden huidige aandrijfsystemen in eigen beheer ontwikkelt of worden deze ingekocht?

…………………………………………………………………………………………………

1.6. Hoe interessant is een stil, lichtvermogen en zuinige aandrijving voor uw potentiële klanten?

…………………………………………………………………………………………………

1.7. Wat mag het totale voertuig kosten om binnen de doelgroep het product te kunnen afzetten, gebruikmakend van de SLZ aandrijflijn?

…………………………………………………………………………………………………

2. Wat zijn de huidige *prestaties* van uw voertuigen? Wat zijn de beoogde *prestaties* van een voertuig dat met een SLZ-aandrijving wordt uitgerust?

2.1. Wat voor type motor wordt in het huidige voertuig gebruikt?
wat zijn daarvan de karakteristieken; koppelkromme, motorvermogen.

…………………………………………………………………………………………………

2.2. Van welk type brandstof wordt er gebruik gemaakt?

……………………………………………………………………………………………

2.3. Wat is het brandstofverbruik van huidige voertuigen?

……………………………………………………………………………………………

2.4. Hoe groot is de tankinhoud van het brandstof systeem?

……………………………………………………………………………………………

2.5. Wat is de actieradius van huidige verkochte voertuigen en blijft deze voor toekomstige voertuigen gelijk?

……………………………………………………………………………………………

2.6. Wat zijn de kruissnelheid en maximumsnelheid van het voertuig?

……………………………………………………………………………………………

2.7. Wat zijn de eisen die aan het acceleratievermogen worden gesteld? Zowel vanuit stilstand als tussen acceleraties.

……………………………………………………………………………………………

2.8. Wat voor hoogteverschillen moet het voertuig overbruggen en met welke snelheid moet dit gebeuren?

……………………………………………………………………………………………

2.9. Wat moet de nauwkeurigheid zijn van een automatische snelheidsregeling bij geautomatiseerd rijden?

……………………………………………………………………………………………

3. **Wat zijn de eisen betreft het *comfort* van een voertuig dat met een SLZ-aandrijving wordt uitgerust? Hierbij wordt gedacht aan:**

3.1. Het toelaatbare geluidsniveau (in bijv dB).

……………………………………………………………………………………………

3.2. Welk type overbrenging wordt er in uw huidige voertuigen toegepast?

……………………………………………………………………………………………

3.3. Van welk type overbrenging zou u willen gebruikmaken: Automatische of manuele transmissie?

……………………………………………………………………………………………

3.4. Onderhoudsgevoeligheid. (na hoeveel afgelegde km is er onderhoud benodigd)

……………………………………………………………………………………………

3.5. Bereikbaarheid van componenten.

……………………………………………………………………………………………

3.6. Fueling en/of charging. Benodigde tijd, frequentie, automatisch

……………………………………………………………………………………………

3.7. Wat zijn gewenste elektrische gebruikers in het voertuig. Met welk vermogen.

....

4. Wat zijn de huidige lay out's van uw voertuigen? Wat zijn de eisen aan een SLZ-aandrijflijn met betrekking tot de *implementatie in een voertuig*?

4.1. Wat is de huidige locatie van de aandrijving?

....

4.2. Wat is de voorkeur voor de locatie van de aandrijving? (Voor-, achterwielaandrijving, AWD?)

....

4.3. Wat is het beoogde inbouwvolume?

....

4.4. Waar wordt dit volume geplaatst in het voertuig?

....

4.5. Gaat de voorkeur uit naar een grotere unit, of meerdere kleinere units?

....

4.6. Wat zijn de eisen aan de gewichtsverdeling in het voertuig?

....

4.7. Wat is de bovengrens aan het gewicht van de aandrijflijn?

....

5. Wat zijn de eisen die aan een SLZ-aandrijflijn worden gesteld met betrekking tot *duurzaamheid* van het ontwerp? Wat zijn de eisen voor het beperken van de milieudruk in de verschillende fasen van de levenscyclus van het product?

5.1. Tijdens de productiefase. Welke materialen worden gemeden of worden gestimuleerd om te gebruiken?

....

5.2. Tijdens de gebruiksfase. Bijvoorbeeld het gebruik van fossiele brandstoffen, hernieuwbare energiebronnen, of biobrandstoffen. Het gebruik van een mechanische energieopslag versus accu's of andere opslagmethoden.

....

5.3. Tijdens de verwerking van het product. Design for recycling.

....

5.4. Wat moet de levensduur van de aandrijflijn zijn? Dus hoeveel uren per jaar en hoeveel jaar moet de aandrijflijn meegaan?

....

5.5. Wat zijn de eisen die aan een SLZ-aandrijflijn worden gesteld met betrekking tot kosten van het ontwerp?

…………………………………………………………………………………………………

5.6. Wat mag de aandrijving kosten om de prijs naar klanten interessant te houden?

…………………………………………………………………………………………………

5.7. Wat mogen de Running costs van het voertuig bedragen. Kosten/km

…………………………………………………………………………………………………

6. Wat zijn de eisen die aan een SLZ-aandrijflijn worden gesteld met betrekking tot de veiligheid van het ontwerp?

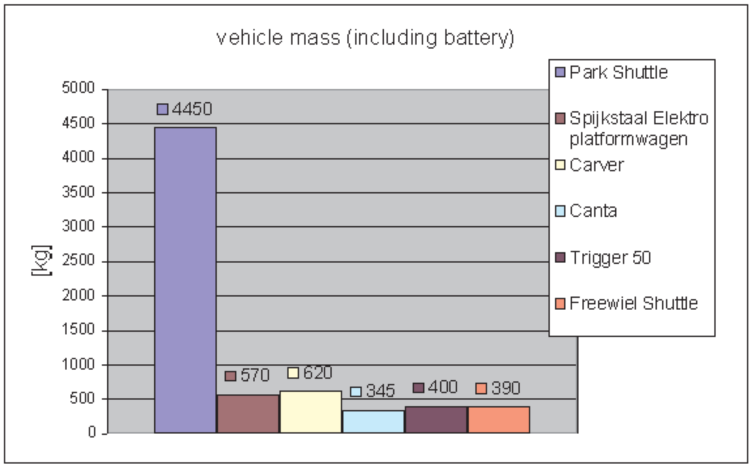
6.1. Wat is het botsgedrag? Hoe zijn massa's gepositioneerd t.o.v. personen.

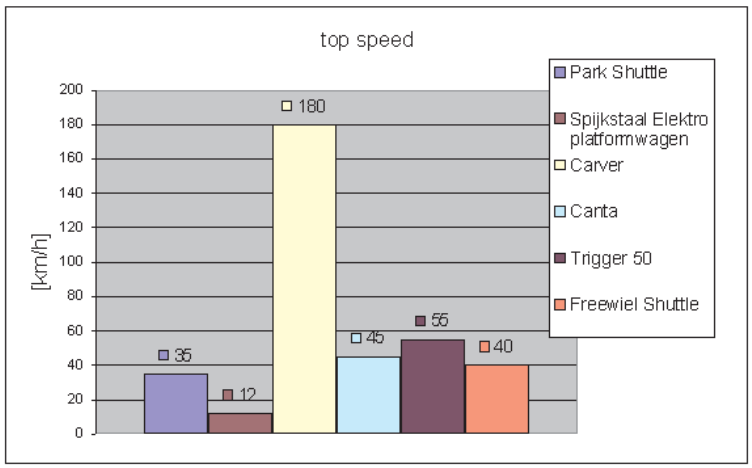
…………………………………………………………………………………………………

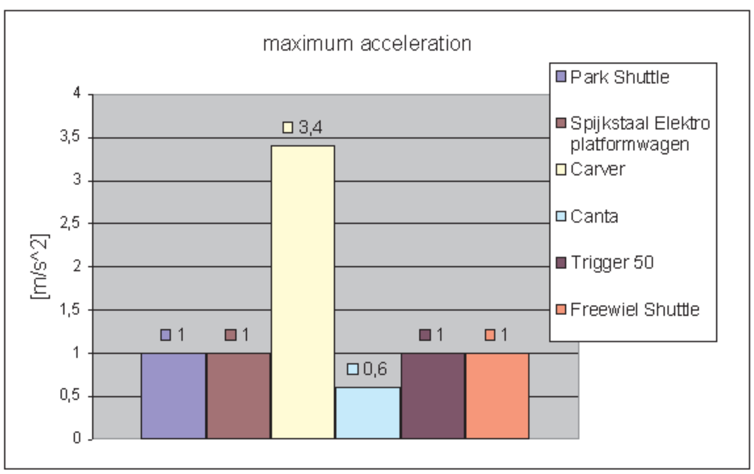
6.2. Hoe staat het met de veiligheid van de energieopslag?

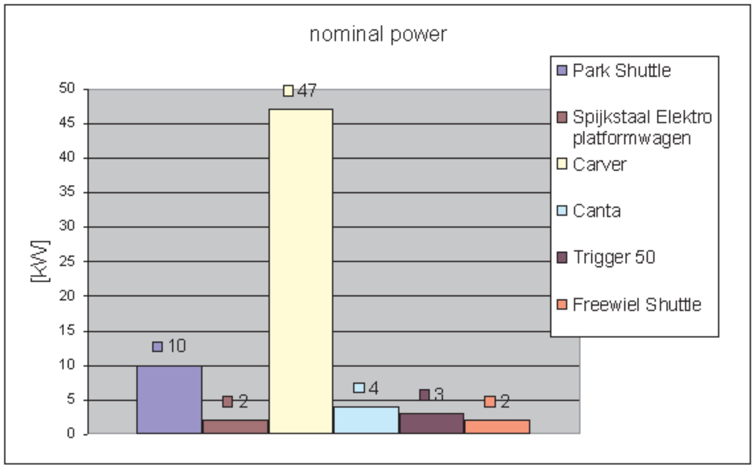
…………………………………………………………………………………………………

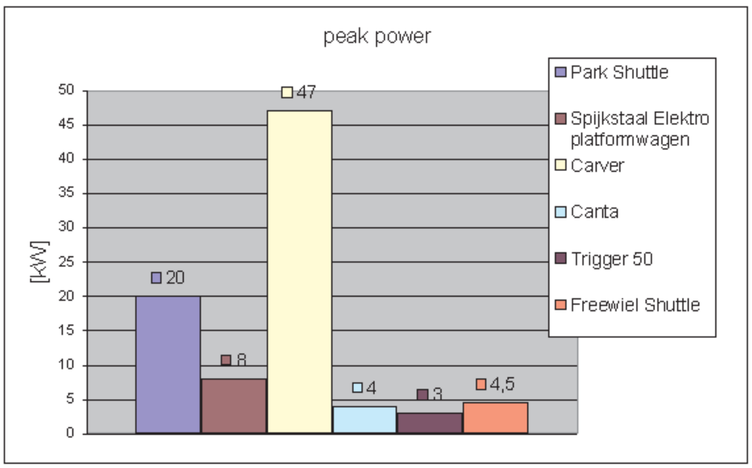
C.2 results

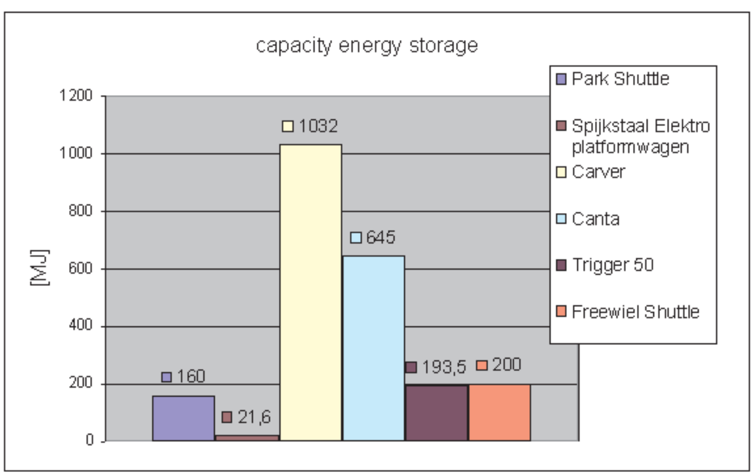

vehicle mass (including battery)
[kg]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
4450
570
620
345
400
390
Park Shuttle
Spijkstaal Elektro platformwagen
Carver
Canta
Trigger 50
Freewiel Shuttle

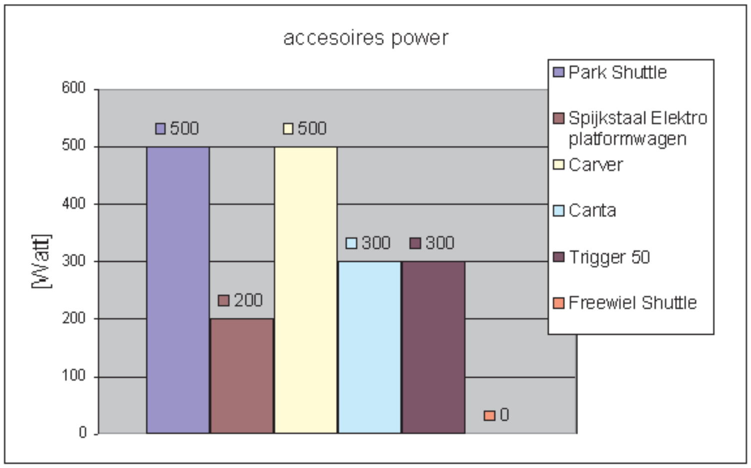

top speed
[km/h]
200
180
160
140
120
100
80
60
40
20
0
35
12
180
45
55
40
Park Shuttle
Spijkstaal Elektro platformwagen
Carver
Canta
Trigger 50
Freewiel Shuttle

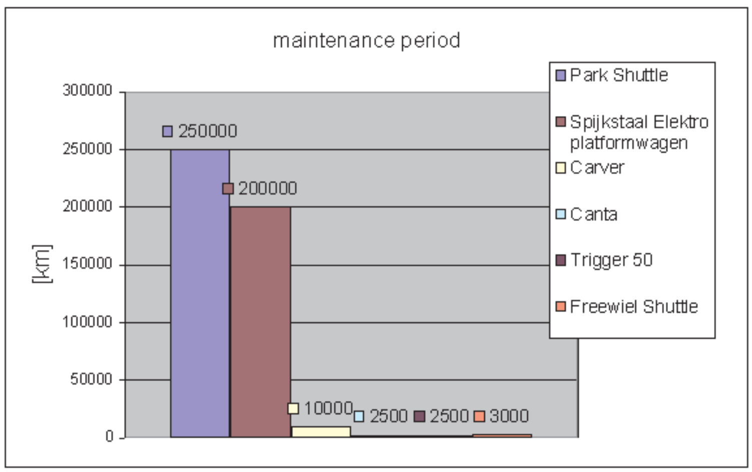

maximum acceleration
[m/s^2]
4
3,5
3
2,5
2
1,5
1
0,5
0
1
1
3,4
0,6
1
1
Park Shuttle
Spijkstaal Elektro platformwagen
Carver
Canta
Trigger 50
Freewiel Shuttle

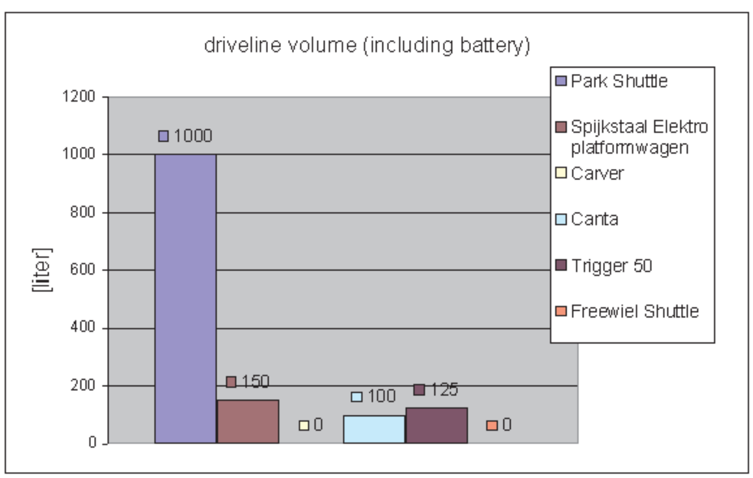

nominal power
[kW]
50
45
40
35
30
25
20
15
10
5
0
10
2
47
4
3
2
Park Shuttle
Spijkstaal Elektro platformwagen
Carver
Canta
Trigger 50
Freewiel Shuttle

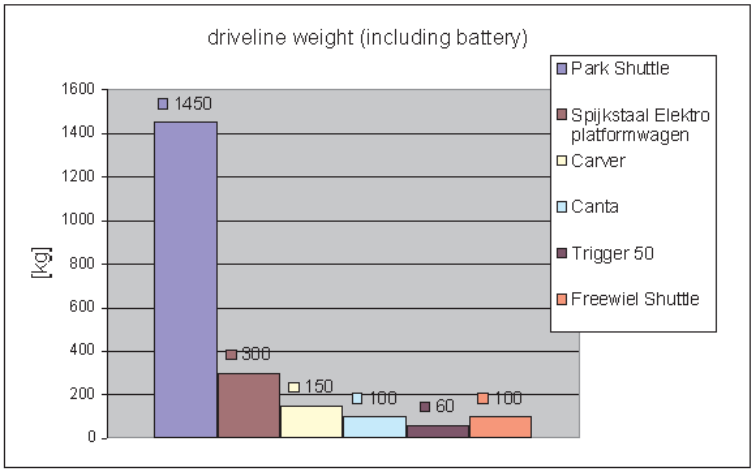

peak power
[kW]
50
45
40
35
30
25
20
15
10
5
0
20
8
47
4
3
4,5
Park Shuttle
Spijkstaal Elektro platformwagen
Carver
Canta
Trigger 50
Freewiel Shuttle

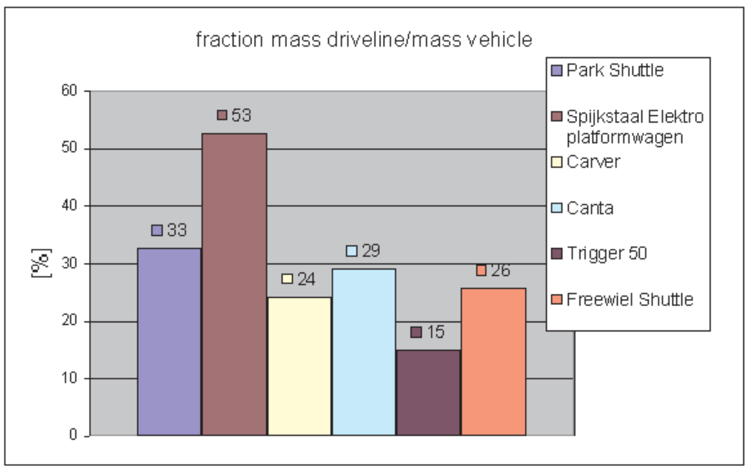

capacity energy storage
[MJ]
1200
1000
800
600
400
200
0
160
21,6
1032
645
193,5
200
Park Shuttle
Spijkstaal Elektro platformwagen
Carver
Canta
Trigger 50
Freewiel Shuttle

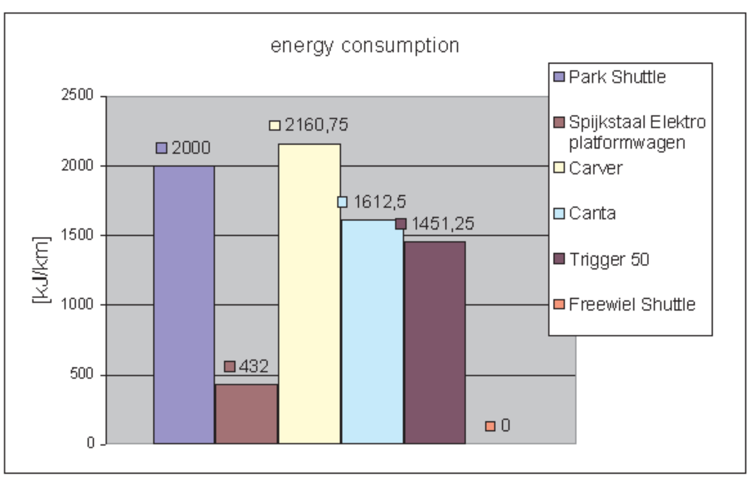

accesoires power
[Watt]
600
500
400
300
200
100
0
500
200
500
300
300
0
Park Shuttle
Spijkstaal Elektro platformwagen
Carver
Canta
Trigger 50
Freewiel Shuttle

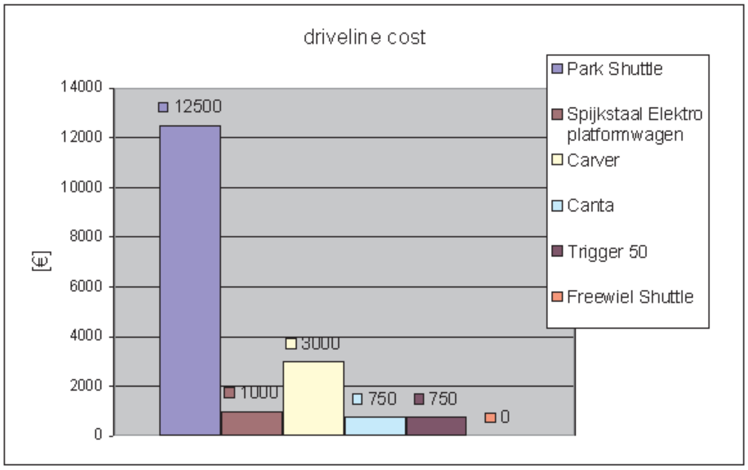

maintenance period
[km]
300000
250000
200000
150000
100000
50000
0
250000
200000
10000
2500
2500
3000
Park Shuttle
Spijkstaal Elektro platformwagen
Carver
Canta
Trigger 50
Freewiel Shuttle

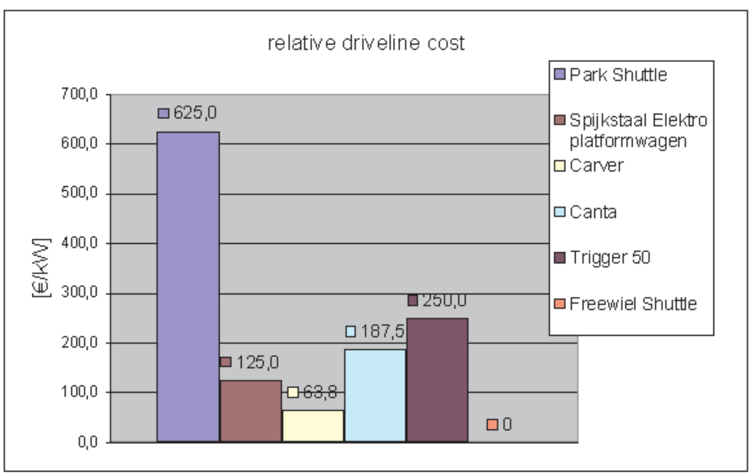

driveline volume (including battery)
[liter]
1200
1000
800
600
400
200
0
1000
150
0
100
125
0
Park Shuttle
Spijkstaal Elektro platformwagen
Carver
Canta
Trigger 50
Freewiel Shuttle


driveline weight (including battery)
[kg]
1600
1400
1200
1000
800
600
400
200
0
1450
300
150
100
60
100
Park Shuttle
Spijkstaal Elektro platformwagen
Carver
Canta
Trigger 50
Freewiel Shuttle


fraction mass driveline/mass vehicle
[%]
60
50
40
30
20
10
0
33
53
24
29
15
26
Park Shuttle
Spijkstaal Elektro platformwagen
Carver
Canta
Trigger 50
Freewiel Shuttle


energy consumption
[kJ/km]
2500
2000
1500
1000
500
0
2000
432
2160,75
1612,5
1451,25
0
Park Shuttle
Spijkstaal Elektro platformwagen
Carver
Canta
Trigger 50
Freewiel Shuttle

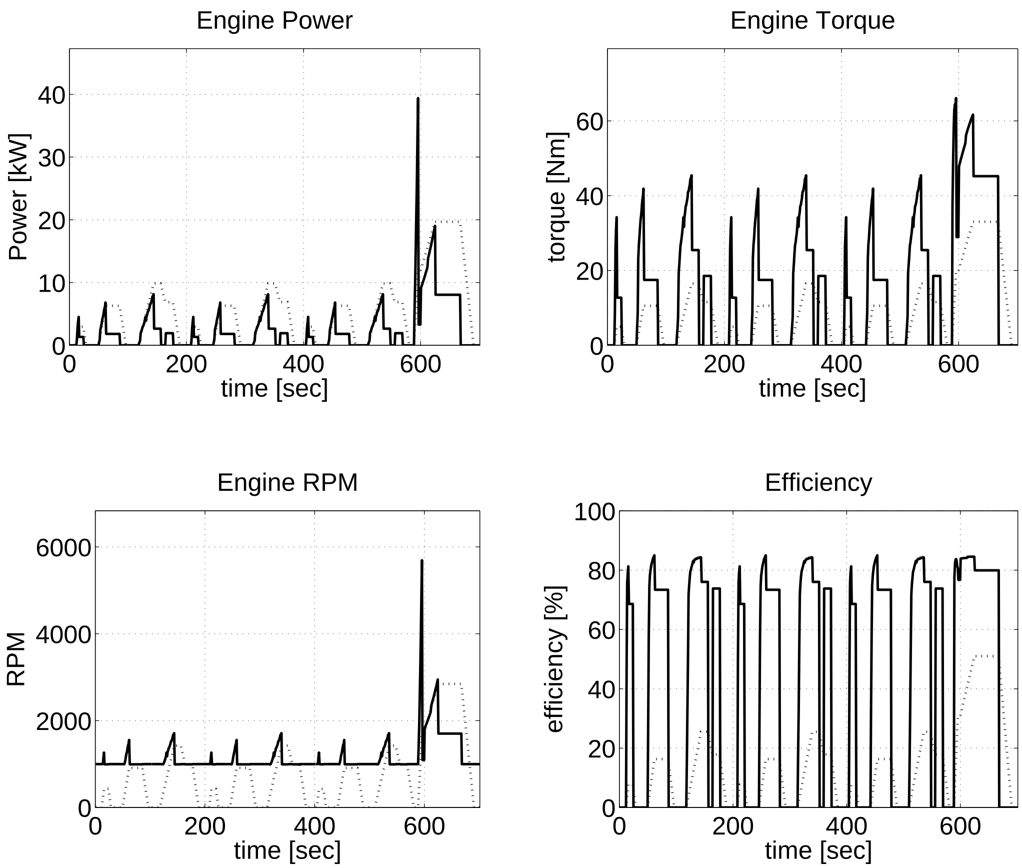

driveline cost
14000
12000
10000
8000
6000
4000
2000
0
[€]
12500
1000
3000
750
750
0
Park Shuttle
Spijkstaal Elektro platformwagen
Carver
Canta
Trigger 50
Freewiel Shuttle

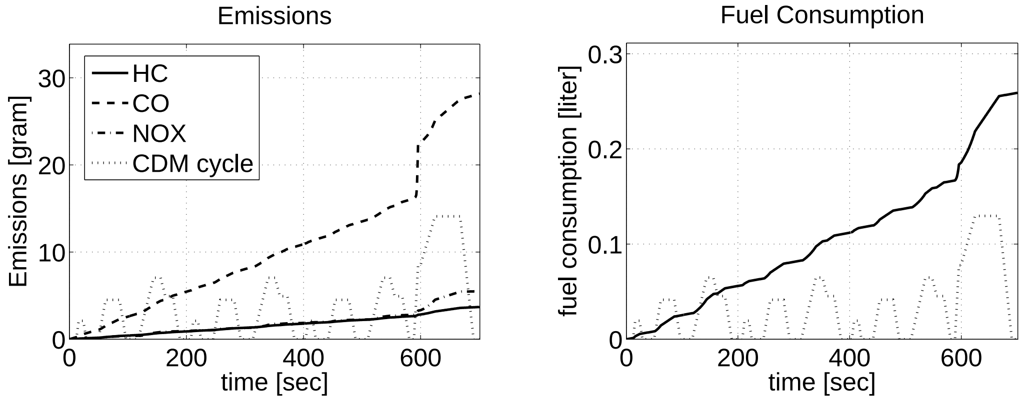

relative driveline cost
700,0
600,0
500,0
400,0
300,0
200,0
100,0
0,0
[€/kW]
625,0
125,0
63,8
187,5
250,0
0
Park Shuttle
Spijkstaal Elektro platformwagen
Carver
Canta
Trigger 50
Freewiel Shuttle

Appendix D

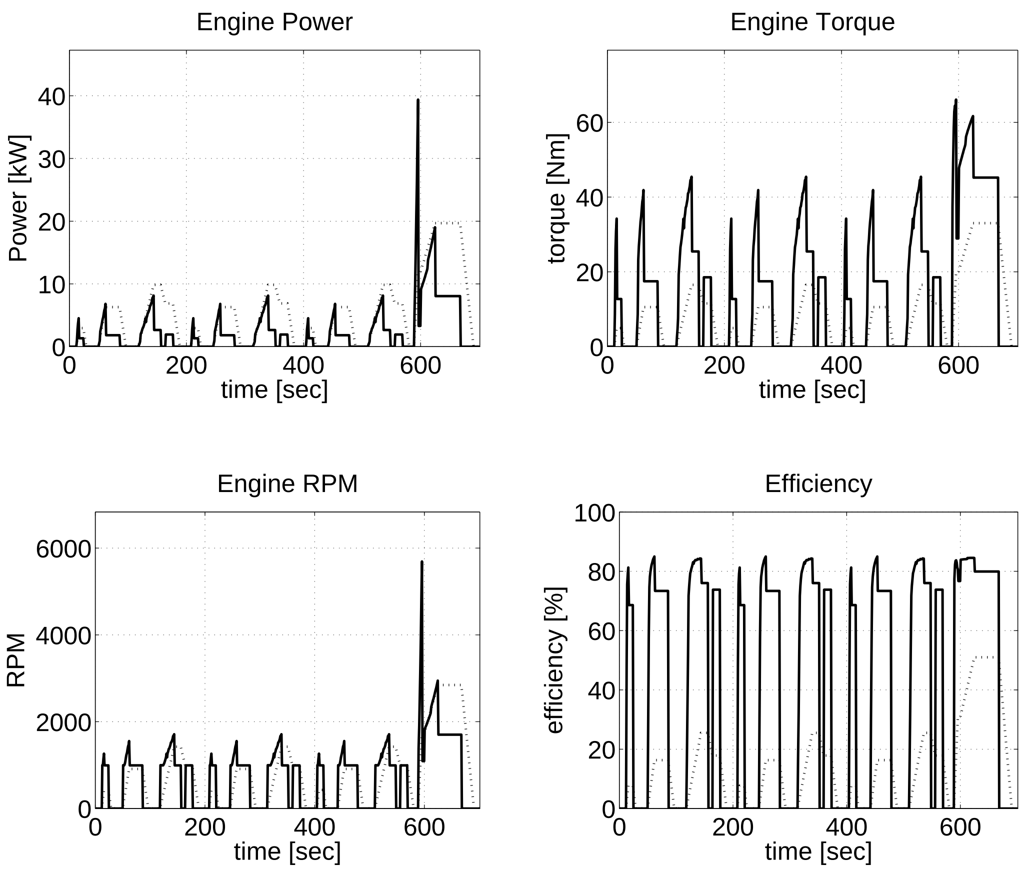
Simulation Results

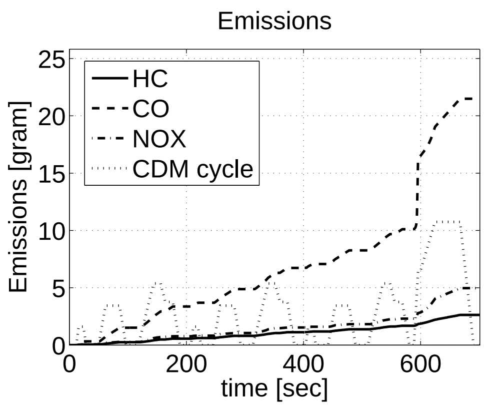
D.1 Conventional drivetrain

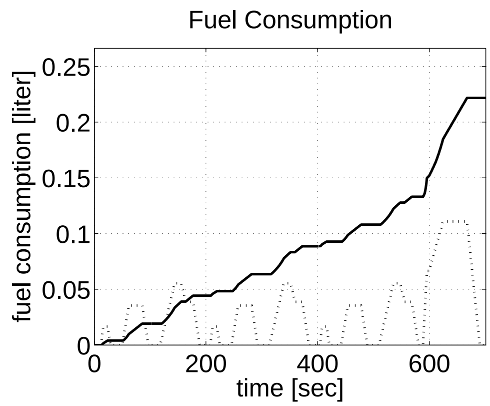




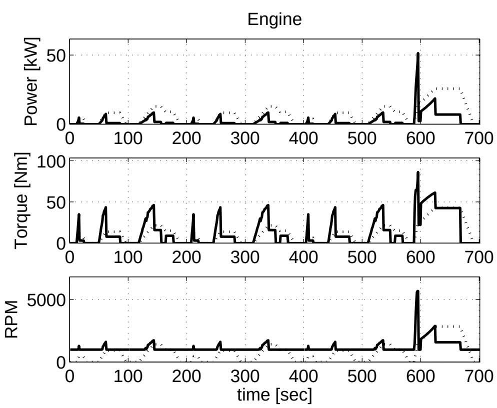
D.2 Parallel hybrid drivetrain

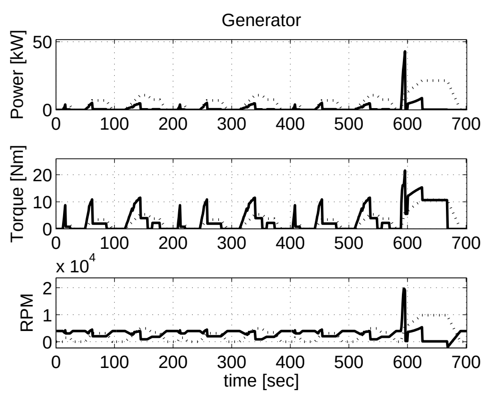


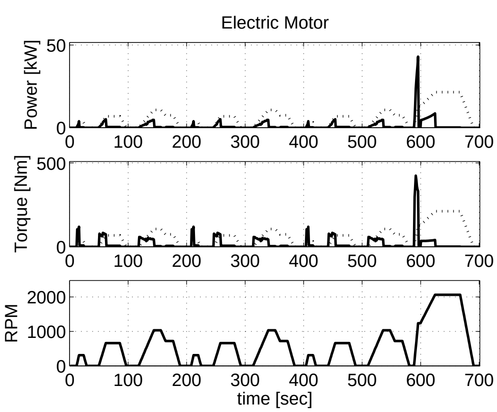


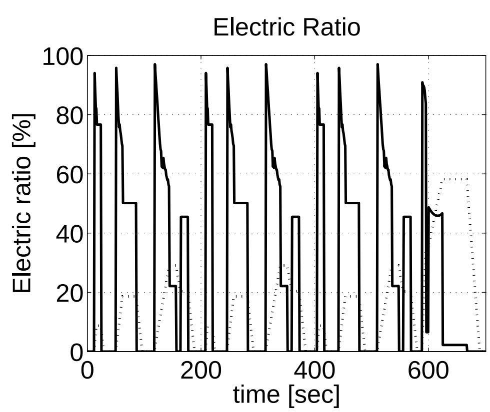


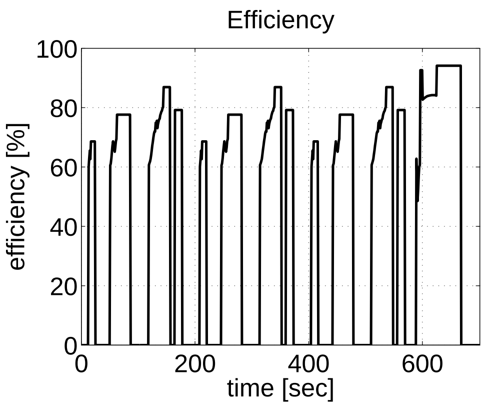
D.3 Power split hybrid drivetrain

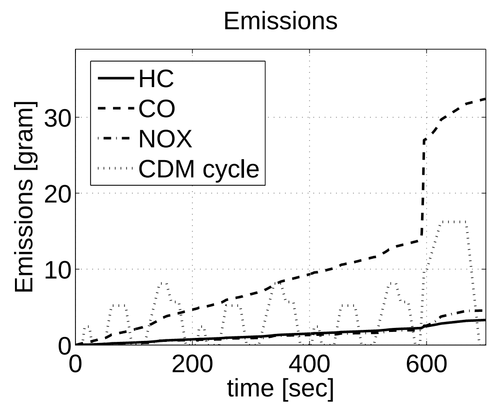


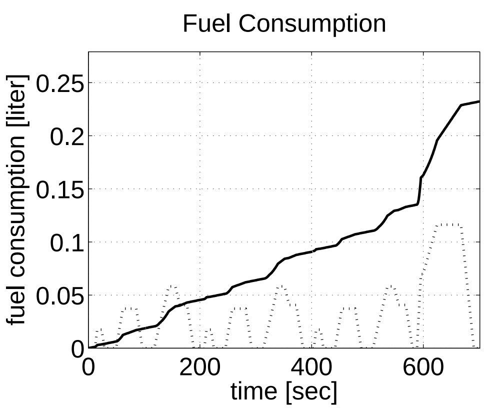




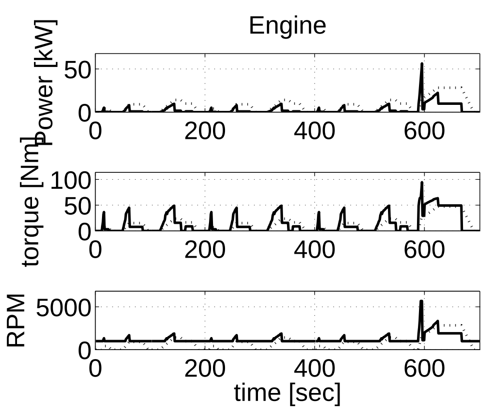


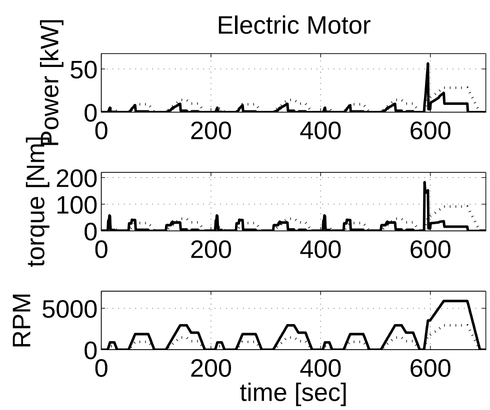


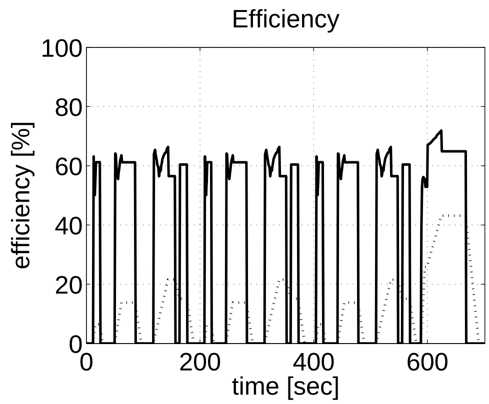


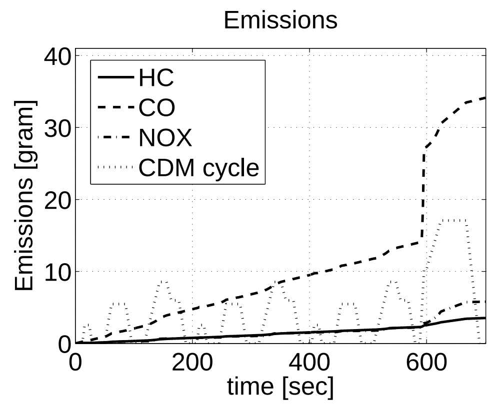


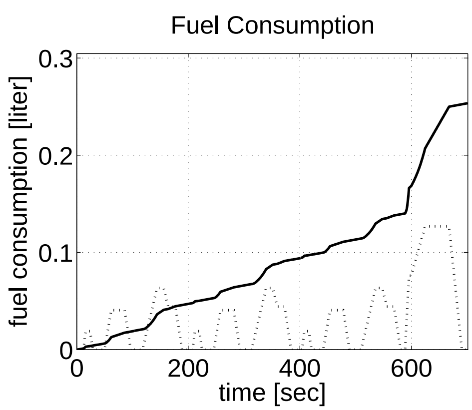
D.4 Series hybrid drivetrain






Efficiency
efficiency [%]
100
80
60
40
20
0
0
200
400
600
time [sec]


Emissions
Emissions [gram]
40
30
20
10
0
HC
CO
NOX
CDM cycle
0
200
400
600
time [sec]


Fuel Consumption
fuel consumption [liter]
0.3
0.2
0.1
0
0
200
400
600
time [sec]

Bibliography

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