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Determination of Weight Elasticity of Fuel Economy for Conventional ICE Vehicles, Hybrid Vehicles and Fuel Cell Vehicles

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Body Department

Final report

Determination of Weight Elasticity of Fuel Economy for Conventional ICE Vehicles, Hybrid Vehicles and Fuel Cell Vehicles

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1 Executive Summary

A comprehensive simulation study in order to investigate the relationship between mass reduction and fuel consumption was conducted. This study was executed by Forschungs-gesellschaft Kraftfahrwesen mbH Aachen (fka) on behalf of the International Iron and Steel Institute Automotive Committee (IISI-AutoCo).

Content of Study

In this study the influence of a weight reduction on the fuel consumption was analysed by simulation. In doing so three different vehicle types (compact, mid-size, SUV), five different propulsion systems (gasoline engine, diesel engine, gasoline hybrid, diesel hybrid, fuel cell) and two different driving cycles (NEDC, HYZEM) were considered. The study also contains a literature survey which analyses the current perceptions about mass sensitivity of internal combustion engine vehicles, hybrid vehicles und fuel cell vehicles. Besides the analysis of the vehicles with its base weight and a reduced weight, vehicles with a reduced weight and an powertrain re-sizing were examined as well in simulation. All simulation results were compared and assessed. In addition the fundamentals of the alternative propulsion systems were explained.

Overview of Results

In the literature survey the most suitable results are found for ICE vehicles. The result values are in a range of 4.5 % to 6 % fuel consumption reduction per 10 % weight saving and 0.15 l/100 km to 0.7 l/100 km fuel consumption reduction per 100 kg weight saving respectively. These results include papers of the automobile, steel and aluminium industry. Unfortunately at most of the literature sources the boundary conditions of measurements or statements are not always clearly defined. One very valuable source was found in [WAL00].

In the simulation approach the vehicle weight reduction was determined considering primary and secondary weight saving effects. The simulations were conducted for vehicles with the base weight, for vehicles with the reduced weight and for vehicles with reduces weight and re-sized powertrain. All simulations are done for three vehicles classes, five propulsion systems and two driving cycles. As a software the widely spread tool Matlab/Simulink® was used. The simulation results are displayed in Fig. 1-1 and Fig. 1-2.

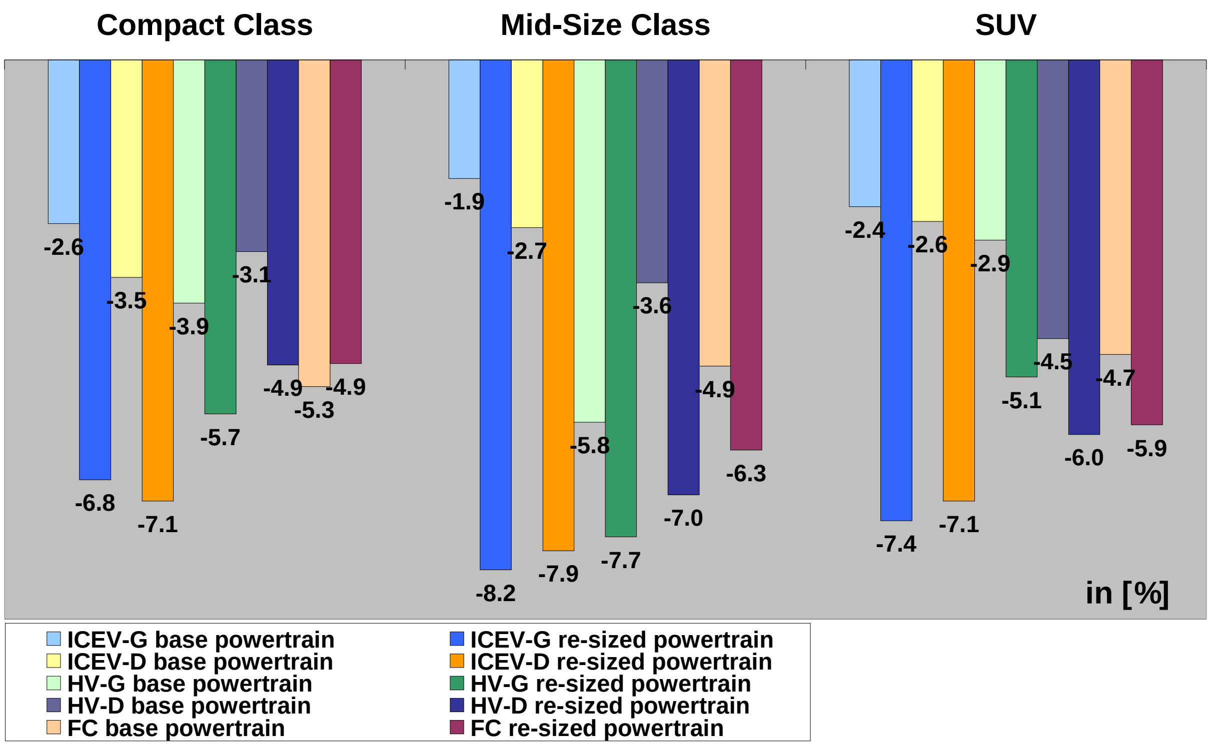

Fig. 1-1: Influence of 10 % weight reduction on fuel consumption in NEDC cycle

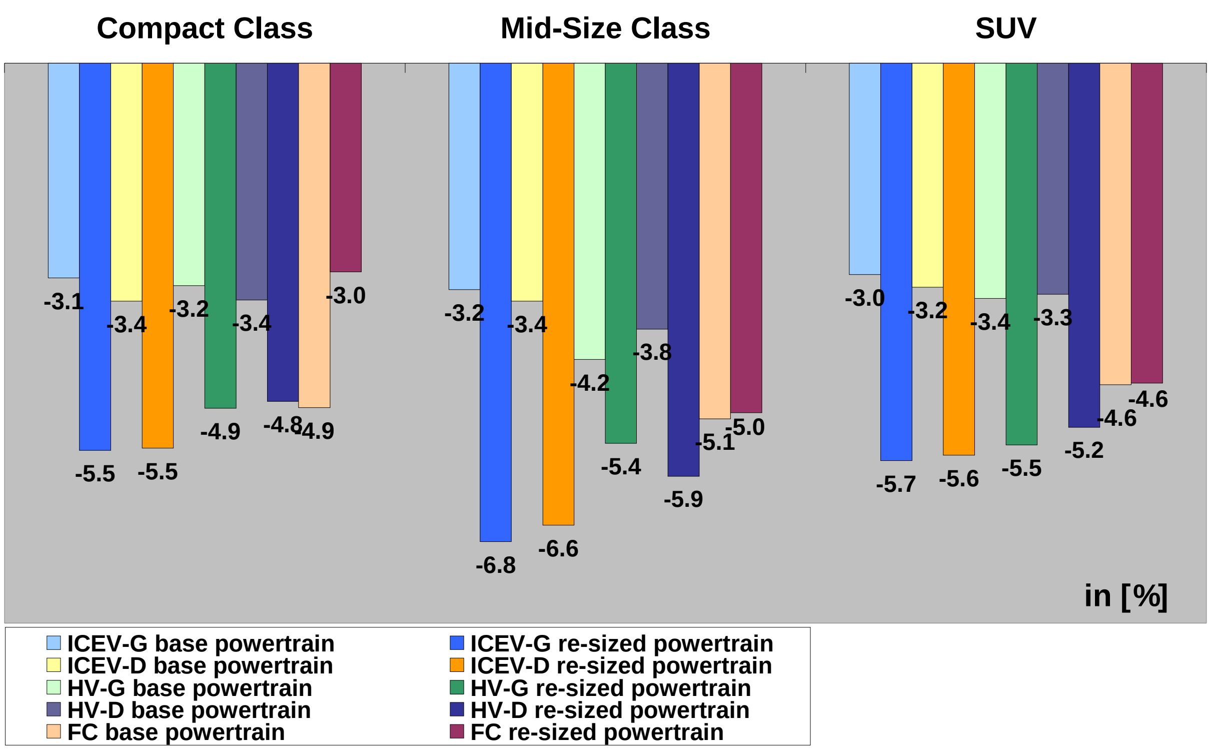

Fig. 1-2: Influence of 10 % weight reduction on fuel consumption in HYZEM cycle

It was found that at a 10 % mass reduction without powertrain re-sizing saves fuel between 1.9 % and 3.2 % in conventional vehicles with gasoline engine and between 2.6 % and 3.4 % with Diesel engine when considering both driving cycles. When considering the powertrain re-sizing at ICE vehicles this effect has a bigger influence than the mass reduction itself, especially in the NEDC cycle. Further on the effect of powertrain re-sizing (in combination with mass reduction) has less effect in hybrid powertrains due to the reduced impact of idling losses and avoidance of low efficiency operating points. It was established that the ICE vehicles are more mass sensitive than hybrids and FC vehicles when considering powertrain re-sizing, but less mass sensitive without considering powertrain re-sizing. But all in all it is important that, when talking about weight sensitivity the used boundary conditions have to be strongly considered, because the results are influenced by many parameters.

2 Introduction

In the scope of the important discussion about the raising CO_2 emissions a simulation study was conducted to analyse the relationship between mass reduction and fuel consumption. The study is commissioned by International Iron and Steel Institute Automotive Committee (AutoCo) to receive exact information about the influence of mass reduction to the amount of fuel consumption. Within this project three different vehicle types with three different propulsion systems will be examined when also considering two driving cycles. All the simulated results will be compared with collected literature information.

In order to get an overview about the current perception of the weight elasticity a literature study will be carried out. In this literature study the relationship of mass reduction and fuel consumption in internal combustion engine vehicles, hybrid vehicles and fuel cell vehicles in combination with the related boundary conditions will be analysed. All information will be compared and documented in tables.

The basis for the simulation itself is built by an analysis of three vehicle types. The generic mass of compact class, mid-size class and sport utility vehicles and their body structures will be determined. The fuel consumption of these generic vehicles will be established, as well as the fuel consumption for these vehicles with reduced mass. In addition the influence of a re-sizing of the powertrains will be considered. The simulation work will also be done for the propulsion systems hybrid and fuel cell.

The simulation will be done with the software Matlab/Simulink®, a tool widely used for dynamic system simulations and control development at all OEMs and mayor suppliers. The simulation is executed using the driving cycles NEDC and HYZEM. The results of all simulations will be analysed and compared, based on that conclusions will be drawn. The results will be filed in tables and illustrated with charts. For every main issue of this study one chapter is prepared. All results are summarised in the corresponding appendices.

The main issues of the simulation study are:

- Literature research (chapter 3)
- Fundamentals (chapter 4)
- Simulation (chapter 5)

3 Literature Research

A literature research is conducted especially in order to find current values of weight elasticity. The weight elasticity value expresses the ratio of the percentage of fuel consumption reduction and the percentage of mass reduction (see appendix 3-1). In addition to that further information about the relationship of mass reduction and fuel consumption is gathered. The aim was to find values of internal combustion engine vehicles, hybrid vehicles and fuel cell vehicles. The literature survey is done in the most important automotive engineering magazines, SAE-papers, papers from technical congresses etc. It has to be considered that the amount of literature with regard to the weight elasticity of fuel consumption published for hybrid vehicles and especially for fuel cell vehicles is much smaller than for vehicles with conventional drive-trains.

3.1 Internal Combustion Engine Vehicles

The most promising results are found for internal combustion engine vehicles. Several results deliver values of fuel consumption reduction when reducing the vehicle weight for 10 %. In further literature sources the fuel consumption reduction in the unit “litre per 100 km” is mentioned when a vehicle weight reduction of 100 kg is considered. Further information is shown in appendix 3-2. The important results are listed in Fig. 3-1.

	Weight Saving	Fuel Consumption Reduction
Source 1 [SCH04]	10 %	4.7 %
Source 2 [THO99]	10 %	4.5 %
Source 3 [RUC99]	10 %	6 %
Source 4 [DAS00]	10 %	5 %
Source 5 [FRE02]	100 kg	0.4 l/100 km
Source 6 [SCH96]	100 kg	0.5 l/100 km
Source 7 [PIE92]	100 kg	0.6 l/100 km
Source 8 [FUR01]	100 kg	~ 0.35 l/100 km
Source 9 [SPR92]	100 kg	~ 0.65 l/100 km
Source 10 [RAU99]	100 kg	~ 0.6 l/100 km
Source 11 [GEB00]	100 kg	0.5 l/100 km
Source 12 [STO96]	100 kg	0.15 l/100 km
Source 13 [AUE01]	100 kg	~ 0.35 l/100 km
Source 14 [RID98]	100 kg	up to 0.6 l/100 km
Source 15 [BAU98]	100 kg	~ 0.65 l/100 km

Fig. 3-1: Important literature results for internal combustion engine vehicles

The sources of the literature research are mainly independent institutes, organisations, OEM and supplier, but also sources of the steel and aluminium industry. In many cases the relationship between weight reduction and fuel consumption is mentioned in only one sentence in the articles. In the most cases the boundary conditions of the measurements and the statements and the consideration of secondary weight saving effects are not always clearly defined. Furthermore it is significant that the result values are spread in relatively wide range.

Very good information is provided by the literature source [WAL00]. This report describes the examination of eleven different gasoline and diesel powered vehicles of different vehicle classes on a dynamic roller test bench. In these tests ten different driving cycles are considered. The measurements are done with the basic vehicle weight and for comparison with 100 kg weight reduction. In every case the fuel consumption is determined. No secondary weight saving effects are considered. All results are in a range of 0.02 to 0.47 l/100km. When analysing only the NEDC driving cycle the average result value of all analysed vehicles is 0.18 l/100km. That means a weight reduction of 100 kg leads to a fuel consumption reduction of 0.18 l/100km. When calculating the corresponding averaged weight elasticity value of all analysed vehicles only for the NEDC driving cycle the result is 0.36. Further analysis values are shown in the corresponding appendix 3-7.

Further information about the relationship of mass reduction and fuel consumption is given in source [RID98]. Lynne Ridge describes the results of a EUCAR survey. The result values are based on technical simulations and empirical data. In this study the fuel reduction of gasoline and diesel powered vehicles in litre per 100 km is determined when reducing the vehicle weight for 100 kg.

Engine Type	without gear ratio change		with gear ratio change	
	Average (Median)	Range	Average (Median)	Range
Gasoline	0,14	0,02 ... 0,50	0,38	0,19 ... 0,60
Diesel	0,12	0,10 ... 0,35	0,29	0,26 ... 0,37

Fig. 3-2: Results of fuel consumption reduction in [l/100km x 100kg] [RID98]

The analysis is done without and with gear ratio change. Based on the result values a WEV of 0.38 is calculated. Unfortunately the way of calculation is not mentioned. Despite of this result of 0.38 a WEV of 0.6 for automotive LCA studies is recommended. The source [SCH04] uses the information of [RID98] for a life cycle assessment in a case study. Further information about [RID98] is shown in the corresponding appendix 3-11.

3.2 Hybrid and Fuel Cell Vehicles

For the literature research on HV all available search engines were used but the paper dealing specific with mass impact in hybrid vehicles are very rare. Several dozen of papers dealing with the fuel economy of hybrid vehicles were read without finding valuable information on mass impact.

The most important source of information concerning HEV is the SAE paper 2004-01-0572 from An/Santini with the title “Mass Impact on Fuel Economics of Conventional vs. Hybrid Electric Vehicles” [AN04]. Therein the correlation between fuel economics and vehicle mass for production HEV with different levels of hybridisation is presented (see appendix 3-14) and it is examined how this relationship evolves from CV to HEV. According to this paper there are two important impacts of shifting from conventional to hybrid vehicles in terms of the mass vs. fuel economy relationship. With little or no change in mass there are significant improvements in fuel economy possible. But, once a switch to hybrid powertrains has been made, the effectiveness of mass reduction in improving fuel economy will be diminished relative to conventional vehicles.

4 Fundamentals

In order to provide some background to the technology of hybrid and fuel cell vehicles, a basic introduction to hybrid and fuel cell powertrain technology is given.

4.1 Hybrid Vehicles

By definition, a hybrid drive system consists of two different drive systems, i.e. at least of two energy converters and two energy storages. This definition shows in principle, that the term “hybrid drive” covers a multiplicity of possible variants. The different essential structures of the combination of combustion engine, e-machine, gas turbine, battery and planetary transmission for the serial, the parallel and the combined/power-split hybrid drive are represented in Fig. 4-1.

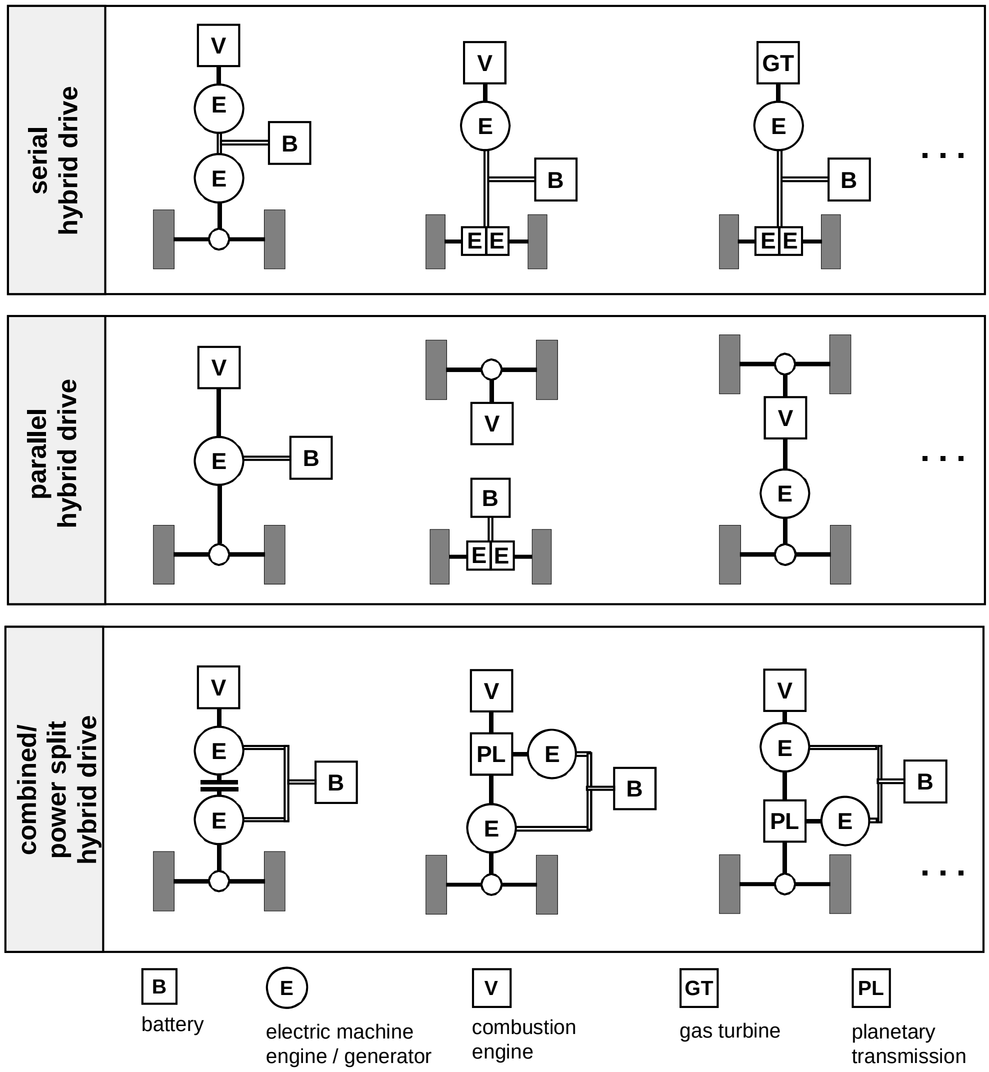

Fig. 4-1: Basic structures of hybrid vehicles

Beside the fundamental hybrid structures, hybrid drives can be differentiated additionally by installed electrical power and stored electrical energy (see Fig. 4-2).

Parallel hybrids of small installed power and electrical energy storage are also designated as starter-generator hybrid. If the electrical power is a little higher dimensioned, it is called power assist hybrid or, related to the energy content of the electrical energy storage, low storage hybrid.

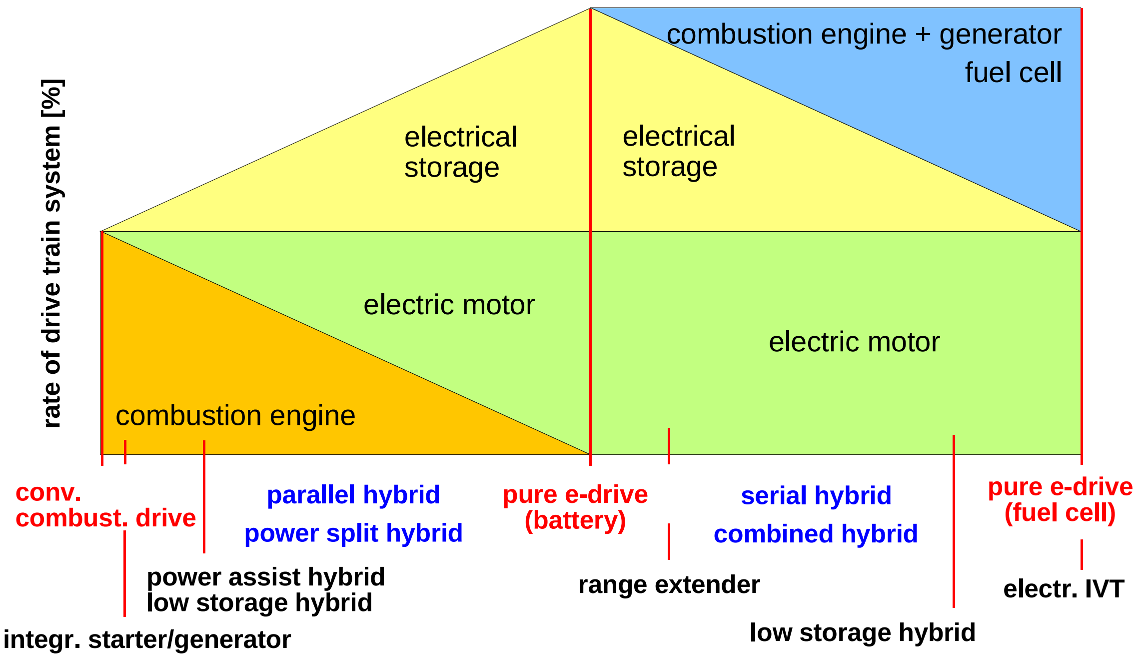

Fig. 4-2: Classification in installed power and storage capacity

The serial hybrid with a large battery and a small auxiliary power unit (APU) is called a range extender. If the energy content of the battery is limited small, which results in a small emission-free range, the hybrid is called a low storage hybrid. If there is not any storage integrated in the electrical intermediate circuit, the drive system works with an electrical IVT (infinite variable transmission). In the broader sense, a fuel cell vehicle with additional electrical energy storage is also a serial hybrid vehicle. Hybrid drives, whose electrical energy storage cannot be charged from electric energy net, are called self-supporting hybrids.

4.1.1 Serial Hybrid Drivetrain

Characteristic of serial hybrid drives is the "series connection" of the energy converter without mechanical coupling of the combustion engine to the drive wheels (see Fig. 4-3). Here, the combustion engine drives a generator, which supplies the electrical drives as well as a storage arranged in the electrical intermediate circuit (usually a battery) with energy. There are variants with a drive engine and a differential as well as concepts with two drive engines per axle, which do not require the differential, up to wheel hub drive motors.

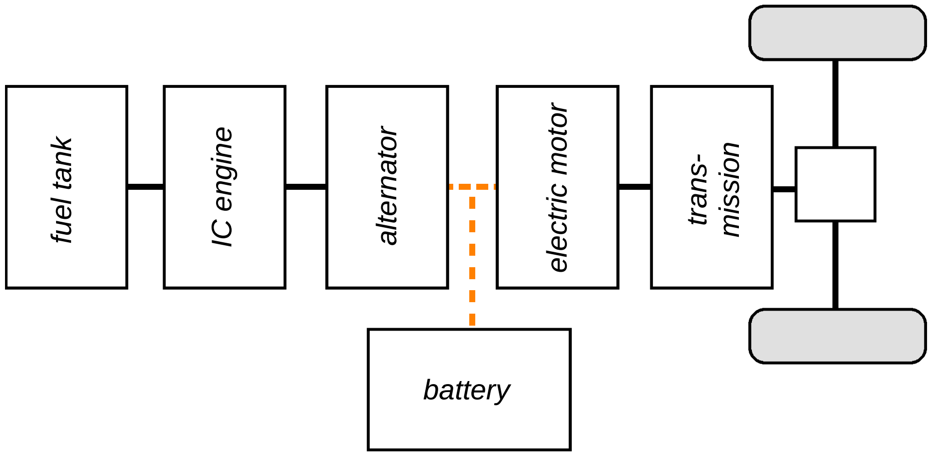

Fig. 4-3: Serial hybrid drive

4.1.2 Parallel Hybrid Drivetrain

In the parallel hybrid drive systems (Fig. 4-4), combustion engine and electric motor are mechanically coupled to the drive wheels. Beside the two drive units (engine/motor) and two storages, a parallel concept contains one or several transmissions, clutches, or freewheeling clutches. The two propulsion systems can be used individually and at the same time for the propulsion of the vehicle. Due to the power addition they can be laid out relatively small. Usually the electric drive type is designed for city traffic (limited, emission-free driving operation), while the combustion engine provides higher performances for overland traffic and motorways. The produced electrical and combustion engine energy can be overlaid mechanically by means of speed-addition (with a planetary transmission), torque-addition (with gearbox with spur-cut gear or chain), or traction power addition (electric motor and combustion engine affect different drive axles). For torque-addition, the relation between the torques of two energy converters can be varied freely, while the speed relation is fixed. A decoupling of the two drive systems can be realized by a freewheeling clutch or the clutch.

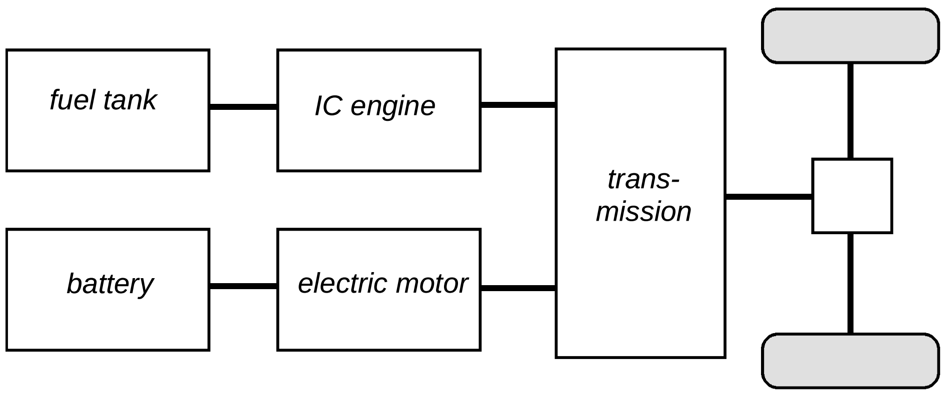

Fig. 4-4: Parallel hybrid drive

For the addition of speeds, the powers of the energy converters are added by a planetary transmission, whereby the torque relation is fixed and the speed of the drive systems can be selected independently. In the physical sense, a hybrid with traction power addition is likewise a torque addition concept, in which the two energy converters affect different axles of the vehicle (e.g. the electric drive influences the front axle, the combustion engine is coupled on the rear axle).

A further possibility for the distinction of parallel hybrids occurs due to an arrangement of the energy converters. If both drive systems (electric motor and combustion engine) are coupled directly to the input shaft of the transmission, it is called a single-shaft hybrid. A two-shaft hybrid consists of an electric motor and a combustion engine arranged on different transmission shafts (transmission in or output shaft).

4.1.3 Combined and Power Split Hybrid Drive

A combination of parallel and serial structures is the so-called combined or power split hybrid [ESS98]. With combined hybrids (Fig. 4-5), it is possible to transfer the power of the combustion engine directly to the wheels by closing the clutch, which is an improvement of the overall efficiency in certain operating conditions (e.g. the high power demand of motorway driving). At the same time both electric machines can deliver their power additionally, like a parallel hybrid and briefly increase the maximum power. The higher expenditure faces the improved efficiency by the clutch and the more complex operating strategy. Furthermore, the arrangement of combustion engine and generator cannot be designed freely any longer, as a direct mechanical coupling to the drivetrain must take place.

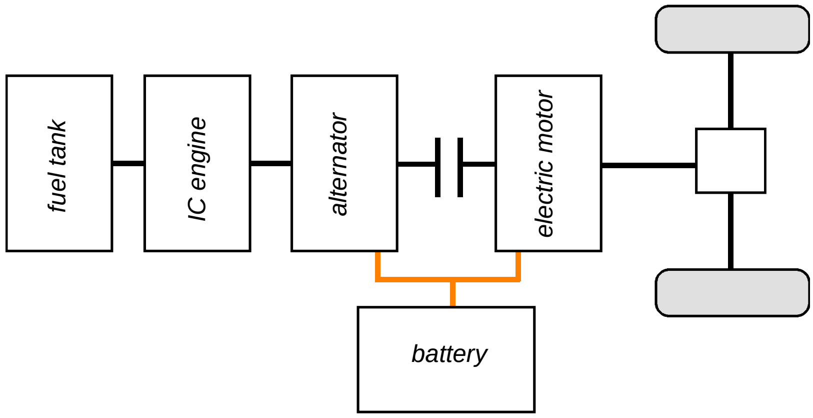

Fig. 4-5: Combined hybrid drive

Power split hybrid drives represent a further, however, very complex possibility of hybrid drives. With these structures a part of the power of the combustion engine is transferred directly mechanically to the drive wheels; the remaining power is transferred e.g. by a planetary transmission and two electric motors to the drive wheels. Generally a battery is used for energy storage. With this arrangement of the electric motors, the system works as a continuous variable transmission, so that an additional transmission is not necessary for the combustion engine. In principle, the combustion engine can be operated speed and power-independently of the other powertrain components. The efficiency level is higher than with serial structures due to the partial direct mechanical power transfer.

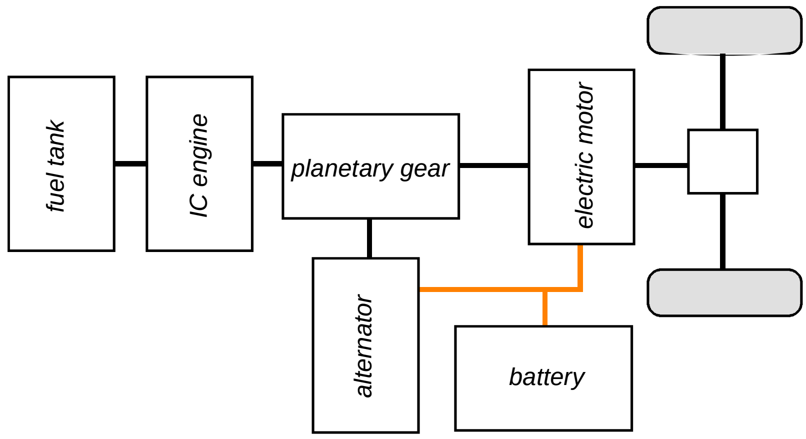

Fig. 4-6: Power split hybrid drive

The Toyota Hybrid System II (THS II) is such a power split parallel hybrid drive consisting of a 1.5 l, 4-cylinder, 57 kW Otto engine that works according to the Atkinson/Miller process and a 50 kW permanent magnet electric motor. These components together with a generator are connected by a planetary transmission, which facilitates a power split. Here, the combustion engine is connected with the bar, a generator with the sun wheel. The electric motor is coupled with the ring gear on the one hand and directly supplied by a chain drive with the system on the other hand (Fig. 4-7). The planetary gear splits the power of the combustion engine between the wheels and the generator in dependence on the vehicle operating condition.

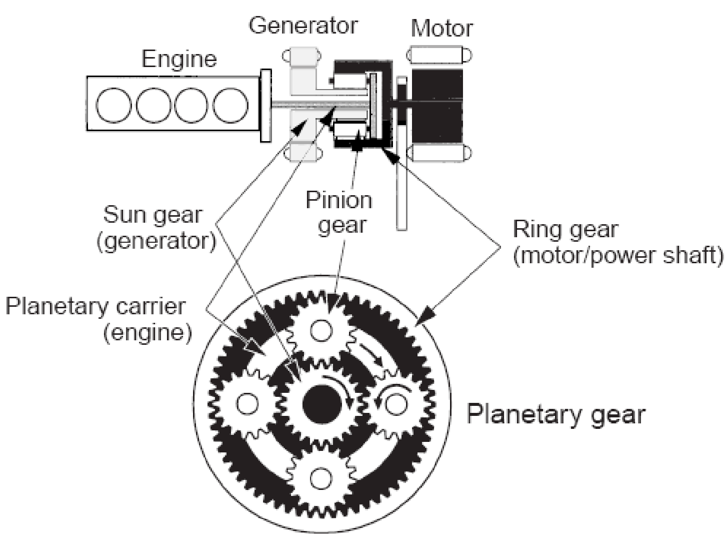

Fig. 4-7: Power split hybrid with planetary gear

This facilitates to operate the combustion engine on a mostly consumption-favourable range. By using the planetary transmission and the generator, the system works similar to an electronically regulated CVT and does not need a clutch. The generator speed regulates the speed control of the planetary gear and thus, the combustion engine (Fig. 4-8). The generator supplies its energy either directly to the electric motor or stores it into a battery.

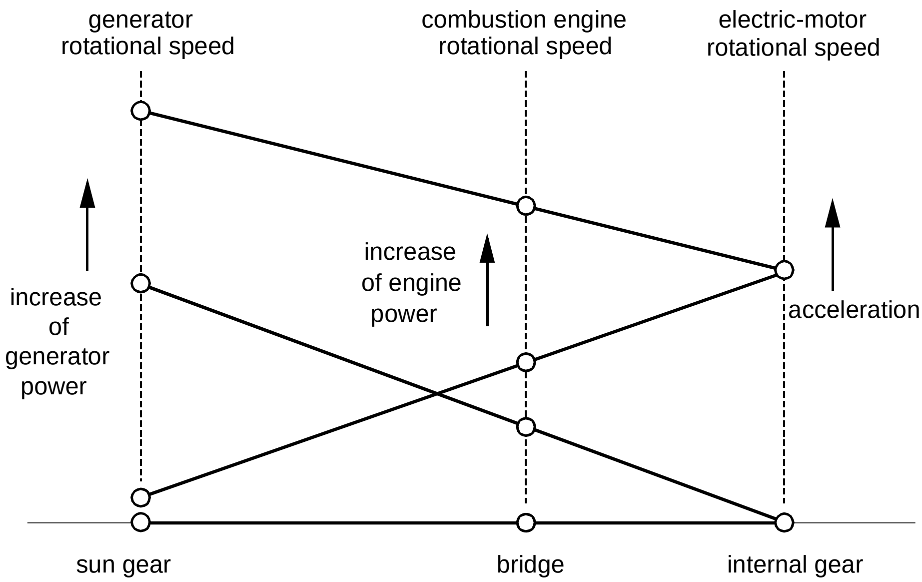

Fig. 4-8: Speed dependency in Kutzbach plan

The concept represents a self-supporting vehicle, i.e. a charge of the batteries by the electric energy network is not intended since the operating strategy possibly keeps the battery in a certain charging status. In principle, the hybrid drive in the Toyota Prius has only one operating mode, which regulates the drive engines automatically. A purely electrical operation is only possible at low speeds.

4.2 Fuel Cell Vehicles

A fuel cell vehicle is propelled by an electric motor, which is powered by the fuel cell stack. Hydrogen or hydrogen-rich gas and air are converted into electricity and heat in the fuel cell stack. The heat which is released during the process has to be cooled off. Fuel gas and air streams have to be pressurized and humidified. In direct hydrogen fuel cell vehicles, the hydrogen is stored in high pressure tanks, cryogenic tanks, or metal hydride storage containers. Indirect methanol or other indirect hydrocarbon fuel cell vehicles carry a fuel reformer to produce a hydrogen-rich synthesis gas from a liquid fuel. The complexity of the process makes detailed models for the prediction of vehicle characteristics necessary.

The fuel cell system comprises the fuel cell stack, the air and fuel conditioning, and the water and thermal management. Output of the fuel cell system is electricity, which is supplied to the electrical motor or to the energy storage.

In the fuel cells itself hydrogen and oxygen are combined to water. Hydrogen molecules are split into protons and electrons at the fuel cell anode. A proton exchange membrane conducts the protons to the cathode, while the electrons induce an electrical current which can be used as a power source. Electrons, protons, and oxygen molecules are combined at the fuel cell cathode in the presence of a platinum catalyst. The electrical current is proportional to the amount of hydrogen molecules converted. Ideally, the difference in the electro-chemical potential between anode and cathode dictates the voltage. This open-circuit voltage is reduced when a current between the two electrodes flows. With increasing current these losses increase. They can be attached to different mechanisms:

- Anode overpotential losses: reaction losses due to oxidation of hydrogen at the anode catalyst
- Cathode overpotential losses: reaction losses due to the reduction of oxygen at the cathode catalyst
- Gaseous diffusion losses in the anode and cathode backing layer
- Ionic resistance to the proton conduction in the membrane
- Electronic resistance of the catalyst, backing layer, and bipolar plates
- Water management in the membrane
- Pressure drops in the anode and cathode channel and the effect on the partial pressure of hydrogen and oxygen, respectively, at the catalyst layers
- Anode air bleed to mitigate effect of CO poisoning

A decrease of cell efficiency can be observed when the partial pressures of hydrogen or oxygen are lowered. Insufficient membrane humidification also decreases the cell efficiency. Unconverted hydrogen in the anode exhaust stream can only be recycled to the anode feed in direct hydrogen fuel cell systems. In indirect fuel cell systems the hydrogen concentration in the original reformate stream is too low, further dilution with the depleted anode exhaust would have an additional negative impact on the cell efficiency. Hydrogen remaining in the anode exhaust can instead be burnt in a burner. A major power sink in pressurized fuel cell system is the air compressor. The air supplied to the cathode is in some systems compressed to 2 to 3 atmospheres (absolute). Sometimes, part of the compression energy is recovered in an expander that is placed in the cathode exhaust stream. In load-following vehicles the air compressor has to be responsive to changes in the power demand to supply the necessary amount of oxygen to the fuel cell. The control of the air compressor has to keep the performance close to the most efficient operating point.

Compressors usually have a minimum amount of air that has to be turned over and cannot be switched off completely. This minimum power is decisive for the energy consumption of the vehicle at low power demands.

Although average efficiencies of fuel cell stacks are higher than those of internal combustion engines (ICE), the cooling system is more challenging. In ICE vehicles a large part of the heat is released in the hot exhaust gas, only about half of the heat (roughly 30 % of the energy contained in the fuel) has to be removed by cooling fluids and dissipated by the radiator. Maximal cooling fluid temperatures for ICE can be around 120 °C. The heat generated by the fuel cell stack (about 60 % of the fuel energy) is released at a lower temperature (80 °C) and has to be cooled off by a radiator primarily. Only a small fraction of the heat is carried out of the system via the exhaust stream. A larger amount of excess heat at a lower temperature necessitates a bigger radiator surface. Another challenge to the water and thermal management (WTM) is the need for humidification of the proton exchange membrane. Its conductivity is related to the saturation with water. Humidification of the membrane is obtained by saturating the fuel gas and supplied air. Drying up of the membrane leads to losses and can eventually burn out the cell. The necessary water can be taken from the cathode exhaust stream but has to be condensed, causing again higher radiator surface. Too much humidification of the input streams, on the other hand, can lead to flooding of the cell. The term ”flooding” describes the effect of blocking of diffusion paths in the gas diffusion backing layer and of reaction sites on the catalyst on the cathode side by liquid water.

In most fuel cell vehicle designs a common power bus distributes the energy supplied by the fuel cell stack to the motor, the fuel cell stack accessories, and some of the auxiliary systems like heating and air conditioning. In hybrid fuel cell vehicles the system also contains an energy storage device, which is charged in times of lower power demand from the motor, and discharged when the power demand of the motor is high. The operation strategies for the energy storage can be complex. Unlike in electric vehicles, the design of the battery is not optimised towards high energy capacities to guarantee the range requirement of the vehicle. Instead important criteria are high maximum current, high power, and short response times.

The efficiency of the electric motor, defined as the ratio of power at the motor shaft to electrical power at the motor terminals, depends on the motor speed and the torque at the motor shaft. While the available motor torque is limited by a maximum torque value at low motor speeds, the maximum torque at higher motor speeds is dictated by the total motor power. Since the maximum current that the motor can handle is limited, the available motor power at higher motor speeds decreases with lower system voltage, which is the voltage that the fuel cell stack and the battery can provide [HAU00b]. Fuel cell stack voltage and battery voltage decrease at high power outputs. This is one of the complex interrelationships between the components in the fuel cell vehicle that makes also the modelling a challenging task.

5 Simulation

5.1 Vehicle Analysis

In order to achieve a realistic vehicle weight reduction the body-in-white is analysed for a potential weight reduction and the possible influences on the complete vehicle weight. It is assumed that the body-in-white weight can be reduced by using an optimised design, more high strength steels or further lightweight materials. This data is necessary as an input for the simulation process.

In this study three different vehicle types are analysed. Therefore the vehicle weight and the body-in-white weight for typical vehicles of these vehicle classes are determined (see appendix 5-1). Based on this data generic values are generated. The generic vehicle characteristics are shown in Fig. 5-1.

Class	Engine	Capacity	Power	Mass	Example
Compact	4 Cylinder	1600 cm^3	85 kW	1260 kg	Ford Focus
Mid-size	6 Cylinder	3000 cm^3	181 kW	1640 kg	Mercedes E-Class
SUV	8 Cylinder	4500 cm^3	235 kW	2195 kg	BMW X5

Fig. 5-1: Determination of generic vehicles

Based on the determined generic body-in-white weight the primary weight saving is calculated. The assumption is made, that it is possible to reduce the body-in-white weight for about 20 to 40 %. Therefore these both limits are considered for the further weight calculations (Fig. 5-2). The weight values of both paths are used in the simulations.

Class	Vehicle mass	Body structure mass	Primary weight saving	Secondary weight saving	Reduced vehicle mass
Compact	1260 kg	360 kg	72/144 kg	22/43 kg	1166/1073 kg
Mid-size	1640 kg	400 kg	80/160 kg	24/48 kg	1536/1432 kg
SUV	2195 kg	540 kg	108/216 kg	32/65 kg	2055/1914 kg

Fig. 5-2: Weight values of generic vehicles (at 20 and 40 % primary weight saving)

The secondary weight saving is assumed to be 30 % of the primary weight saving. This weight reduction step considers weight reduction in further vehicle components due to the less body-in-white weight (see appendix 5-6). The reduction of the secondary weight saving is estimated based on to a suitable method from ThyssenKrupp Steel used in the NSB® study (see appendix 5-7). This secondary weight saving value is calculated for both paths of the calculation (for 20 and 40 % primary weight saving). In addition to that a separate simulation is done for both paths with considering the powertrain re-sizing. In doing so the powertrain is adapted to the lower weight in order to achieve the same acceleration as the basis vehicle. This method is described in chapter 5.2.

5.2 Simulation Approach

For the calculation of the fuel consumptions of the contemplated vehicle classes and powertrain configurations the simulation tool Matlab/Simulink® is used. This tool is used for dynamic system simulation and control development by all OEMs and major suppliers in the automotive industry (see appendix 5-12). The required characteristic values and maps of all vehicle components are stored in Matlab in the form of vectors and matrices. Simulink provides the modelling of the physical dependencies in a graphical user interface which is shown in appendix 5-21. The single components, e.g. combustion engine, electric motor, transmission and clutch, are available in special libraries at fka and can be connected in a modular architecture to build up different powertrain configurations. Matlab/Simulink® permits the investigation of the time dependent system behaviour so that e.g. shifting and clutch operations can be displayed (see appendix 5-19).

The following vehicle simulations are executed in the driving cycles NEDC and HYZEM. The NEDC, shown in appendix 5-17, is the standard synthetic cycle for consumption measurement in Europe. The HYZEM is a common cycle used to represent the real world traffic which means a more dynamical course of velocity containing higher acceleration and deceleration values (see appendix 5-18).

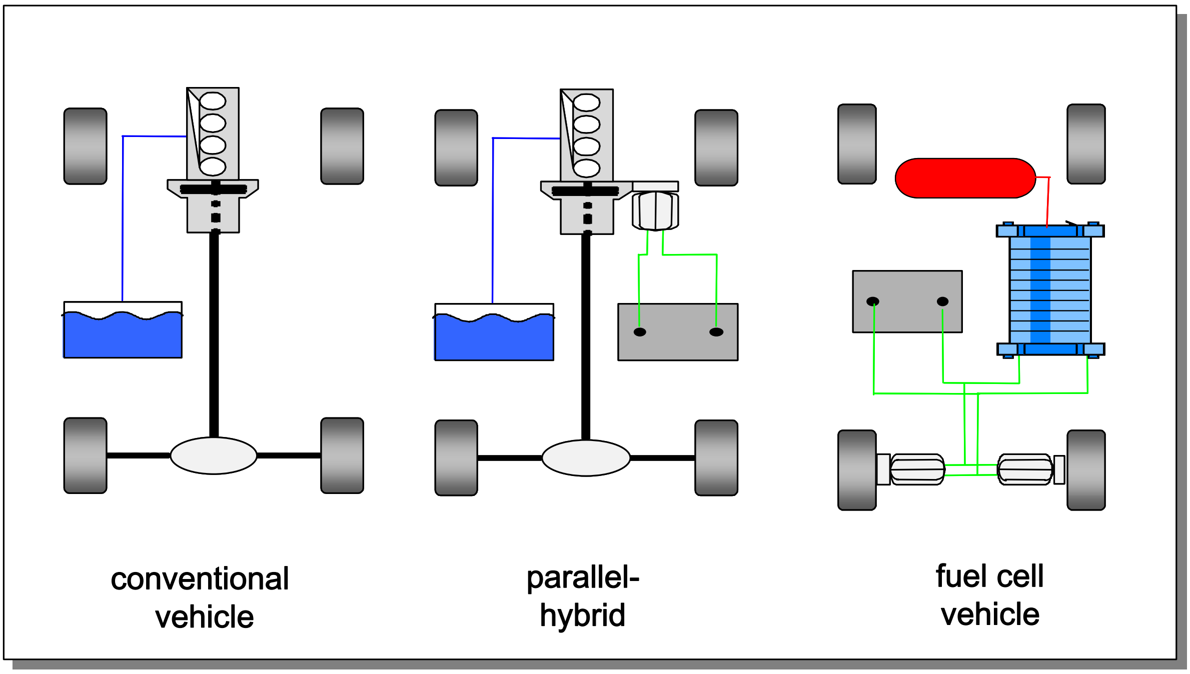

Fig. 5-3: Overview of the powertrain configuration used in the simulation

In the course of the simulative investigation three different powertrain technologies are analysed in three different vehicle segments. An overview of the powertrain architectures is depicted in Fig. 5-3. The basis vehicles (ICEV) are equipped with an internal combustion engine and a manual transmission (see appendix 5-26). The hybrid vehicles (HV) contain a parallel arrangement with a clutch between the combustion engine and the electric motor and another clutch between the electric motor and the transmission (see appendix 5-29). This arrangement in conjunction with a traction battery offers the possibility of pure electric propulsion as well as electric boost power and recuperation of braking energy. In the change from conventional ICEV to a hybrid vehicle the size and power of the internal combustion engines keeps unchanged. This adds some extra weight to the vehicle because of the hybrid components, but at the same time power from the electric motor is added, so that the acceleration performances of the hybrid vehicle is actually better than the one of the internal combustion engine.

The fuel cell vehicles (FCV) are equipped with a fixed gear ratio and a battery (see appendix 5-32) which enables the recuperation of braking energy as well as the phlegmatic operation of the fuel cell. The fuel cell powertrain in the vehicles is sized to provide the same acceleration performances as the ICEV have. It is assumed that the weight of the powertrain is a little bit more than that of a conventional one. Current fuel cell powertrains implemented in prototype vehicles weigh a lot more than ICEV powertrains, but the aims for the power density of fuel cell powertrains of all major developers are to reach a power density close to that of an ICE powertrain. For the simulations performed, the same weight as for the hybrid vehicles is assumed. The considered vehicle segments contain the compact class, the middle class and SUV.

For the analysis of the influence of weight reduction in conjunction with powertrain re-sizing, vehicle models with same performances are compared. Therefore the 0 to 100 kph acceleration values of the basis vehicle (ICEV, HV, FCV) are calculated in the first step. After that the vehicle weight is reduced by the defined primary and secondary weight saving. In the next step the powertrain is scaled down so that the acceleration values of the lightweight vehicle and the basis vehicle correspond (see appendix 5-20). In the simulation of the lightweight hybrid vehicle the combustion engine and the electric motor are scaled down by the same factor. For the fuel cell vehicle the electric traction motor and with it the fuel cell system are scaled down.

5.3 Simulation Results

For an analysis of the weight influence on the fuel consumption several comparisons are required. In the first step the influence of a simple weight reduction on the fuel consumption is compared to the effect of weight reduction in conjunction with powertrain re-sizing. Additionally the effects of weight reduction on the fuel consumption are compared for three considered vehicle segments and for five considered powertrain set-ups. Besides the influence of different load profiles is analysed by using a standard driving cycle (NEDC) and a more dynamic driving cycle (HYZEM). An overview of the simulation results is shown in Fig. 5-4 and Fig. 5-5.

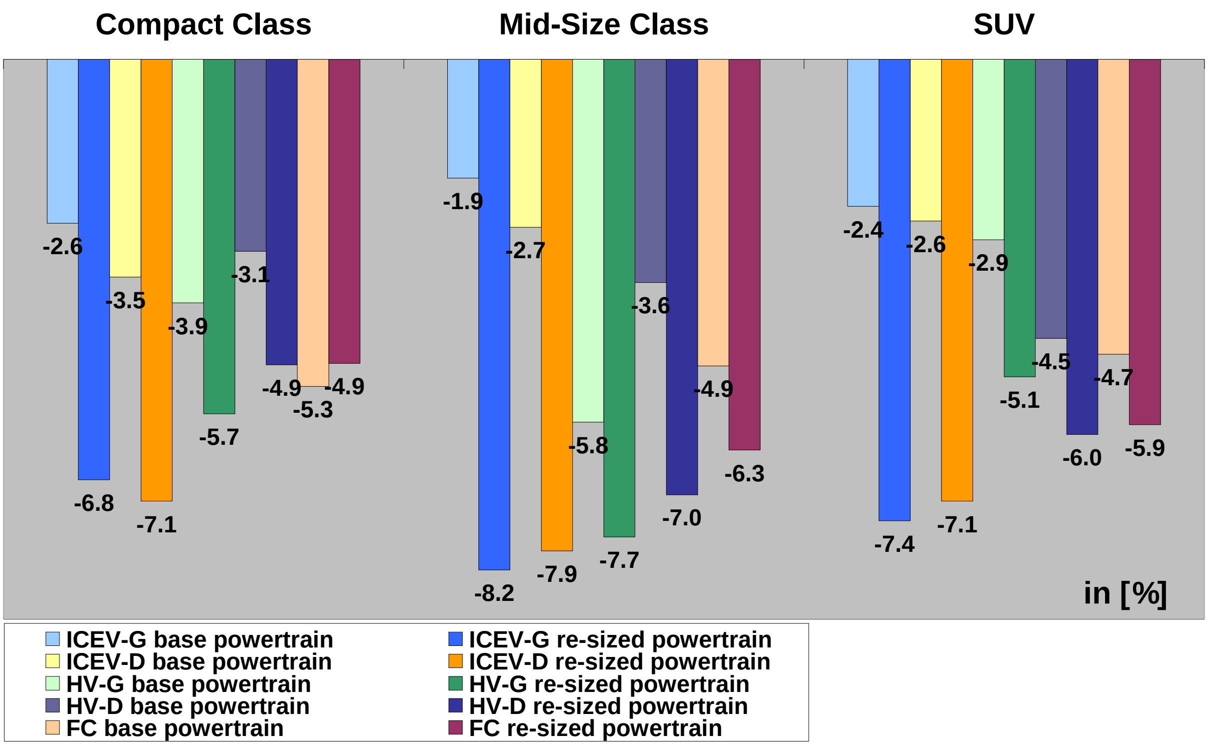

Fig. 5-4: Influence of 10 % weight reduction on fuel consumption in NEDC

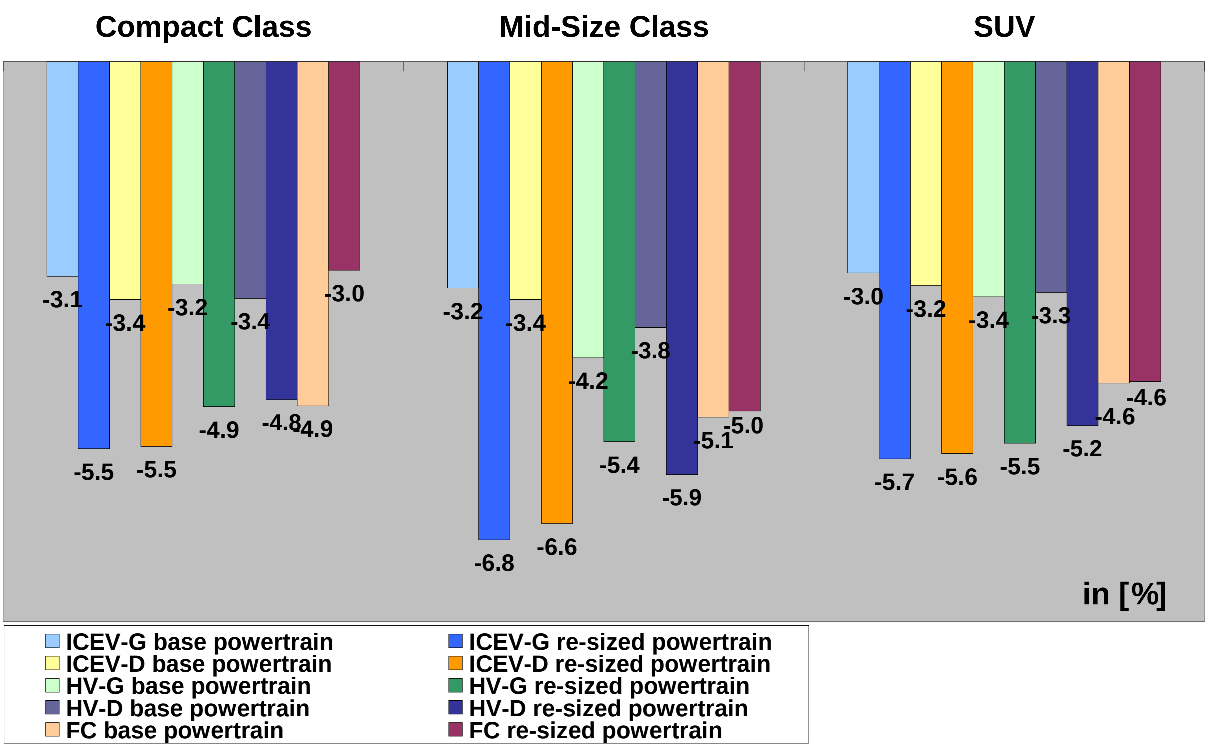

Fig. 5-5: Influence of 10 % weight reduction on fuel consumption in HYZEM

5.3.1 Influence of Powertrain Re-Sizing

The results of the simulations in appendix 5-43 show that for conventional cars with gasoline engine (ICEV-G) the influence of powertrain re-sizing on the consumption reduction in the HYZEM driving cycle is about as important as the weight reduction. In the NEDC the fuel benefit by powertrain re-sizing is more than twice as big as the weight influence because of the low load profile in this cycle (see appendix 5-42). In conventional cars with Diesel engine (ICE-D) the powertrain re-sizing is slightly less effective due to the higher part load efficiency which results from the lack of throttling losses.

For the hybrid vehicles (HV-G and HV-D) the effect of powertrain re-sizing is much smaller. This is due to the avoidance of lower part load operating points of the combustion engine by means of pure electric propulsion and regenerative load. In contrast the influence of a simple weight reduction to the absolute consumption reduction compared to ICEV is ambivalent (see appendix 5-46 – 5-49). On the one hand the HV generally offers a higher tank to wheel efficiency. That means that in the HV less fuel is necessary to provide a fixed amount of energy for propulsion. As a result the corresponding reductions of driving energy for the ICEV and the HV caused by the weight savings lead to less absolute consumption reduction in the HV. On the other hand the efficiency of the ICEV becomes worth by lowering the load level at same engine speed whereas the HV efficiency remains relatively constant due to an consumption-optimised adaptation of the engine operating points to the lower load profile or rather an extension of pure electric propulsion.

For the fuel cell powertrain the powertrain re-sizing can even have a negative impact on the fuel savings. But the tendency changes with the vehicle categories and the driving cycle. The reason for this is that contrary to an ICE powertrain the efficiency of the fuel cell powertrain reaches a maximum at loads of 15 to 30 %, while the efficiency decreases at very low loads and at high loads. The differences between the characteristics are depicted in Fig. 5-6.

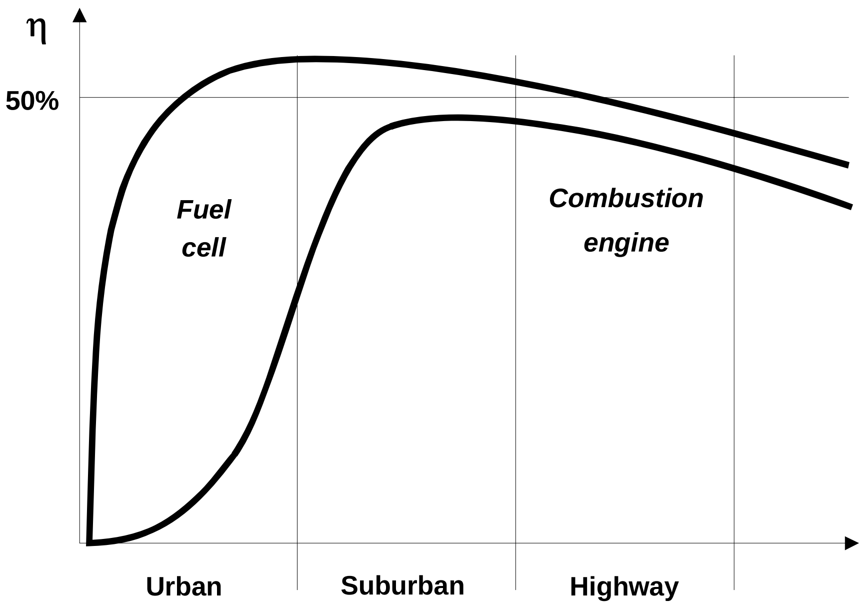

Fig. 5-6: Comparison of the efficiencies of ICE and fuel cell powertrains at different loads

The characteristics of fuel cell powertrains lead to the changing tendency of the fuel consumption reduction when re-sizing the powertrain system. In some cases a bigger system (base powertrain) leads to a lower fuel consumption, because with constant power demands of the driving cycle, the percentage load on the system decreases if the system maximum power is increased.

In the NEDC the middle-sized car and the SUV show a higher fuel consumption with the bigger system. Here the higher losses and therefore low efficiency at very low loads of the bigger fuel cell systems are determining and can not be compensated by the better efficiencies at higher loads, because the power demand of the NEDC cycle is very low. Only the compact class vehicle benefits of the bigger system and has a lower fuel consumption with the bigger system. The reason for the different tendency of the compact class vehicle is the lower power to weight ratio, which was sized according to the acceleration demands for this class, which is lower than for a middle-sized car or a SUV. The fuel savings of the compact class vehicle with reduced weight are a little bit lower with the bigger system (base engine) than with the re-sized system in the NEDC, where the power demand in not very high.

In driving cycles with very high power requirements, bigger fuel cell systems have an advantage, since the efficiency of a fuel cell system is lower at high power outputs than at middle and low power outputs. Thus in the HYZEM cycle there is almost no difference between the two fuel cell systems for the middle-sized car and the SUV, since even after the re-sizing the systems are still very powerful. But in the compact class a difference between the two powertrain sizes can clearly be seen. The compact class vehicles consumes more fuel with the smaller (re-sized powertrain) fuel cell system. The re-sized powertrain is operated at its maximum power output many times during the driving cycle, where the efficiency drops down a lot, thus the consumption increases and the fuel consumption reduction with 10 % of weight reduction is lower (see Fig. 5-5).

5.3.2 Influence of the Vehicle Class

The dependency of the absolute consumption reduction on the different vehicle segments, compact class, middle class and SUV, is mainly influenced by the different characteristic weights and motorisations (see appendix 5-27). As expected, the highest absolute consumption improvement is achieved in the heaviest vehicle segment, with the most powerful engine, the SUV. In contrast the lowest reduction is reached in the smallest considered vehicle segment, the compact class (see appendix 5-42/43). An exception for the HV-G is the relation between the consumption reduction of the middle class and the SUV in the NEDC. Contrary to expectations the consumption improvement is lower for the SUV (see appendix 5-46). This can be due to the non-linear system behaviour of the hybrid powertrain, which results from the changeover between pure electric propulsion, pure combustion-engine powered driving, parallel driving mode etc. In this particular case the adaptation of the energy management of the hybrid SUV is not fitted as well to the NEDC as the energy management of the middle class. In contrast the consumption reduction of the hybrid SUV in the HYZEM driving cycle is evidently higher than in the other segments, as expected (see appendix 5-47).

5.3.3 Influence of the Powertrain Technology

The influence of advanced powertrains on the consumption improvement by weight reduction is analysed in a comparison of two conventional powertrain set-up with a gasoline or a Diesel engine (ICEV-G and ICEV-D), two parallel dual clutch hybrid system with an electric motor between the engine and the transmission, one with gasoline engine (HV-G) and one with Diesel engine (HV-D) and a fuel cell vehicle (FCV) with an additional battery. The results of the simulation study show that the absolute consumption improvement by weight saving including powertrain re-sizing becomes smaller in the contemplated advanced powertrain set-ups, HV and FCV. The smallest reduction is achieved with the FCV, whereas the highest fuel savings appear in the ICEV in particular in the ICEV-G due to the strong influence of powertrain re-sizing (see appendix 5-53/54). Regarding the percentage changes of the fuel consumption in appendix 5-34/36, the differences between the different powertrain technologies are much smaller as a result of the inherent base consumptions which are very low for the FCV and relative high for the ICEV.

5.3.4 Influence of the Driving Cycle

The influence of different load profiles on the fuel consumption improvement by weight saving is analysed by means of the standard driving cycle NEDC and the more dynamic driving cycle HYZEM. The absolute consumption reduction by weight reduction including powertrain re-sizing is smaller in the HYZEM due to the higher engine base efficiency which is a result of the higher load profile in this cycle. Besides the difference between the ICEV and the HV in the total fuel consumption is much less in the HYZEM than in the NEDC. This is due to the high power requirement which means that the engine also runs in the range of low specific fuel consumption in the ICEV whereas the advantage for the HV by a consumption-optimised choice of the engine operating range becomes less important and the additional weight compared to the ICEV is disadvantageous. The effect of powertrain re-sizing is also much less in the HYZEM as a result of the extensive avoidance of lower part load operating due to the high power requirement. In contrast the vehicle weight is more important for the fuel consumption in the HYZEM (see appendix 5-35/37). This is a result of the more dynamic run of the cycle which means that the mass dependent acceleration resistance takes a bigger share of the total resistance.

5.3.5 Conclusions

The results of the simulation study have shown that for conventional powertrains the effect of powertrain re-sizing has a bigger influence on the consumption reduction than the mass reduction itself, especially in the NEDC. The absolute consumption improvement by weight saving including powertrain re-sizing becomes smaller in the contemplated advanced powertrain set-ups, HV and FCV.

Furthermore the WEV have been calculated by means of the simulation results (see appendix 5-59). In general the WEV with powertrain re-sizing in the NEDC are higher than in the HYZEM cycle. This is due to the bigger share of part load operating points in the NEDC which can be reduced effectively by powertrain re-sizing. With the change from conventional to alternative powertrains, the WEV with powertrain re-sizing decrease. This is due to the smaller impact of the mass in alternative powertrains which means much less absolute consumption reduction for HV and FCV at same weight reduction. Without powertrain re-sizing the WEV in HV are bigger than in ICEV which is not due to a higher absolute consumption reduction, but to a lower base consumption and the higher absolute weight of the HV. In general the significance of the WEV alone is not sufficient for an assessment of the mass impact in different powertrain technologies. For this purpose the absolute consumptions at different masses are important.

6 Summary

For the investigation of the relationship between mass reduction and fuel consumption a simulation study was conducted. In a first step the perception of the public was established by surveying published literature. The determination of the weight reduction was done by calculating the primary weight saving at the body-in-white and the secondary weight savings at further vehicle components. In addition an powertrain re-sizing due to the lower vehicle weight was performed. In the simulation step the three different vehicle types compact class vehicle, mid-size class vehicle and sport utility vehicle were analysed. All of them were combined with the five different propulsion systems gasoline engine, Diesel engine, gasoline hybrid system, Diesel hybrid system and fuel cell system. The simulations were done with considering two common driving cycles, the New European Driving Cycle (NEDC) and the HYZEM cycle.

The literature survey delivers some suitable results for internal combustion engine vehicles (ICEV). The result values are in a range of 4.5 % to 6 % fuel consumption reduction per 10 % weight saving and 0.15 l/100 km to 0.7 l/100 km fuel consumption reduction per 100 kg weight saving respectively. These results include papers of the automobile, steel and aluminium industry. Unfortunately at most of the literature sources the boundary conditions of measurements or statements are not always clearly defined. One very valuable source was found in [WAL00]. Concerning hybrid and fuel cell vehicles very less results were found.

For the vehicle weight reduction primary and secondary weight saving effects were considered. The simulations were conducted for vehicles with the base weight, for vehicles with the reduced weight and for vehicles with reduces weight and re-sized powertrain. All simulations are done for three vehicles classes, five propulsion systems and two driving cycles. As a software the widely spread tool Matlab/Simulink® was used.

All results were compared and conclusions were drawn. It was found that at a 10 % mass reduction without powertrain re-sizing saves fuel between 1.9 % and 3.2 % in conventional vehicles with gasoline engine and between 2.6 % and 3.4 % with Diesel engine when considering both driving cycles. When considering the powertrain re-sizing at ICE vehicles this effect has a bigger influence than the mass reduction itself, especially in the NEDC cycle. Furthermore the powertrain re-sizing (in combination with mass reduction) has less effect in hybrid powertrains due to the reduced impact of idling losses and avoidance of low efficiency operating points. It was established that the ICE vehicles are more mass sensitive than hybrids and FC vehicles when considering powertrain re-sizing, but less mass sensitive without considering powertrain re-sizing. But all in all it is important that, when talking about weight sensitivity the used boundary conditions have to be strongly considered, because the results are influenced by many parameters.

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8 Appendix

Content

Appendix for
Chapter 3:
Literature Research

Chapter 3: Literature Research
Weight Elasticity Value (WEV)

fka

- Necessary input data:
  - Curb weight (e.g. 1500 kg)
  - Fuel consumption (e.g. 10.4 l / 100km)
  - Mass reduction (e.g. 100 kg = 6.7 %)
  - Fuel consumption reduction (e.g. 0.3 l / 100 km = 2.9 %)

$$\text{fuel cons. reduction [\%]} = \frac{\text{abs. fuel cons. reduction [l]}}{\text{fuel consumption [l]}} = \frac{0.3\ \text{l}}{10.4\ \text{l}} = 2.9\ \%$$

$$\text{mass reduction [\%]} = \frac{\text{abs. mass reduction [kg]}}{\text{curb weight [kg]}} = \frac{100\ \text{kg}}{1500\ \text{kg}} = 6.7\ \%$$

$$\text{WEV} = \frac{\text{fuel cons. reduction [\%]}}{\text{mass reduction [\%]}} \qquad \text{e.g. WEV} = \frac{2.9\ \%}{6.7\ \%} = 0.43$$

Chapter 3: Literature Research
Available Data for ICEV (1)

fka

		Curb Weight [kg][1]	Fuel Consumption	Weight Savings (absolute) / kg		Reduction of Fuel Consumption (absolute) / litre	
Wallentowitz, H.; e.a.	Untersuchungen d. Zusammenhangs zw. Pkw-Gewicht u. Kraftstoffverbrauch (2000)	X *	X *	100	X *	X *	X *
Volkhausen, W.	Methodische Beschreibung und Bewertung der umweltgerechten Gestaltung von Stahlwerkstoffen und Stahlerzeugnissen (2003)	X *	X *	100	X *	X *	X *
Schmidt, W.P.; e.a. “EUCAR-Source”	Life Cycle Assessment of Lightweight and End-of-Life Scenarios for Generic Compact Class Passenger Vehicles (2004)	1000	8.1 l/100km	100	10 %	0.38	4.7 % **
Freitag, H.	A-Klasse und Polo setzen auf Leichtbau (2002)	-	-	100	-	0.4	-
Schäper, S.	Ganzheitliche Betrachtung im Automobilbau (1996)	-	-	100	-	0.5	-

1) weight of the complete vehicle including filled tank (90%) and 75 kg for driver and baggage

* manifold data

** calculated value

Chapter 3: Literature Research Available Data for ICEV (2)

fka

		Curb Weight[1]	Fuel Consumption	Weight Savings (absolute) / kg		Reduction of Fuel Consumption (absolute) / litre	
Piech, F.	3 Liter / 100km im Jahr 2000? (1992)	chart	chart	100	chart	0.6	chart
Stockmar, J.	Leichtbau - Eine besondere Herausforderung für die Großserie (1996)	chart	chart	100	chart	0.15 / 0.4 ***	chart
---	Keine Monokultur (2001)	-	-	100	-	0.3 - 0.4	-
Bauer, D.	Vor- und Nachteile von Aluminium als Karosseriewerkstoff (1998)	-	-	100	-	0.6 - 0.7	-
Rau, G.	Aluminium- und Eisenwerk-stoffe im Vergleich (1999)	-	-	100	-	0.5 - 0.7	-
Thorwald, E.	Und es bewegt sich doch (1999)	-	-	-	10 %	-	4.5 %
Ruckstuhl, B.	Kostengünstiger Leichtbau im System Konstruktion, Werkstoff und Fertigungstechnik (1999)	-	-	-	10 %	-	6 %

1) weight of the complete vehicle including filled tank (90%) and 75 kg for driver and baggage

*** wo/w secondary weightsavings

Chapter 3: Literature Research
Available Data for ICEV (3)

fka

		Curb Weight[1]	Fuel Consumption	Weight Savings (absolute) / kg		Reduction of Fuel Consumption (absolute) / litre	
Gebhard, P.	Gesamtfahrzeugparameter und die Auswirkungen auf Fahrleistung und Verbrauch	-	-	100	-	0.5	-
Springe, G.	Durchbruch der Aluminium-Anwendung beim Bau von Automobil-Karosserien (2000)	-	-	100	-	0.6 - 0.7	-
Furrer, P.	Aluminium Karosseriebleche (2001)	-	-	100	-	0.3 - 0.4	-
Ridge, L.	EUCAR – Automotive LCA Guidelines – Phase 2 (1998)	-	-	100	-	0.02 - 0.60	-
Das, S.	The Life-Cycle Impacts of Aluminium Body-in-White Automotive Material (2000)	-	-	-	10 %	-	5 %

1) weight of the complete vehicle including filled tank (90%) and 75 kg for driver and baggage

Chapter 3: Literature Research
Available Data for ICEV (4)

fka

Dick, M.	Der 3-Liter Lupo - Technologien für den minimalen Verbrauch (1999)	Possible ways of fuel consumption reduction
Automobil Entwicklung	Ein Kilogramm kostet einen Euro (2002)	Possible use of different materials for lightweight construction purposes; costs of weight reduction process (Opel)
Engelhart, D.	Die Entwicklung des Audi A2, ein neues Fahrzeugkonzept in der Kompaktwagenklasse (1999)	Development of fuel consumption
Hellmann, K. H.	Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2004 (2004)	Fuel consumption of light trucks (up to 8000 lbs.)
Feng, A.	Assessing the Fuel Economy Potential of Light-Duty Vehicles (2001)	Simulation of advantages through advanced engine and transmission, lightweight materials, integrated starter-generator, and hybrid drive for five car classes
Sovran, G.	A Contribution to Understanding Automotive Fuel Economy and Its Limits (2003)	Basic physics of automotive fuel consumption for conventional and unconventional powertrains

Sources contains no suitable values for purposes of this project

Chapter 3: Literature Research
Available Data for ICEV (5)

fka

Schweimer, G.; e.a.	Life Cycle Inventory for the Golf A4 (2000)	Life cycle analysis with series vehicles of Volkswagen; no relationship between weight reduction and fuel consumption reduction mentioned

Louis, S.	Life Cycle Assessment and Design-Experience from Volvo Car Corporation; SAE 980473 *
---	Life Cycle Analysis – Data and Methodologies Phase 2; EUCAR Final Report *
Kaniut, C.	Life Cycle Assessment of a Complete Car – The Mercedes-Benz Approach; SAE Paper 971166 *
LeBorgne, R.	Life Cycle Analysis: a European Automotive Experience *
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* not considered for purposes of this project, because no more new results expected; partly old documents

Chapter 3: Literature Research
Detailed Results for ICEV (selected)

fka

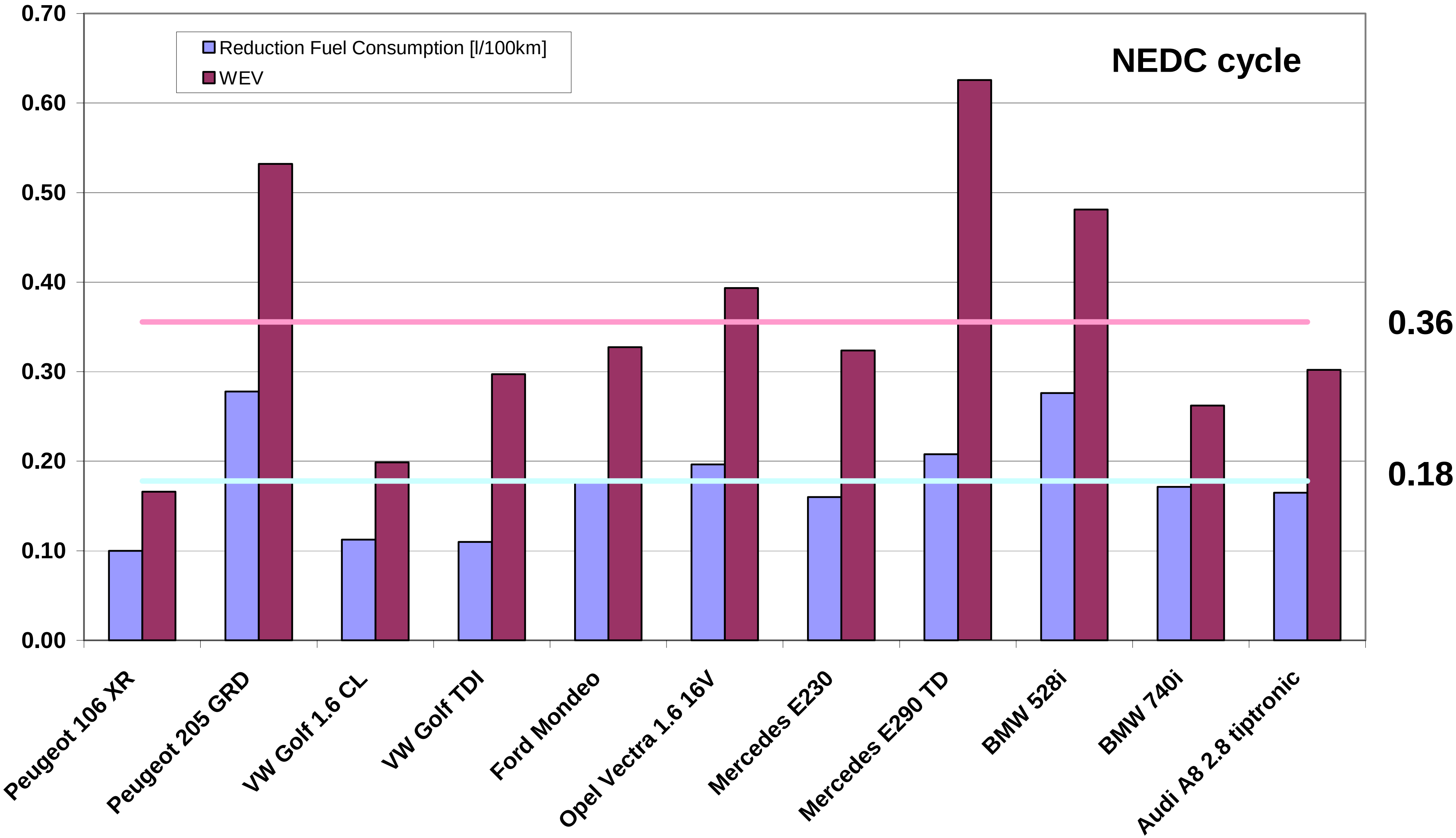
Source [WAL00]: H. Wallentowitz; e.a.
“Untersuchungen des Zusammenhangs zwischen Pkw-Gewicht und Kraftstoffverbrauch – Messungen an 11 Fahrzeugen auf dem dynamischen Rollenprüfstand”, Research Report P374 of Studiengesellschaft Stahlanwendung e.V., 2000

- Examination of 11 different vehicles (gasoline- and diesel-powered) on a dynamic roller testbench
- Consideration of 10 different driving cycles
- Weight reduction of 100 kg without secondary effects
- Determination of reduction in fuel consumption
- Results:
  - Reduction in fuel consumption of 0.02 to 0.47 l/100km (all driving cycles)
  - Reduction in fuel consumption 0.10 to 0.28 l/100km (only NEDC cycle)

Chapter 3: Literature Research
Detailed Results for ICEV (selected)

fka

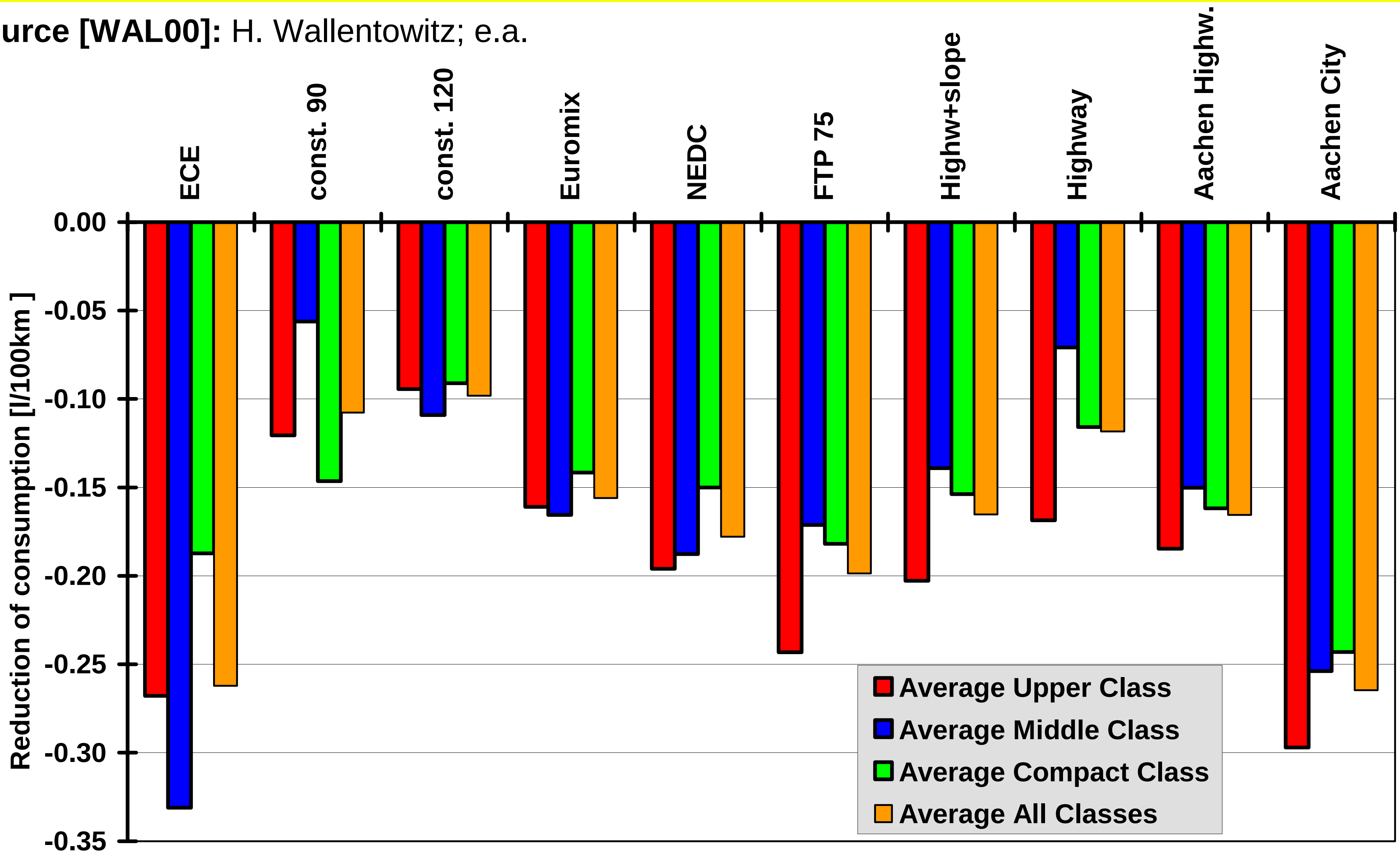
Source [WAL00]: H. Wallentowitz; e.a. - Range of possible fuel savings for 11 vehicles (NEDC only)



Chapter 3: Literature Research
Detailed Results for ICEV (selected)

fka

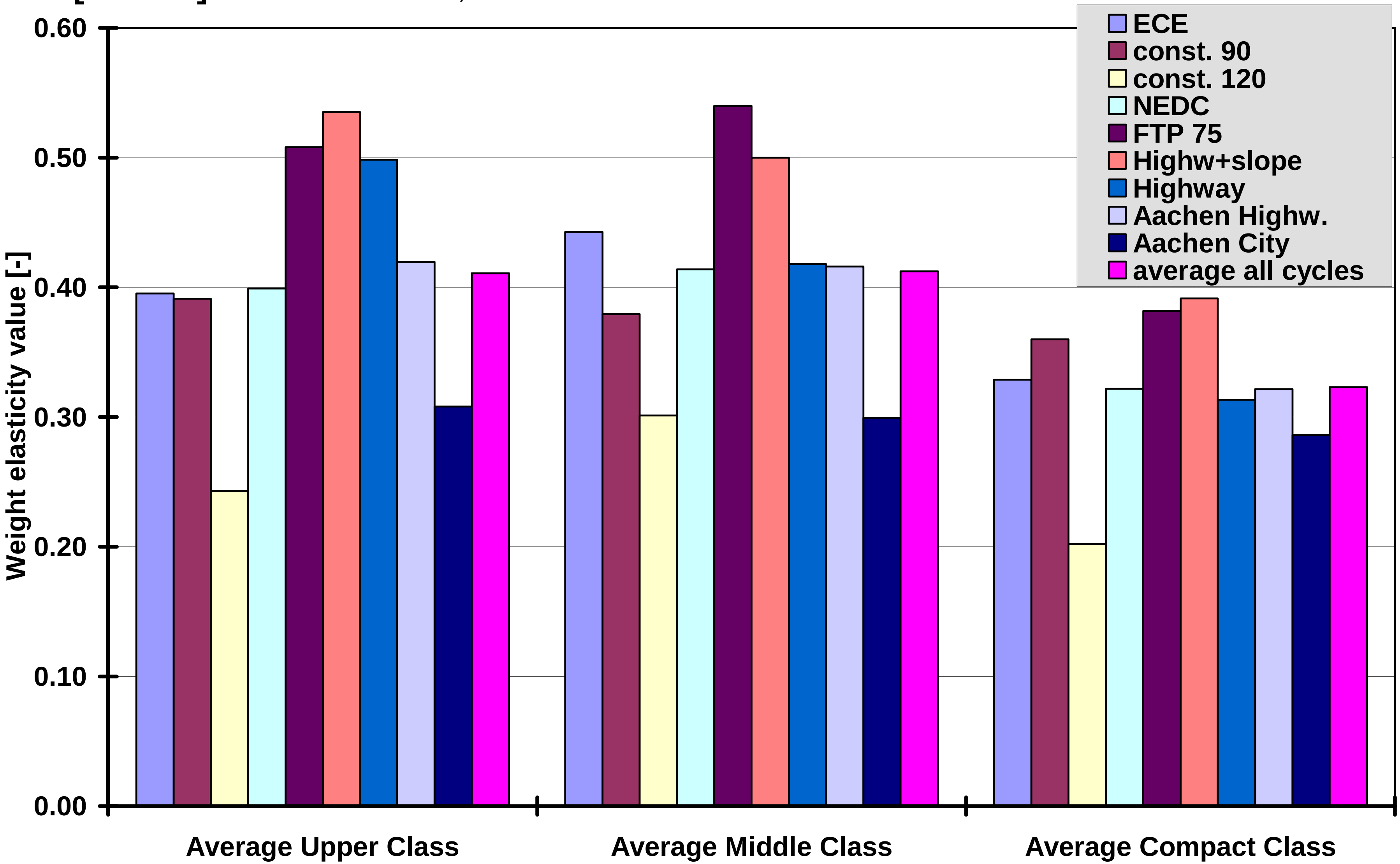
Source [WAL00]: H. Wallentowitz; e.a.



Chapter 3: Literature Research
Detailed Results for ICEV (selected)

fka

Source [WAL00]: H. Wallentowitz; e.a.



Chapter 3: Literature Research
Detailed Results for ICEV (selected)

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Source [RID98]: L. Ridge
"EUCAR – Automotive LCA Guidelines – Phase 2"; SAE Paper 982185, 1998

Fuel reduction values [litres/(100kg * 100km)] for passenger cars with different engine types:

Engine Type	without gear ratio change		with gear ratio change	
	Average (Median)	Range	Average (Median)	Range
Gasoline	0,14	0,02 ... 0,50	0,38	0,19 ... 0,60
Diesel	0,12	0,10 ... 0,35	0,29	0,26 ... 0,37

- Results from a EUCAR survey: low data - as a rule - do not include any change of gear/ axle ratio in connection with a mass reduction, while higher data include these and additional measurements to keep the previous vehicle performance in combination with a lower fuel consumption
- Average: 0.38, nevertheless the paper suggests to set an average for the FRV to 0.6 for automotive LCA studies
- Quote from paper: "Further controlled practical tests to accepted test parameters are necessary to qualify this position."

Chapter 3: Literature Research
Summary of ICEV Results

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- Several literature sources deliver general information about the correlation of weight reduction and fuel reduction
- Found results are in a range of 0.3 to 0.7 l/100 km per 100 kg weight reduction or
  in a range of 4.5 % to 6 % fuel reduction per 10 % weight reduction (papers of aluminium industry included)
- Found results provide less information about used boundary conditions
- Extensive study of ika was conducted – result values are up to 0.47 l/100 km per 100 kg weight reduction (average of all is 0.18)

Chapter 3: Literature Research Results for HV

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Weiss, Heywood, Drake et al.	On The Road In 2020	Evaluation of possible new passenger cars, developed and sold in 2020;
General Motors Corp. et al.	Well-to-Wheel Energy Use and Greenhouse Gas Emission of Advanced Fuel/Vehicle Systems - North American Analysis	Analysis of 15 conventional and hybridized vehicles in three parts: well-to-tank, tank-to-wheel, well-to-wheel;
Graham, R., et al.	Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options	Evaluation of different hybrid vehicles (with ADVISOR and others), hybrid vehicles with different masses, but also with different powertrain layouts presented
An, F., and D. Santini.	Assessing Tank-to-Wheel Efficiencies of Advanced Technology Vehicles	Comparison of 4 studies assessing advanced vehicle technologies according to glider and powertrain masses, fuel energy use,
An, F., A. Vyas, J. Anderson, and D. Santini	Evaluating Commercial and Prototype HEVs	Comparison of 5 commercial or prototype hybrids according to fuel benefits and performance
Hermance, D.	New Efficiency Baseline 2004 Toyota Prius	Presentation of the Toyota Prius
An, F., and Santini, D.	Mass Impacts on Fuel Economies of Conventional vs. Hybrid Electric Vehicles	The shift from conventional to hybrid powertrain can provide significant improvements in fuel economy with little or no change in mass; Once the switch to hybrid powertrains has been made, the effectiveness of mass reduction in improving fuel economy decreases

Chapter 3: Literature Research Results for HV (selected)

Source: SAE Paper 2004-01-0572: An/Santini: „Mass Impacts on Fuel Economies of Conventional vs. Hybrid Electric Vehicles“

- An/Santini present correlations between fuel economies and vehicle mass for production HEV with different levels of hybridisation and examine how this relationship evolves from CV to HEV
- A very simplified method using the tractive work formula and drive
- Comparison of different CV and HEV vehicles according to mass shows little influence of hybridisation on vehicle mass (not the same body type for CV and HEV!)
- Shifting from CV to HEV can bring significant improvements in fuel economy with little or no change in mass
- Effectiveness of mass reduction in improving fuel economy will be reduced once the switch from CV to HEV has been made
- When changing vehicle mass for examination of fuel consumption, the engine is downsized, too, <u>so consumption reduction is partly due to downsizing of the engine</u>

Chapter 3: Literature Research
Results for HV (selected)

fka

Source: SAE Paper 2004-01-0572: An/Santini: „Mass Impacts on …"

Table 10 – Mass Elasticity on MPGs for a Midsize Prius-like CV, FWD and 4WD FHVs, CAFE Cycle.

Prius	MPG			Elasticity		
Mass (lb.)	CVs	FWD FHV	4WD FHV	CVs	FWD FHV	4WD FHV
-10%	42.6	69.5	77.1	-8.8%	-7.3%	-6.7%
2890	**39.2**	**64.7**	**72.2**			
+10%	36.2	60.6	67.9	-7.6%	-6.4%	-5.9%
Average				-8.2%	-6.9%	-6.3%

Table 11 – Mass Elasticity on MPGs for a small SUV Escape-like CV, FWD and 4WD FHVs, CAFE Cycle.

Escape	MPG			Elasticity		
Mass (lb.)	CVs	FWD FHV	4WD FHV	CVs	FWD FHV	4WD FHV
-10%	25.3	44.4	47.8	-8.4%	-7.1%	-6.7%
3875	**23.3**	**41.4**	**44.8**			
+10%	21.6	38.8	42.1	-7.2%	-6.3%	-5.9%
Average				7.8%	6.7%	6.3%

Calculation of WEVs from the paper:

Prius	l/100km			Weight Elasticity Value		
Mass [kg]	CVs	FWD FHV	4WD FHV	CVs	FWD FHV	4WD FHV
-10%	5.53	3.39	3.05	0.80	0.69	0.64
1311	6.01	3.64	3.26			
+10%	6.51	3.89	3.47	0.83	0.69	0.64
Average				0.82	0.69	0.64

Escape	l/100km			Weight Elasticity Value		
Mass [kg]	CVs	FWD FHV	4WD FHV	CVs	FWD FHV	4WD FHV
-10%	9.31	5.3	4.93	0.79	0.69	0.63
1758	10.11	5.69	5.26			
+10%	10.9	6.07	5.59	0.78	0.67	0.63
Average				0.79	0.68	0.63

1 lb = 0.453592 kg;   1 MPG = 235.5 l/100km

Chapter 3: Literature Research Results for FCV

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Journal (J)/ Book (B)	Title	Year	
SAE SP-1691	Fuel Cell Power for Transportation 2002	2002	sifted trough 18 papers - nothing specific to mass impact
SAE SP-1635	Fuel Cells and Alternative Fuels/ Energy Systems	2001	sifted trough 14 papers - nothing specific to mass impact
SAE SP-1790	Fuel Cells: Technology, Alternative Fuels, and Fuel Processing	2003	sifted trough 7 papers- nothing specific to mass impact
SAE SP-1741	Fuel Cell Power for Transportation 2003	2003	sifted trough 31 papers - nothing specific to mass impact
SAE SP-1589	Fuel Cell Power for Transportation 2001	2001	sifted trough 16 papers - nothing specific to mass impact
SAE PT-84	Fuel Cell Technology for Vehicles	2001	sifted trough 30 papers - nothing specific to mass impact

and many other papers sifted

Chapter 3: Literature Research
Summary of FCV

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- All available search engines used
- No specific papers/articles found on mass impact on fuel cell vehicles
- Very many papers/articles on fuel cell technology are internally available and have been scanned (e.g. more than 100 SAE papers)
- Impact of mass changes was investigated in an fka simulation study for an OEM, report and results are confidential, but mass impact was investigated and the WEVs for a methanol fuel cell vehicle resulted to 0.46 for the NEDC and 0.35 for the HYZEM driving cycle

Appendix for Chapter 4: Fundamentals

Chapter 4: Fundamentals
Powertrain Losses (ICEV)

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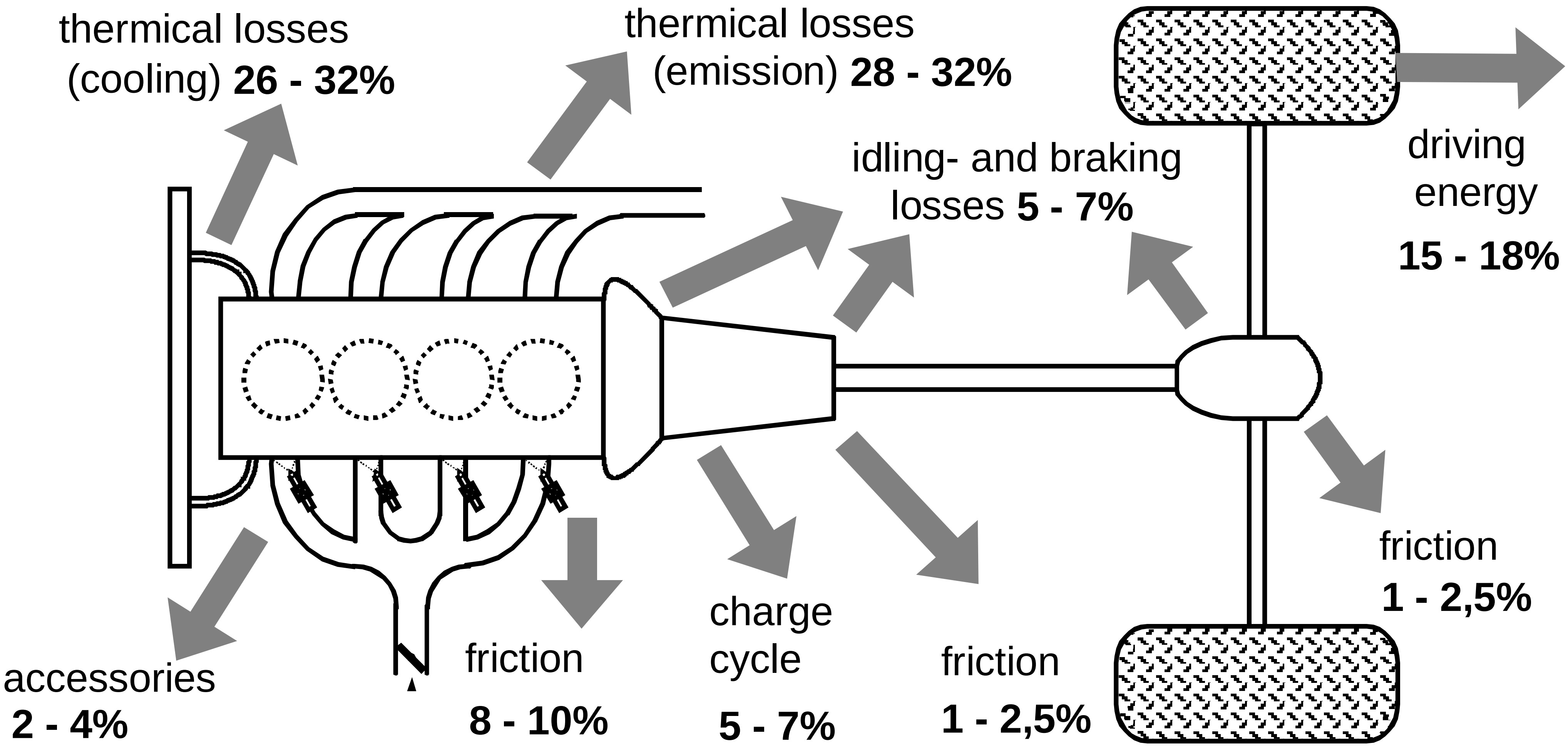

Chapter 4: Fundamentals
Examples of Current Parallel Hybrid Systems

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The fuel consumptions of parallel hybrids are similar to power split hybrid systems!

→ paper…

"Parallel, kombiniert oder leistungsverzweigt?
Ein simulationsgestützter Konzeptvergleich!"
Christian Renner, fka

published at "Tag des Hybrids" 4th October 2005 in Aachen

Golf Eco.Power (2004)

Diesel 77 kW; EM 15 kW; 3.8 l/100km

Honda Civic IMA (2003)

Otto 61 kW; EM 6.5 kW; 4,9 l/100km

ika-Inmove (2001)

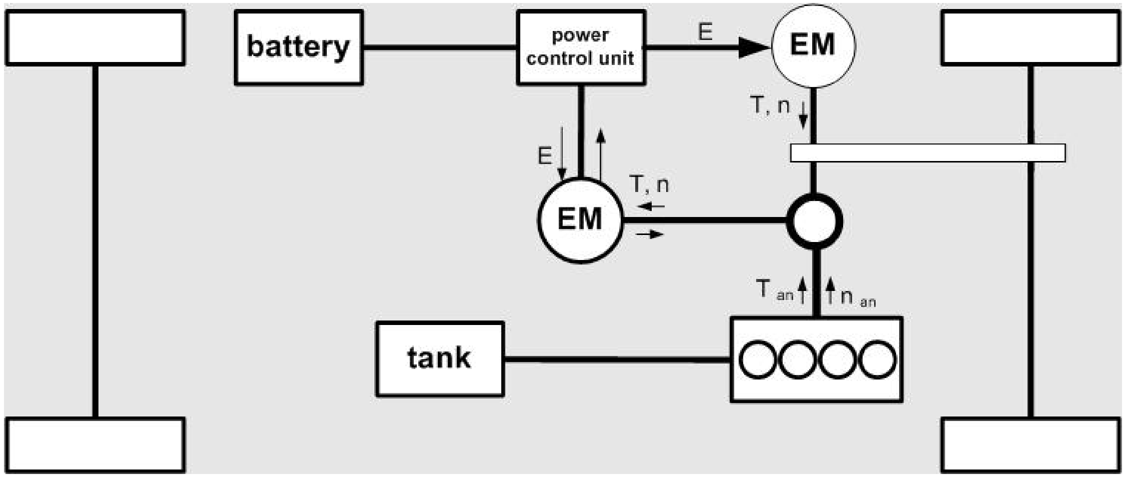
Otto 55 kW; EM 25 kW; 6.2 l/100km

Chapter 4: Fundamentals
Different Hybrid System: Toyota Prius THS II (2004)

fka

- Engine:
  - 1.5 l gasoline engine, 4 cylinder
  - 57 kW @ 5000 rpm
  - 115 Nm @ 4200 rpm
- Synchronous AC Motor:
  - Maximum output: 50 kW, 1200-1540 rpm
  - Maximum torque: 400 Nm, 0-1200 rpm
- NiMH Battery:
  - 6.5 Ah
  - 202 V

Power Split Hybrid System



Chapter 4: Fundamentals
Different Hybrid System: Toyota Prius THS II

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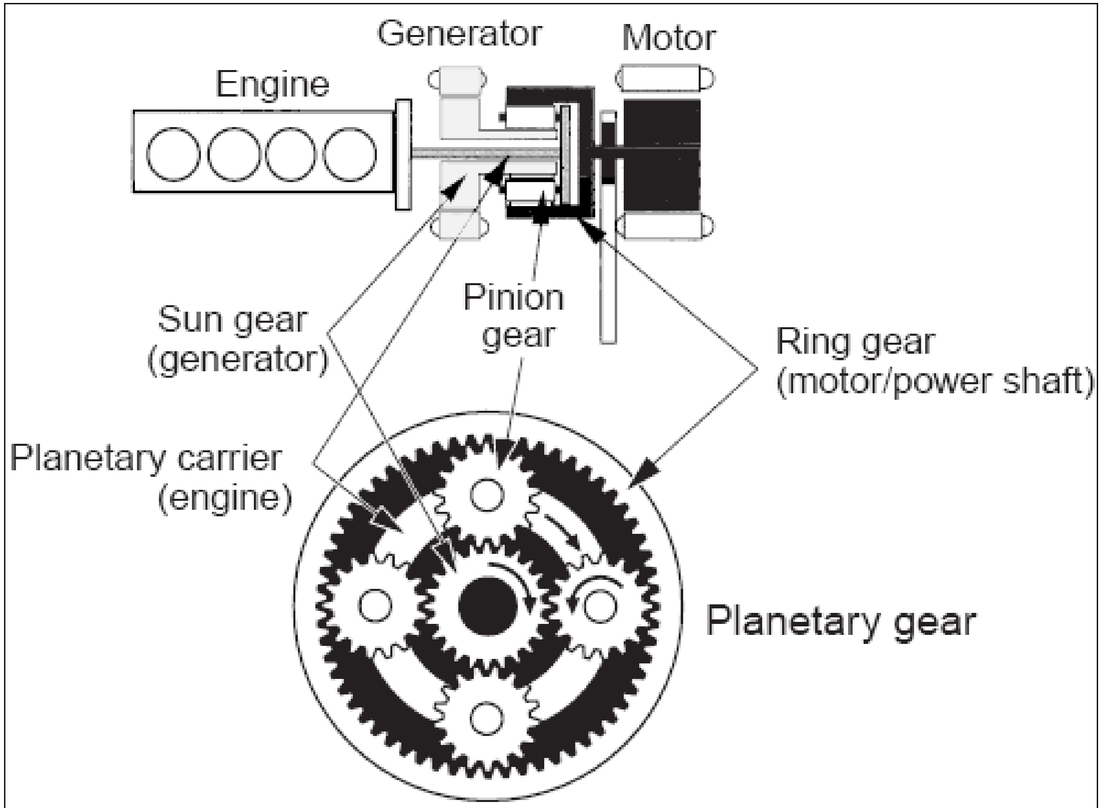
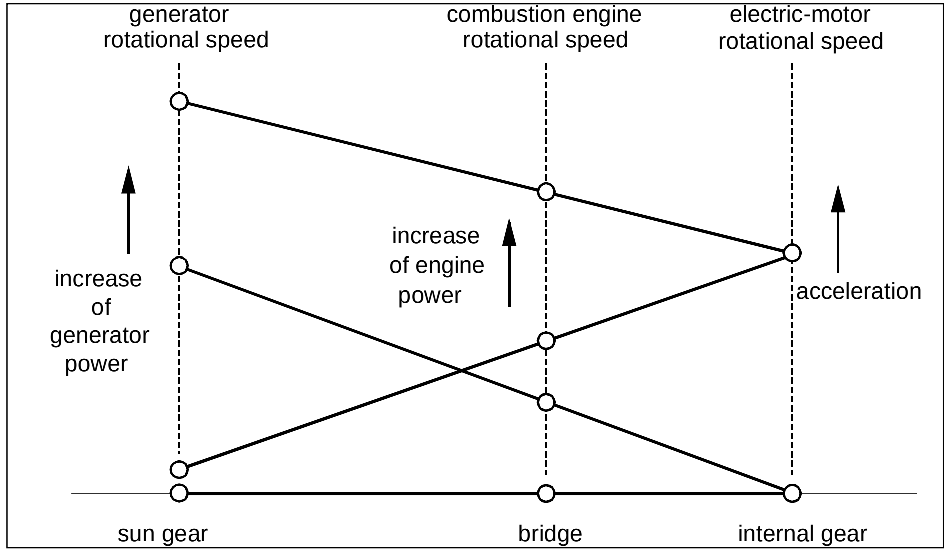
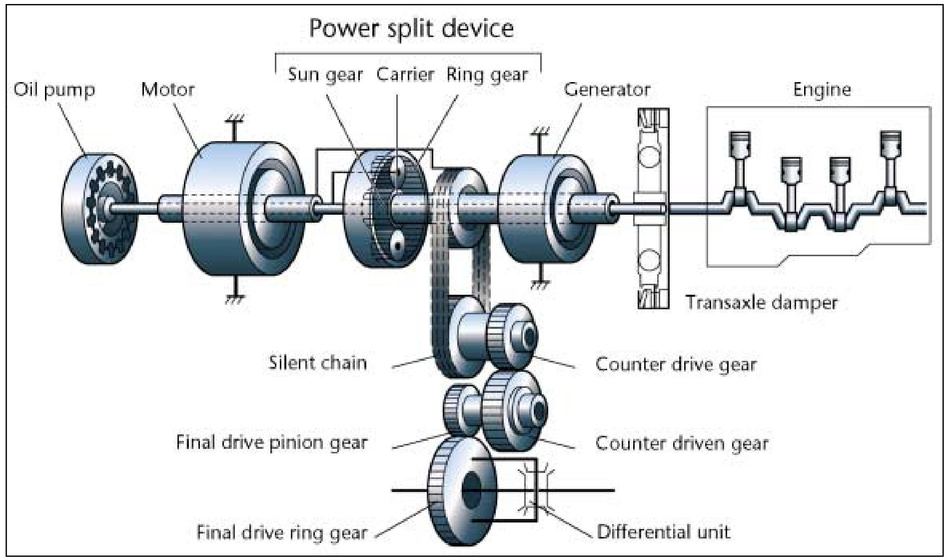
Power Split Device







Appendix for Chapter 5: Simulation

Chapter 5: Simulation – Vehicle Analysis Determination of Weight Reduction (1)

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Aim of weight reduction

- Determination of weight reduction value of body-in-white (body structure with closures, fenders) due to substitution of steel with new high strength steels etc.

Approach

- Determination of vehicle weights and body-in-white (BIW) weights as basic data for:
  - Sport Utility Vehicles (SUV), Compact Class Vehicles and Middle-Size Class Vehicles
- Substitution of steel with new high strength steels, optimised design or substitution with other materials in body-in-white
- All values are calculated with two assumptions (20 % and 40 % reduction of BIW-weight in the primary weight saving step)

Chapter 5: Simulation – Vehicle Analysis
Sport Utility Vehicles (SUV)

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SUV (2000 - 2500 kg)						
OEM	Model	Engine	Capacity [cm^3]	Engine Power [kW / PS]	Curb Weight [kg]	Gross Vehicle Weight Rating [kg]
Porsche	Cayenne	V8	4511	250 / 340	2320	3080
Volkswagen	Touareg	V8	4172	228 / 310	2411	2945
BMW	X5	V8	4398	235 / 320	2195	2700
Volvo	XC90	V8	4414	232 / 315	2171	2650
Mercedes	M-Class	V8	4966	225 / 306	2175	2830
Generic Car	-	8 Cylinder	4500	235 / 320	2195	2840

Chapter 5: Simulation – Vehicle Analysis
Compact Class Vehicles

Compact Class (1200 - 1400 kg)						
OEM	Model	Engine	Capacity [cm^3]	Engine Power [kW / PS]	Curb Weight [kg]	Gross Vehicle Weight Rating [kg]
Volkswagen	Golf V	R4	1598	85 / 115	1271	1770
Opel	Astra	R4	1598	77 / 105	1230	1705
Audi	A3	R4	1598	85 / 115	1225	1785
BMW	1-Series	R4	1596	85 / 115	1280	1705
Ford	Focus	R4	1596	85 / 115	1277	1720
Generic Car	-	4 Cylinder	1600	85 / 115	1260	1740

Chapter 5: Simulation – Vehicle Analysis
Middle-Sized Class Vehicles

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Middle-Sized Class (1500 - 1800 kg)						
OEM	Model	Engine	Capacity [cm^3]	Engine Power [kW / PS]	Curb Weight [kg]	Gross Vehicle Weight Rating [kg]
Audi	A6	V6	3123	188 / 255	1540	2120
Mercedes	E-Class	V6	2996	170 / 231	1650	2175
BMW	5-Series	R6	2996	190 / 258	1565	2050
Volvo	S80	R6 (Bi-Turbo)	2922	200 / 272	1719	2160
Peugeot	607	V6	2946	155 / 211	1719	2144
Generic Car	-	6 Cylinder	3000	181 / 245	1640	2130

Chapter 5: Simulation – Vehicle Analysis Determination of Weight Reduction (2)

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Calculation Process

- Calculating of primary weight saving as 20 % or 40 % of the BIW-weight
- Results are an absolute and a relative value of primary weight saving
- Calculating of secondary weight saving as 30 % of the primary weight saving which is approximately the reduction used at the NSB of ThyssenKrupp Stahl *
- Results are an absolute and a relative value of secondary weight saving

* Source: NSB NewSteelBody – Technische Dokumentation, ThyssenKrupp Stahl

Chapter 5: Simulation – Vehicle Analysis
Procedure for Weight Reduction

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Process

Conventional car → **Primary weight reduction** → **Secondary weight reduction** → **Lightweight car**

Explanation

Conventional car
- **Steel unibody**

Primary weight reduction
- **Constructive measures (e.g. usage of tailored blanks)**
- **Material measures (e.g. high strength steels)**
- **Production process optimisation (e.g. hydroforming)**

Secondary weight reduction
- **Effect on vehicle properties (e.g. driving dynamics)**
- ***Resizing:* Due to less weight smaller components sufficient (engine, drivetrain, chassis)**

Chapter 5: Simulation – Vehicle Analysis
Weight Reduction - Example NSB

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Process

Conventional car

Primary weight reduction

Secondary weight reduction

Lightweight car

Development of weight reduction

basic weight: 1,393 kg

body weight: 317 kg

primary weight reduction: 77 kg

27 %

secondary weight reduction: 21 kg

basic weight: - 7.03 %

body weight: -24.29 %

basic weight: 1,295 kg

body weight: 240 kg

Chapter 5: Simulation – Vehicle Analysis
Weight Reduction Results of Generic Cars

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SUV (2000 - 2500 kg) Generic Car								
	Basic Weights		Weight Reduction					
Range	Curb Weight [kg]	Weight Body Structure with closures [kg]	Primary Weight Saving [kg]	Ratio Prim. WS / Curb Weight [%]	Secondary Weight Saving [kg]	Total Weight Saving [kg]	Reduced Curb Weight [kg]	Ratio Total WS / Curb Weight [%]
Min. WS (-20%)	**2195**	**540**	**108.0**	**4.9**	**32.4**	**140.4**	**2055**	**6.4**
Max. WS (-40%)	**2195**	**540**	**216.0**	**9.8**	**64.8**	**280.8**	**1914**	**12.8**

Compact Class (1200 - 1400 kg) Generic Car								
	Basic Weights		Weight Reduction					
Range	Curb Weight [kg]	Weight Body Structure with closures [kg]	Primary Weight Saving [kg]	Ratio Prim. WS / Curb Weight [%]	Secondary Weight Saving [kg]	Total Weight Saving [kg]	Reduced Curb Weight [kg]	Ratio Total WS / Curb Weight [%]
Min. WS (-20%)	**1260**	**360**	**72.0**	**5.7**	**21.6**	**93.6**	**1166**	**7.4**
Max. WS (-40%)	**1260**	**360**	**144.0**	**11.4**	**43.2**	**187.2**	**1073**	**14.9**

Middle-Sized Class (1500 - 1800 kg) Generic Car								
	Basic Weights		Weight Reduction					
Range	Curb Weight [kg]	Weight Body Structure with closures [kg]	Primary Weight Saving [kg]	Ratio Prim. WS / Curb Weight [%]	Secondary Weight Saving [kg]	Total Weight Saving [kg]	Reduced Curb Weight [kg]	Ratio Total WS / Curb Weight [%]
Min. WS (-20%)	**1640**	**400**	**80.0**	**4.9**	**24.0**	**104.0**	**1536**	**6.3**
Max. WS (-40%)	**1640**	**400**	**160.0**	**9.8**	**48.0**	**208.0**	**1432**	**12.7**

Chapter 5: Simulation – Approach
Driving Resistance Power

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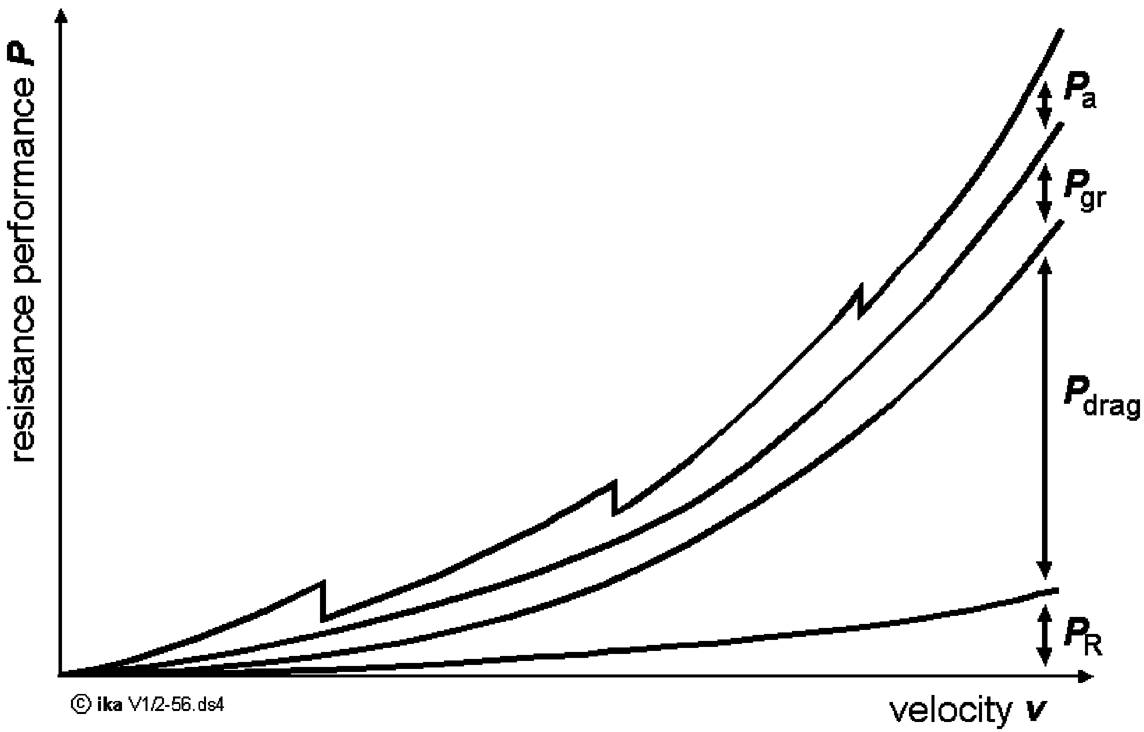
Base equation of vehicle longitudinal dynamic:

$$P_{dem} = \boxed{m} \cdot g \cdot f_R \cdot v + \boxed{m} \cdot g \cdot p \cdot v + \left(e_i \cdot \boxed{m_{veh}} + \boxed{m_{load}}\right) \cdot a \cdot v + c_d \cdot A \cdot \frac{\rho_{air}}{2} \cdot v^3$$



- m: vehicle total weight ($m = m_{veh} + m_{load}$)
- g: acceleration of gravity
- f_R: road resistance factor
- v: vehicle speed
- p: ascending coefficient
- e_i: mass factor
- m_{Veh}: vehicle empty weight
- m_{load}: mass of payload
- a: vehicle acceleration
- c_d: air drag coefficient
- A: vehicle face surface
- ρ_{air}: density of air

source: ika

Chapter 5: Simulation – Approach
Powertrain Losses (Example SUV at NEDC)

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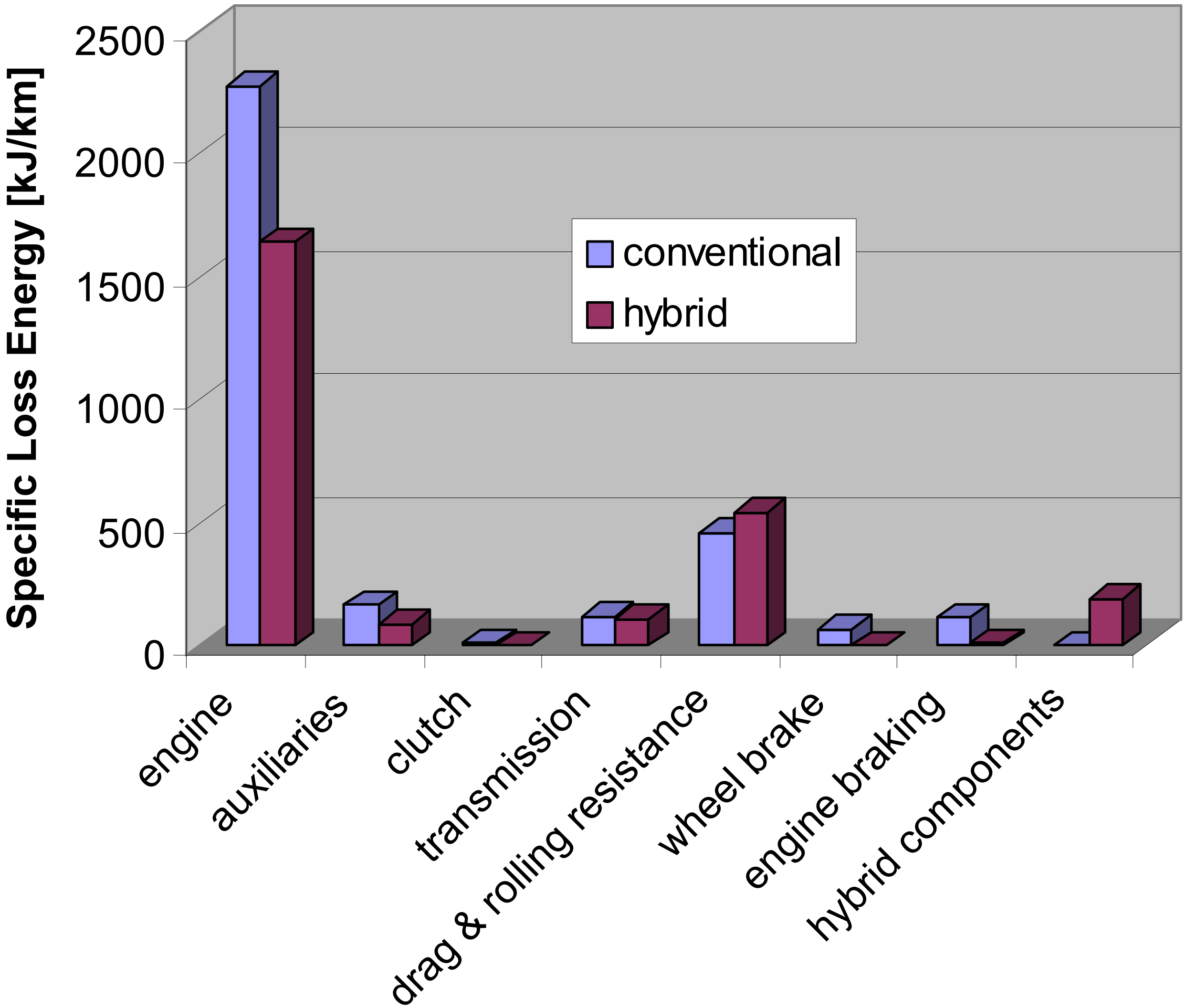

Chapter 5: Simulation – Approach
Longitudinal Vehicle Models in Matlab®/Simulink®

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The used Matlab®/Simulink® models are dynamical models of the powertrains and vehicles, which provide an allocation of the second by second energy flows. The model can be used for

- Prediction of consumption and driving performance
- Comparison of vehicle and powertrain concepts
- Design of the control algorithm
- Transfer of the control strategy by automatic code generation
- Modular architecture of the models
- Modelling according to the principle of cause and effect (Bond Graph Principle)

Chapter 5: Simulation – Approach

MATLAB®/Simulink® - Standard Simulation Tool in the Automotive Industry

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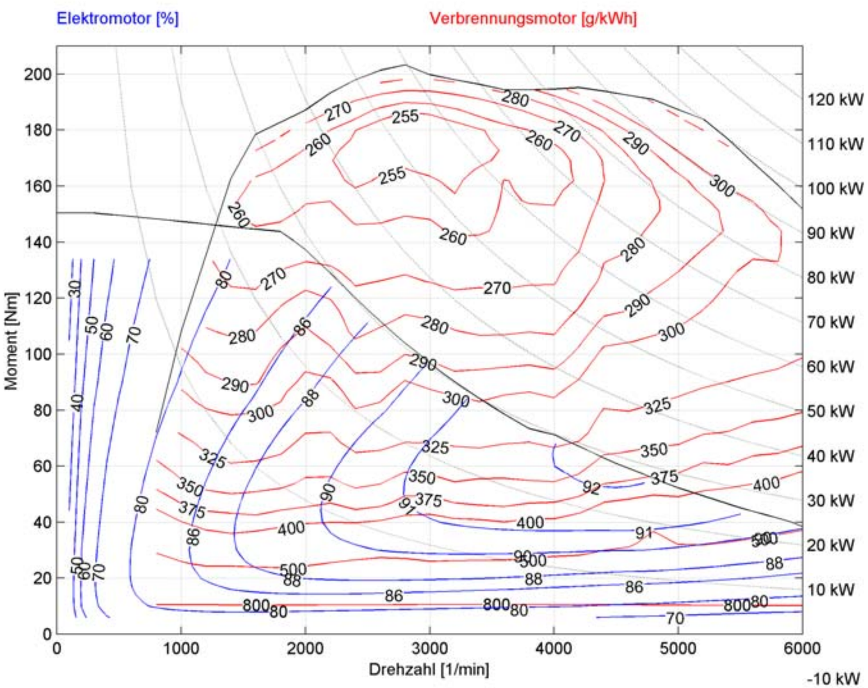
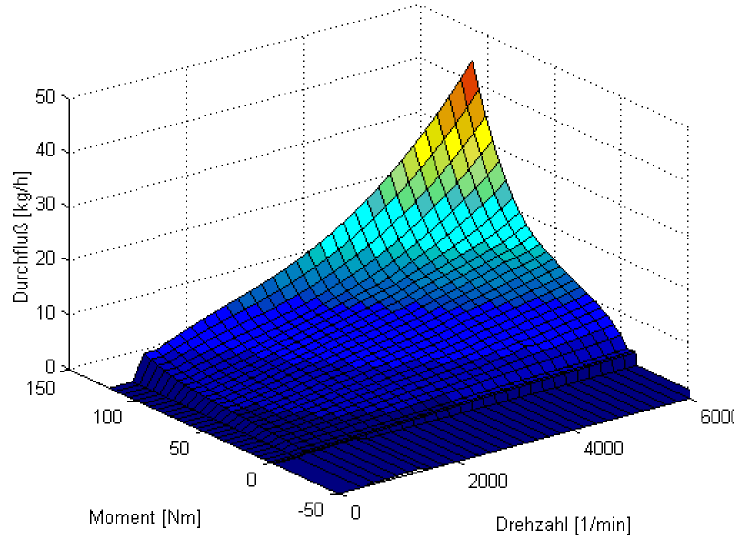
Automotive

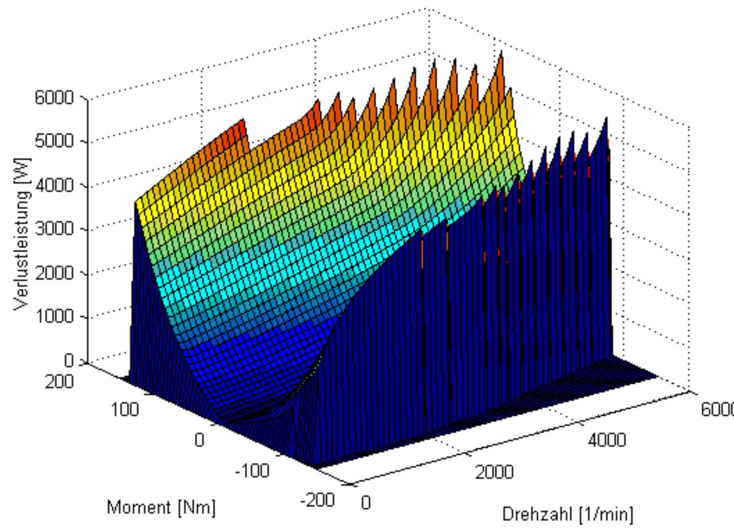
Customers
(representative list)

Autoliv	Motorola
Borg-Warner	Navistar International
Cummins Engine	Newman Haas Racing
DaimlerChrylser	New Venture Gear
Deere	OnStar
Delphi	PSA
Denso	Renault
Detroit Diesel	Ricardo
Federal-Mogul	Robert Bosch
Eaton	Tenneco Automotive
EcoStar	Sachs Automotive
Fiat	SAGEM
Ford Motor	Siemens
GKN Automotive	Toyota
Hitachi	TNO
Honda	TRW
International Truck and Engine	Valeo
Johnson Controls	Visteon
Magneti Marelli	Volkswagen

Chapter 5: Simulation – Approach Representation of the Drivetrain Components in Maps and Equations



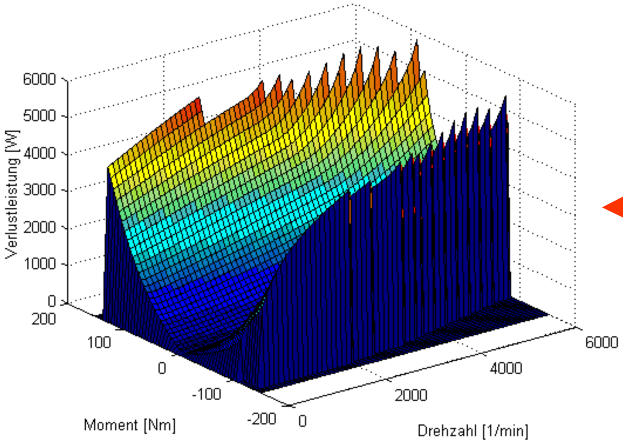


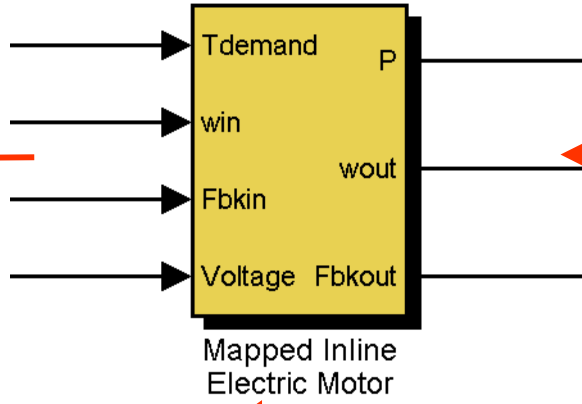


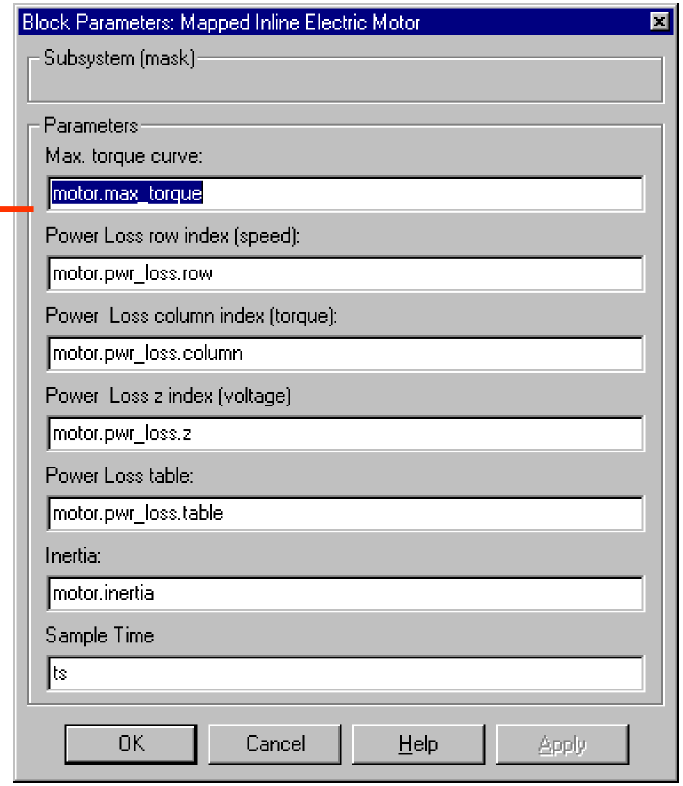
$$V = \int a_x \, dt$$

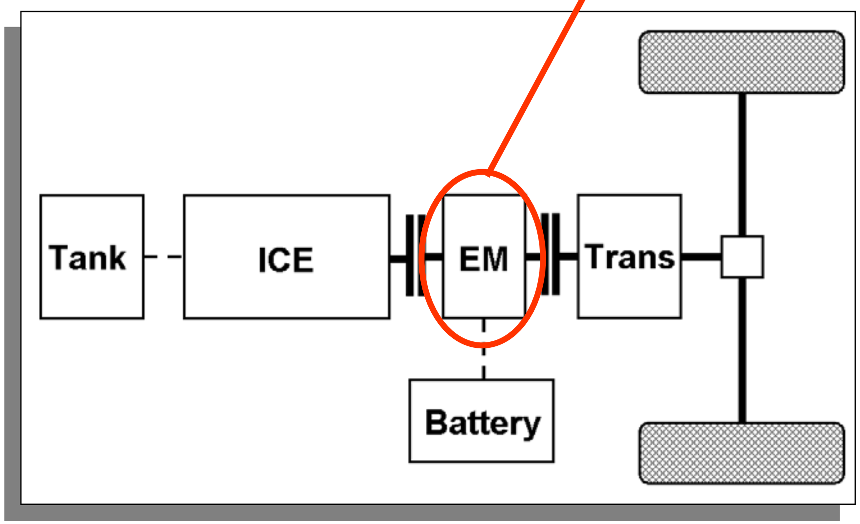
$$a_x = \frac{F_{dem} - F_Z \cdot (p + f_R) + c_w \cdot A \cdot \frac{\rho_L}{2} \cdot v^2}{(e_i \cdot m_F + m_{Zu})}$$

Chapter 5: Simulation – Approach
Example Component Model Module
“Mapped Inline Electric Motor“

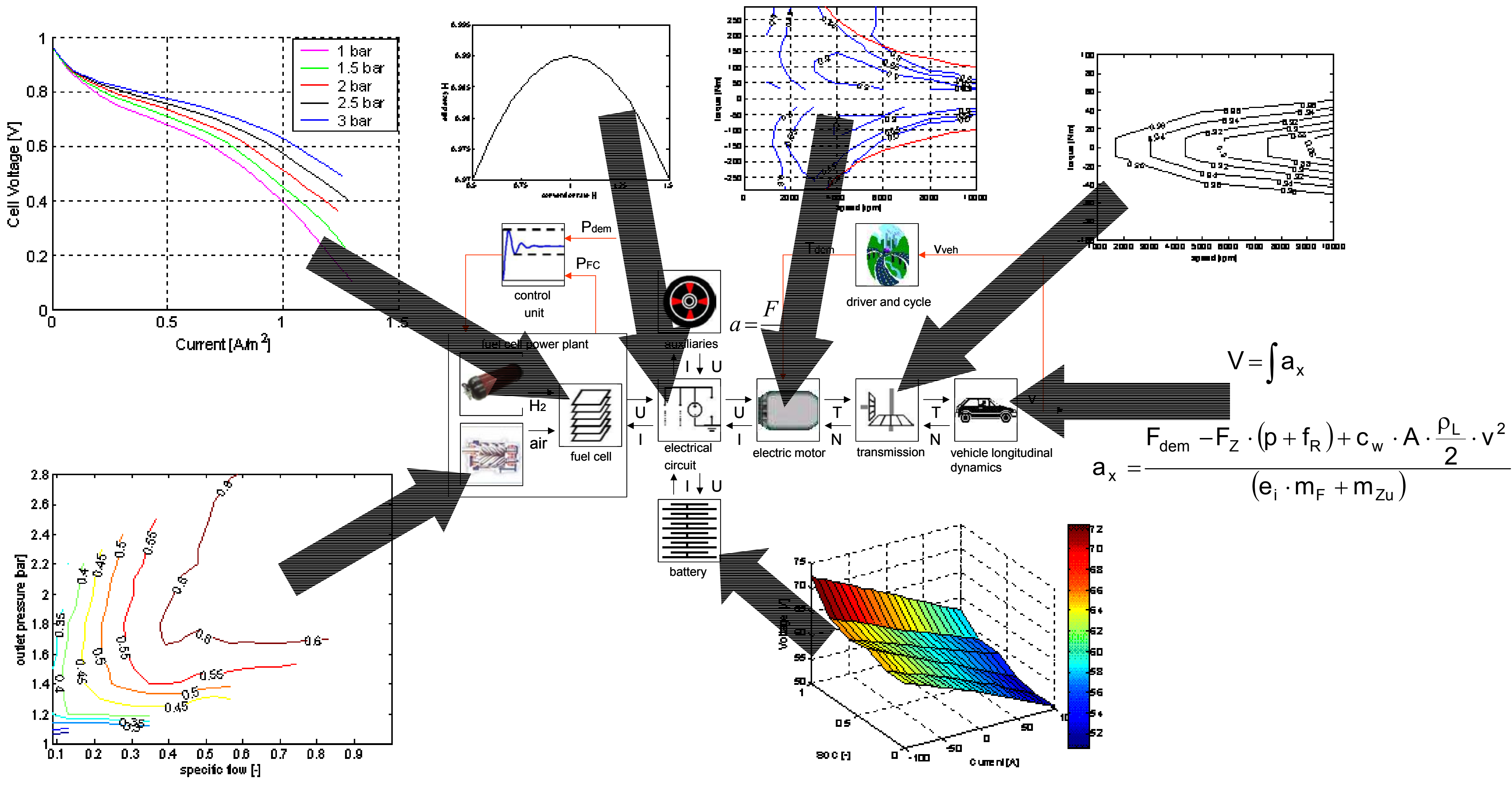




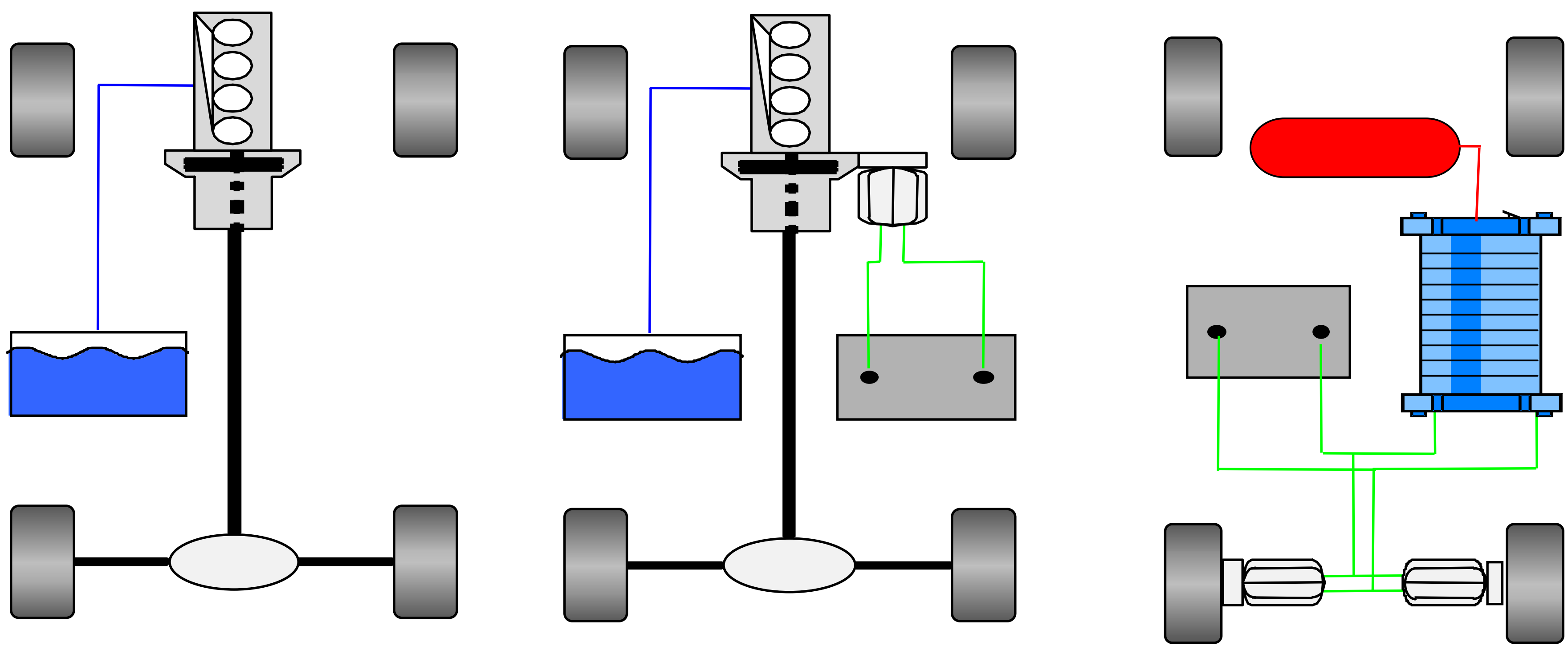




Chapter 5: Simulation – Approach
Example for the necessary input data



Chapter 5: Simulation – Approach
Vehicle Architectures (Examples)

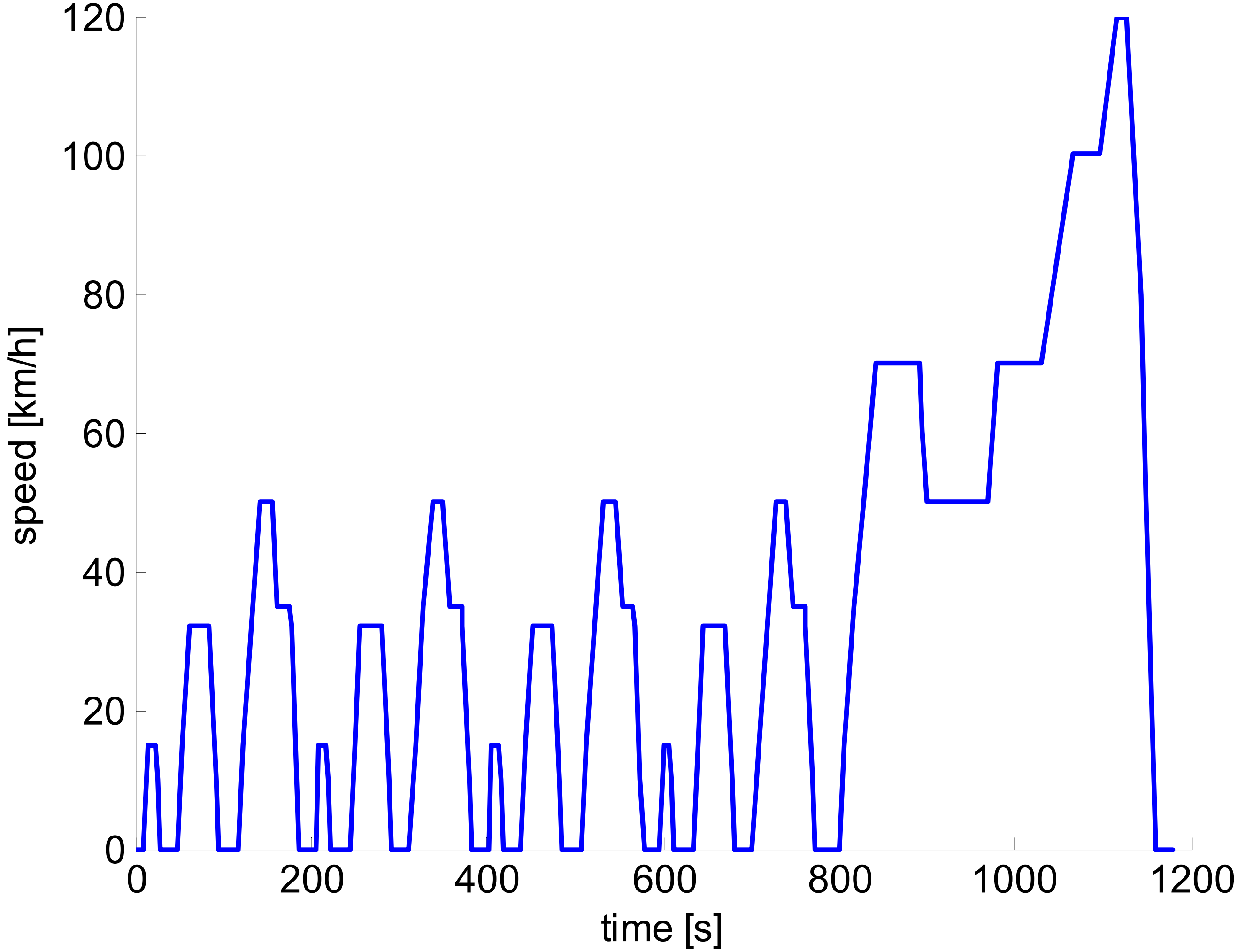


conventional
vehicle

parallel-
hybrid

fuel cell
vehicle

Chapter 5: Simulation – Approach
Used Cycles: NEDC



- Standard synthetic cycle for consumption measurement in Europe
- Maximum acceleration is low: 1.04 m/s²
- Average speed is low: 33.2 km/h

Chapter 5: Simulation – Approach
Used Cycles: HYZEM

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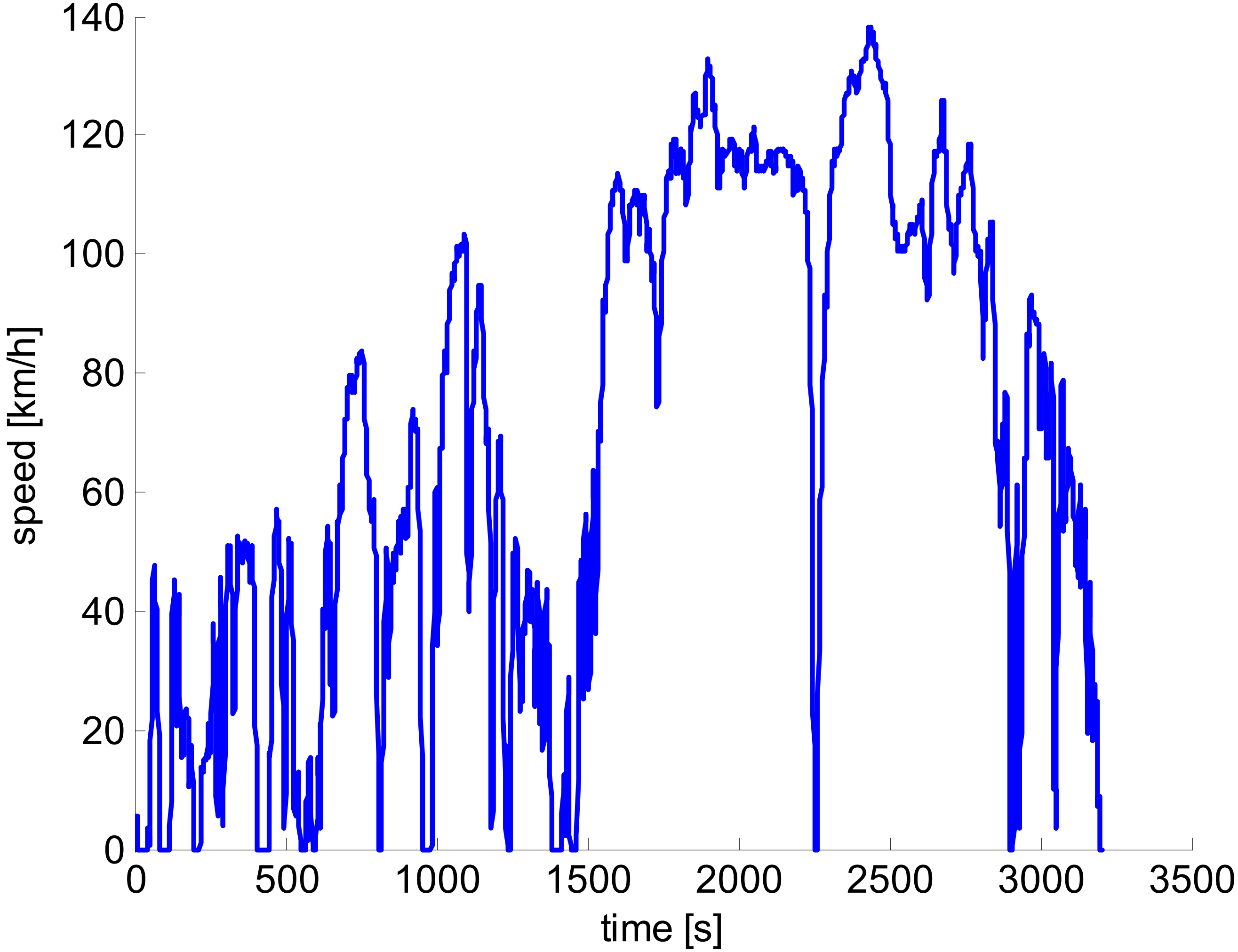

- Common cycle representing real world traffic
- Nearly similar to FTP75 cycle
- Maximum acceleration is high: 3.1 m/s² (peak)
- Average speed is high: 68.36 km/h

Chapter 5: Simulation – Approach Time Record of Vehicle Parameters (Hybrid Vehicle)

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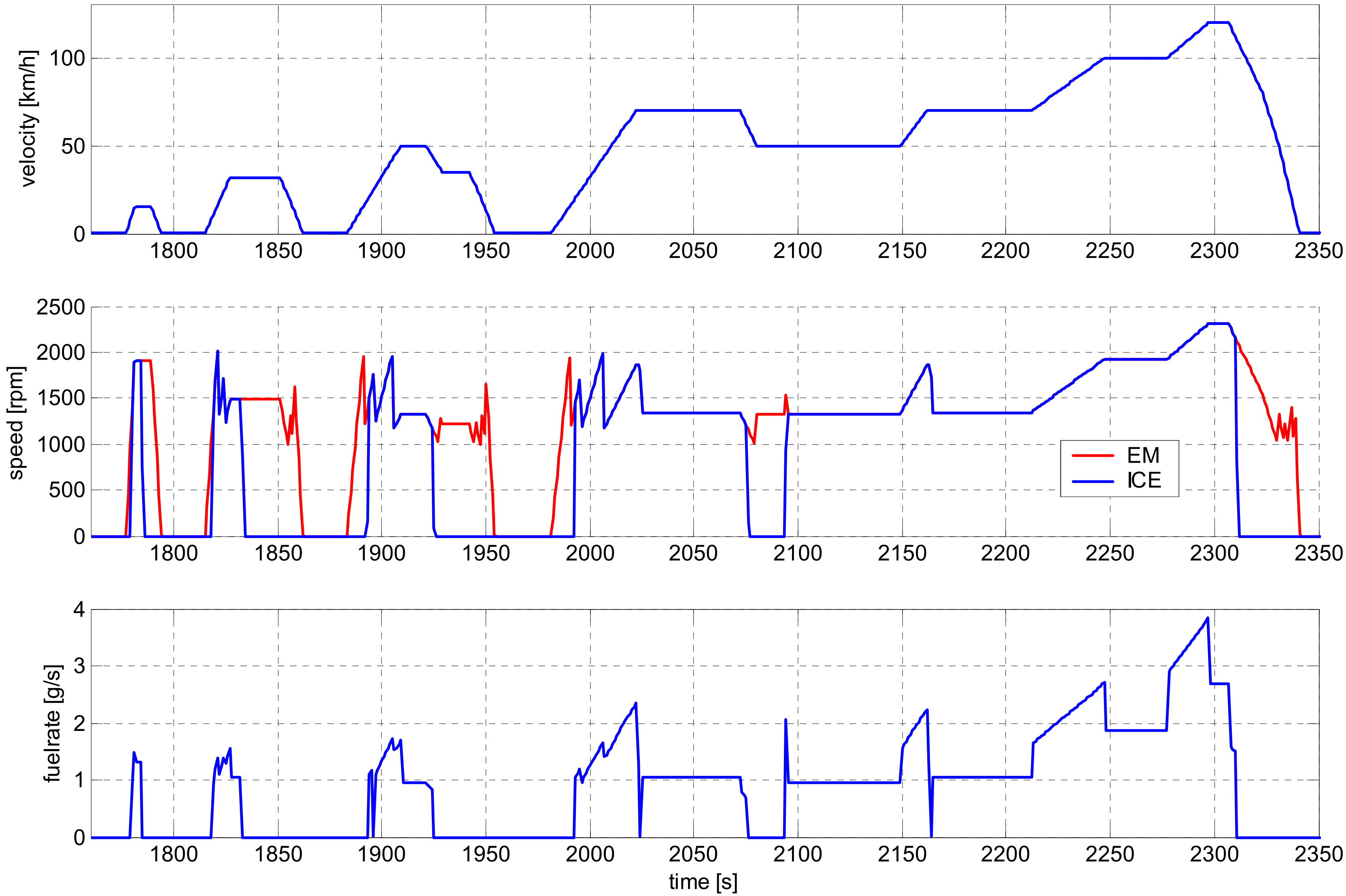

Chapter 5: Simulation – Approach
Adaptation of Engine Power

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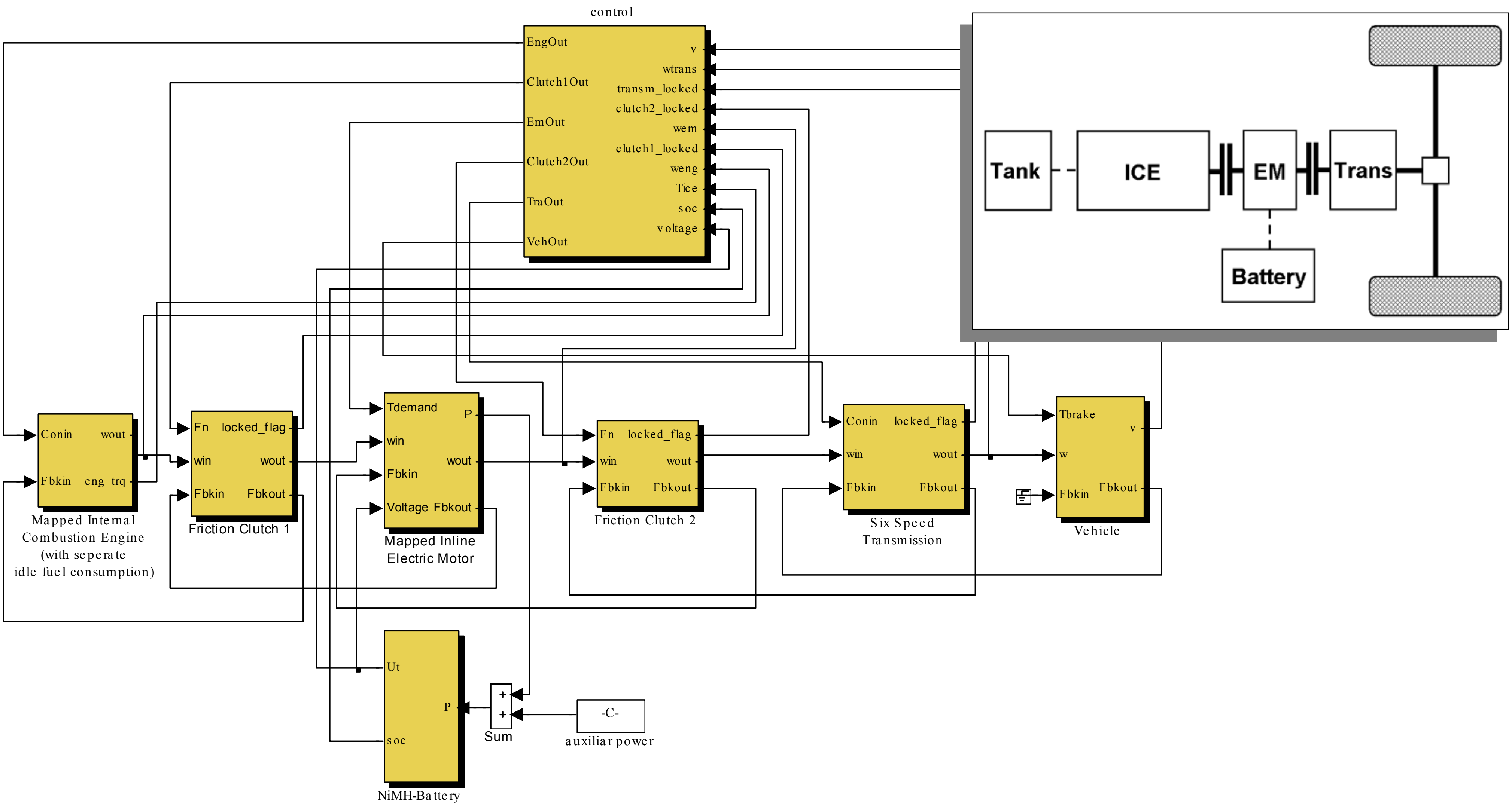
1. Determination of acceleration figures of the basic vehicle (Generic Car, 85 kW)
2. Reduction of vehicle weight (Min / Max Weight Saving)
3. Reduction of engine power so that acceleration figures of lightweight vehicle and basic vehicle correspond

	Generic Car (85 kW)	Min WS (85 kW)	Max WS (85 kW)	Min WS **(79 kW)**	Max WS **(74 kW)**
	[s]	[s]	[s]	[s]	[s]
0-50 km/h	**3.5**	3.3	3.1	3.5	3.4
0-80 km/h	**6.5**	6.1	5.7	6.5	6.4
0-100 km/h	**9.8**	9.2	8.5	9.9	9.8
0-130 km/h	**16.2**	15.0	13.9	16.3	16.3

(example: Compact Class)

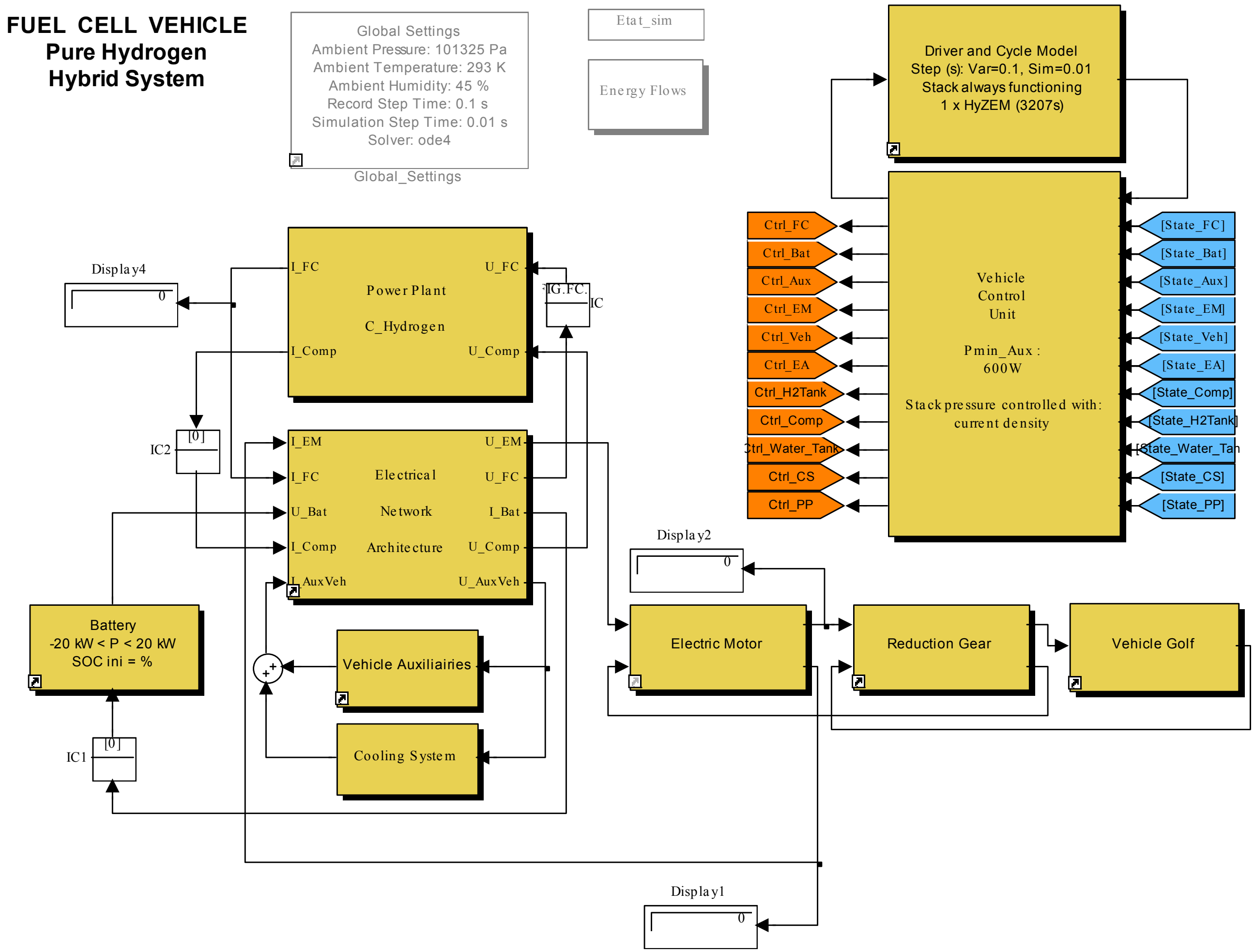
Chapter 5: Simulation – Approach
Longitudinal Model of a parallel Hybrid Vehicle (Matlab®/Simulink®)

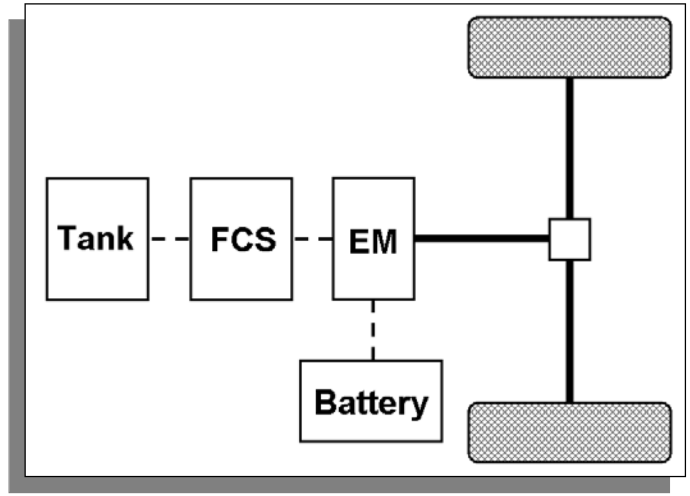
fka



Chapter 5: Simulation – Approach
FCV Model in Matlab®/Simulink®

fka

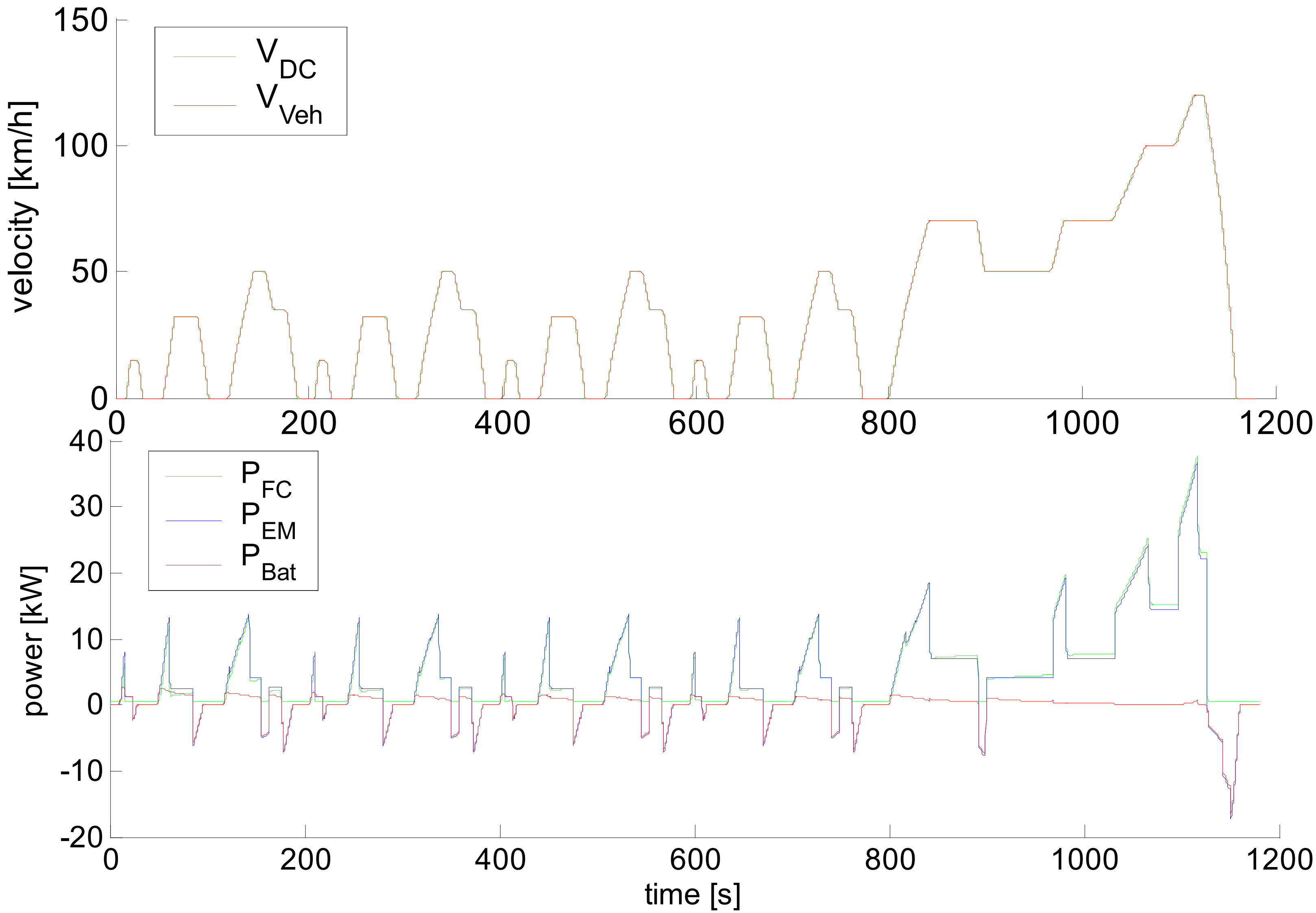




Hybrid fuel cell system

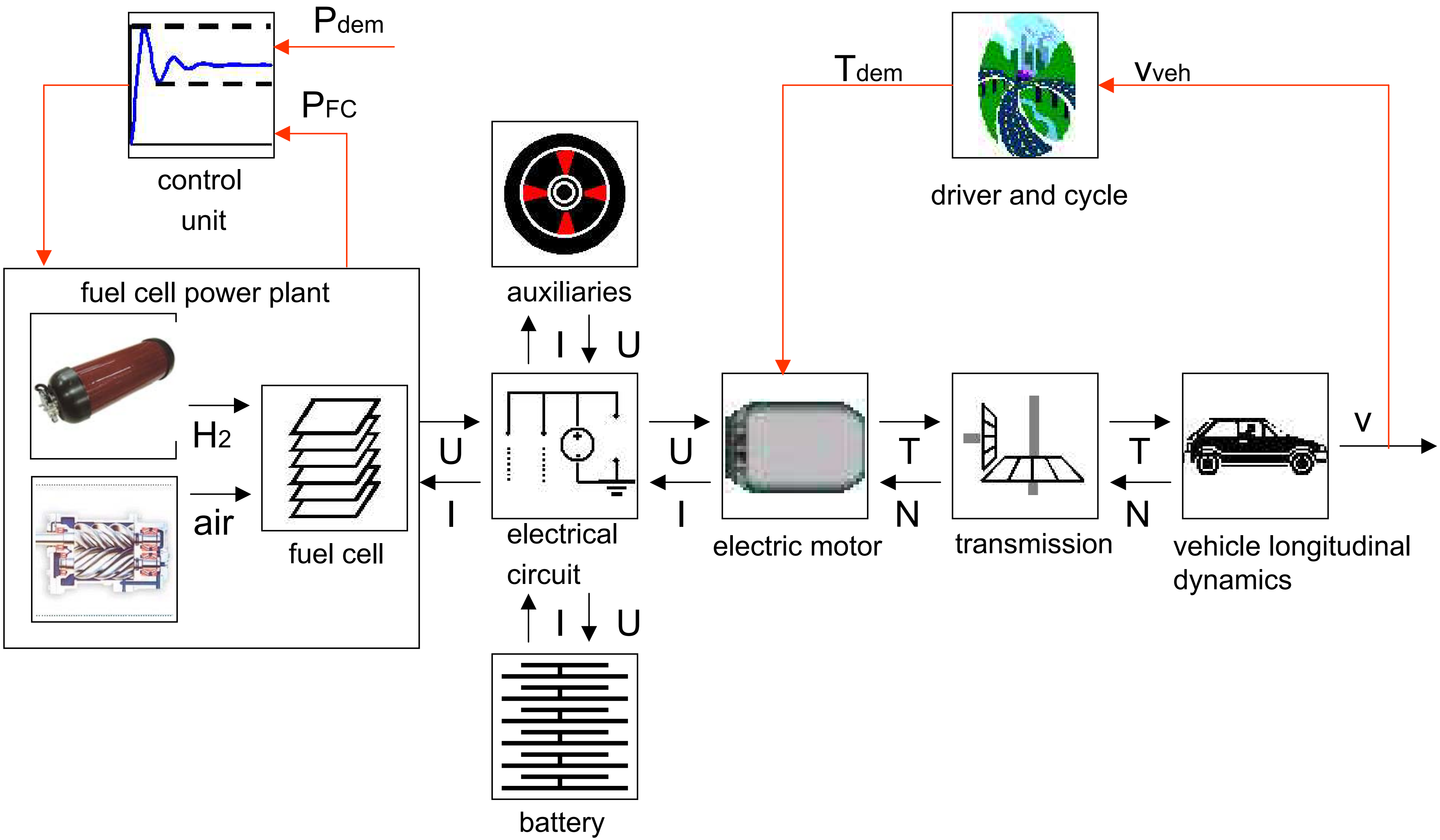
Chapter 5: Simulation – Approach Time Record of Vehicle Parameters (Fuel Cell Vehicle)

fka



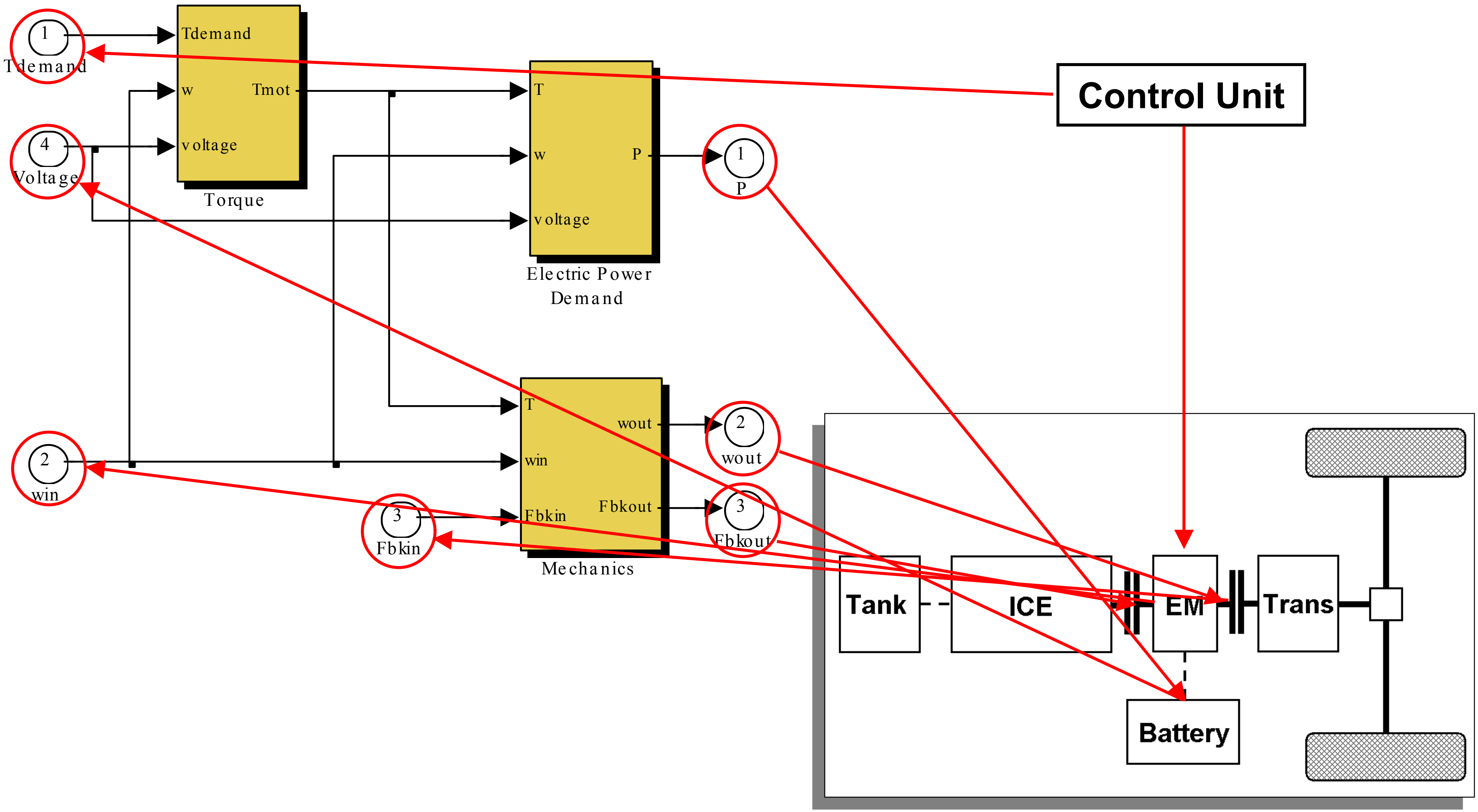
Chapter 5: Simulation – Approach
Configuration of a Fuel Cell Vehicle (Hybrid) Model

fka

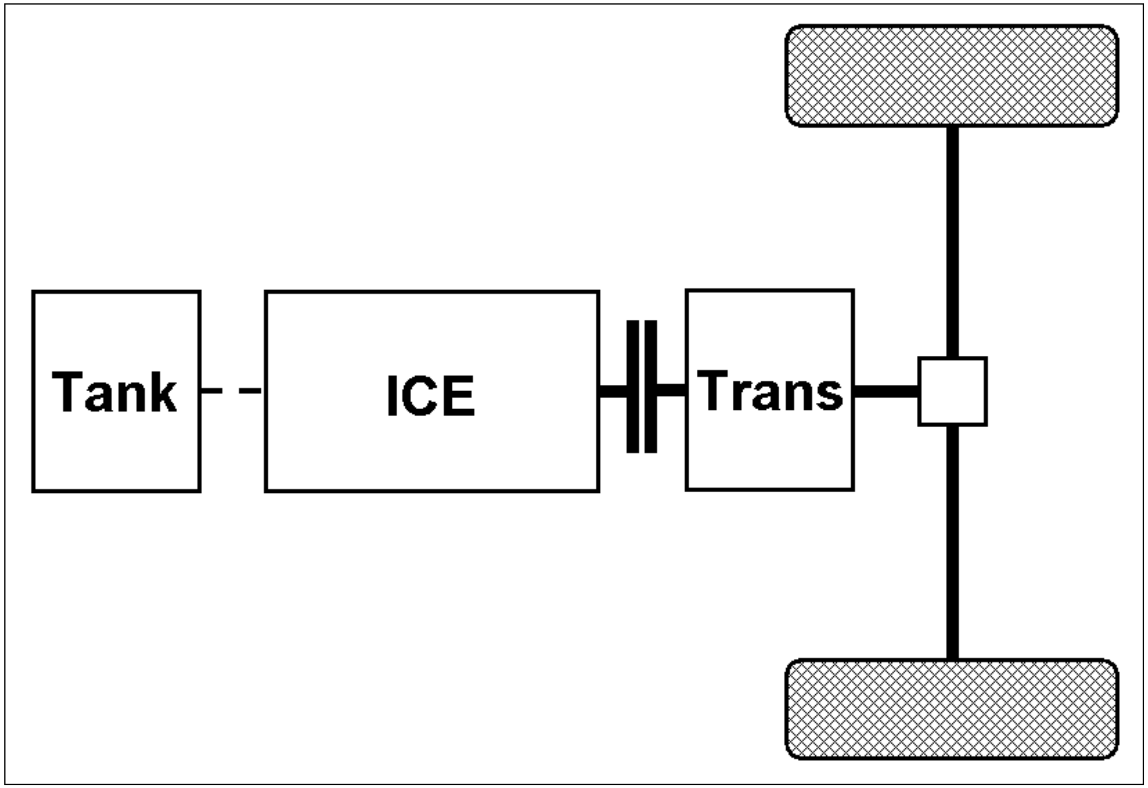


Chapter 5: Simulation – Approach
Example Component Model Module
“Mapped Inline Electric Motor“

fka



Chapter 5: Simulation – Results
Principle of ICEV



Chapter 5: Simulation – Results
ICEV-G Data in Simulation

fka

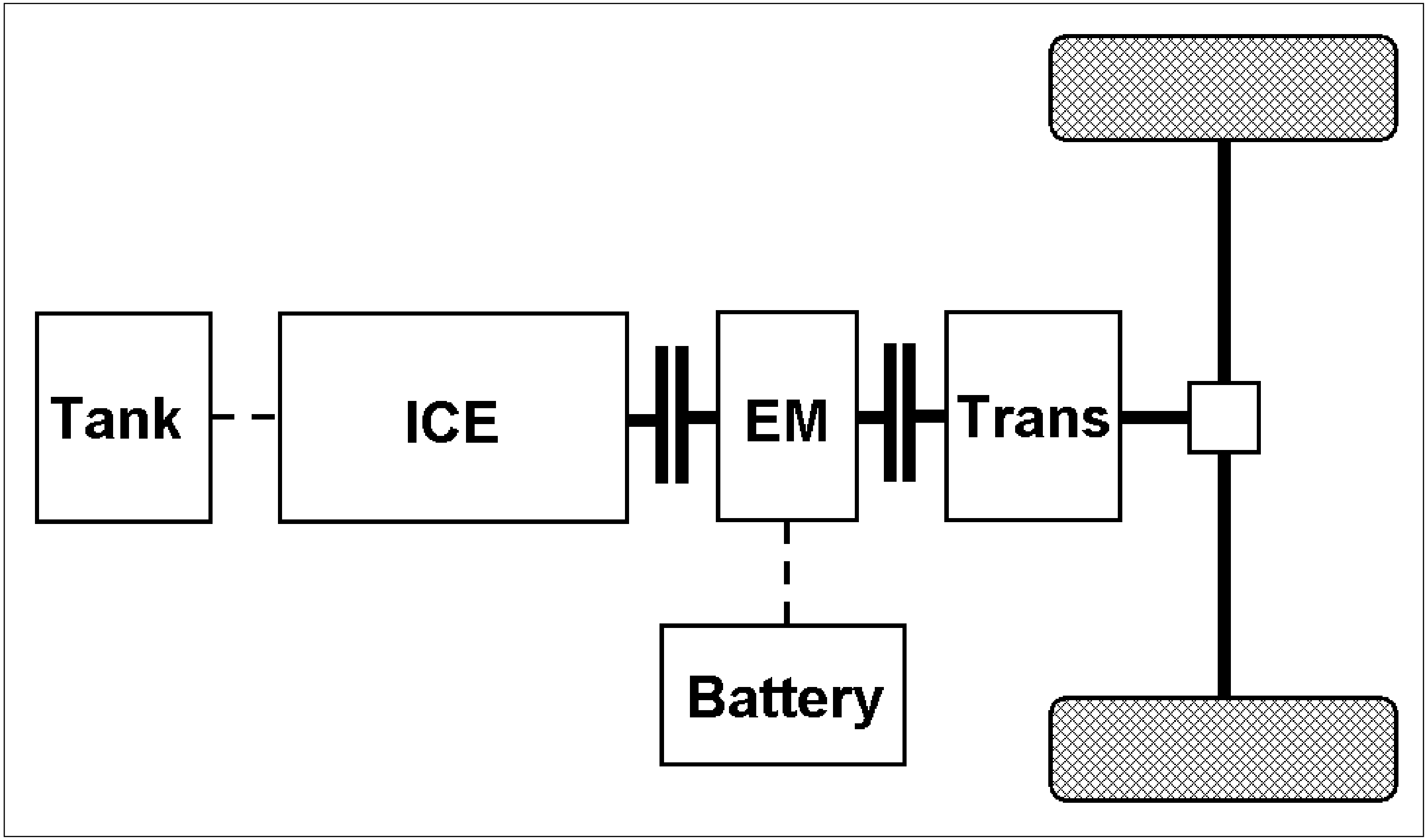
	Generic Car Compact Class	Generic Car Middle-Sized Class	Generic Car SUV
Vehicle Weight [kg]	1260	1640	2195
Engine Power [kW]	85	181	235
C_D [-]	0.31	0.27	0.36
A [m²]	2.16	2.24	2.78

Chapter 5: Simulation – Results
ICEV-D Data in Simulation

fka

	Generic Car Compact Class	Generic Car Middle-Sized Class	Generic Car SUV
Vehicle Weigh [kg]	1350	1740	2320
Engine Power [kW]	100	170	220
C_D [-]	0.31	0.27	0.36
A [m²]	2.16	2.24	2.78

Chapter 5: Simulation – Results
Principle of HV



Chapter 5: Simulation – Results
HV-G Data in Simulation

fka

	Generic Car Compact Class	Generic Car Middle-Sized Class	Generic Car SUV
Vehicle Weight [kg]	1335	1752	2345
Engine Power [kW]	85	181	235
Motor Power [kW]	20	30	40
C_D [-]	0.31	0.27	0.36
A [m²]	2.16	2.24	2.78

- ICE same power as conventional vehicle
- Electric motor sized to enable regenerative breaking and partial electric propulsion

Chapter 5: Simulation – Results
HV-D Data in Simulation

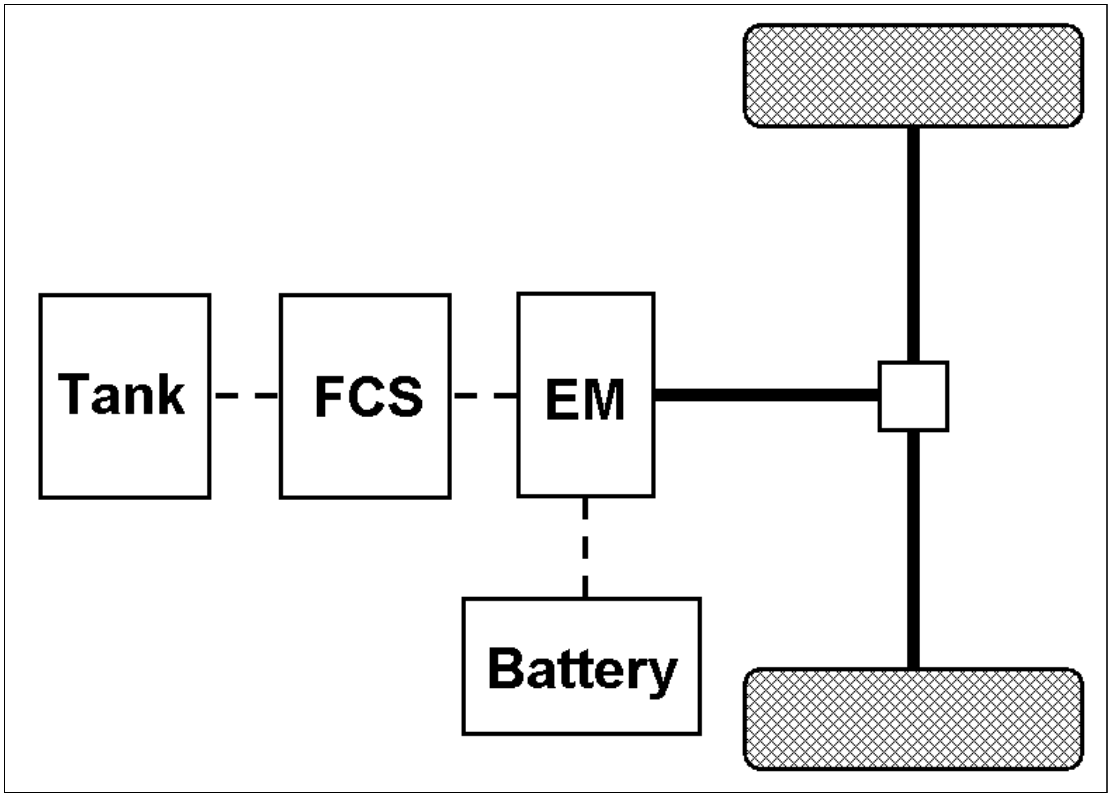
fka

	Generic Car Compact Class	Generic Car Middle-Sized Class	Generic Car SUV
Vehicle Weight [kg]	1425	1852	2470
Engine Power [kW]	100	170	220
Motor Power [kW]	20	30	40
C_D [-]	0.31	0.27	0.36
A [m²]	2.16	2.24	2.78

- ICE same power as conventional vehicle
- Electric motor sized to enable regenerative breaking and partial electric propulsion

Chapter 5: Simulation – Results
Principle of FCV

fka



Chapter 5: Simulation – Results
FCV Data in Simulation

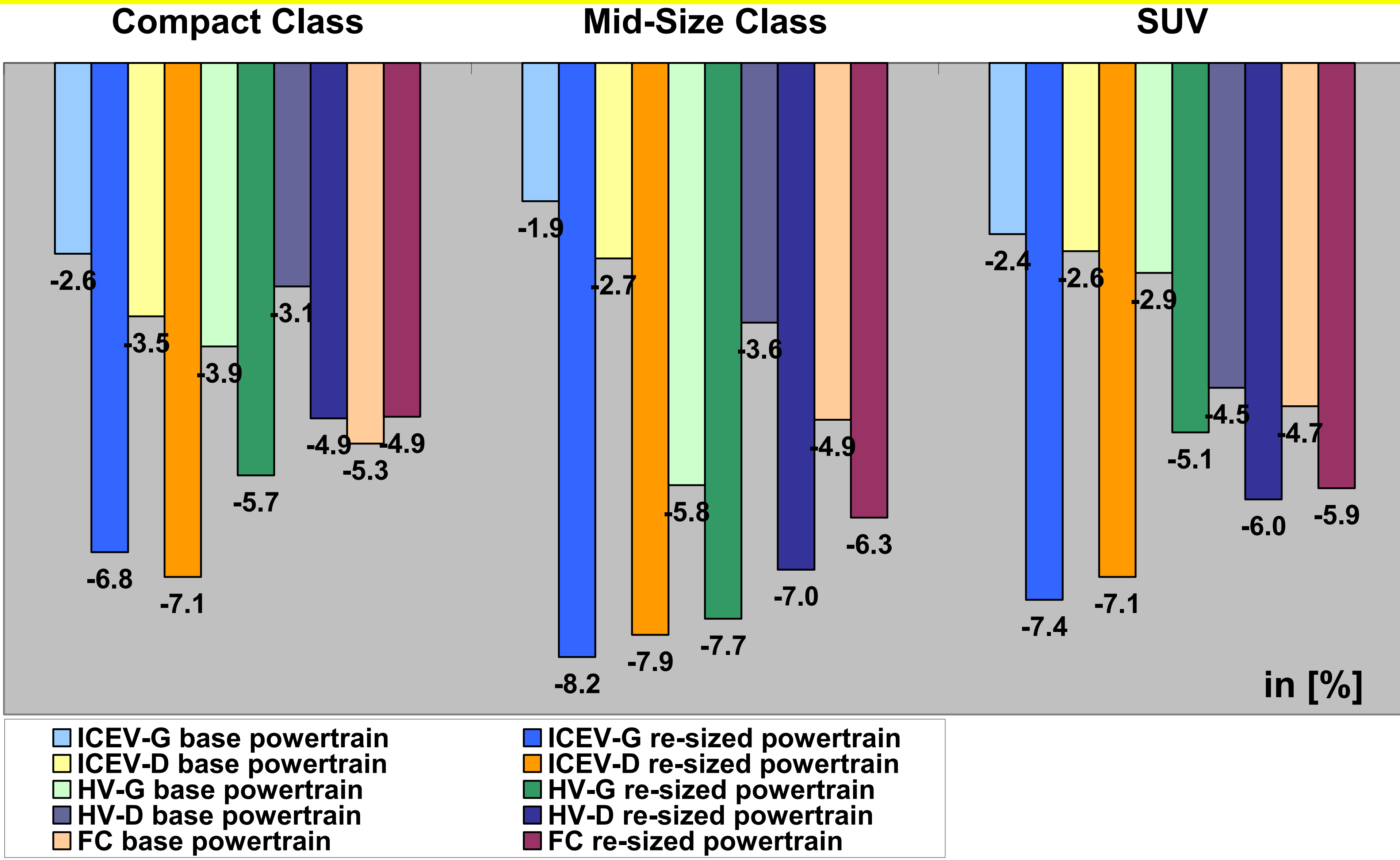
fka

	Generic Car Compact Class	Generic Car Middle-Sized Class	Generic Car SUV
Vehicle Weight [kg]	1335	1752	2345
Min WS [kg]	1241 (-94)	1648 (-104)	2205 (-140)
Max WS [kg]	1148 (-187)	1544 (-208)	2065 (-181)
Electric Motor Peak Power [kW]	64-73	116-131	173-194
C_D [-]	0.3	0.3	0.4
A [m²]	2.2	2.2	2.8
0 to 100 km/h [s]	9.8	6.9	6.5

- Electric motor sized to enable same acceleration as the ICEV
- Fuel cell system sized to provide the electric motor with the maximum continuous power, during full acceleration additional power is provided by the battery
- Acceleration 0 to 100 km/h is calculated for the curb weight without any payload (catalogue data is measured for ½ max. payload)

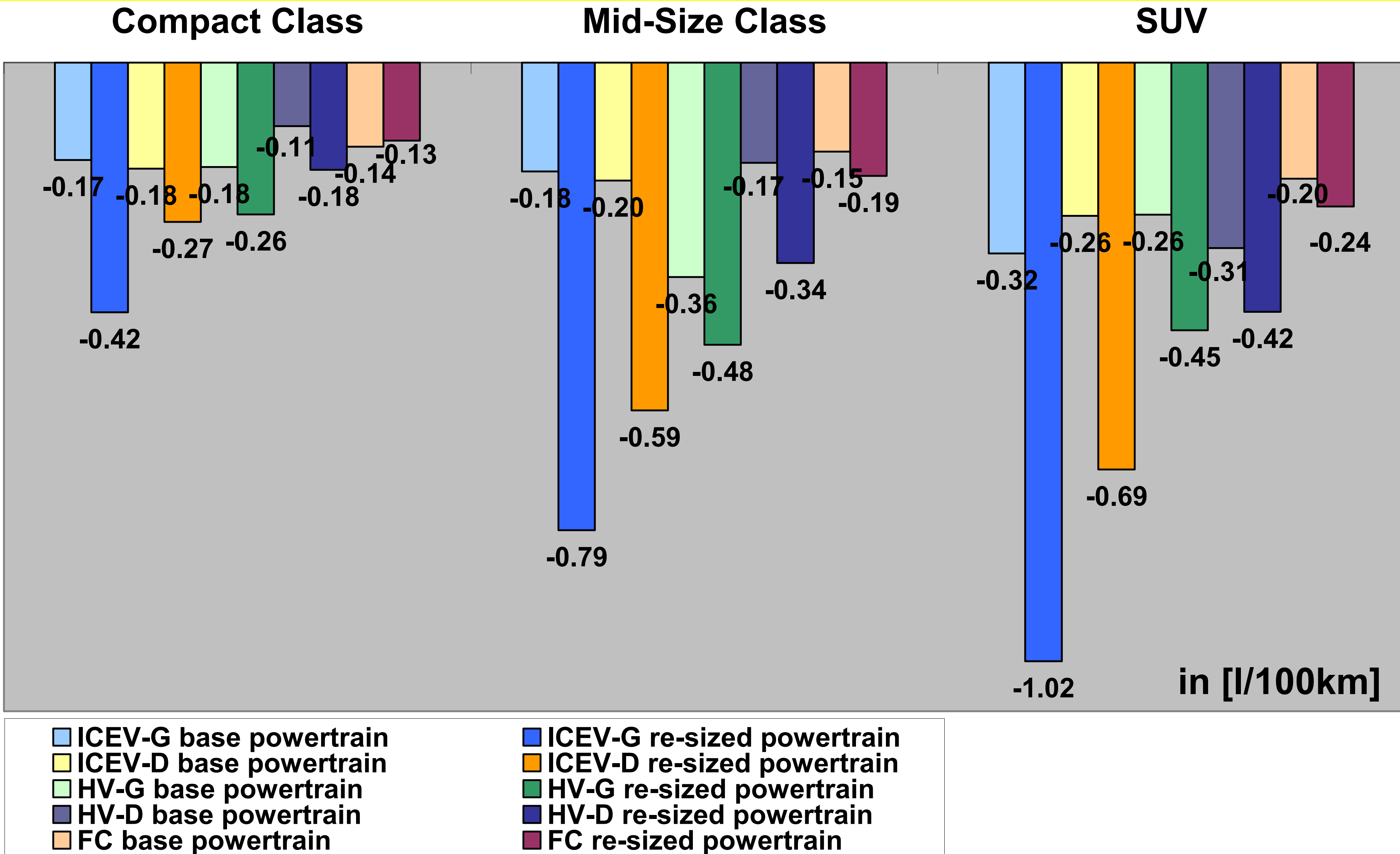
Chapter 5: Simulation – Results
10 % Weight Reduction, NEDC

fka



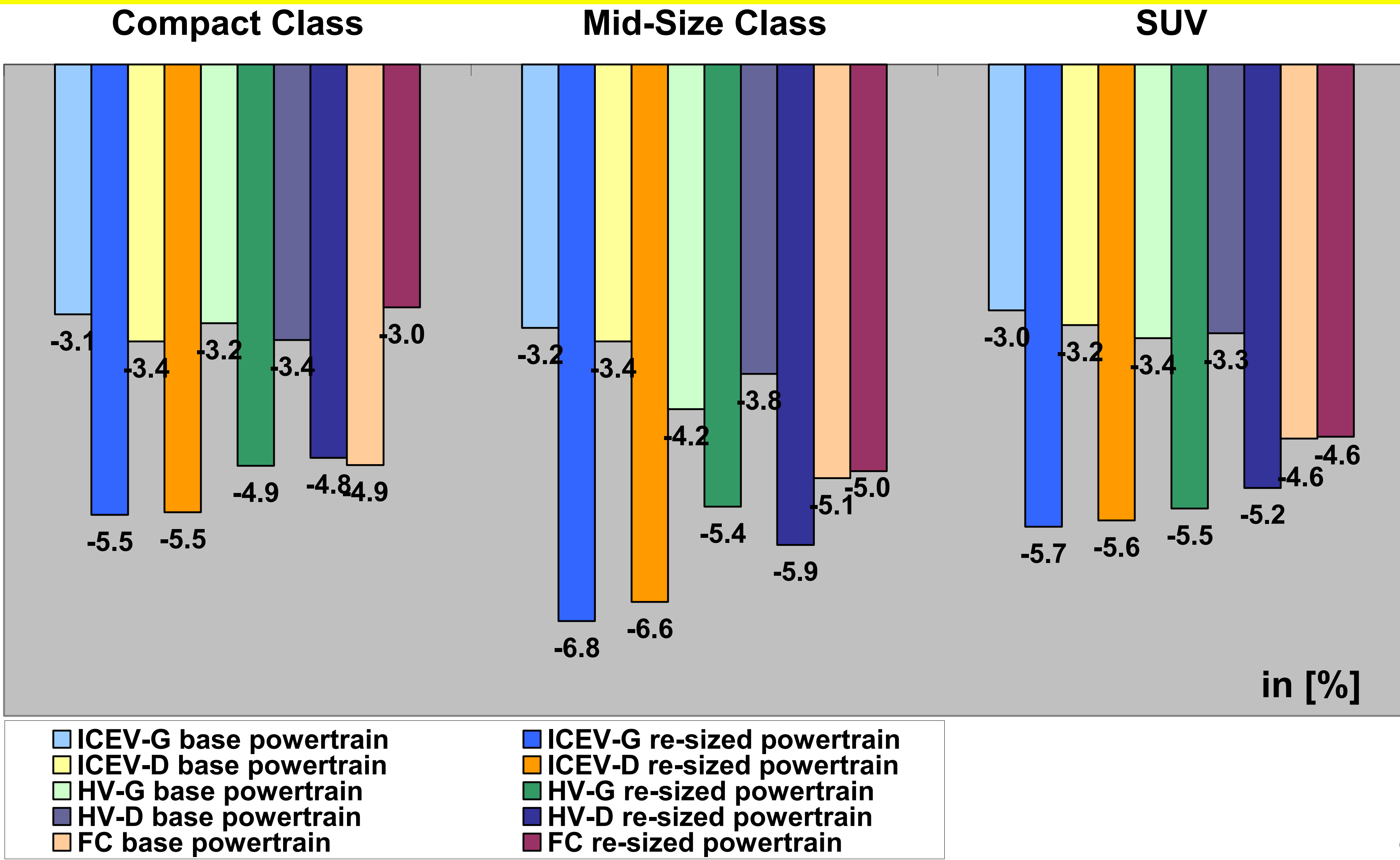
Chapter 5: Simulation – Results
10 % Weight Reduction, NEDC

fka



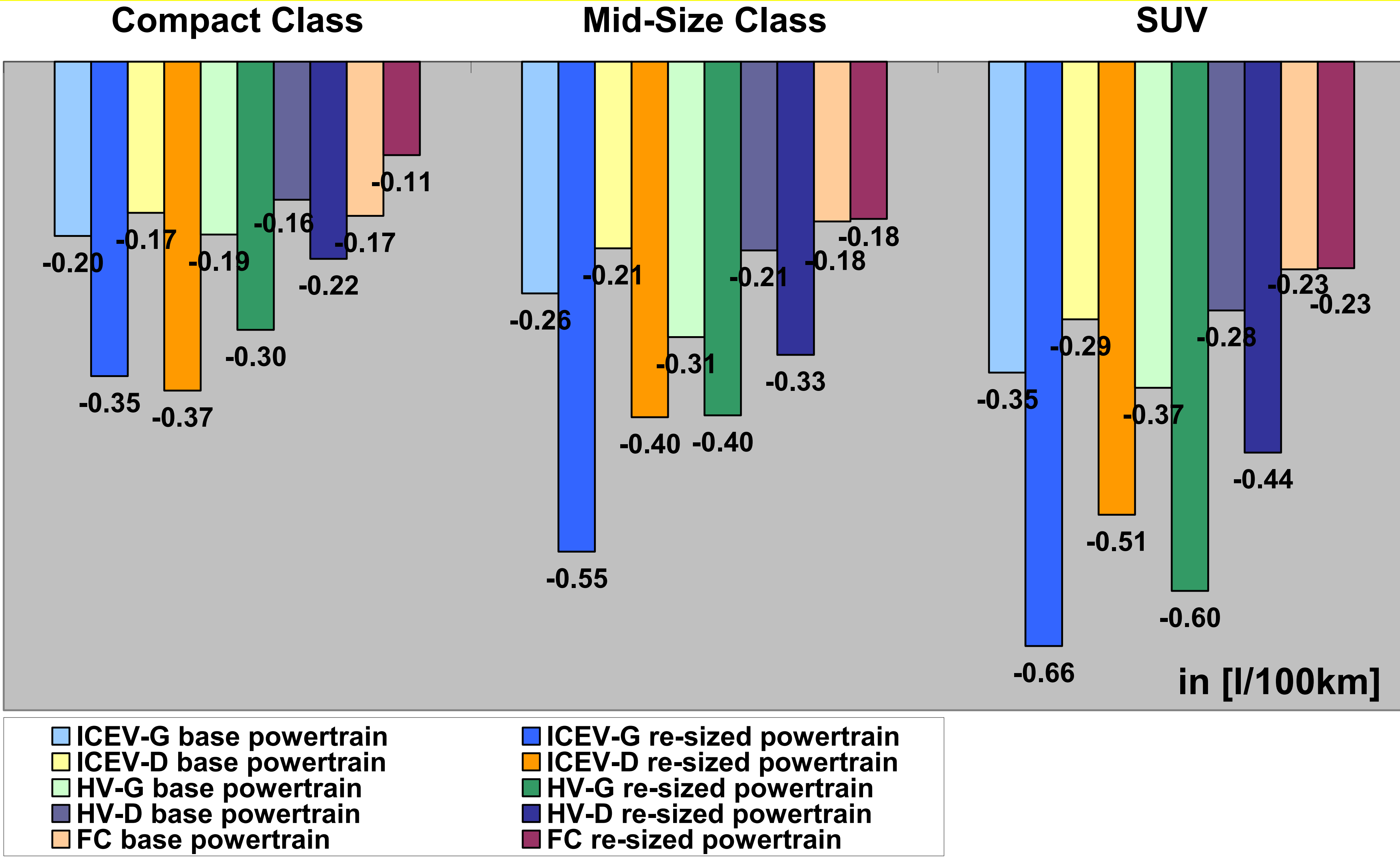
Chapter 5: Simulation – Results
10 % Weight Reduction, HYZEM

fka



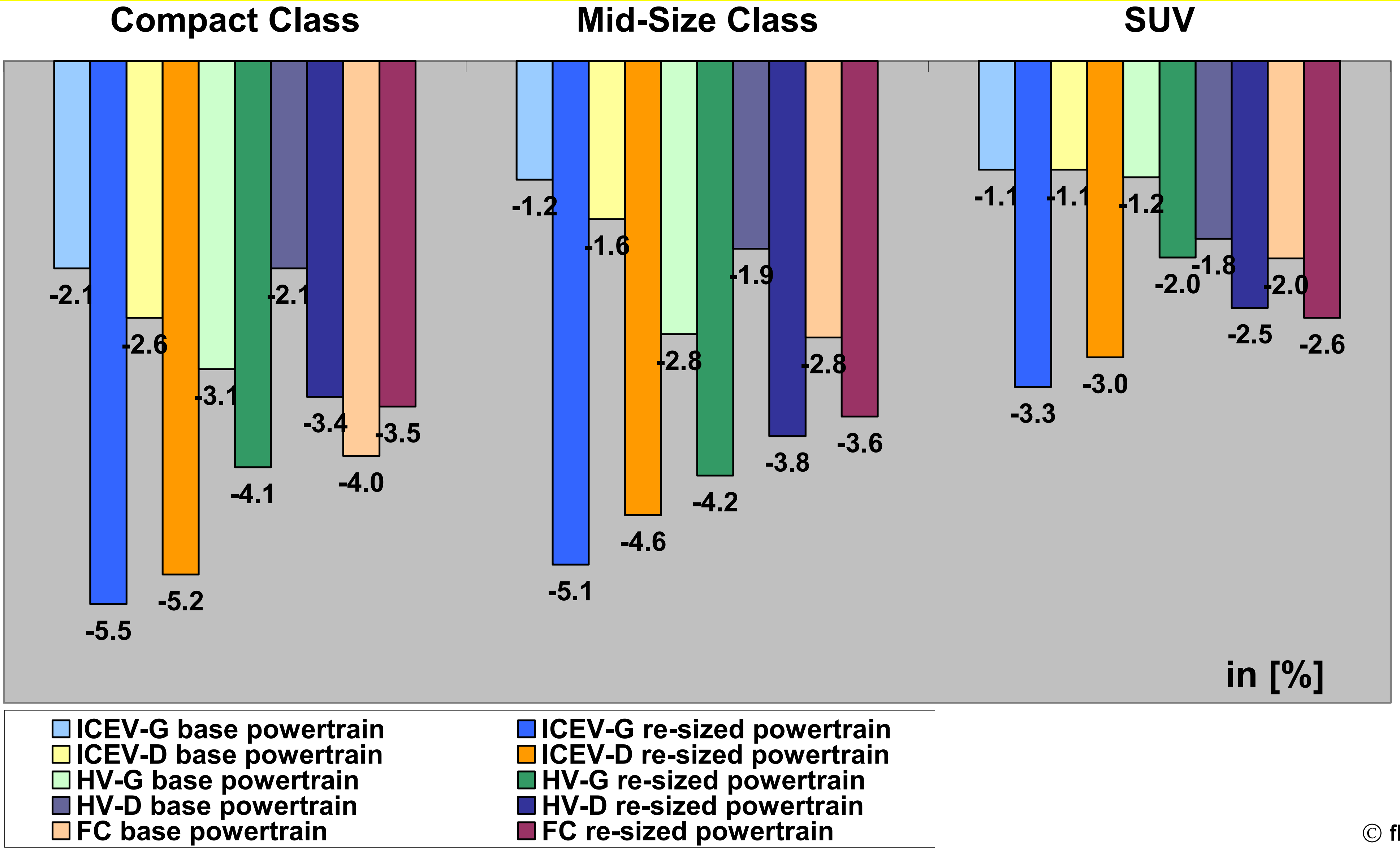
Chapter 5: Simulation – Results
10 % Weight Reduction, HYZEM

fka



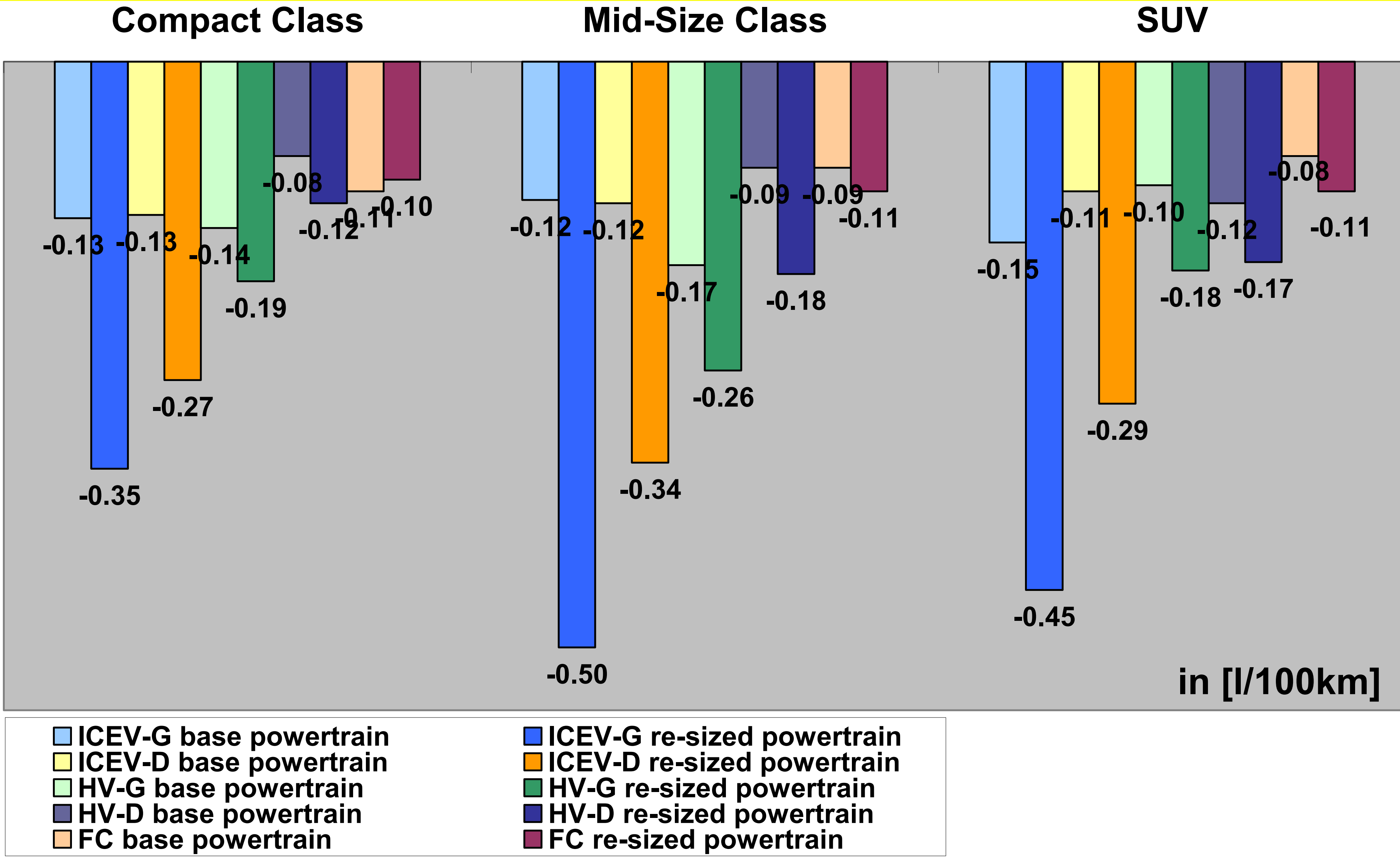
Chapter 5: Simulation – Results
100 kg Weight Reduction, NEDC

fka



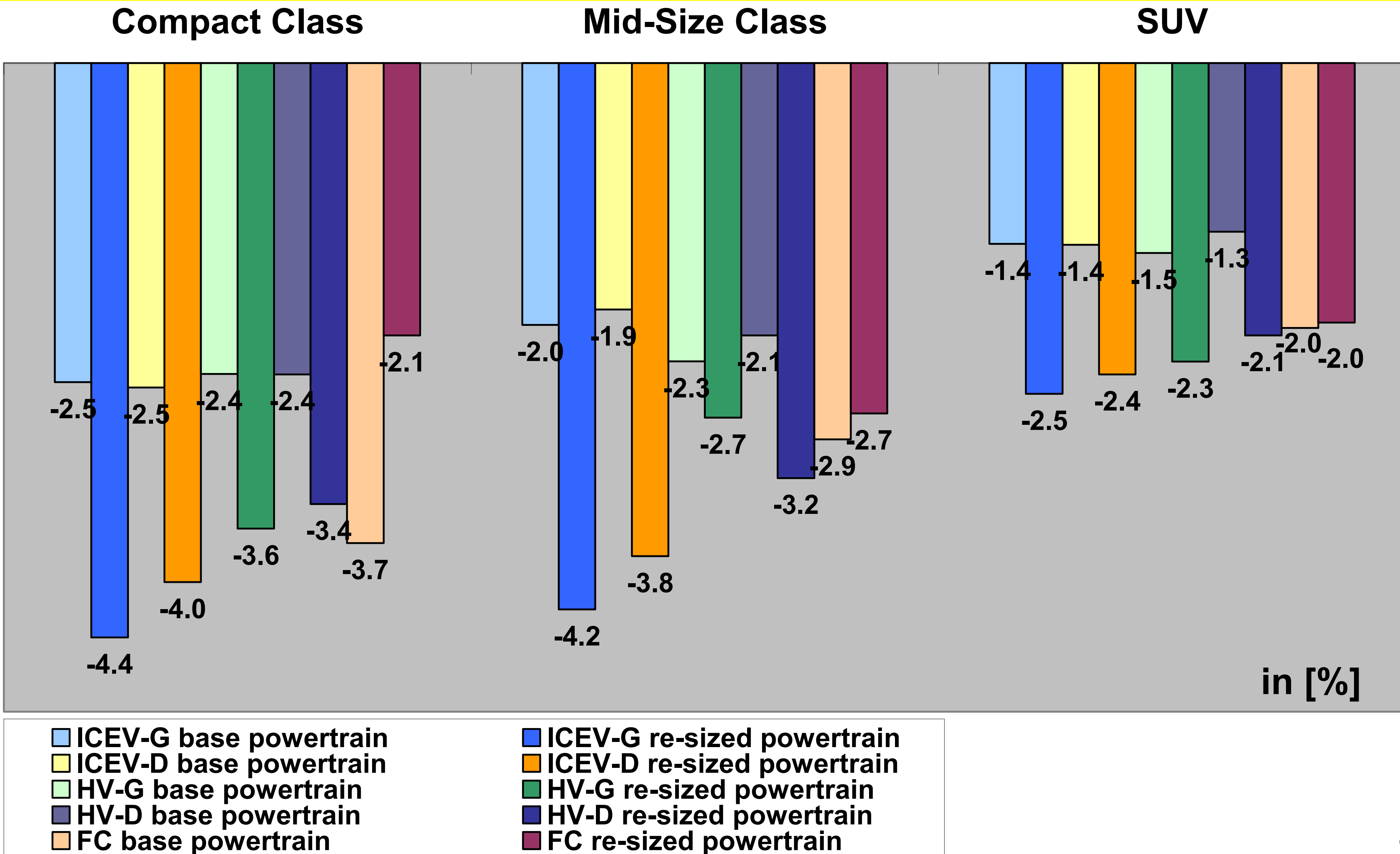
Chapter 5: Simulation – Results
100 kg Weight Reduction, NEDC

fka



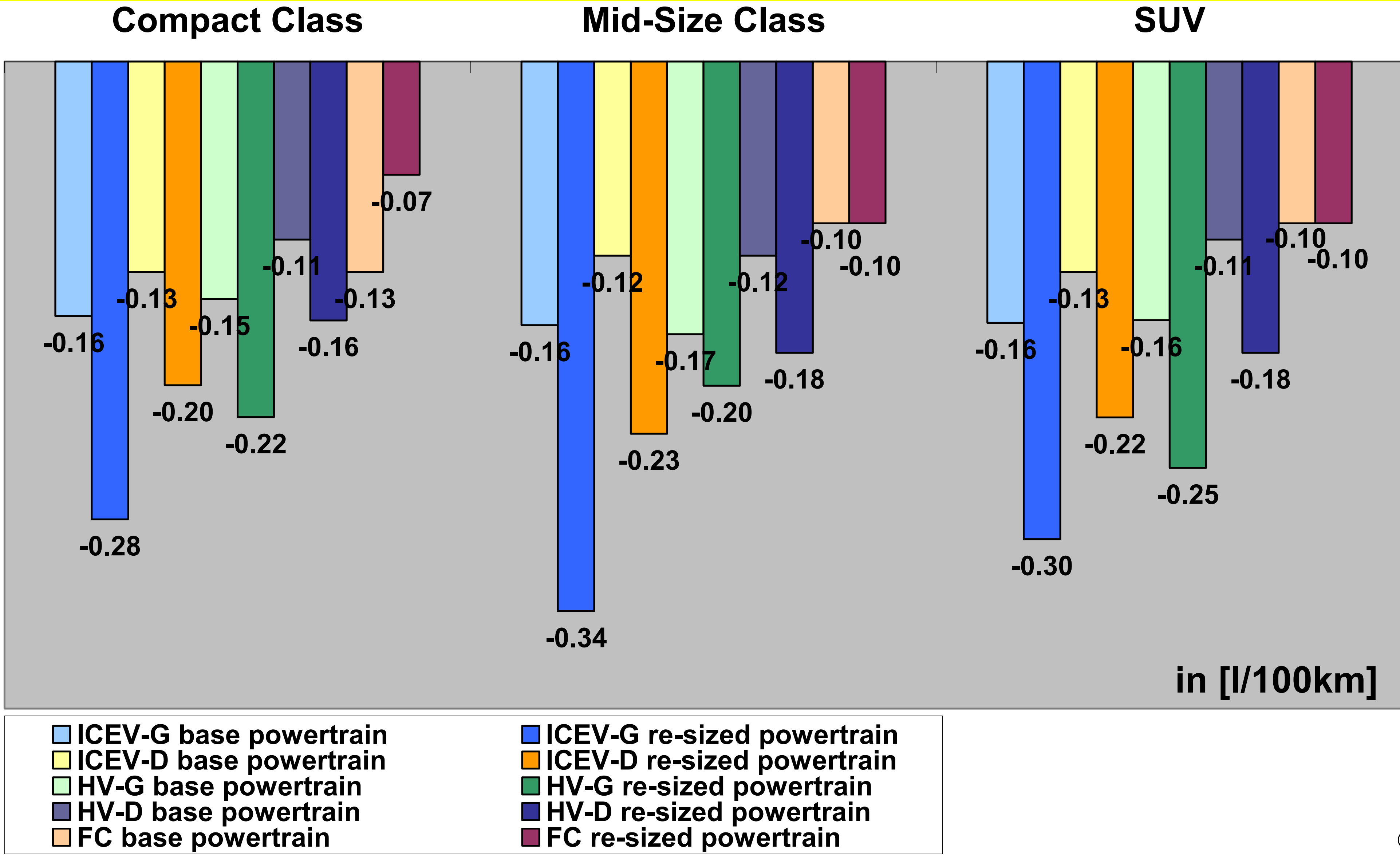
Chapter 5: Simulation – Results
100 kg Weight Reduction, HYZEM

fka



Chapter 5: Simulation – Results
100 kg Weight Reduction, HYZEM

fka



Chapter 5: Simulation – Results
Weight Elasticity Values ICEV-G, NEDC

fka

Vehicle Class	Weight Saving	Engine Power [kW]	Fuel Consumption			Vehicle Weight			WEV
			absolute [l/100km]	Reduction [l/100km]	Reduction [%]	absolute [kg]	Reduction [kg]	Reduction [%]	
Compact Class	-	85	6.27	-	0.0	1260	-	0.0	**-**
	Min WS	85	6.14	0.12	2.0	1166	94	7.5	**0.27**
	Max WS	85	6.02	0.24	3.9	1073	187	14.8	**0.26**
	Min WS	79	5.94	0.32	5.2	1166	94	7.5	**0.69**
	Max WS	74	5.65	0.61	9.8	1073	187	14.8	**0.66**
Middle-Sized Car	-	181	9.66	-	0.0	1640	-	0.0	**-**
	Min WS	181	9.54	0.12	1.3	1536	104	6.3	**0.20**
	Max WS	181	9.43	0.23	2.4	1432	208	12.7	**0.19**
	Min WS	170	9.15	0.52	5.3	1536	104	6.3	**0.84**
	Max WS	160	8.67	1.00	10.3	1432	208	12.7	**0.81**
SUV	-	235	13.69	-	0.0	2195	-	0.0	**-**
	Min WS	235	13.48	0.21	1.6	2055	140	6.4	**0.25**
	Max WS	235	13.29	0.41	3.0	1914	281	12.8	**0.23**
	Min WS	222	13.07	0.63	4.6	2055	140	6.4	**0.72**
	Max WS	207	12.38	1.32	9.6	1914	281	12.8	**0.75**

Chapter 5: Simulation – Results
Weight Elasticity Values ICEV-G, HYZEM

fka

Vehicle Class	Weight Saving	Engine Power [kW]	Fuel Consumption			Vehicle Weight			WEV
			absolute [l/100km]	Reduction [l/100km]	Reduction [%]	absolute [kg]	Reduction [kg]	Reduction [%]	
Compact Class	-	85	6.40	-	0.0	1260	-	0.0	**-**
	Min WS	85	6.25	0.15	2.3	1166	94	7.5	**0.31**
	Max WS	85	6.11	0.29	4.5	1073	187	14.8	**0.30**
	Min WS	79	6.13	0.27	4.2	1166	94	7.5	**0.56**
	Max WS	74	5.87	0.52	8.1	1073	187	14.8	**0.55**
Middle-Sized Car	-	181	8.07	-	0.0	1640	-	0.0	**-**
	Min WS	181	7.90	0.17	2.1	1536	104	6.3	**0.33**
	Max WS	181	7.74	0.33	4.1	1432	208	12.7	**0.32**
	Min WS	170	7.71	0.35	4.4	1536	104	6.3	**0.69**
	Max WS	160	7.37	0.70	8.6	1432	208	12.7	**0.68**
SUV	-	235	11.59	-	0.0	2195	-	0.0	**-**
	Min WS	235	11.36	0.23	2.0	2055	140	6.4	**0.31**
	Max WS	235	11.14	0.45	3.8	1914	281	12.8	**0.30**
	Min WS	222	11.17	0.41	3.6	2055	140	6.4	**0.56**
	Max WS	207	10.74	0.85	7.3	1914	281	12.8	**0.57**

Chapter 5: Simulation – Results
Weight Elasticity Values ICEV-D, NEDC

fka

Vehicle Class	Weight Saving	Engine Power [kW]	Fuel Consumption			Vehicle Weight			WEV
			absolute [l/100km]	Reduction [l/100km]	Reduction [%]	absolute [kg]	Reduction [kg]	Reduction [%]	
Compact Class	-	100	5.13	-	0.0	1350	-	0.0	**-**
	Min WS	100	5.00	0.12	2.4	1256	94	7.0	**0.35**
	Max WS	100	4.88	0.25	4.8	1163	187	13.9	**0.35**
	Min WS	94	4.88	0.25	4.9	1256	94	7.0	**0.71**
	Max WS	87	4.62	0.51	9.9	1163	187	13.9	**0.71**
Middle-Sized Car	-	170	7.50	-	0.0	1740	-	0.0	**-**
	Min WS	170	7.37	0.13	1.8	1636	104	6.0	**0.29**
	Max WS	170	7.26	0.24	3.2	1532	208	12.0	**0.27**
	Min WS	161	7.14	0.36	4.8	1636	104	6.0	**0.81**
	Max WS	152	6.80	0.71	9.4	1532	208	12.0	**0.79**
SUV	-	220	9.72	-	0.0	2320	-	0.0	**-**
	Min WS	220	9.56	0.16	1.6	2180	140	6.1	**0.27**
	Max WS	220	9.41	0.31	3.2	2039	281	12.1	**0.26**
	Min WS	209	9.31	0.40	4.2	2180	140	6.1	**0.69**
	Max WS	197	8.89	0.83	8.5	2039	281	12.1	**0.71**

Chapter 5: Simulation – Results
Weight Elasticity Values ICEV-D, HYZEM

fka

Vehicle Class	Weight Saving	Engine Power [kW]	Fuel Consumption			Vehicle Weight			WEV
			absolute [l/100km]	Reduction [l/100km]	Reduction [%]	absolute [kg]	Reduction [kg]	Reduction [%]	
Compact Class	-	100	4.93	-	0.0	1350	-	0.0	**-**
	Min WS	100	4.81	0.12	2.4	1256	94	7.0	**0.35**
	Max WS	100	4.70	0.23	4.7	1163	187	13.9	**0.34**
	Min WS	94	4.75	0.18	3.7	1256	94	7.0	**0.54**
	Max WS	87	4.55	0.38	7.7	1163	187	13.9	**0.55**
Middle-Sized Car	-	170	6.15	-	0.0	1740	-	0.0	**-**
	Min WS	170	6.03	0.12	2.0	1636	104	6.0	**0.33**
	Max WS	170	5.90	0.25	4.0	1532	208	12.0	**0.34**
	Min WS	161	5.90	0.24	4.0	1636	104	6.0	**0.66**
	Max WS	152	5.67	0.48	7.8	1532	208	12.0	**0.66**
SUV	-	220	9.13	-	0.0	2320	-	0.0	**-**
	Min WS	220	8.95	0.18	2.0	2180	140	6.1	**0.33**
	Max WS	220	8.77	0.36	3.9	2039	281	12.1	**0.32**
	Min WS	209	8.83	0.30	3.3	2180	140	6.1	**0.55**
	Max WS	197	8.51	0.62	6.8	2039	281	12.1	**0.56**

Chapter 5: Simulation – Results
Weight Elasticity Values HV-G, NEDC

fka

Vehicle Class	Weight Saving	Engine Power [kW]	Motor Power [kW]	Fuel Consumption			Vehicle Weight			WEV
				absolute [l/100km]	Reduction [l/100km]	Reduction [%]	absolute [kg]	Reduction [kg]	Reduction [%]	
Compact Class	-	85	20	4.52	-	0.0	1335	-	0.0	**-**
	Min WS	85	20	4.39	0.13	2.9	1241	94	7.0	**0.42**
	Max WS	85	20	4.28	0.24	5.3	1148	187	14.0	**0.37**
	Min WS	80	19	4.35	0.17	3.9	1241	94	7.0	**0.55**
	Max WS	75	18	4.15	0.37	8.2	1148	187	14.0	**0.58**
Middle-Sized Car	-	181	30	6.23	-	0.0	1752	-	0.0	**-**
	Min WS	181	30	6.05	0.18	2.9	1648	104	5.9	**0.48**
	Max WS	181	30	5.78	0.45	7.2	1544	208	11.9	**0.61**
	Min WS	172	29	5.96	0.27	4.4	1648	104	5.9	**0.74**
	Max WS	161	27	5.66	0.57	9.2	1544	208	11.9	**0.78**
SUV	-	235	40	8.90	-	0.0	2345	-	0.0	**-**
	Min WS	235	40	8.75	0.15	1.6	2205	140	6.0	**0.28**
	Max WS	235	40	8.58	0.31	3.5	2064	281	12.0	**0.29**
	Min WS	223	38	8.65	0.25	2.8	2205	140	6.0	**0.47**
	Max WS	212	36	8.34	0.56	6.2	2064	281	12.0	**0.52**

Chapter 5: Simulation – Results
Weight Elasticity Values HV-G, HYZEM

fka

Vehicle Class	Weight Saving	Engine Power [kW]	Motor Power [kW]	Fuel Consumption			Vehicle Weight			WEV
				absolute [l/100km]	Reduction [l/100km]	Reduction [%]	absolute [kg]	Reduction [kg]	Reduction [%]	
Compact Class	-	85	20	6.12	-	0.0	1335	-	0.0	**-**
	Min WS	85	20	5.99	0.14	2.3	1241	94	7.0	**0.32**
	Max WS	85	20	5.85	0.27	4.4	1148	187	14.0	**0.32**
	Min WS	80	19	5.92	0.21	3.4	1241	94	7.0	**0.48**
	Max WS	75	18	5.69	0.43	7.0	1148	187	14.0	**0.50**
Middle-Sized Car	-	181	30	7.33	-	0.0	1752	-	0.0	**-**
	Min WS	181	30	7.15	0.18	2.4	1648	104	5.9	**0.40**
	Max WS	181	30	6.96	0.37	5.1	1544	208	11.9	**0.43**
	Min WS	172	29	7.12	0.21	2.8	1648	104	5.9	**0.48**
	Max WS	161	27	6.84	0.49	6.6	1544	208	11.9	**0.56**
SUV	-	235	40	10.92	-	0.0	2345	-	0.0	**-**
	Min WS	235	40	10.70	0.22	2.0	2205	140	6.0	**0.34**
	Max WS	235	40	10.49	0.44	4.0	2064	281	12.0	**0.33**
	Min WS	223	38	10.57	0.35	3.2	2205	140	6.0	**0.54**
	Max WS	212	36	10.21	0.72	6.6	2064	281	12.0	**0.55**

Chapter 5: Simulation – Results
Weight Elasticity Values HV-D, NEDC

fka

Vehicle Class	Weight Saving	Engine Power [kW]	Motor Power [kW]	Fuel Consumption			Vehicle Weight			WEV
				absolute [l/100km]	Reduction [l/100km]	Reduction [%]	absolute [kg]	Reduction [kg]	Reduction [%]	
Compact Class	-	100	20	3.70	-	0.0	1425	-	0.0	**-**
	Min WS	100	20	3.63	0.07	1.9	1331	94	6.6	**0.29**
	Max WS	100	20	3.55	0.15	4.1	1238	187	13.1	**0.31**
	Min WS	94	19	3.58	0.12	3.2	1331	94	6.6	**0.48**
	Max WS	89	18	3.46	0.24	6.4	1238	187	13.1	**0.49**
Middle-Sized Car	-	170	30	4.80	-	0.0	1852	-	0.0	**-**
	Min WS	170	30	4.70	0.09	1.9	1748	104	5.6	**0.35**
	Max WS	170	30	4.60	0.19	4.0	1644	208	11.2	**0.36**
	Min WS	161	28	4.60	0.19	4.0	1748	104	5.6	**0.72**
	Max WS	155	27	4.43	0.37	7.6	1644	208	11.2	**0.68**
SUV	-	220	40	7.01	-	0.0	2470	-	0.0	**-**
	Min WS	220	40	6.84	0.17	2.5	2330	140	5.7	**0.44**
	Max WS	220	40	6.65	0.36	5.1	2189	281	11.4	**0.45**
	Min WS	209	38	6.77	0.24	3.5	2330	140	5.7	**0.61**
	Max WS	198	36	6.53	0.48	6.9	2189	281	11.4	**0.60**

Chapter 5: Simulation – Results
Weight Elasticity Values HV-D, HYZEM

fka

Vehicle Class	Weight Saving	Engine Power [kW]	Motor Power [kW]	Fuel Consumption absolute [l/100km]	Fuel Consumption Reduction [l/100km]	Fuel Consumption Reduction [%]	Vehicle Weight absolute [kg]	Vehicle Weight Reduction [kg]	Vehicle Weight Reduction [%]	WEV
Compact Class	-	100	20	4.59	-	0.0	1425	-	0.0	**-**
	Min WS	100	20	4.49	0.10	2.3	1331	94	6.6	**0.34**
	Max WS	100	20	4.39	0.20	4.4	1238	187	13.1	**0.34**
	Min WS	94	19	4.44	0.15	3.2	1331	94	6.6	**0.49**
	Max WS	89	18	4.30	0.29	6.3	1238	187	13.1	**0.48**
Middle-Sized Car	-	170	30	5.62	-	0.0	1852	-	0.0	**-**
	Min WS	170	30	5.49	0.12	2.2	1748	104	5.6	**0.39**
	Max WS	170	30	5.38	0.24	4.2	1644	208	11.2	**0.38**
	Min WS	161	28	5.43	0.19	3.4	1748	104	5.6	**0.60**
	Max WS	155	27	5.26	0.36	6.5	1644	208	11.2	**0.58**
SUV	-	220	40	8.57	-	0.0	2470	-	0.0	**-**
	Min WS	220	40	8.42	0.15	1.8	2330	140	5.7	**0.31**
	Max WS	220	40	8.24	0.33	3.8	2189	281	11.4	**0.34**
	Min WS	209	38	8.33	0.24	2.8	2330	140	5.7	**0.50**
	Max WS	198	36	8.05	0.52	6.0	2189	281	11.4	**0.53**

Chapter 5: Simulation – Results
Weight Elasticity Values FCV, NEDC

Vehicle Class	Weight Saving	Motor Power [kW]	Fuel Consumption absolute [l/100km]	Fuel Consumption Reduction [l/100km]	Fuel Consumption Reduction [%]	Vehicle Weight absolute [kg]	Vehicle Weight Reduction [kg]	Vehicle Weight Reduction [%]	WEV
Compact Class	-	73	2.71	-	0.0	1335	-	0.0	**-**
	Min WS	73	2.61	0.10	3.8	1241	1241	7.0	**0.53**
	Max WS	73	2.51	0.20	7.3	1148	1148	14.0	**0.52**
	Min WS	68	2.62	0.09	3.3	1241	1241	7.0	**0.47**
	Max WS	64	2.52	0.19	7.0	1148	1148	14.0	**0.50**
Middle-Sized Car	-	131	3.06	-	0.0	1752	-	0.0	**-**
	Min WS	131	2.97	0.09	3.0	1648	104	5.9	**0.50**
	Max WS	131	2.88	0.18	5.8	1544	208	11.9	**0.49**
	Min WS	123	2.95	0.11	3.7	1648	104	5.9	**0.62**
	Max WS	116	2.83	0.23	7.6	1544	208	11.9	**0.64**
SUV	-	194	4.15	-	0.0	2345	-	0.0	**-**
	Min WS	194	4.04	0.12	2.9	2205	140	6.0	**0.48**
	Max WS	194	3.92	0.24	5.7	2064	281	12.0	**0.47**
	Min WS	184	4.00	0.15	3.7	2205	140	6.0	**0.62**
	Max WS	173	3.86	0.29	7.1	2064	281	12.0	**0.59**

results in gasoline equivalent: LHV of gasoline 42500 kJ/kg, density: 0.75 kg/l

Chapter 5: Simulation – Results
Weight Elasticity Values FCV, HYZEM

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Vehicle Class	Weight Saving	Motor Power [kW]	Fuel Consumption			Vehicle Weight			WEV
			absolute [l/100km]	Reduction [l/100km]	Reduction [%]	absolute [kg]	Reduction [kg]	Reduction [%]	
Compact Class	-	73	3.52	-	0.0	1335	-	0.0	**-**
	Min WS	73	3.40	0.12	3.5	1241	94	7.0	**0.50**
	Max WS	73	3.28	0.24	6.9	1148	187	14.0	**0.49**
	Min WS	68	3.46	0.07	2.0	1241	94	7.0	**0.28**
	Max WS	64	3.37	0.15	4.4	1148	187	14.0	**0.31**
Middle-Sized Car	-	131	3.54	-	0.0	1752	-	0.0	**-**
	Min WS	131	3.43	0.11	3.0	1648	104	5.9	**0.51**
	Max WS	131	3.33	0.21	6.0	1544	208	11.9	**0.51**
	Min WS	123	3.44	0.10	2.8	1648	104	5.9	**0.48**
	Max WS	116	3.33	0.21	6.0	1544	208	11.9	**0.50**
SUV	-	194	5.09	-	0.0	2345	-	0.0	**-**
	Min WS	194	4.95	0.14	2.8	2205	140	6.0	**0.46**
	Max WS	194	4.81	0.28	5.5	2064	281	12.0	**0.46**
	Min WS	184	4.94	0.15	2.9	2205	140	6.0	**0.48**
	Max WS	173	4.81	0.28	5.4	2064	281	12.0	**0.45**

results in gasoline equivalent: LHV of gasoline 42500 kJ/kg, density: 0.75 kg/l

Chapter 5: Simulation – Results
Overview of all WEVs

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Vehicle Class	Weight Saving	Engine Power [kW]	NEDC ICEV-G	NEDC ICEV-D	NEDC HV-G	NEDC HV-D	NEDC FC	HYZEM ICEV-G	HYZEM ICEV-D	HYZEM HV-G	HYZEM HV-D	HYZEM FC
Compact Class Car	Min WS	same as base	0.27	0.35	0.42	0.29	0.53	0.31	0.35	0.32	0.34	0.50
	Max WS	same as base	0.26	0.35	0.37	0.31	0.52	0.30	0.34	0.32	0.34	0.49
	Min WS	re-sized 1	0.69	0.71	0.55	0.48	0.47	0.56	0.54	0.48	0.49	0.28
	Max WS	re-sized 2	0.66	0.71	0.58	0.49	0.50	0.55	0.55	0.50	0.48	0.31
Middle-Sized Car	Min WS	same as base	0.20	0.29	0.48	0.35	0.50	0.33	0.33	0.40	0.39	0.51
	Max WS	same as base	0.19	0.27	0.61	0.36	0.49	0.32	0.34	0.43	0.38	0.51
	Min WS	re-sized 1	0.84	0.81	0.74	0.72	0.61	0.69	0.66	0.48	0.60	0.48
	Max WS	re-sized 2	0.81	0.79	0.78	0.68	0.63	0.68	0.66	0.56	0.58	0.50
SUV	Min WS	same as base	0.25	0.27	0.28	0.44	0.48	0.31	0.33	0.34	0.31	0.46
	Max WS	same as base	0.23	0.26	0.29	0.45	0.47	0.30	0.32	0.33	0.34	0.46
	Min WS	re-sized 1	0.72	0.69	0.47	0.61	0.61	0.56	0.55	0.54	0.50	0.48
	Max WS	re-sized 2	0.75	0.71	0.52	0.60	0.58	0.57	0.56	0.55	0.53	0.45

Chapter 5: Simulation – Results
Overview of all Powertrain Technologies in the Compact Class, NEDC

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Powertrain Technology	Weight Saving	Engine / Motor Power	Fuel Consumption			Vehicle Weight			WEV
			absolute [l/100km]	Reduction [l/100km]	Reduction [%]	absolute [kg]	Reduction [kg]	Reduction [%]	
ICEV-G	-	base	6.27	-	0.0	1260	-	0.0	**-**
	Min WS	same as base	6.14	0.12	2.0	1166	94	7.5	**0.27**
	Max WS	same as base	6.02	0.24	3.9	1073	187	14.8	**0.26**
	Min WS	downsized 1	5.94	0.32	5.2	1166	94	7.5	**0.69**
	Max WS	downsized 2	5.65	0.61	9.8	1073	187	14.8	**0.66**
ICEV-D	-	base	5.13	-	0.0	1350	-	0.0	**-**
	Min WS	same as base	5.00	0.12	2.4	1256	94	7.0	**0.35**
	Max WS	same as base	4.88	0.25	4.8	1163	187	13.9	**0.35**
	Min WS	downsized 1	4.88	0.25	4.9	1256	94	7.0	**0.71**
	Max WS	downsized 2	4.62	0.51	9.9	1163	187	13.9	**0.71**
HV-G	-	base	4.52	-	0.0	1335	-	0.0	**-**
	Min WS	same as base	4.39	0.13	2.9	1241	94	7.0	**0.42**
	Max WS	same as base	4.28	0.24	5.3	1148	187	14.0	**0.37**
	Min WS	downsized 1	4.35	0.17	3.9	1241	94	7.0	**0.55**
	Max WS	downsized 2	4.15	0.37	8.2	1148	187	14.0	**0.58**
HV-D	-	base	3.70	-	0.0	1425	-	0.0	**-**
	Min WS	same as base	3.63	0.07	1.9	1331	94	6.6	**0.29**
	Max WS	same as base	3.55	0.15	4.1	1238	187	13.1	**0.31**
	Min WS	downsized 1	3.58	0.12	3.2	1331	94	6.6	**0.48**
	Max WS	downsized 2	3.46	0.24	6.4	1238	187	13.1	**0.49**
Fuel Cell	-	base	2.71	-	0.0	1335	-	0.0	**-**
	Min WS	same as base	2.61	0.10	3.8	1241	94	7.0	**0.53**
	Max WS	same as base	2.51	0.20	7.3	1148	187	14.0	**0.52**
	Min WS	downsized 1	2.62	0.09	3.3	1241	94	7.0	**0.47**
	Max WS	downsized 2	2.52	0.19	7.0	1148	187	14.0	**0.50**

Chapter 5: Simulation – Results
Overview of all Powertrain Technologies in the Compact Class, HYZEM

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Powertrain Technology	Weight Saving	Engine / Motor Power	Fuel Consumption			Vehicle Weight			WEV
			absolute [l/100km]	Reduction [l/100km]	Reduction [%]	absolute [kg]	Reduction [kg]	Reduction [%]	
ICEV-G	-	base	6.40	-	0.0	1260	-	0.0	**-**
	Min WS	same as base	6.25	0.15	2.3	1166	94	7.5	**0.31**
	Max WS	same as base	6.11	0.29	4.5	1073	187	14.8	**0.30**
	Min WS	downsized 1	6.13	0.27	4.2	1166	94	7.5	**0.56**
	Max WS	downsized 2	5.87	0.52	8.1	1073	187	14.8	**0.55**
ICEV-D	-	base	4.93	-	0.0	1350	-	0.0	**-**
	Min WS	same as base	4.81	0.12	2.4	1256	94	7.0	**0.35**
	Max WS	same as base	4.70	0.23	4.7	1163	187	13.9	**0.34**
	Min WS	downsized 1	4.75	0.18	3.7	1256	94	7.0	**0.54**
	Max WS	downsized 2	4.55	0.38	7.7	1163	187	13.9	**0.55**
HV-G	-	base	6.12	-	0.0	1335	-	0.0	**-**
	Min WS	same as base	5.99	0.14	2.3	1241	94	7.0	**0.32**
	Max WS	same as base	5.85	0.27	4.4	1148	187	14.0	**0.32**
	Min WS	downsized 1	5.92	0.21	3.4	1241	94	7.0	**0.48**
	Max WS	downsized 2	5.69	0.43	7.0	1148	187	14.0	**0.50**
HV-D	-	base	4.59	-	0.0	1425	-	0.0	**-**
	Min WS	same as base	4.49	0.10	2.3	1331	94	6.6	**0.34**
	Max WS	same as base	4.39	0.20	4.4	1238	187	13.1	**0.34**
	Min WS	downsized 1	4.44	0.15	3.2	1331	94	6.6	**0.49**
	Max WS	downsized 2	4.30	0.29	6.3	1238	187	13.1	**0.48**
Fuel Cell	-	base	3.52	-	0.0	1335	-	0.0	**-**
	Min WS	same as base	3.40	0.12	3.5	1241	94	7.0	**0.50**
	Max WS	same as base	3.28	0.24	6.9	1148	187	14.0	**0.49**
	Min WS	downsized 1	3.46	0.07	2.0	1241	94	7.0	**0.28**
	Max WS	downsized 2	3.37	0.15	4.4	1148	187	14.0	**0.31**

Chapter 5: Simulation – Results
Overview of all Powertrain Technologies in the Middle-Sized Class, NEDC

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Powertrain Technology	Weight Saving	Engine / Motor Power	Fuel Consumption absolute [l/100km]	Fuel Consumption Reduction [l/100km]	Fuel Consumption Reduction [%]	Vehicle Weight absolute [kg]	Vehicle Weight Reduction [kg]	Vehicle Weight Reduction [%]	WEV
ICEV-G	-	base	9.66	-	0.0	1640	-	0.0	**-**
	Min WS	same as base	9.54	0.12	1.3	1536	104	6.3	**0.20**
	Max WS	same as base	9.43	0.23	2.4	1432	208	12.7	**0.19**
	Min WS	downsized 1	9.15	0.52	5.3	1536	104	6.3	**0.84**
	Max WS	downsized 2	8.67	1.00	10.3	1432	208	12.7	**0.81**
ICEV-D	-	base	7.50	-	0.0	1740	-	0.0	**-**
	Min WS	same as base	7.37	0.13	1.8	1636	104	6.0	**0.29**
	Max WS	same as base	7.26	0.24	3.2	1532	208	12.0	**0.27**
	Min WS	downsized 1	7.14	0.36	4.8	1636	104	6.0	**0.81**
	Max WS	downsized 2	6.80	0.71	9.4	1532	208	12.0	**0.79**
HV-G	-	base	6.23	-	0.0	1752	-	0.0	**-**
	Min WS	same as base	6.05	0.18	2.9	1648	104	5.9	**0.48**
	Max WS	same as base	5.78	0.45	7.2	1544	208	11.9	**0.61**
	Min WS	downsized 1	5.96	0.27	4.4	1648	104	5.9	**0.74**
	Max WS	downsized 2	5.66	0.57	9.2	1544	208	11.9	**0.78**
HV-D	-	base	4.80	-	0.0	1852	-	0.0	**-**
	Min WS	same as base	4.70	0.09	1.9	1748	104	5.6	**0.35**
	Max WS	same as base	4.60	0.19	4.0	1644	208	11.2	**0.36**
	Min WS	downsized 1	4.60	0.19	4.0	1748	104	5.6	**0.72**
	Max WS	downsized 2	4.43	0.37	7.6	1644	208	11.2	**0.68**
Fuel Cell	-	base	3.06	-	0.0	1752	-	0.0	**-**
	Min WS	same as base	2.97	0.09	3.0	1648	104	5.9	**0.50**
	Max WS	same as base	2.88	0.18	5.8	1544	208	11.9	**0.49**
	Min WS	downsized 1	2.95	0.11	3.7	1648	104	5.9	**0.62**
	Max WS	downsized 2	2.83	0.23	7.6	1544	208	11.9	**0.64**

Chapter 5: Simulation – Results
Overview of all Powertrain Technologies in the Middle-Sized Class, HYZEM

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Powertrain Technology	Weight Saving	Engine / Motor Power	Fuel Consumption absolute [l/100km]	Fuel Consumption Reduction [l/100km]	Fuel Consumption Reduction [%]	Vehicle Weight absolute [kg]	Vehicle Weight Reduction [kg]	Vehicle Weight Reduction [%]	WEV
ICEV-G	-	base	8.07	-	0.0	1640	-	0.0	**-**
	Min WS	same as base	7.90	0.17	2.1	1536	104	6.3	**0.33**
	Max WS	same as base	7.74	0.33	4.1	1432	208	12.7	**0.32**
	Min WS	downsized 1	7.71	0.35	4.4	1536	104	6.3	**0.69**
	Max WS	downsized 2	7.37	0.70	8.6	1432	208	12.7	**0.68**
ICEV-D	-	base	6.15	-	0.0	1740	-	0.0	**-**
	Min WS	same as base	6.03	0.12	2.0	1636	104	6.0	**0.33**
	Max WS	same as base	5.90	0.25	4.0	1532	208	12.0	**0.34**
	Min WS	downsized 1	5.90	0.24	4.0	1636	104	6.0	**0.66**
	Max WS	downsized 2	5.67	0.48	7.8	1532	208	12.0	**0.66**
HV-G	-	base	7.33	-	0.0	1752	-	0.0	**-**
	Min WS	same as base	7.15	0.18	2.4	1648	104	5.9	**0.40**
	Max WS	same as base	6.96	0.37	5.1	1544	208	11.9	**0.43**
	Min WS	downsized 1	7.12	0.21	2.8	1648	104	5.9	**0.48**
	Max WS	downsized 2	6.84	0.49	6.6	1544	208	11.9	**0.56**
HV-D	-	base	5.62	-	0.0	1852	-	0.0	**-**
	Min WS	same as base	5.49	0.12	2.2	1748	104	5.6	**0.39**
	Max WS	same as base	5.38	0.24	4.2	1644	208	11.2	**0.38**
	Min WS	downsized 1	5.43	0.19	3.4	1748	104	5.6	**0.60**
	Max WS	downsized 2	5.26	0.36	6.5	1644	208	11.2	**0.58**
Fuel Cell	-	base	3.54	-	0.0	1752	-	0.0	**-**
	Min WS	same as base	3.43	0.11	3.0	1648	104	5.9	**0.51**
	Max WS	same as base	3.33	0.21	6.0	1544	208	11.9	**0.51**
	Min WS	downsized 1	3.44	0.10	2.8	1648	104	5.9	**0.48**
	Max WS	downsized 2	3.33	0.21	6.0	1544	208	11.9	**0.50**

Chapter 5: Simulation – Results
Overview of all Powertrain Technologies in SUV, NEDC

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Powertrain Technology	Weight Saving	Engine / Motor Power	Fuel Consumption absolute [l/100km]	Fuel Consumption Reduction [l/100km]	Fuel Consumption Reduction [%]	Vehicle Weight absolute [kg]	Vehicle Weight Reduction [kg]	Vehicle Weight Reduction [%]	WEV
ICEV-G	-	base	13.69	-	0.0	2195	-	0.0	**-**
	Min WS	same as base	13.48	0.21	1.6	2055	140	6.4	**0.25**
	Max WS	same as base	13.29	0.41	3.0	1914	281	12.8	**0.23**
	Min WS	downsized 1	13.07	0.63	4.6	2055	140	6.4	**0.72**
	Max WS	downsized 2	12.38	1.32	9.6	1914	281	12.8	**0.75**
ICEV-D	-	base	9.72	-	0.0	2320	-	0.0	**-**
	Min WS	same as base	9.56	0.16	1.6	2180	140	6.1	**0.27**
	Max WS	same as base	9.41	0.31	3.2	2039	281	12.1	**0.26**
	Min WS	downsized 1	9.31	0.40	4.2	2180	140	6.1	**0.69**
	Max WS	downsized 2	8.89	0.83	8.5	2039	281	12.1	**0.71**
HV-G	-	base	8.90	-	0.0	2345	-	0.0	**-**
	Min WS	same as base	8.75	0.15	1.6	2205	140	6.0	**0.28**
	Max WS	same as base	8.58	0.31	3.5	2064	281	12.0	**0.29**
	Min WS	downsized 1	8.65	0.25	2.8	2205	140	6.0	**0.47**
	Max WS	downsized 2	8.34	0.56	6.2	2064	281	12.0	**0.52**
HV-D	-	base	7.01	-	0.0	2470	-	0.0	**-**
	Min WS	same as base	6.84	0.17	2.5	2330	140	5.7	**0.44**
	Max WS	same as base	6.65	0.36	5.1	2189	281	11.4	**0.45**
	Min WS	downsized 1	6.77	0.24	3.5	2330	140	5.7	**0.61**
	Max WS	downsized 2	6.53	0.48	6.9	2189	281	11.4	**0.60**
Fuel Cell	-	base	4.15	-	0.0	2345	-	0.0	**-**
	Min WS	same as base	4.04	0.12	2.9	2205	140	6.0	**0.48**
	Max WS	same as base	3.92	0.24	5.7	2064	281	12.0	**0.47**
	Min WS	downsized 1	4.00	0.15	3.7	2205	140	6.0	**0.62**
	Max WS	downsized 2	3.86	0.29	7.1	2064	281	12.0	**0.59**

Chapter 5: Simulation – Results
Overview of All Powertrain Technologies in SUV, HYZEM

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Powertrain Technology	Weight Saving	Engine / Motor Power	Fuel Consumption absolute [l/100km]	Fuel Consumption Reduction [l/100km]	Fuel Consumption Reduction [%]	Vehicle Weight absolute [kg]	Vehicle Weight Reduction [kg]	Vehicle Weight Reduction [%]	WEV
ICEV-G	-	base	11.59	-	0.0	2195	-	0.0	**-**
	Min WS	same as base	11.36	0.23	2.0	2055	140	6.4	**0.31**
	Max WS	same as base	11.14	0.45	3.8	1914	281	12.8	**0.30**
	Min WS	downsized 1	11.17	0.41	3.6	2055	140	6.4	**0.56**
	Max WS	downsized 2	10.74	0.85	7.3	1914	281	12.8	**0.57**
ICEV-D	-	base	9.13	-	0.0	2320	-	0.0	**-**
	Min WS	same as base	8.95	0.18	2.0	2180	140	6.1	**0.33**
	Max WS	same as base	8.77	0.36	3.9	2039	281	12.1	**0.32**
	Min WS	downsized 1	8.83	0.30	3.3	2180	140	6.1	**0.55**
	Max WS	downsized 2	8.51	0.62	6.8	2039	281	12.1	**0.56**
HV-G	-	base	10.92	-	0.0	2345	-	0.0	**-**
	Min WS	same as base	10.70	0.22	2.0	2205	140	6.0	**0.34**
	Max WS	same as base	10.49	0.44	4.0	2064	281	12.0	**0.33**
	Min WS	downsized 1	10.57	0.35	3.2	2205	140	6.0	**0.54**
	Max WS	downsized 2	10.21	0.72	6.6	2064	281	12.0	**0.55**
HV-D	-	base	8.57	-	0.0	2470	-	0.0	**-**
	Min WS	same as base	8.42	0.15	1.8	2330	140	5.7	**0.31**
	Max WS	same as base	8.24	0.33	3.8	2189	281	11.4	**0.34**
	Min WS	downsized 1	8.33	0.24	2.8	2330	140	5.7	**0.50**
	Max WS	downsized 2	8.05	0.52	6.0	2189	281	11.4	**0.53**
Fuel Cell	-	base	5.09	-	0.0	2345	-	0.0	**-**
	Min WS	same as base	4.95	0.14	2.8	2205	140	6.0	**0.46**
	Max WS	same as base	4.81	0.28	5.5	2064	281	12.0	**0.46**
	Min WS	downsized 1	4.94	0.15	2.9	2205	140	6.0	**0.48**
	Max WS	downsized 2	4.81	0.28	5.4	2064	281	12.0	**0.45**

Chapter 5: Simulation – Results Summary

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- At 10 % weight saving and <u>without</u> powertrain re-sizing the percentage fuel consumption reductions are as follows:

	NEDC ICEV-G	NEDC ICEV-D	NEDC HV-G	NEDC HV-D	NEDC FCV	HYZEM ICEV-G	HYZEM ICEV-D	HYZEM HV-G	HYZEM HV-D	HYZEM FCV
Compact Class	-2.6 %	-3.5 %	-3.9 %	-3.1 %	-5.3 %	-3.1 %	-3.4 %	-3.2 %	-3.4 %	-4.9 %
Mid-Size Class	-1.9 %	-2.7 %	-5.8 %	-3.6 %	-4.9 %	-3.2 %	-3.4 %	-4.2 %	-3.8 %	-5.1 %
SUV	-2.4 %	-2.6 %	-2.9 %	-4.5 %	-4.7 %	-3.0 %	-3.2 %	-3.4 %	-3.3 %	-4.6 %

- At 10 % weight saving and <u>with</u> powertrain re-sizing the percentage fuel consumption reductions are as follows:

	NEDC ICEV-G	NEDC ICEV-D	NEDC HV-G	NEDC HV-D	NEDC FCV	HYZEM ICEV-G	HYZEM ICEV-D	HYZEM HV-G	HYZEM HV-D	HYZEM FCV
Compact Class	-6.8 %	-7.1 %	-5.7 %	-4.9 %	-4.9 %	-5.5 %	-5.5 %	-4.9 %	-4.8 %	-3.0 %
Mid-Size Class	-8.2 %	-7.9 %	-7.7 %	-7.0 %	-6.3 %	-6.8 %	-6.6 %	-5.4 %	-5.9 %	-5.0 %
SUV	-7.4 %	-7.1 %	-5.1 %	-6.0 %	-5.9 %	-5.7 %	-5.6 %	-5.5 %	-5.2 %	-4.6 %