STRATEGIC ORIENTATION OF AUTOMOTIVE SUPPLIERS - THE CASE STUDY OF THE HYBRID POWERTRAIN VALUE CHAIN

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ABSTRACT

The aim of the thesis is to provide a comprehensive study that describes the forces determining how automotive suppliers will have to strategically orient their companies. The work is designed to be of value both for employees in management and for employees in technical functions.

Due to the hybridization of the automotive powertrain many amendments will occur in the coming years. Not only because new components must be supplied and further developed, also the shape of the supply chain as we know it will look different in ten years. For this reason, the thesis raises some hypotheses. If it comes to a hybridization rate above 50% of new passenger cars by 2020, then powertrain components, which are now essential for the differentiation of a vehicle brand, will be only purchased parts. Moreover, if there is such a strong electrification of the drivetrain, the gradual market launch of modular designed powertrain components is expected by reason of higher flexibility and cost advantages.

To support the hypothesis the supply chain and the possibilities for its improvement are explained first. Furthermore, the powertrain components of the hybrid vehicle are described. This includes engine, transmission, electric motor, control strategy, energy storage system and additionally power electronics. Subsequently, fundamental aspects of hybrid vehicles are discussed. Based on that, three case studies are presented for those hybrid concepts that have the greatest chance of success. Finally it is shown, at which stage of development the hybrid technology currently resides and how it could develop up to 2020.

To validate the hypotheses a survey of international specialists, who work in the automotive industry, was conducted. The analysis shows, however, that even these experts, who have been in the industry for many years, do not agree about where the development goes. Consequently, the assumptions are not clearly confirmed. The hypothesis that there will be very few engine producers in ten years, which sell their products to other OEMs, was rejected by the respondents. The trend towards modular design is acknowledged. The financial winners and losers crystallized out clearly in the survey and approve the assumptions of the thesis.

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ACRONYMS

AC	*Alternating Current*
AER	*All Electric Range*
AT	*Automatic Transmission*
B	*Brake*
b-emf	*Back Electromotive Force*
BLDC	*Brushless Direct Current*
C	*Clutch*
CD	*Charge-Depleting*
CDR	*Charge-Depleting Range*
Com	*Commodity*
CoO_2	*Cobalt-Oxide*
CS	*Charge-Sustaining*
C-S	*Control Strategy*
CVT	*Continuous Variable Transmission*
DC	*Direct Current*
DCT	*Dual Clutch Transmission*
DIP	*Driver's Intention Predictor*
DOD	*Depth of Discharge*
DP	*Dynamic Programming*
DSP	*Digital Signal Processor*
EDI	*Electronic Data Interchange*
EM	*Electric Motor*
ESS	*Energy Storage System*
EV	*Electric Vehicle*
EVKM	*Electric Vehicle Kilometres*
F	*One-Way Clutch*
FLC	*Fuzzy Logic Controller*
FRB	*Fuzzy Rule-based*
GPS	*Global Positioning System*
HCCI	*Homogeneous Charge Compression Ignition*
HEV	*Hybrid Electric Vehicle*
ICE	*Internal Combustion Engine*
IP	*Intellectual Property*
IPM	*Interior Permanent Magnet*
ISA	*Integrated Starter Alternator*
IVT	*Infinitely Variable Transmission*
LiPo	*Lithium Polymer*
L/U	*Lock-Up Clutch*
M/G	*Motor Generator*
mmf	*Magnetic Motive Force*
MnO_2	*Manganese-Oxide*
NOx	*Nitrous Oxides*
OEM	*Original Equipment Manufacturer*
OWC	*One Way Clutch*
PBC	*Power Balance Controller*
PE	*Power Electronics*
PHEV	*Plug-In Hybrid Electric Vehicle*
PM	*Particulate Matter*
PMSM	*Permanent Magnet Synchronous Motor*
PPS	*Peaking Power Source*
S/A	*Starter Alternator*
SOC	*State of Charge*
SOP	*Start of Production*
SRM	*Switched Reluctance Motor*
T	*Transmission (Gearbox)*
TFM	*Transverse Flux Motor*

1. INTRODUCTION

The key to winning in business is getting first to where the value will be generated next.

Since the end of the oil era has already begun, the automotive industry is in very exciting times. The need to achieve cleaner and more fuel efficient vehicles without compromising vehicle utility, performance and driveability is widely recognised. The number of hybrid vehicles and pure electric vehicles is going to increase, but no one can really tell in these uncertain times what powertrain concepts will be enforced in the future. The smartest companies will gain in size during this period of diversification, while others will lose.

According to experts all companies are doomed to extinction which do not recognize that they have to evolve in line with constantly changing markets due to business dynamics. Enterprises which implement the "if it aint´t broke, don´t fix it" attitude to their businesses will be displaced by more resistant and adaptive types of companies. (Camerinelli 2009)

In the automotive industry in the area of powertrain manufacturing not much has changed in the last 100 years. In essence this was always the core competence of vehicle manufacturers, although much has already been outsourced, even complex parts as the navigation system. Due to various influences, especially the hybridization of passenger cars, the hypothesis is that it now comes to big changes. Original equipment manufacturers (OEMs) are going to get powertrain expertise from outside, as technologies become increasingly networked. Where the pressure was already higher, as with trucks with smaller numbers produced, these changes have been revealed. Cummins, for example, manufactures engines already for various truck OEMs. This change will now follow in the car. Internal combustion engines are no longer the only source of motion and must therefore be only efficient, low maintenance and cheap.

In addition, according to a study by the Roland Berger Strategy Consultants (2009) a new market of approximately € 20-50 billion will develop due to the electrification of the drivetrain by 2020. These components now play no significant role, but in the third level of automotive products extremely profitable business areas will be created as shown in Figure 1.

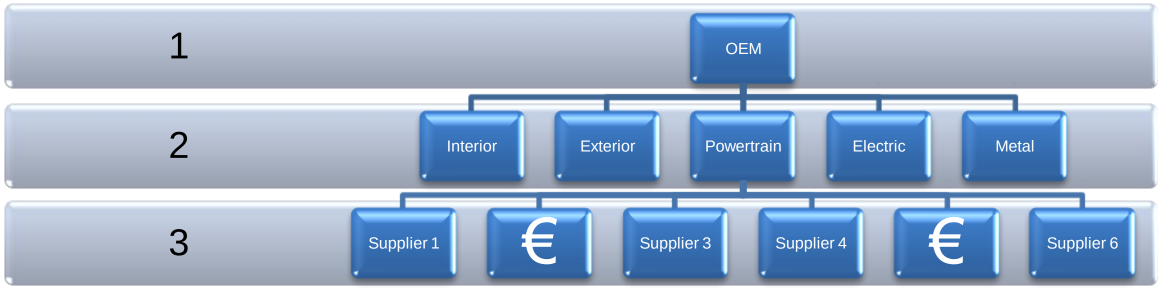


Figure 1: Levels of automotive products

For adaptive suppliers of the new powertrain it is necessary to know what the value chain looks like and what opportunities are there to improve it. Only the cooperation with partners is leading to a strategic advantage. In addition one must know where areas form that can maximize the economic value. Hence detailed knowledge about the elements of the hybrid powertrain is beneficial. The changes will induce a new supplier landscape and generate a new value chain.

1.1 THE NEW VALUE CHAIN

What needs to be changed to earn attractive profits in the value chain of the future?

Due to a new theory of profitability the power to earn high profits shifts away from enterprises which design and assemble the product for end-users to the end of the value chain. In particular to enterprises which supply subsystems with internal architectures that are still technologically interdependent. Suppliers must design modular products, to compete on these new dimensions. The interfaces between the modular components and subsystems have to be specified clearly. In the end, these interfaces converge into industry standards. In addition this enables suppliers to meet the demand of customers in ever smaller market niches by bringing more flexible products and customizing the products. (Christensen, Raynor & Verlinden 2001)

It is obvious that modular architectures will help to introduce new products faster because subsystems can be improved without need to remodel everything. OEMs can mix and match the best components from the best suppliers to respond to the specific needs. Subsequently after modular architectures and the requisite industry standards have been defined, the integration is no longer critical to a suppliers success. In fact, it becomes a competitive disadvantage as regards of price, speed and flexibility. In the 1980s the PC industry decided to outsource components. Some dominant companies which were integrated, could be displaced by specialists that competed horizontally in the value chain. Today IBM and Dell are only designing and assembling. The change in the car industry these days is similar. Vertically integrated automakers have had to break up their value chains so they can more quickly and flexibly incorporate the best components from the best suppliers. GM subsequently spun out its component operations into a separate company, Delphi Automotive Systems, and Ford has spun out its component operations as Visteon. Thus, the same thing is happening to the auto industry that happened to computers, when IBM's PC business out-sourced its microprocessor to Intel and its operating system to Microsoft to become fast and flexible. However, in the process, IBM hung onto where the money had been - the design and assembly of the computer system - and put into business the two companies that were positioned where the money would be. Intel and Microsoft captured the big profits. GM and Ford have just done exactly the same thing. They have spun out the pieces of the value chain where the value will be generated in order to stay where the value generation has been. Hence Delphi and Visteon had more success in the first years. (Christensen & Clayton 2002)

On the other hand, still enormous value can be found and unlocked in the value chain which consists of handling orders, sourcing components, building products, and getting them to customer. The old supply chain got the job done but did not provide the basis for true marketplace differentiation. A new design can set companies apart by making business highly flexible, fast and reliable. This helps to deliver service and customized products in ways that delight customers and keep them coming back for more. New products will be brought to the market faster and orders will be delivered to the end customer quicker. Suppliers and customers are trading over the internet in real time. It is the emerging of a network economy. Information flows are created by using digital technology. This helps to eliminate mountains of aging high-tech inventory by spanning layers of production and distribution. The value generating design to discuss in this thesis combines the executive culture, which speaks the language of business reinvention and strategy and on the other hand the operational world of manufacturing and logistics. Since the border between these two cultures is seldom crossed so many profits remain hidden. In fact therefore it is necessary to treat business design and supply chain in a unified and strategic way. That is to say, the strategy about future powertrain modular design and the supply chain management. (Bovet & Martha 2000)

Other experts propose that by integrating the flows of material, resources, technology and information in a supply chain, the end customer can benefit from a true value creating system. It is unique to treat the topic from an integrated managerial perspective since others have only discussed the individual processes associated with purchasing materials, manufacturing them and shipping them to customers. In more detail the supply business depends on strategic relations with customers to create value nets which are able to provide a competitive edge in the market. (Handfield & Nichols 2002)

Stancu and Varzaru (2008) state that the virtual collaboration is a reality, with enterprises outsourcing a huge range of activities including distribution, manufacturing and design, and others in order to be able to focus on their core competencies. Some OEMs are still opposed to strategic relationships. They prefer to stay on commodity level so that they can push the price. This has the advantage that they control the whole system.

In addition many companies realized that in the future the only real path to obtain sustained growth is to manage costs across multiple companies in the supply chain. To be successful in difficult and also good economic times, enterprises in the supply chain need to simultaneously "step on the gas" or "step on the brakes" in a collaborative manner. After the two phases of industrial renewal where individual functions were optimized and cost and quality was improved between individual organizations a third stage will lead to the competitive advantage. Therefore the management of the entire supply chain needs to have synchronized goals and involved managers in different companies to set a common strategy. (Handfield & Nichols 2002)

The powertrain supplier industry is in a good position since Christensen, Raynor and Verlinden (2001) state that those may capture the most profit who rule the interlaced links in a value chain.

1.2 THE NEW POWERTRAIN

The powertrain is the part of the car responsible for delivering propulsion power at the driver´s request. Conventionally the powertrain consists of an engine, clutch and transmission (Stobard & Childs 2002). However, the thesis will describe the five elements of the future powertrain plus the power electronics, hence:

- Power Electronics (PE)
- Internal Combustion Engine (ICE)
- Transmission (T)
- Electric Machine (EM)
- Control Strategy (C-S)
- Energy Storage System (ESS)

1.3 OBJECTIVES

The aim is to design the thesis for powertrain suppliers to support the strategic orientation in the time horizon of 10 years. The elaboration of the thesis was supported by AVL List. The objective in the first chapter is to explain the necessary steps to improve the value chain. Subsequently the strategic orientation to gain attractive profits will be discussed. Therefore the evolution of the company has to be steered in the right direction. The process to find the way will be shown by narrowing down the wide range of possibilities for future powertrain concepts to a few which are most likely. This has to be done since the automotive industry is very mature. The big majority of car and car-component developments seems to be tending towards very similar solutions. Needless to say it appears very unlikely that a particular powertrain architecture would be suitable for all vehicles in all markets. For this reason, three case studies are performed for two different vehicles, a compact car (two variants: mild hybrid and series parallel full hybrid) and a sedan (one variant: plug-in hybrid). The objective of the final chapter is to provide information which allows a strategic orientation for hybrid powertrain suppliers. It contains data about which parts will generate the highest values in the future. The powertrain landscape will also be categorized in mature and new fields to determine where there is most of the pressure. The strength of the work is not to give information about the possible technologies or the various concepts. This can already be found on the Internet. The strength is to show those concepts and technologies that have the highest chances to be successful in the volume segments. In other words, the thesis should provide information for employees in technical functions and the management which guides the company to success, since the volume segment allows the highest sales figures.

1.4 Limits of Investigation

Although the thesis should show a broad field of powertrain options, it is necessary to make early limitations, since the topic is very extensive. Commercial vehicles, luxury cars, pure electric vehicles, fuel cells and range extender are not treated due to the limited time of the project. These possibilities are expected to have no chance of large volume by 2020.

Attention is focused on hybrid technologies that are combined with diesel or gasoline ICEs. Compression ignition diesel engines already operate at 40% efficiency so that gains to be realised by adding a hybrid system will be marginal for the cost invented. Gasoline engines have more potential to gain efficiency in the next years. (Miller 2004)

The only type of EM excluded in general from hybrid electric vehicle (HEV) application and plug-in hybrid electric vehicle (PHEV) applications is the direct current (DC) motor, since the low efficiency and specific power makes it unattractive for implications in vehicles. However, brushless DC motors are potentially able to make a contribution. (Roland Berger Strategy Consultants 2009)

Post-transmission HEV will not be considered since pre-transmission power split and series parallel designs have pointed out as master implementation in the mid-size and compact segment of passenger vehicles. Sub-compact vehicles, including minivans, are being converted to continuously variable transmission (CVT) hybrids, where the CVT, generally of the belt type, has integrated into it the traction motor/generator (M/G). (Miller 2004)

Mechanical flywheels will not be considered to limit the scope of the investigation.

The limits of investigation, that are shown in Table 1, determine which components are observed.

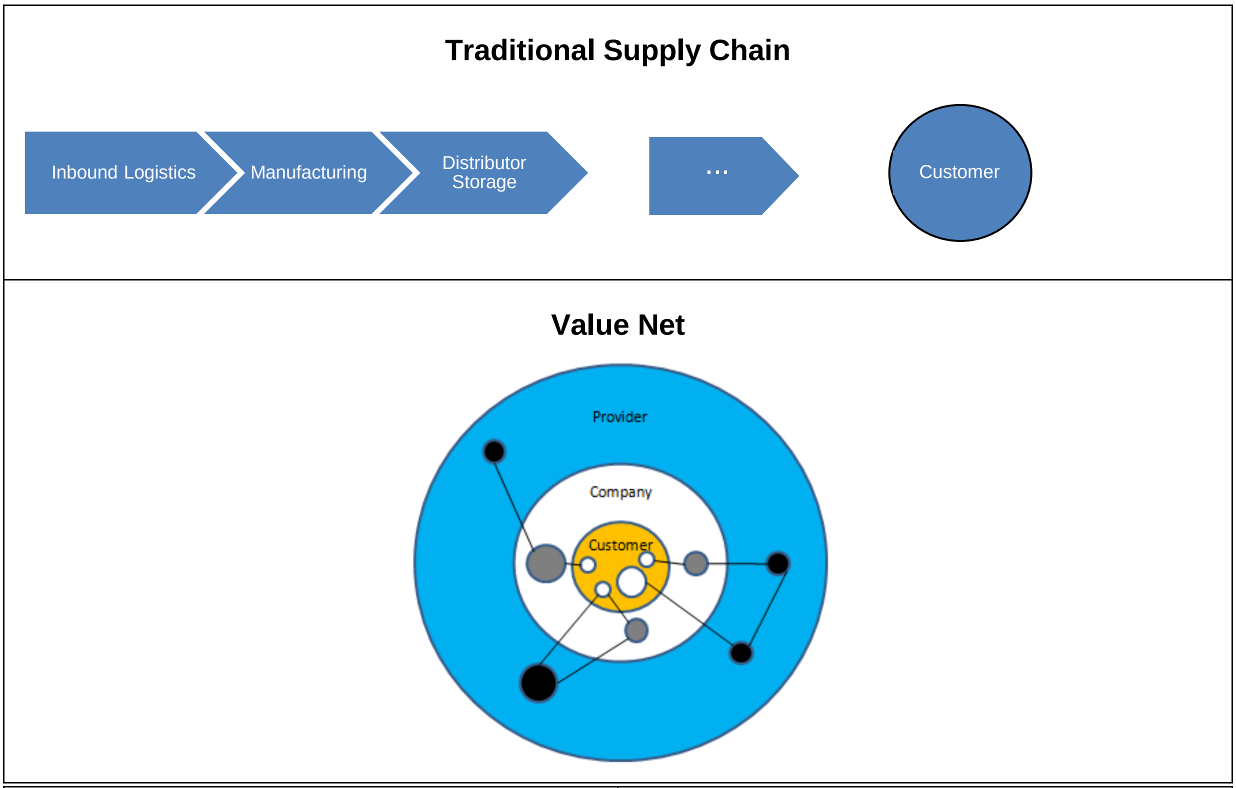
Table 1: Considered and non-considered items

Considered Items	Non-Considered Items
• PHEV and HEV with Gasoline ICE • PHEV and HEV with Diesel ICE	• Commercial Vehicles • Luxury Cars (German D-Segment) • Fuel Cell Vehicles • Pure Electric Vehicles • Post-transmission HEV • Manual Transmission • Flywheel • Range Extender • Gas Engines/Bio Fuel Engines • DC Electric Motors

2. Review of Value Chain in Powertrain

A successful strategy is characterized by operationalizing and internalization of the company. Operationalization means that the strategic intentions are broken down to the business design, in this case the value net. Internalization implies the acceptance of the strategy held by each individual employee. In order to unlock hidden profits it is necessary to create a value net as a business design. It contains all benefits, which are honoured by the customer. This may be directly monetary or indirectly through improving customer-supplier relationship. (Suter 2004)

The value net is built on a digital supply chain to obtain company profitability and also superior customer satisfaction. The biggest difference between the dynamic value net and the conventional supply chain is that the new approach creates a highly-performing network of customer/supplier information flows and partnerships as shown in Figure 2. The supply chain traditionally only produced and pushed the products into distribution channels. (Helaakoski at al. 2006)



Traditional Supply Chain		Value net
• Rigid, Inflexible	⇨	• Agile, scalable
• Any size fits all	⇨	• Customer-aligned
• Analogue	⇨	• Digital
• Slow, static	⇨	• Fast-flow
• Sequential and arm´s length	⇨	• Collaborative and systemic

Figure 2: Traditional supply chain versus value net (Bovet & Martha 2000, p. 6)

The change drivers cause value migration - to wit, the flux of value and profits away from old-fashioned business designs toward better ones developed to maximize usefulness for customers and gains for companies. Bovet & Martha (2000) found that companies are concerned with only three things:

1. The growth rate of profits
2. Capital efficiency
3. Ability to sustain profitable growth

The management consulting company Mercer used these three to develop a framework that defines a value-creating business design consisting of 5 elements. As part of the thesis a partly new business design on basis of the previous mentioned one was developed and is shown in Figure 3 and Figure 4.

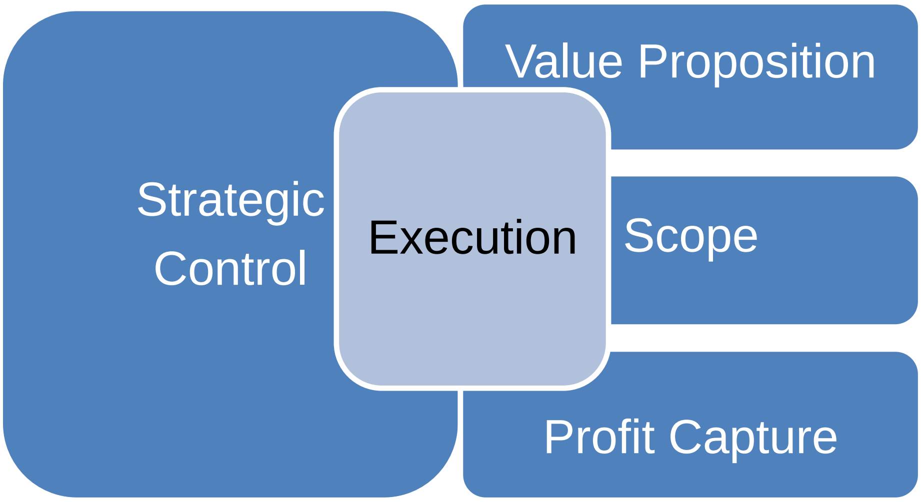


Figure 3: Five elements of value net (Bovet & Martha, 2000, p. 26)

1. Strategy Development
   Strategic Control: Finding of strategic advantages to keep the profit stream over time

2. Operationalization
   2.1. Value proposition: What the company offers to potentially profitable customers.
   2.2. Scope: About the activities that have to be performed, and by whom.
   2.3. Profit capture: Company´s objectives to earn a stunning return on shareholder capital

3. Internalization
   Execution: Human resources and technology that connects all previous elements together

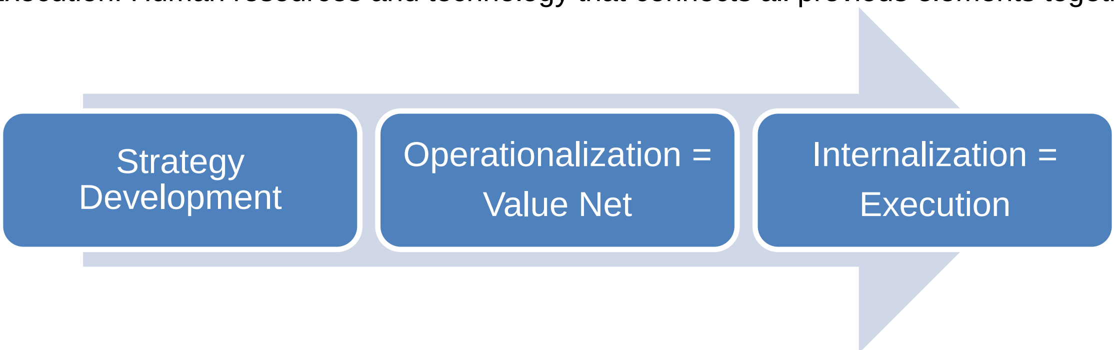


Figure 4: Business design as link between strategy development and strategy implementation

2.1 STRATEGY DEVELOPMENT

Concrete ideas are necessary for the operationalization and the internalization of the strategy. The focus on external growth and the development of the stock price shifts the perspective away from operational business. Though, the understanding of operational business is necessary for strategy development and implementation. The implementation of a business design like the value net is an intervention in the enterprise so that the organization can be aligned to the strategy. In general, the disclosure of the strategy is no competitive disadvantage. A publication on the contrary leads to a company's obligation to implement the strategy effectively. If the implementation succeeds quickly, then the company has often a decisive competitive advantage. Through the involvement of all employees, the condition is created that the strategy is understood and implemented at the base. Thus, the strategy can be internalized, and as behaviour patterns deeply rooted in the company. (Suter 2004)

Strategic control is the element of business design that companies develop to protect their profits over time. Value nets can use the following strategic control mechanism:

- Brand: that provides differentiation in view of the customer
- Provider relationships: collaboration with other suppliers
- Innovative design: to puts the company´s service far ahead
- Low price: that competitors find tough to match

No company is immune to imitation. Not many have patent or copyright protection of its mechanism of strategic control. A brand creates customer loyalty and provides longer-lasting profit protection. An innovation can be replicated and a low price can be matched. Thus, strategic control, like every other element of business design, must continuously change and adapt to current market conditions. (Bovet & Martha 2000, pp. 157-158)

2.1.1 VALUE NET BRAND

A brand is built on consistently superior service, on total solutions, or on the ability to deliver a customized product. Exceptional speed, reliability, convenience, and other service aspects can provide the strong differentiation that every company wants to maintain in the eyes of its customers. When these service qualities become routinely associated with a company´s name, that company enjoys brand power. Over time, the supplier can spend less on customer acquisition, experience fewer customer defections, and charge a premium price relative to competing, unbranded options. (Slywotzky & Morrison 1998)

2.1.2 PROVIDER RELATIONSHIPS

Bovet and Martha (2000, p. 162) claim that 'strong relationships with suppliers and service providers impart strategic control to the extent that those relationships cannot readily be copied'. Investing in deep relationships with carefully selected providers creates a value net that is hard to beat.

2.1.3 INNOVATIVE DESIGN

Being first to market with a new product or technology is a proven strategy for growth and differentiation. Innovation in value net design also confers first-mover advantages. The first company to offer exceptional service levels or customized product at the same prices as mass-produced competing products is able to differentiate itself and gain strategic control for as long as it takes competitors to catch up. In fact, an innovative operating design can be more difficult to replicate than a product or technology innovation. Though, it is important to keep in view how customer expectations, digital technology, competition, and globalization will evolve in the coming years so that the new value net design is most relevant and effective. Information technology will still offer significant opportunities for innovative design in the coming years. (Bovet & Martha 2000, p. 164)

One objective of digitized communication across the value net is to achieve quick and effective transfer of information between customers and suppliers. Supply partners are connected digitally. If the supplier receives an order from the customer it is automatically transferred to the contract manufacturer, to the own assembly area, and to the transport company which picks up and delivers the products. A business culture where information is shared by digital interfaces between supplier substantially reduces process and inventory costs. In addition it improves service reliability and accuracy. The greater impact of digitization, however, comes when companies combine instant information with analytical tools to improve complex decisions. VW supplier use GPS-equipped trucks. It issues a digital parts release to its lead logistics provider, who transmits the pickup sheet to the supplier, receives electronic confirmation, dispatches the truck, and alerts the plant. So, if the manufacturer is waiting for a certain component, plant personnel can type the component number into the system and find out from which truck it will be delivered and at what time it will arrive. This will boost the built-to-order production. (Bovet & Martha 2000).

2.1.4 Low Price

Companies that can deliver products to customers at dramatically lower prices than competitors have distinct competitive advantages, all else being equal. However, low price alone is a relatively weak source of strategic control because low price, driven by low costs, is a difficult strategy for any business to defend over time. One manufacturer may drive low prices through high volume buying. A start-up may slash the overhead structure. A third company may leverage the scale economies of partners by orchestrating its supplier network. (Bovet & Martha 2000, pp. 165-166)

2.2 Operationalization

2.2.1 Value Proposition

It is necessary to spot the opportunity before competitors do and to make the move while others still think it cannot be done. Due to the new theory of profitability the power to earn high profits shifts to suppliers that offer modular powertrain components.

Hence the following four headings found by Bovet and Martha (2000) cover a wide range of requirements:

- Super service (especially speed and reliability),
- Convenient solutions
- Customization
- Modularization

2.2.1.1 Super Service

Super service especially means to be quick and reliable. It could be an easy return, in formations, high availability of products and quality service. The ability to speak languages can also be value-adding. (Gee & Gee 1999)

2.2.1.2 Convenience

Companies that intend to offer convenient solutions must do two things well:
- Pinpoint the convenience needs of the customer and
- Deliver the solution without a slip.

Value nets pinpoint need by capturing critical customer information at each touch points. That means where the company interacts with its customer like the ordering and selection process, tracking of order status, the delivery process, and ongoing maintenance. (Bovet & Martha 2000, p. 46)

2.2.1.3 Customization

Customization allows the purchaser to choose the favoured product- and service characteristic from a set of substantial but controlled choices. The customer benefits by getting exactly what is needed. The provider benefits by avoiding potential high costs because of inaccurate demand forecasting and building to stock. (Bovet & Martha 2000)

2.2.1.4 Modularization

The modular architecture allows the fulfilment of all three aforementioned points like super service, convenience and customization. A powertrain architecture is called modular, if defined interfaces between the components exist, and it works in spite of high variation among the parts. Modular architectures significantly increase the flexibility and form the basis for a volume business in spite of customized mass requirements. It is presumed that high profits will be made in the future by enterprises which supply subsystems and modularized products (Suter 2004).

The implications of these ideas is that the power to achieve appealing benefits moves to those functions where the OEM is not yet satisfied with the operating mode of existing manufactured items. Especially for future powertrain components interdependent integration creates greater opportunities for differentiation and hence value creation. On the other hand the value generation will shift away from activities where the OEM is satisfied because it will become standard. For example internal combustion engines. To compete in this way, car manufacturers can apply modular architectures for their mainstream models. Rather than connect individual components from diverse suppliers, they can assemble modular powertrain components from fewer tier-one suppliers. The architecture within each powertrain component becomes more interdependent as these suppliers work to meet the car manufacturers cost and performance demands. The economics when external interfaces become more modular in several car models will compensate any compromise in performance that might occur. (Christensen, Raynor & Verlinden 2001)

2.2.2 Scope

Bovet and Martha (2000) show that the following three activities are necessary within the value net:

- Production
- Customer choice
- Delivery

In maturing industries, such as automobiles, value-creating activities should not only be performed internally. Companies have to leverage outside capabilities to their advantage by:

- Outsourcing
- Collaborative relationships

2.2.2.1 Production

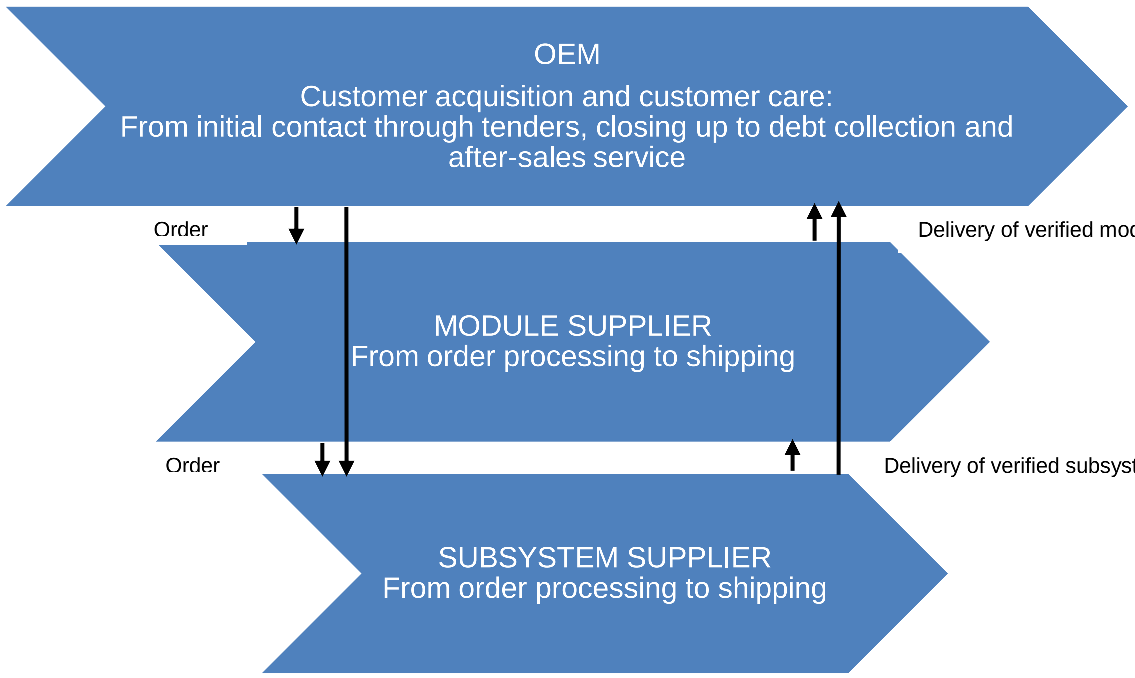


Figure 5: Cascading system for the supply of modules or subsystem (Suter 2004, p. 98)

The company´s production network should be synchronized and efficiently perform together as one integrated unit, even if spread geographically or organizationally. For example, if the customer wants to change the delivery date, the information immediately moves through the value net. Thereby impacting labour- and material requirements, precedence, time-table, and transportation form. In case of a shortage of parts a requirement for a backup supplier is automatically activated and hence their delivery accelerated. All transactions should be done by whomever has the ability to execute them with superior efficiency and with the highest potential for adding value. Hence outsourcing and strategic relationships between OEM, module supplier and subsystem supplier are very important. A model can be seen in Figure 5. Strategic outsourcing can also lead to asset minimization. (Richardson 2000)

2.2.2.2 Customer Choice

Different to traditional supply chains, value nets do not push products and do not operate to satisfy demand forecasts. It is targeted to fill real demand but can do this only if it knows what customers want. In addition the customers desires have to linked to its operating design. A choiceboard overcomes these two constraints. The choiceboard enables a quick two-way conversations between the supplier and customer. In particular it is useful for complex product decision like automobile acquisition. The choiceboard enables to exactly investigate what customers want and to send information digitally to supply partners. It can become the basement essential for knowledge about the customer and for quick turnaround. (Bovet & Martha 2000)

2.2.2.3 Delivery

There are limitless possibilities to add value though a broadly defined delivery process. This is an opportunity to take the ever changing pulse of the customer and to amplify the overall relationship, making delivery an important element of value net scope. For example, batteries can be returned or exchanged at filling stations so that the customer must not take care of it. (Bovet & Martha 2000)

2.2.2.4 Outsourcing

Companies should concentrate on the own core competencies and outsource residual functions. The core skill of a company is the paramount control of the business in terms of competitive key performance parameters such as speed, precision business, quality, service levels or costs. The consequent adjustment of the overall organization with business objectives. Core capabilities, based on the specific control elements of value creation, are protected from imitation, because the building process of skills usually takes several years. In contrast, competencies, which consist primarily of transferable knowledge and skills, provide only little protection of imitation. Technological advantages are often short-lived. Therefore, the success of many mechanical engineers is a result of distinct process control in the engineering and manufacturing sector. The procedural skills are personal or organizational rooted and only transferable by long, enterprise learning. The extension of the core capability to many people can ensure continuity. Otherwise it could go lost quickly due to emigration. (Suter 2004)

When suppliers acquire or extend their operations across borders, the best place to play in the chain of value-adding activities varies. It also changes as company and supplier capabilities evolve, when the ability to communicate in real time improves, and when intercompany relations become more open and collaborative. The supplier can even take over the quality control to the standards of the customer like Cisco suppliers. The extended network of Cisco can be used at the suppliers assembly, and data is transacted directly on Cisco´s quality and operational systems. (Bovet and Martha 2000)

2.2.2.5 Collaborative Relationships

The opportunity for collaboration is great in the automotive industry which is characterized by antagonistic relationships. Especially when the following conditions dominate:

- The supply base is consolidating
- Businesses have become commoditized

2.2.2.5.1 Suppliers

Co-operation should create value for everyone in the net. Supplier collaboration will enable a better service design, improve the inventory management and alleviate product development. A general precondition for collaborative supplier relationships is to reduce the number of suppliers. No company can maintain close and effective relationships with more than a small set of other parties. Once the number of participants exceeds an optimal level, collaboration gives way to transactions. Products should not be shifted from the suppliers to other suppliers immediately. If subsystem suppliers know that it will motivate them to give input into design for serviceability, quality problems, design for manufacturability, solutions to problems, and that helps to improve products and overall services for the customer. Opening up information to suppliers, which is kept internal, and giving them equal access rights to knowledge as the own employees demonstrates the extent to which organizational boundaries must be removed to achieve execution excellence. However, more important than the physical extension of an enterprise is the approach to work close-partnered in long term. Therefore collaborative improvement and mutual trust provides the basis. It is advantageous to understand the partners' business and provide training and supervision to his employees. The co-operation needs to be a real hands-on partnership. (Bovet & Martha 2000)

According to Eisenstein (1998) reduced supplier rationalization the number of automotive suppliers in North America from 30,000 in 1988 to 4,000 in 1998. The outcome of this contraction has been positive: greater information sharing, a higher level of collaboration in product development, stricter standards, and process improvements that have reduced inventories, costs, and cycle times.

2.2.2.5.2 Customers

The most costly customers to serve are those making minimal use of electronic ordering. Hence it is beneficial to build up a digital ordering system to improve the collaboration. It is beneficial to choose partners large enough to accommodate significant increase in production and orders but also those who show that maintaining the relationship is very important to them as well. The agility or flexibility helps ensure that the value net arrangements can last. P&G has set up incentives for customers who agree to take delivery of shipments within two hours or less. It is also possible to provide a bigger time window for the delivery if there is an increased demand and therefore offer a better price to customers who accept. Thus, all needs are met. (Bovet & Martha 2000)

2.2.2.5.3 Competitors

The least intuitive and least explored context for collaborations is that which occurs among competitors. Collaborations with competitors can be mutually beneficial in some cases. Ford, for example, gained scale efficiencies and cost savings through a distribution arrangement with Daimler-Chrysler´s Mopar division. By agreement, the two automakers ship parts to dealers on the same delivery trucks, managed by Exel Logistics. Hence, it is not necessary that each supplier maintains the distinct inventory of replacement parts for the same customer when a third-party stock provider can keep a single storage at one location and much cheaper. Also to solve the customer´s disposal problems could become an income-increasing part of the business. The benefits accruing from competitors working together are also illustrated by the emerging success of a Joint Venture formed by United Airlines, Air Canada, and Lufthansa Technik. In early 1998 these three airlines were carrying $2 billion of parts inventories. The surplus parts were turning over less than once a year. In search of a better solution to this parts inventory problem, the airlines formed AirLiance Materials for the purpose of providing joint management of technical maintenance materials. As of late 1999, more than 100 airlines were on the AirLiance Customer list. The main benefit of the AirLiance venture for the industry as a whole is cost savings resulting from the increased use of pre-owned parts, which AirLiance sells at approximately a 30% discount relative to new OEM list prices. In addition by reductions in overall inventory holdings, and from economies of scale on joint purchasing of new material. This is also possible between suppliers for modulated powertrain parts or between OEM. (Bovet & Martha 2000, pp. 97-98)

2.2.3 Profit Capture

The right mechanism is necessary for capturing profits from an attractive value proposition. According to Bovet and Martha (2000) this can be done by:

1. Generating profitable revenues from enhanced operating capabilities
    a. Super Service
    b. Money in solutions
2. By radically improving a company´s cost and asset positions

2.2.3.1 Super Service

Speed, reliability and convenience is valued by customers and businesses. Each can drive profitable new revenues for an enterprise. (Gee & Gee 1999)

2.2.3.2 Money in Solutions

It is very beneficial to respond to customer demand for broader solutions by expanding from the product base to a business model designed to address a larger portion of customers´ service needs, moving to a higher margin revenue base. Therefore it is necessary to ask what creates utility for the customers. A possibility is to stock parts from competitors, for example different types of batteries. Another way is to be a third-party logistics provider (3PL) to leverages existing capabilities and to earn new revenues. This generates a barrier against the natural cycles of the core business. The supplier can become a integrated provider of logistics services. Integration results in higher turnover for clients, improved service rates, reduced inventory, lower distribution costs and is where the company can add value. (Bovet & Martha 2000)

2.2.3.3 Costs and Assets

An order-of-magnitude reduction in inventory holdings is accomplished by building to order, the consolidation of inventories, substituting physical stocks with detailed information, avoiding complexity, standardizing components (Modularization), and the cooperation with partners for higher reliability.

Sage (2000) states that in the U.S. auto industry stockpiles an estimated $50 billion in finished goods inventory on the way to dealers and in their showrooms each day, although the supply time is about 60 days. High values can be gained by changing this situation. In fact very close co-operation with suppliers enables razor-thin inventory by good information, ensuring supply reliability, reduced complexity and reliance on standard components.

2.2.3.3.1 Information

Obviously, as suppliers get access to actual order or sales data and are allowed to track supply and demand in real time the need for buffer stocks at all levels can be reduced. Therefore it is necessary to work closely with partners to get them to share information.

2.2.3.3.2 Reduced Complexity

The second important factor in shrinking inventory stockpiles is reduced product complexity. With 10% of a company´s total product line often 90% of customer demand is fulfilled. The remaining 90% creates complexity, takes up space and cash in the form of inventory holdings, and adds no value to the vast majority of customers. Complexity reduction is beneficial for mass production and is absolutely essential for a value net design, which must effectively and quickly sort through any set of combinations made available to a customer. Hence companies have to concentrate on a few that are sold most. (Bovet & Martha 2000, pp. 126-127)

2.2.3.3.3 Standard Components

The use of modulated components is also very important for the value net design to reduce stocks. It makes the utilization of equal parts for different automobile producers possible, can flatten the manufacturing curves of upstream suppliers and therefore reduce the stocks and the expenses for parts in the whole system. (Bovet & Martha 2000)

2.2.3.3.4 Building to Order

It is apparent that in the high-tech industries less obsolescence is what improves margins. Product innovation is absolutely critical, the ability to focus on the newest, hottest products translates into superior financial performance. If machines are built to order, there is no finished goods inventory to store, insure, and finance. (Bovet & Martha 2000)

2.2.3.3.5 Leveraging Customer

Companies like Amazon, Dell, and Gateway have been able to minimize or eliminate working capital requirements. They are paid by customers before they have to pay their suppliers. As a result, Amazon operated with negative working capital in its initial years. Customers paid at the time of order, and Amazon held onto their cash for several days before paying suppliers. (Bovet and Martha 2000)

2.3 INTERNALIZATION

Execution links all other design decisions like value proposition, where the company will play in the scope of value net activities, its mechanism of profit capture, and how it will strategically control its position in the market.

Therefore, according to Bovet and Martha (2000) a breakthrough culture is necessary, which comprises:

- Leadership vision
- Entrepreneurial team
- Clear set of goals
- Right people skills for the job

2.3.1 LEADERSHIP VISION

The temerity of the vision used in making an explicit break with former times is one of the chief representative traits of the value net design. The CEO hast to "get it". The executive team has to get it. All people in the company should have an explicit vision and see the advantages of the new business design. The vision has to be customer-inspired. As soon as the leadership has adopted the vision, there is the challenge of getting employees to apply it to constitute the breakthrough culture. (Bovet & Martha 2000)

2.3.2 ENTREPRENEURIAL TEAM

The biggest cradle for changes in companies is the present establishment. This includes the politics, the bureaucracy, the protected lawn, the way people do things around in the company. Bringing an entrepreneurial spirit to all levels of the enterprise and to business partners is a challenge for every organization. Aims and incentives support to make it happen. Whether change happens within the existing companies or via a new one, every successful case of change involves a tightly entrepreneurial team that takes responsibility for every aspect of the mutation. Instead of bureaucracy it is useful to create a strong but small team, that understands the vision. Hence it will identify the right target to build the value net by working across functions. The value net implementation will not be improved by a formal organization structure. (Bovet & Martha 2000)

2.3.3 SIMPLE AND CLEAR GOALS

This could be the importance of speed and reliability that is deeply ingrained in the culture of the company and all its employees. For example mention the goal of shipping 100% complete and error-free orders on time. These simple goals differ from commonly used abstract measures. The formulation should be so that all staff can understand it easily, follow it day by day. Then it will provide immediate performance feedback. It is important to reach commitment and broad based identification with a common goal. For instance if a delivery is determined to depart fully loaded by 5 pm but leaves one hour later, it goes to the books as a total miss. Another way could be to ask one employee each day what the record for consecutive days of 100% on-time shipments is and how many days in a row the company had 100% on-time shipments. If the employee answers these two questions right, he or she will get handed over a € 100 bill. The person can take the money or take one extra day off. This is a way to tell people what the company expects and then reward employees for doing it . Also a bonus for customer satisfaction measured by a scale is possible. Cisco has introduced such a system and motivates employees to think from a customer´s perspective. (Bovet & Martha 2000)

2.3.4 NEW SKILLS

The final key ingredient of the cultural revolution is arming the right people with the right skills. Value nets need intensive collaboration and coordination. Hence most companies need new policies, new processes, and people who can effectively manage these relationships. A value net company may outsource hundreds of millions of dollars worth of production and services, and this requires corresponding management expertise. (Bovet & Martha 2000, p. 192)

2.4 PROSPECTS

The described components of the proposed business design must be considered in every case to generate a value net, but the activities will vary for each company. The strategic development is not something stable that can be determined and worked out point by point. It has to be constantly changed as the economic environment changes.

Recent developments in the automotive industry are currently shaking the well-organized value chain structure, hence the entire industry is facing profound changes. While OEMs focus on the downstream-business, supplier take development, production and logistics challenges of OEMs. In addition supplier take over an incrementally fundamental function in the coordination of complex supply networks. In addition OEMs have to make the right decisions about economic changes because of the hybridization.

Given this change in value structures and the new roles for companies in the automotive industry, a high network capacity becomes a competitive factor. It is a prerequisite in order not to end the market or be taken over by competitors. It also allows to adapt to the changing market demands, strengthen business relationships with key partners and to respond to the market dynamic.

More and more clearly new value-adding models find the way into the auto industry: On one hand, the auto manufacturers are increasingly focusing on marketing and after-sales service since the downstream business promises significantly better returns with lower capital requirements. Hence, by virtue of a studies, the contribution of the OEMs is reduced to an average of € 2670 per vehicle and is connected with the outsourcing of design, production and logistics volumes. This on the other hand increases the value added by their suppliers. On the supplier side first tier suppliers with extensive integration skills through modules and systems control a complex network of subcontractors and take over an increasingly central role in product creation as technology leaders. In extreme cases, the outsourcing trend of OEMs goes so far that the entire development and production of niche models with small volumes are allocated to Tier 0.5 suppliers, such as Porsche to Valmet and BMW to Magna Steyr. The innovation potential of the supply industry reflects in the fact that suppliers will take over about 63% of development costs until 2015, which represents a growth of 70% since 2002. Increased innovation in the supply network leads also to a brain drain of engineers from the manufacturers to the supplier side. (Accenture 2006)

Since the internal optimization potential is largely exhausted in the automotive industry, the overall process management and optimization become the most important starting point for improving the performance of the value net. Prerequisite is a consistent view of organizational interfaces with the objective of optimization of processes and information flows along the entire product life cycle - from the initial concept through product development and vehicle production to the product use phase and subsequent the disposal and recycling.

Development services are increasingly being outsourced to suppliers and engineering service provider, this leads to an increasingly distributed product development. The consequence is that product information throughout the product development has to be exchanged between the development partners, from product specifications to construction drawings and to product data in the form of parts lists. With distributed product development it is also necessary to structure the development more and to define the organizational interfaces to allow for an inter-enterprise project management.

The potential benefits of electronic integration of processes have been recognized by the automotive industry earlier than in other sectors. This has led to the early use of EDI (Electronic Data Interchange). So far, however, even the large OEMs are far away from a worldwide electronic process integration. To cover the process and information need for coordination in the emerging value chain structures, companies should increasingly share documents and management information by electronic data exchange in the future.

To use the internet for electronic co-ordination with external partners, manufacturers and some large Tier supplier created portals for its suppliers and build it steadily. These supplier portals, such as VWGroupSupply.com, are developing very powerful platforms that are built on successively starting from purchasing. Besides the pure information provision increasingly internal applications are involved in these portals, through which external partners can retrieve quality metrics or edit complaints. Thus, the portals will not only support the information-related, but also the reporting- and process-related coordination.

The portal solutions are indeed a convenient solution for operators, but not for the supplier side. For example, a large first-tier supplier, on average, has to serve 30-50 portals and to transfer data from and often in their own systems. The company-specific design and application of different portal technologies increase the cost of training and data maintenance for users. The contractually required short response times, e.g. for comment of amendments, require frequent, sometimes daily or hourly check of the portal content.

It is important to find a solution that is applicable between companies. Such an m: n ability in inter-business relationships is reached only if certain standards and platforms for industry-wide cooperation form out within the net value.

3. REVIEW OF HEV POWERTRAIN

This chapter will explain the technology of the HEV powertrain. According to the AVL definition the hybrid powertrain of vehicles consists of the following five components: Internal combustion engine, transmission, electric motor, control strategy and energy storage system. However, the first section of the chapter describes the power electronics in addition, since it is an increasingly import part due to the electrification of the drivetrain. The last section of the chapter will narrow down these components by explaining how they are implemented in the few HEV architectures that are most likely.

3.1 POWER ELECTRONICS

The electric power necessary for the hybrid propulsion M/G must pass via the power electronics. It is the link from the battery to the electric unit by converting the high voltage of the battery into the alternating current which is needed to run the EM. Hence the power electronics uses information to process power in contrast to control electronics which uses power to process information.

The power electronics of an electric powertrain comprise four main components that can be seen in Figure 6:

- Traction inverter: controls electric motor and provides required power from battery
- Battery charger: connects battery to an external power supply for recharging
- DC/DC converter: provides required power level for standard vehicle electric
- Generator inverter: recharges battery in case a range extender is used on-board

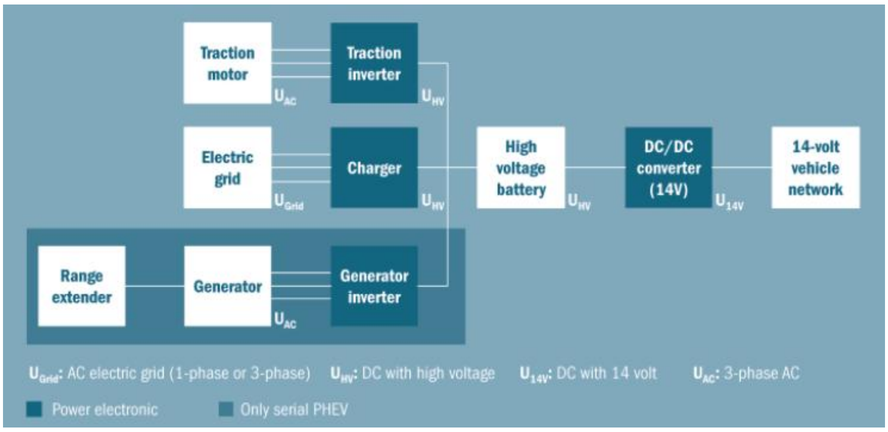


Figure 6: Components of power electronics (Roland Berger Strategy Consultants 2009, p. 41)

3.1.1 TRACTION INVERTER

The electric machines mainly used in vehicles will be alternating current (AC) motors. Hence a traction inverter transforms the high-voltage DC obtained from the energy storage system into AC for the electric motor. The electronic motor controller (similar to an ICE engine management system) which is usually part of the inverter translates the from the gas pedal required power level into the necessary levels of frequency and current amplitude for all three AC phases going to the motor. Three electronic circuits, one for each AC phase, are actually performing the control of current sent to the stator windings. Key components in the windings are and high-power capacitors and semiconductor switches (IGBTs or MOSFETs). The traction inverter is used as well to transform electrical energy from recuperation by the electric motor into DC when braking. The obtained energy recharges the battery. (Roland Berger Strategy Consultants 2009)

3.1.2 Battery Charger

When a PHEV is plugged in the external grid, a battery charger converts the single or three-phase AC supply to the right voltage level necessary for charging the battery. The AC – now at the right voltage level – is rectified through diodes into DC and smoothed out via capacitors. (Roland Berger Strategy Consultants 2009)

3.1.3 DC/DC Converter

The high-power energy storage system in PHEVs delivers power to the standard electric system in the vehicle. The DC/DC converter utilizes semiconductor switches, likewise to the ones in the traction inverter, to transform the energy storage system DC into AC. Then it converts the high voltage level down to the necessary level. Finally, the AC is rectified via diodes into DC and flattened through capacitors. (Roland Berger Strategy Consultants 2009)

3.1.4 Generator Inverter

For HEVs with a combustion engine based range extender a separate generator inverter is necessary to transform the AC, which is delivered by the generator, into DC for reloading the energy storage system while driving. The functionality is alike to the traction inverter in energy recuperation mode. Generator inverters work simply one way, as it were, since they provide a cost and weight reduction over traction converters. (Roland Berger Strategy Consultants 2009)

3.2 Elements of Advanced Powertrain

3.2.1 Internal Combustion Engine

3.2.1.1 Future Trends - Optimization Thermodynamic Efficiency

A higher injection pressure plus multi hole injection nozzles can improve carburetion. Hence the combustion process is improved. Today for diesel and gasoline direct injection an injection pressure of more than 2,000 and 200 bars respectively can be achieved. Engineering developments at an advanced stage increase these pressure levels even further – up to 3,000 bar for diesel. The use of multiple injection pulses per cycle increases the possibility of combustion process control and therefore enables different combustion modes such as improved comfort, higher performance or better fuel economy, depending on the load level. Multiple injection cycles are enabled by the enhanced reaction time of the injector actuators, for example through the replacement of solenoids by piezo actuators. Moreover, direct injection has the positive effect that evaporation heat cools down the cylinder. As a result, higher compression ratios are possible. (Roland Berger Strategy Consultants 2007, p. 32)

3.2.1.1.1 Homogeneous combustion process

Variable valve timing costs about € 100 to € 200, while the cost for variable valve lift technology is € 300 to € 400. First variable valve timings were on the market as mechanical systems in 1992. One example is the system used in the BMW 5-Series in the M50 engine called Vanos system. The engine can run at the optimum operating point by replacing the fixed relationship between the valve opening and the crankshaft's angle and dimensions with a variable one. The next step in variable valve timing technology is variable valve lift. Two technologies currently exist: Fully variable and stepwise variable valve lift. An example of a fully variable valve lift is BMW's valvetronic, which does not require a throttle valve. Stepwise variable valve lifts are currently used by Porsche (dual cam) and by Honda (V-Tec). In the long term even a camless valve actuation with current costs of € 650 is possible. Replacing mechanical or hydraulic actuators with electro-mechanic or electro-hydraulic actuators enables the closing and opening sequences of valves to be freely configured. However, reliability and power demand (> 2 kW) are still an issue, as is cost. Variable valve lift and camless valve timing are therefore not an option for the volume segment. However, the final goal in the homogeneous combustion process in the long run is homogeneous charge compression ignition (HCCI), which is a combination of gasoline and diesel technology and processes. A HCCI diesel engine works with an homogeneous combustion process and is based on self-ignition like a conventional diesel engine. However the fuel-air mixture does not burn in a diffusion flame, but ignites spontaneously in an premixed flame as it does in gasoline engines. This combination results in a nearly total reduction of nitrous oxide (NOx) and particulate matter (PM) emissions and is accompanied with higher fuel efficiency and lower CO_2 emissions. Nevertheless, this process is hard to control outside a certain operating window. If not adequately controlled, the process tends to knock and misfire. A possible countermeasure is pilot injection in certain load levels allowing the combustion process to be timed better and to use "closed loop combustion control" using combustion chamber pressure sensors. (Roland Berger Strategy Consultants 2007, p. 33)

HCCI works regardless of the absence of an electric spark. The shift from spark-controlled combustion to HCCI is smooth. During HCCI, cycle-to cycle P_{max} becomes much more uniform, and the engine runs more smoothly and quietly, and without knock. During light to moderate loads, HCCI stabilizes the learn-burn charge, essentially eliminates the misfires typical of the two stroke cycle, and thereby significantly reduces fuel consumption. A diagram of cylinder pressure curves reveals a uniform rise and fall in pressure over multiple cycles that is unequalled by the traditional combustion process. Because HCCI is not dependent on spark ignition, however, once established it can produce a runaway condition. Variable compression ratio and control of chare air temperature are used to control HCCI combustion. HCCI occurs at high inlet temperatures and high compression ratios. Because combustion is homogeneous and very lean mixtures are used, combustion temperatures are lower, which results in very low NOx emissions. Though, low combustion temperatures also tend to produce greater amounts of unburned hydrocarbons. Part-load fuel economy, however, is greatly improved, and overall fuel economy is also greater. Fuel consumption in a vehicle powered by an HCCI engine can be as little as one-half that of an equivalent vehicle powered by a conventional spark-ignition engine. Because HCCI combustion is difficult to maintain at light loads and low engine speeds, an engine typically transitions between HCCI combustion and spark-ignition combustion, depending on the operating condition. (Riley 2004, pp. 161-162)

3.2.1.1.2 Lean Combustion Process

Lean combustion causes a locally restricted flammable fuel-air mixture in the cylinders without wall contact in contrast to the homogeneous combustion process. The main advantage is that less fuel is burned per stroke in partial load situations. Recently this was only enabled by a special piston design which has a series of disadvantages such as increase in piston weight, poor running comfort and loss of fuel efficiency due to the wall contact of fuel. Currently, the second generation of lean direct injection is being pioneered by Daimler and BMW. In these second generation models, the stratified mixture is achieved by a spray guide fuel injection. This has all the advantages of the lean combustion process minus the former issues. However, this might still increase NOx and PM emissions. Homogeneous combustion injection technology is very robust and can be used with most fuels available. On the other hand, lean combustion processes have the potential to reduce CO_2 further, but they can only be implemented in combination with high quality fuel. This is a major problem preventing broad use in emerging markets. (Roland Berger Strategy Consultants 2007, p. 35)

3.2.1.2 Future Trends - Reduction of Mechanical Friction

Regarding tribology the biggest lever to obtain less friction is the cylinder sleeve. Currently developments focus on special coatings, special finish and honing technologies. Another point is to reduce moving mass. This was the reason why European OEMs started to use assembled camshafts. However, while assembled camshafts were both cheaper and lighter two to three years ago, today they are not cheaper than cast camshafts, costing around € 15. Optimized engine friction leads to additional costs of about € 40-60. Downsizing helps to reduce overall ICE weight and the weight of moving mass, which leads to less mechanical friction in the engine. A smaller combustion chamber surface implies less heat emission and thus increases the combustion efficiency. A powerful measure to allow downsizing is turbocharging, since it is a prerequisite to enabling sufficient power in small engine displacements. Downsizing is already standard for diesel. A optimization up to 80 kW/l is normal. It will also become standard for medium and large gasoline engines which will be equipped with turbochargers and direct injection. Only low-cost engines will remain without turbocharger and with port-fuel injection for cost reasons. Downsizing for gasoline engines leads to additional costs of € 200-500. To optimize turbocharging further, automotive manufacturers have a number of avenues to consider like variable turbine geometry, dual stage turbocharging and electric driven turbochargers. A variable turbine geometry allows an enhanced boost pressure at low exhaust gas volumes, while dual stage turbocharging works with two similar or different turbochargers or with a supercharger and turbocharger combination like the VW TSI. This leads to higher torque at low revs. An electric driven turbocharger at low revs would have the same effect. This allows very small ICE designs with low CO_2 emissions. The disadvantage is that turbocharged engines produce a high amount of heat, up to 1,200°C in gasoline engines. Hence needs for cooling and materials used in the engine are higher. (Roland Berger Strategy Consultants 2007, pp. 36-37)

Via cylinder deactivation and start-stop-mechanisms power on demand can be achieved directly in the engine or in engine auxiliaries mainly by electrification. Cylinder deactivation helps to save fuel in partial load situations. The deactivated cylinders can be quickly reactivated if necessary. This is an appropriate measure for engines with a minimum of 6 cylinders, as implemented by DaimlerChrysler in its M113 engine (8 cylinder). Costs for this technology are about € 50-60. Start-stop systems reduce fuel consumption by switching off the engine when the car stops. The engine then restarts when the driver pushes the accelerator or lifts his foot from the brake. (Roland Berger Strategy Consultants 2007, p. 37)

One more possibility to reduce mechanical friction are the mechanical water pumps which are utilized by nearly all OEMs at the moment. As main disadvantage it is to mention that they are always connected to the engine mechanically. The electrification of the water pump has the potential to reduce fuel consumption. Costs for that technology are about € 120. An efficient solution for smaller engines is a mechanical controlled water pump like the one used in the new BMW–PSA engine. It is attached to the ICE by a friction wheel. This offers similar advantages at a fraction of the cost. Those pumps run in a range of 200 W to 2 kW power consumption, thus saving energy and fuel. The electric water pump also allows an improved warming-up phase of the engine and thus to less emissions at cold start. This fact is especially important for the NEDC driving cycle. The same also applies to electrified power steering, which costs about € 100. The next component to be electrified could be the oil pump, which would bring similar effects. However, the enormous power consumption of about 10 kW is currently an issue. Furthermore, an intelligent generator control as well as an integrated starter and alternator in one device can improve the start-up phase of the engine. (Roland Berger Strategy Consultants 2007, p. 38)

3.2.2 TRANSMISSION

The main objective in developing a vehicle transmission is the ideal implementation of the traction supply of the drive assembly in the tensile force of the vehicle in a wide speed range. This must be such that a good compromise between the number of gears, climbing ability, acceleration ability and fuel consumption of the vehicle is produced. (Naunheimer, Bertsche & Lechner 2007)

Since it is necessary to optimize the ICEs operating point the transmission can play a major role in automatic control gearboxes as well as for manual gearboxes. The different options are compared in Figure 7. In manual gearboxes the lever to optimize the engine's operating point is a larger final gear ratio. Optimized automatic switching strategies can reduce fuel consumption even for inexperienced drivers. An increasing number of gears minimizes the steps while shifting gears and allows the engine to operate near the optimized operating point. More speeds are usually combined with a larger gear ratio spread and a longer final transmission ratio. For example Mercedes' 7 speed automatic gearbox NAG 2 has a 25 percent larger gear ratio spread compared to the 5 speed gearbox. (Roland Berger Strategy Consultants 2007, p. 41)

	CVT[1)]	Manual gearbox	Automatic gearbox	DCT[2)]
Description	> Transmission in which the rotational speed ratio of two shafts can be varied continuously	> Gear ratios can be selected by engaging pairs of gears inside the transmission	> Can change gear ratios automatically as the vehicle moves	> Semi-automatic transmission with separate clutches for odd and even gears
Problems	> Low endurance > High costs > Low efficiency	> Only six gears possible	> Low efficiency > High costs	> Low availability
Influence on increase of operating point	●	◔	◑	●
Measures to optimize operating point	> Free variation of gear ratio	> Gear ratio step up	> More gears ➨ greater gear ratio inclination	> More gears

1) Continuous variable transmission. A hybrid vehicle basically realizes an E-CVT 2) Dual clutch transmission

Figure 7: Impact of gearbox technology on optimizing operating point (Roland Berger Strategy Consultants 2007, p. 42)

3.2.2.1 CVT

The continuously variable transmission CVT itself can be either a belt (Reeves, Van Doorne) or a toroidal (Torotrak) system.

3.2.2.1.1 Composite V-Belt

Centrifugal force produced by engine velocity causes weight to fly outward and force the movable face against the fixed face of the driver pulley. This can be seen in Figure 8. The higher the engine revolution, the greater the force squeezing the two pulley faces together. This causes the belt to ride farther out on the rim as the gap between the fixed and movable faces closes. Concurrently, the belt is pulled deeper into the driven pulley, forcing its two faces apart. Torque-sensitive units employ a cam on the driven pulley that is constructed to boost belt squeeze in response to enhance torque. Torque increases when the vehicle meets larger resistance or when the operator adds power. Thus, the continuous balance between the centrifugal force of the driver pulley and the counteracting force of the driven pulley controls the actual shift position. (Riley 2004).

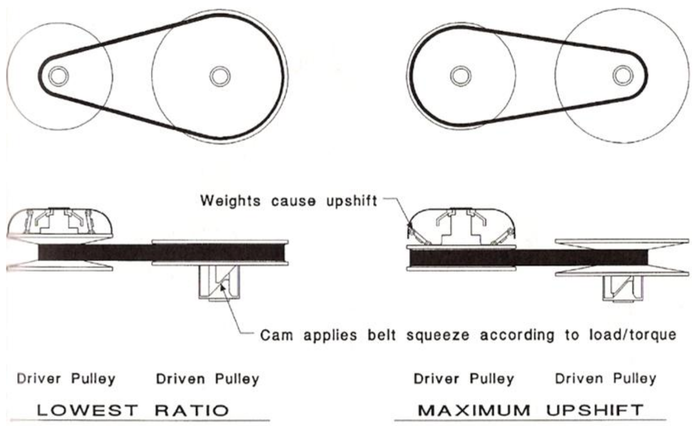


Figure 8: Salsbury torque-sensitive CVT (Riley, 2004, p. 165)

3.2.2.1.2 Steel-Belt

The lubricated-steel-belt CVT of Van Doorne works in a similar way. Though, the design relies on a lubricated steel belt instead of a composite belt to transfer power. And it employs hydraulic pressure to provide belt squeeze and effect changes in shift position. Also, the unit can use electronic feedback and logic to analyze vehicle and road conditions to modify the shift schedule accordingly. In CVT terminology, the pulley and the belt assembly comprises the variator. The variator is then combined with other components such as a fixed-ratio reverse gear, hydraulic pumps, governors and actuators, and an automatic clutch or a hydraulic torque converter. With a steel-belt CVT it is possible to transfer much greater power and to improve wear characteristics. This type of design also provides more precise control over belt squeeze and shift position. Unfortunately, parasitic losses to subsystems and the torque converter are essentially on par with those of a conventional automatic transmission. However, the fuel consumption of the automobile can be momentous improved because of the ability to take advantage of engine operating characteristics,. (Riley 2004, p. 166).

This type of CVT will feature fuel savings of 8% when matched to common 4-speed automatic transmission. This fuel saving is similar to 6-speed automatic transmission. In addition the CVT offers better acceleration performance. The steel-belt CVT having offset axes is optimal for mounting in small front wheel drive vehicles. Hence it is most popular as the transmission in sub-compact and compact passenger cars. In Figure 9, the belt type CVT has the engine input applied to its primary side through a mechanical clutch and an M/G connected permanently at the primary, but outboard of the engine. The secondary side of the CVT is connected via gears to the transmission final drive as shown. (Miller 2004)

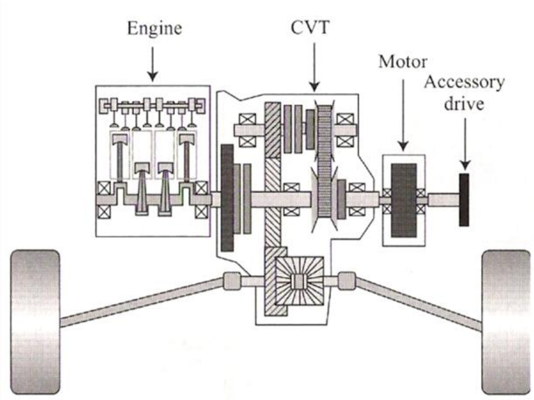


Figure 9: CVT hybrid (Miller 2004, p. 75)

Traction drives are also continuously lubricated by oil. Except the rolling elements have no teeth, these drives control input and output ratios and convert power in a manner similar to gears. Instead, they rely on the hydroelastic properties of the lubricating fluid to convert shear loads at the contact points between the rollers and discs. New lubricants can transfer approximately 6 percent of the roller contact pressure in the shear direction, compared to about 1 percent for conventional transmission oil. Traction drives are simple, responsive, and compact. (Riley 2004, p. 167)

3.2.2.1.3 Toroidal

Figure 10 shows design layouts called toroidal or the half-toroidal. In general, half-toroidal variators feature lower spin losses. However, the axial load on rollers and input and output discs are extremely high. Consequently, excessive internal loads and reduced bearings life are common difficulties. A full-toroidal layout virtually eliminates axial loads on the roller, and better lubricants have solved the historical disadvantage in the load transfer capability. (Riley 2004, p. 167)

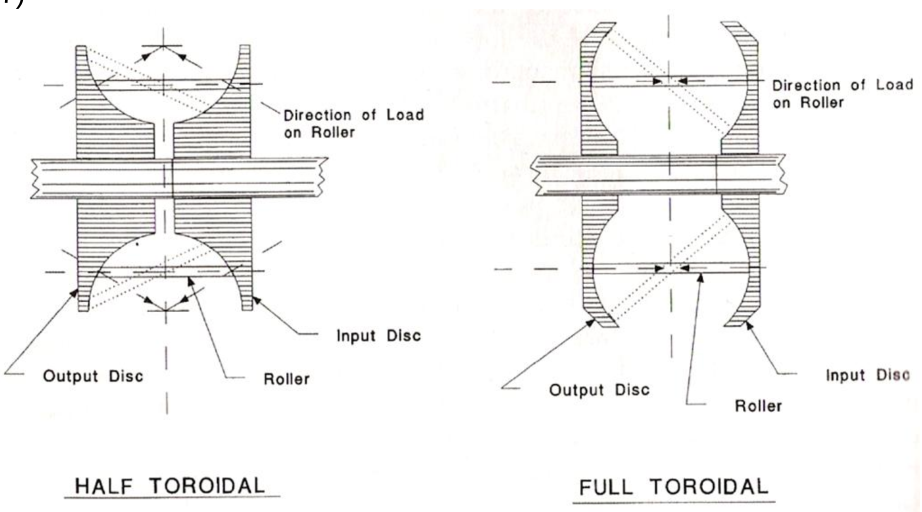


Figure 10: Toroidal and half-toroidal variator (Riley 2004, p. 168)

The toroidal CVT suits better to larger passenger cars with high displacement engines that offer a 400 Nm torque range. Fuel economy in larger cars is improved because the CVT offers wider gear shift ratio coverage that can push the ICE farther into its lugging range than a traditional transmission. The limitation of toroidal CVTs in the past has been the design of the variator, particularly its limited cross-section space allocation due to vehicle design. Dual cavity toroidal CVTs are most suitable for rear wheel drive vehicles - larger passenger cars, light trucks and sport utility vehicles. Low variator efficiency occurs when there is excessive contact pressure on the torus rollers in the low ratio position and when large ratio spreads are demanded. Efficiency at ratio spreads greater than 5.6:1 can fall from 94 to 89% at full load. (Miller 2004, p. 75)

3.2.2.1.4 Torotrak

The British Technology Group developed the full toroidal Torotrak transmission with assistance from Ford Motor Company. It is the most successful design to date. The Torotrak design utilizes a two-cavity layout, with the output disc in the centre and an input disc at each end. Roller pressure is maintained by the hydraulic clamping action of the two input discs, which traps the rollers between them. The dual-cavity Torotrak variator enables 94 percent efficiency. In addition the shift rate is extremely rapid and smooth. Rollers can migrate across the discs in as little as one-half revolution of the ICE, and changes in ratio are virtually unfelt by the occupants of the car. (Riley 2004, p. 167)

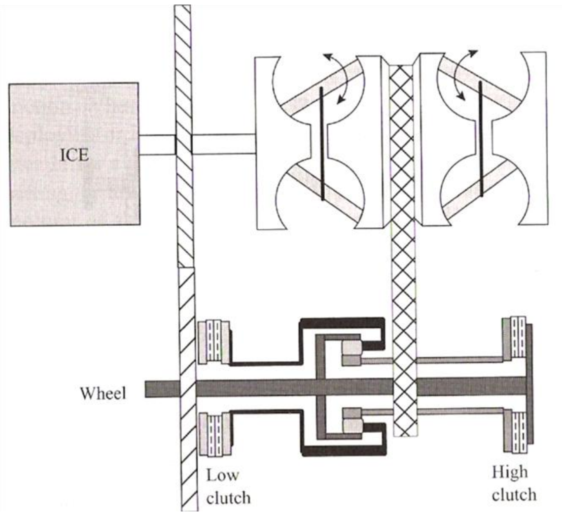


Figure 11: Torotrak IVT, toroidal CVT (Miller 2004, p. 76)

One more unique characteristic of the Torotrak unit is what is called the "geared neutral". It makes possible that the automobile remains at rest, crawls forward, or pulls away with high acceleration by using an infinitely variable start-up gear that makes traditional torque converters or clutches needless. Since the variable ratio ability is infinitely from neutral to full upshift in forward and reverse without having a discrete reverse gear, the producer named the unit an infinitely variable transmission (IVT), instead of CVT. The planetary gearset is the most important part of the construction. It is shown in Figure 11. (Riley 2004)

IVT offers high and low operating regimes. Neutral, reverse and low velocity is captured in the low regime. All other forward velocities as well as overdrive are captured in the high operating regime. (Miller 2004)

In case that the sun gear is driven at speed N_a, and the planet carrier is "grounded" with the planet gears free to rotate, then the annulus gear rotates in the opposite direction at a velocity that is fixed by the relative size of the gears. Likewise, if the planet carrier is free to rotate, the planet gears are rotating with the same velocity as before, and the carrier will still remain stationary. However, in case that the velocity of the annulus is reduced or increased, however, the planet carrier will start to rotate in either the forward or reverse direction so that the sum of the velocities of the epicyclical elements remains constant. By connecting the variator input shaft and the sun gear, the variator output disc to the annulus, and the vehicle wheels to the planet carrier, a slight change in variator ratio will begin to move the vehicle in either the forward or reverse direction. If the variator ratios are matched, the vehicle will not move, although it is still "in gear". The geared neutral in combination with the variator provides a new level of freedom to power plant engineers. With Torotrak´s IVT, the shape of the torque curve is no longer limited by vehicle dynamics, but instead is free to comply with the optimum characteristics of the ICE. The engine and transmission form a much more fluid and synergistic package when their individual management schedules are more integrated. Cars can now be tuned for maximum performance, maximum fuel efficiency, and minimum emissions within a dynamic system of integrated controls and continuous feedback. (Riley 2004, p. 169)

3.2.2.2 Manual Gear Transmission

Manual gear transmission consists of a clutch, a gearbox, a final drive, and a drive shaft. The final drive has a constant gear ratio. The common practice of requiring direct drive (nonreducing) in the gearbox to be in the highest gear determines this ratio. The gearbox provides a number of gear ratios ranging from four to six for passenger cars and more for heavy commercial vehicles that are powered with gasoline or diesel engines. The vehicles´ maximum velocity determines the gear ratio of the highest gear (i.e., the smallest ratio). On the other hand, the gear ratio of the lowest gear (i.e., the maximum ratio) is defined by the required maximum tractive effort or the gradeability. Ratios between them can be spaced in a way that will provide the tractive effort-speed characteristics as near to the ideal as feasible. (Kirchner 2007)

3.2.2.3 Automatic Transmission

Automatic transmissions (AT) are still a very popular choice, although they will lose significance due to power split systems in future HEV. To illustrate the various stepped automatic transmission architectures this work will consider the following three transmission types.

3.2.2.3.1 Simpson type

In this construction a double planet epicycle gear set receives its input torque from the torque converter turbine at the inner planted and outputs its torque to the Simpson base transmission on the countershaft via the second planet set. The transmission schematic, including torque converter with integral M/G rotor, can be seen in Figure 12. It also shows clutches (Cs), brakes (Bs) and one-way-clutches (Fs). Notice that input torque enters via a clutch to either the double planet sun or inner carrier and exits via the outer carrier. Control is imposed over the transmission by brakes on the sun and ring gears (i.e. diode symbols for a one-way-clutch (OWC)). Clutch C1 is always the transmission input clutch on the turbine side of the torque converter. The torque converter impeller and turbine are locked through the lock-up clutch, L/U. The Electrical connections to the M/G are via the stator of the EM packaged around the torque converter. The M/G rotor is mounted to the torque converter at the flex plate (impeller) and aligned with the torque converter into a finished assembly at the torque converter assembly plant. M/G rotor encoder assemblies would also be mounted and aligned at the torque converter plant. The M/G and T/C become a complete subassembly that would be delivered to the transmission plant for assembly to the final product. Vehicle powertrain assembly starts with the transmission, followed by integration with a fully dressed engine, including all necessary electronics modules and wiring harnesses. (Miller 2004, p. 115).

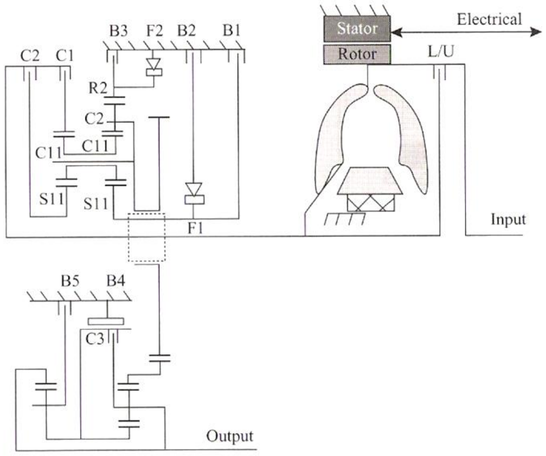


Figure 12: Simpson type stepped automatic transmission (Miller 2004, p. 115)

3.2.2.3.2 Wilson type

Since there is no counter shaft the Wilson stepped automatic transmission is simpler than the Simpson type. The 5-speed Wilson type, however, requires three epicyclical gear sets, clutches (Cs) and brakes (Bs) along with an OWC. Figure 13 is the schematic for a Wilson type automatic having an M/G for hybrid functionality mounted to the torque converter impeller as was the case for the Simpson type. The M/G with torque converter would again be a complete assembly that is aligned and balanced at the manufacturing plant and delivered to the transmission assembly plant. Both the Wilson type and the Simpson type rely on one-way clutches (C1 to C3) for their operations. If it were possible to eliminate the OWCs, the transmission would have fewer components and be simpler to build. (Miller 2004, p. 116)

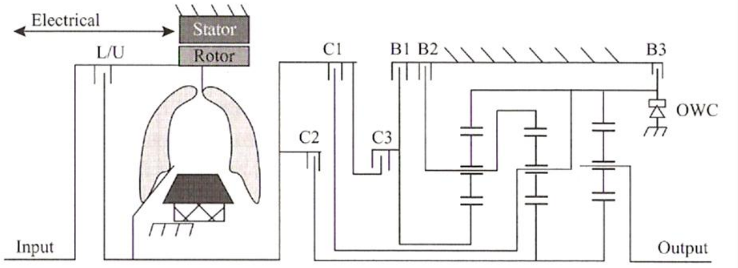


Figure 13: Wilson type stepped automatic transmission (Miller 2004, p. 116)

3.2.2.3.3 Lepelletier type

The Lepelletier type transmission, which is known since 1990, enables to build a stepped ratio automatic transmission without one-way clutches. To realise this, a single planetary gear set and a compound or Ravigneaux planetary gear set are combined along with five shift elements. In the process, a 6-speed transmission evolved. The Lepelletier transmission with hybrid M/G is shown schematically in Figure 14. It has to be mentioned that, whereas the Simpson and Wilson type have the output shaft taken from the carrier of the output planetary set, in the Lepelletier the output shaft connects to the ring gear of the Ravigneaux set. The key features of the Lepelletier transmission are input shaft to planetary ring gear with its sun gear blocked to chassis. The input planetary runs in all gears with the same ratio. The feature of the single input planetary is the splitting of engine velocity at the ring (true speed) and carrier (reducing engine speed). These two power flow paths are then selected by either clutch C1 or C3 (1:1 into secondary planetary) and applied to the Ravigneaux compound planetary set. Output is taken from the Ravigneaux ring gear. One drawback, if it could be called that, is that a Lepelletier architecture is not able to realise a direct drive (1:1) ratio from input to output as both the Simpson and Wilson types do. (Miller 2004, p. 116)

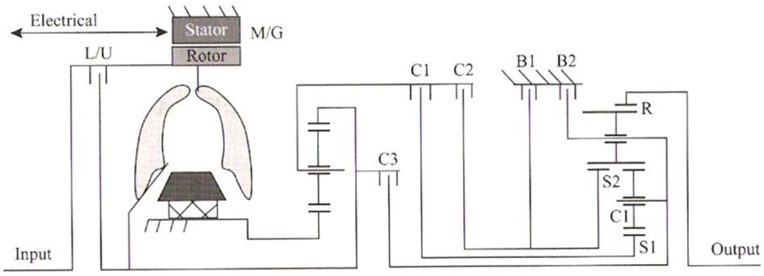


Figure 14: Lepelletier transmission (Miller 2004, p. 117)

3.2.2.4 Dual Clutch Transmission

The DCT gearbox consists of two independent transmission structures. The two gears on two drive shafts are each alternately connected to the engine friction by the dual-clutch gearbox. The double clutch allows an automatic switching operation without torque interruption. The transmission is controlled via a so-called mechatronic module in which the electronic transmission control unit, various sensors and the hydraulic actuation are combined as one compact unit. The DCT transmission permits fully seamless and smooth gear changes and offers the convenience of an automatic transmission. Fuel consumption models with DCT transmission is to some extent even among those with manual transmissions. This depends on driving style. (Kirchner 2007)

3.2.3 Electric Motor

An electric machine is at the core of hybrid propulsion which is via an AC drive system consisting of an energy storage unit, a power processor and the M/G. Attention is focused on the five classes of electric machines of most interest for hybrid propulsion:

- Induction/asynchronous machine
- Permanent magnet motor
- Current-excited motor
- Switched reluctance motor
- Transverse flux motor

These machines in current use are all of the drum design. That means, rotor flux is radial across a cylindrical air gap. Figure 15 shows a comparison between different options.

Input/stator current	AC					DC
Rotor speed relative to stator field	Asynchronous	Synchronous				Current-commutated
Rotor field generation	Induction	Permanent magnet	Current-excited	None – usage reluctance	Other	Permanent magnet[2)]
Type	Induction motor	PMSM (or IPMM)	SM	SRM[3)]	TFM	DC motor (with brushes)
Peak efficiency	> 90%	> 94%	> 90%	> 92%	> 95%	< 90%
Spec. power[1)] (kW/kg)	Approx. 1.0	Approx. 1.6	< 1	Approx. 1	Approx. 1.4	< 0.5
Manufacturing costs	Low	High	Medium	Low	High	Medium
Automotive application	✓	✓	✓	?	?	No
Key reasons	Low costs	Low weight, compact design	No permanent magnets	Low costs	High efficiency	Low efficiency, heavy motors

Figure 15: Current status of electric motor technology (Roland Berger Strategy Consultants 2009, p. 39)

3.2.3.1 Induction Motor

The induction motor or AC asynchronous motor is definitely the most customary type of electric motor. The reasons are its simple design that is shown in Figure 16 and Figure 17 and the low production costs. As compact electronic inverters became available in the 1980s, engineers first started using this type of motor in vehicles. (Roland Berger Strategy Consultants 2009, p. 37)

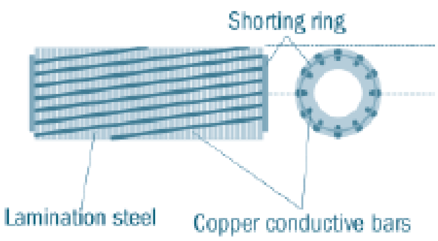


Figure 16: Rotor of induction motor (Roland Berger Strategy Consultants 2009, p. 38)

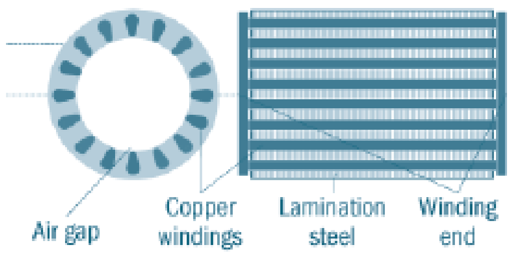


Figure 17: Stator with three-phase winding (Roland Berger Strategy Consultants 2009, p. 38)

There are two types of induction motors. The squirrel-cage and the wound-rotor motor. Because of the lack of strength durability, need for servicing and high cost, wound rotor induction motors are less attractive than their squirrel-cage counterparts, especially for eclectic propulsion in HEV. Hence, squirrel-cage induction motors are loosely named a induction motors. The most common types of induction motor rotors are the squirrel-cage motors in which aluminium bars are cast into slots in the outer periphery of the rotor. The aluminium bars are short-circuited together at both ends of the rotor by cast aluminium end rings, which also can be shaped as fans. (Ehsani, Gao & Emadi 2010)

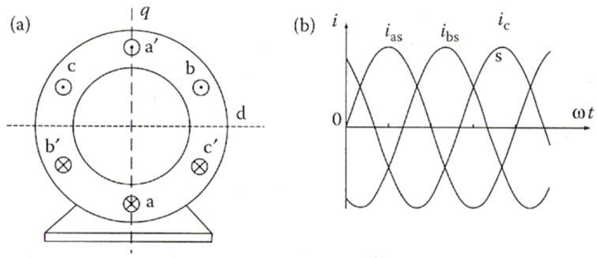


Figure 18: Induction motor stator and stator winding current: (a) spatially symmetric three-phase stator windings; (b) phase currents (Ehsani, Gao & Emadi 2010, p. 169)

In Figure 18 above, a cross section of the stator of a three-phase two-pole induction motor can be seen schematically. Each phase is fed with a sinusoidal AC current, which has a frequency of ω and a 120° phase difference between each other. Current i_{as}, i_{bs}, and i_{cs} in the three stator coils a-a´, b-b´, and c-c´ produce alternative magnetic motive forces (mmfs), F_{as}, F_{bs}, and F_{cs}, which are space vectors. The reaction between the rotating stator mmf and the rotor conductors induces a voltage in the rotor and hence electric current in the rotor. In turn, the rotating mmf produces a torque on the rotor, which is carrying the induced current. It is clear that the induced current in the rotor is essential for producing torque, and in turn the induced current is controlled by the relative movements amongst the stator mmf and the rotor. That is why there must exist a discrepancy between the angular speed of the rotating stator mmf and the angular speed of the rotor. The frequency ω, or angular velocity of the rotating stator mmf in equation, depends only on the frequency of the alternative current of the stator; thus it is referred to as electrical angular velocity. For the machine with two poles, the electrical angular velocity is identical to the mechanical angular velocity of the rotating stator mmf. However, for the machine with more than two poles, the mechanical angular velocity differs from the electrical one. For $\omega_m<\omega_{ms}$ (rotor speed and stator speed), the relative speed is positive; consequently, the rotor-induced voltages have the same phase sequence as the stator voltages. the three-phase current flowing through the rotor produces a magnetic field, which moves with respect to the rotor at the slip speed in the same direction as the rotor speed. Consequently, the rotor field moves in the space at the same speed as the stator, and a steady torque is produced. For $\omega_m=\omega_{ms}$, the relative speed between the rotor and the stator field becomes zero. Consequently, no voltages are induced and no torque is produced by the motor. For $\omega_m>\omega_{ms}$, the relative speed between the stator field and the rotor speed reverses. Consequently, the rotor-induced voltages and currents also reverse and have a phase sequence opposite to that of the stator. Moreover, the developed torque has a negative sign, suggesting generator operation. The generator is used to produce regenerative braking. (Ehsani, Gao & Emadi 2010, p. 169-172)

3.2.3.2 Permanent Magnet Motor

Permanent magnet synchronous motors (PMSMs) today fall into two broad categories depending on the permanent magnet employed: weak magnet PMSM and strong magnet PMSM. The strong magnet PMSM may be adequate for line-start applications like large fans and industrial equipment for which synchronous running is beneficial. Since continuous operation is at a synchronous speed the magnets can be sized to provide AC synchronous machine performance at near unity power factor at rated conditions. Traction drives, on the other hand, have gravitated to the weak magnet PM. This has been a somewhat surprising trend because a weak magnet PM is in reality a variable reluctance machine or, more precisely, a switched reluctance machine that happens to have some magnet content. Switched reluctance motors will be explained in this chapter as well. (Miller 2004, p. 215)

Permanent magnet synchronous motors (PMSMs) are mainly used by car manufacturers for high-end applications. Compared to induction motors the main difference in the design is that PMSMs have permanent magnets in the rotor that generate the second magnetic field. This allows the rotor to spin at equal velocity as the by the stator generated revolving magnetic field (therefore called "synchronous"). The entire supply current can be used to generate the stator field, providing more torque per power input than induction motors, especially at low motor speeds. PMSMs also have disadvantages, however. These include higher production costs (due to the expensive permanent magnets and more complex manufacturing process), lower efficiency at higher speeds (due to undesired currents in the stator created by the permanent magnets) and a high braking torque in case of short circuit. One kind of permanent magnet motors are brushless DC motors (BLDC), which are described below. (Roland Berger Strategy Consultants 2009, pp. 38-39)

The BLDC motor drive consists mainly of the BLDC machine, the digital signal processor (DSP) based controller, and the power electronics-based power converter, as shown in Figure 19. Position sensors H1, H2, and H3 sense the position of the machine rotor. The rotor position information is fed to the DSP-based controller, which, in turn, supplies gating signals to the power converter by turning on turning off the proper stator pole windings of the machine. In this way, the torque and speed of the machine are controlled. (Ehsani, Gao & Emadi 2010, p. 203).

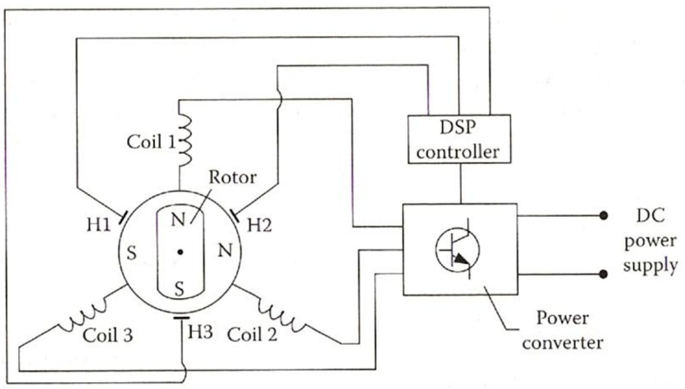


Figure 19: Brushless DC motor (Ehsani, Gao & Emadi 2010, p. 203)

The BLDC motor may be either of the 120° or 180° current conduction in the stator windings. When the back electromotive force (b-emf) due to the permanent magnet rotor has trapezoidal shape, the machine will be brushless DC and having current conduction in block mode of 120° duration. Electronically commutated DC motors require electronic controls. The flux generates trapezoidal versus sinusoidal voltage in a way that the rotor magnet design and magnetization orientation will define the character of the voltage, and to some extent the slot and winding design. Permanent magnets used in electric machines are invariably parallel magnetized with the magnetic field intensity lines oriented across the magnet length, which is generally on the order of 8 to 15 mm for ceramic magnets and 4 to 7 mm for rare earth magnets. Figure 20 illustrates the trend in b-emf as magnetization orientation proceeds from parallel to radial, i.e. sinusoidal to trapezoidal waveform. (Miller 2004, p. 195)

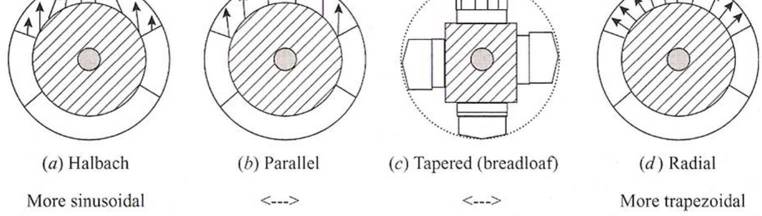


Figure 20: Illustration of permanent magnet magnetization orientation (Miller 2004, p. 196)

BLDC motors allow the highest power density. This is because for a given value of flux in the machine the flat top of the trapezoid results in much higher rms values than a sinusoidal flux for the same iron saturation limited peak value. The same applies for the current since block mode conduction with flat top waveform has a higher rms value than its corresponding sinusoidal cousin for the same current limit in the power electronic inverter. For this reason BLDC motors have found use in industrial machine tools and some traction applications. The spectrum of reluctance torque effects is linearly decreasing for parallel magnetization (sinusoidal b-emf) designs with increasing harmonic number. For a gradual magnetization the effect is a similar linear decrease with harmonic number, but the initial value of reluctance is some 30% higher. For radial magnetization (trapezoidal b-emf) the reluctance torque increases with harmonic number, peaks for the 2nd and 3rd harmonics and then decreases linearly for higher harmonics. This harmonic flux is a serious issue with BLDC motors since the trapezoidal b-emf causes momentous detent torque and consequent vibration. For traction applications the inertia of the driveline may or may not swamp out the reluctance torque induced vibrations. There have been many techniques proposed for minimising reluctance torque production in brushless DC machines, such as skewing the magnets along the rotor axis length, and careful design of the magnet pole arc and interpolar gap. The magnet pole arc can be visualised as the circumferential span of the magnet in Figure 20 versus the pole arc (in the 1-pole case shown this would be pi-radians). It is very usual to have magnet pole arcs of 0.7 to 0.8 times the pole span in order to minimise harmonic production. One of the more effective means to reduce detent torque in a BLDC motor has been the implementation of stator pole notching. The effect is to have the magnet edges pass evenly spaced discontinuities in air gaps rather than just the stator slot gaps at the edges of full pitched coils. However, because of the issue with cogging torque, BLDC machines have not found widespread acceptance as a hybrid propulsion technology, but rather are relegated to electrified ancillary drives where very high power density, low cost, and compact packaging are the overriding considerations. (Miller 2004, pp. 197-198)

3.2.3.3 Current-Excited Motor

Current-excited synchronous motors are a design alternative to PMSMs. This kind of motor does not need permanent magnets that require expensive rare earths. (Roland Berger Strategy Consultants 2009, p. 39)

3.2.3.4 Switched Reluctance Motor

SRM drives are suitable as aspirants for variable speed motor drives because of their convenience in control, high performance over a large revolution range, robust structure, dependable converter topology, and even lower costs than induction motors. (Miller 1993)

The reason for the cost advantage is the very simple rotor structure and lack of permanent magnets. SRMs use magnetic reluctance to generate torque. The stator magnetic field causes a magnetic flux via the specially designed rotor. To follow the path of least magnetic resistance, the rotor starts to move and generates torque. On the other hand the reluctance phenomenon also leads to high fluctuations in torque and micro motions within the structure of the rotor iron, which makes them noisy. (Roland Berger Strategy Consultants 2009)

It has to be mentioned that the SRM rotor is inert and thus easy to manufacture, has no permanent magnets nor field windings and so is robust in high revolution applications. Due to its double saliency it has stator coils that can be simple bobbin wound assemblies. For all its benefits the SRM has been slow to be adopted, partly due to its requirement of precise rotor position detection or estimation, the need for close tolerance mechanical air gap, and a proclivity to generate audible noise from the normal magnetic forces in the excited stator. The issue with audible noise is particularly irksome in hybrid vehicle applications because any periodic noise source has the potential to excite structural resonances of to be the source of structure borne noise and vibration. The tendency of SRMs to generate noise comes from the passage of magnetic flux around the perimeter of the stator from one magnetic pole to its opposite polarity pole, sometimes diametrically opposed. The high normal forces under current excitation then cause the stator to deform into a number of modal vibrations. A second contributor to audible noise comes from the tendency of the rotor and stator saliencies, for example the teeth, to deform under high tangential forces and, when allowed to decay, to start vibrating. Many attempts have been made to quiet the SRM, including structurally reinforced stators, shaped stator and rotor teeth to minimise noise, and inverter current shaping to mitigate any tendency to produce noise. Many of these techniques show that SRMs should be treated as viable hybrid propulsion system alternatives to asynchronous and permanent magnet synchronous machines. (Miller 2004, p. 243)

3.2.3.4.1 Basic Principle of Switched Reluctance Motor

Miller (1993) states that common SRM drive systems are composed of the SRM, control circuit technology like the DSP controller and the peripheral, sensors like current, voltage and position sensors, and the power inverter.

High efficiency in SRM drive systems will be obtained by means of appropriate control. SRM drive inverters are linked to DC power supplies, which will be deduced from the utility lines by means of energy storage systems or front end diode rectifiers. Phase windings of SRMs are linked to the power inverter. In accordance with signals from various sensors and specific control strategies the control circuits provide a gating signal to the switches of the inverter. (Ehsani, Gao & Emadi 2010)

3.2.3.4.2 Basic Magnetic Structure of Switched Reluctance Motor

SRMs have poles on rotor and stator which are sticking out. SRMs have no windings or permanent magnets on the rotor but bunched windings on the stator. In dependence of the size and the number of stator and rotor poles there are multiple designs for SRMs. Designs of the common types 6/4 and 8/6, can be seen in Figure 21. The reluctance of the flux path for a phase winding changes with the rotor position because of its double salience structure. The reluctance of the flux path also changes like the phase current, due to the commonly design of the SRM for high-degree saturation at high phase current. Accordingly, phase incremental inductance, phase bulk inductance, and the stator flux linkage, all fluctuate with the phase current and rotor position. (Ehsani, Gao & Emadi 2010)

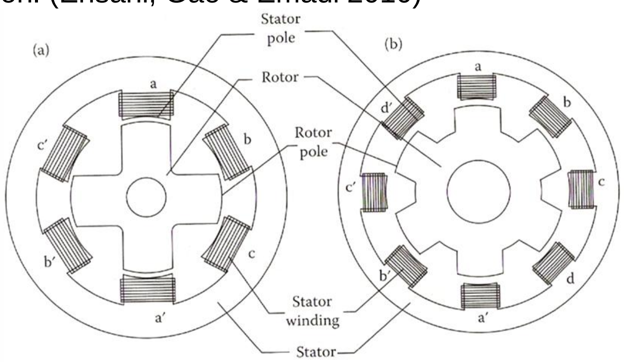


Figure 21: Common SRM designs: (a) 6/4 SRM; (b) 8/6 SRM (Ehsani, Gao & Emadi 2010, p. 219)

3.2.3.5 Transverse Flux Motor

In addition to the switched reluctance motor in particular the transverse flux motor (TFM) is currently in development. TFMs face similar noise and torque fluctuation problems as switched reluctance machines, but they outperform SRMs in terms of their efficiency and specific power. However, they also have a very complex motor design and are currently very expensive to produce. (Roland Berger Strategy Consultants 2009, p. 39)

3.2.4 Control Strategy

The architecture of a powertrain control system is the structure and organization of software and hardware. The design of the control system consists of processes that calculate the control actions which must be applied to the engine and other powertrain components for the car to achieve its performance goals. (Stobard & Childs 2002)

Salmasi (2005) explains that control strategies, which are normally adopted to the automobile central controller, are algorithm laws which regulate the operation of the drivetrain of the car.

The coordination of multiple energy sources and converters is a major challenge for the development of hybrid vehicles since there has to be a power flow control for both the mechanical and the electrical path. All components of the powertrain need to be tuned in order to achieve optimal efficiency. All components have to be physically integrated and component parameters should be adjusted to the framework of the vehicle. The physical integration has a minor impact on the vehicle's CO_2 emission. Savings in CO_2 emissions are enabled by the calibration of 10,000 to 25,000 control parameters in a common powertrain. (Roland Berger Strategy Consultants 2007).

New powertrain technologies are forcing the pace of change with a change from peer-to-peer architectures to a supervisory form of control. Because of the presence of multiple torque sources in the hybrid drivetrain it is necessary to employ torque control of all the sources, including engine and M/G. (Miller 2004)

The control strategy generally inputs the measurements of the automobile working conditions like velocity or acceleration, current roadway type or traffic information, requested torque by the driver, in-advance solutions, and even the information provided by the Global Positioning System (GPS). Outputs of control strategies are decisions to turn on or off certain components or to change their operating regions by commanding local component controllers. For example could the ICE be instructed to work close to its ideal efficiency curve, utilizing an electric motor as a buffer for load balancing. The objectives of hybrid drivetrain energy management systems are mainly to meet the driver's demand for the traction power, sustaining the energy storage system charge and optimization of drivetrain efficiency, fuel economy, and emissions. However, some of these objectives, like efficiency optimization and emission reduction, are conflictive parameters. An attractive control strategy has to satisfy a trade-off between them. In the last years, the drivetrain control strategy also includes the achieving of smooth gear shifts and the minimization of excessive driveline vibrations, which is known as drivability. This thesis classifies and extensively overviews the main proposed approaches to the energy management problem in HEVs. So far, there have been two general trends dealing with the problem: rule-based and optimization-based solutions. A classification can be observed in Figure 22. (Salmasi 2007, p. 2393)

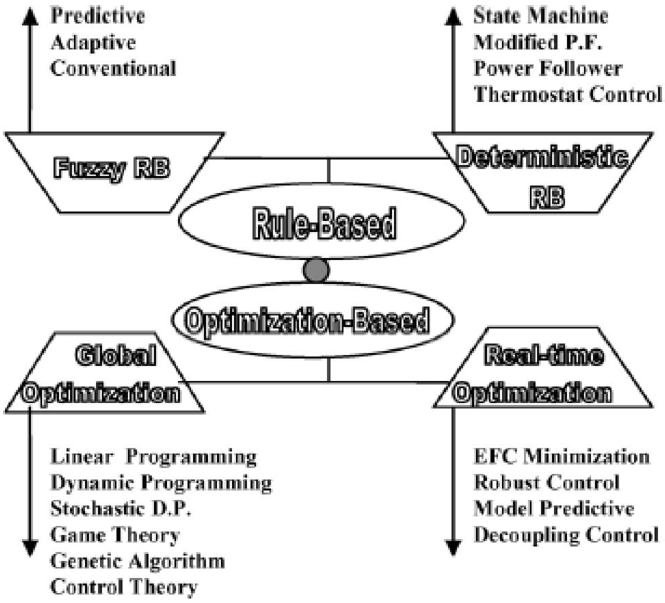


Figure 22: Classification of the hybrid powertrain control strategies (Salmasi 2007, p. 2394)

3.2.4.1 Rule-based Control Strategies

The performance in real-time supervisory control of power flow in a HEV is the key facet participating in rule-based energy management approaches. The rules are styled due to human expertise, heuristics, intuition, and even mathematical models and, generally, without a priori being aware of a predefined driving cycle. These strategies can be classified into fuzzy rule-based and deterministic methods. The latter has become more popular in the last years. (Salmasi 2007, p. 2394)

The basic concept of rule-based strategies mainly implemented from the idea of "load-levelling." The load-levelling strategy is to shift the actual combustion engine operating point as close as possible to the optimal point of efficiency, fuel efficiency, or emissions at a particular ICE velocity. The best fuel economy for this system was found at a lower torque and a lower ICE velocity than the best point of efficiency. In other words, the best fuel economy will be obtained by having smaller accelerator commands. (Baumann et al. 2000)

The difference between the driver's commanded power and the power generated by ICE will be compensated by the EM or used in replenishing the battery based on the measured state of the charge (SOC). Obviously, changing the location of the actual operating point on the efficiency map will require a change of engine torque and engine speed. The engine speed is determined by the actual gear ratio and the vehicle speed. Moreover, the fuel quantity injected into the cylinder, or the torque produced by the ICE, is tuned by the engine control unit. In the following subsections, control strategies based on deterministic and fuzzy rule-based (FRB) approaches, are discussed. (Salmasi 2007, p. 2394)

3.2.4.1.1 Deterministic Rule-Based Methods

Deterministic rules, generally implemented via lookup tables, to spilt requested power between power converters are designed by utilizing heuristics based on analysis of power flow in a hybrid drivetrain, efficiency/fuel or emission maps of an ICE, and human experiences. (Salmasi 2007, p. 2394)

Thermostat (on/off) Control Strategy

It is a simple method, where the energy storage system SOC is always maintained between a preset top and bottom line through switching on/off the ICE. In spite of its plainness, this strategy cannot satisfy power demands by the automobile at all working conditions. Nevertheless, for a series hybrid electric city bus commuting in prescheduled routes, the thermostat control strategy is applicable. (Salmasi 2007, pp. 2394-2395)

Power Follower (Baseline) Control Strategy

The prime resource of power is the ICE, and the electric motor is utilized to make additional power available when necessary by the automobile, while maintaining a charge in the energy storage system. The rule base is set up adapted from the following heuristics by Salmasi (2007, p. 2395):

- The EM loads the energy storage system by regenerative braking
- Below a certain minimum vehicle speed, only the EM is used.
- If the necessary power is larger as the maximum engine power at its operating speed, the motor is used to produce excess power.
- The ICE is shutdown when the power demand drops under a limiting value at the operating speed to prevent inefficient operation of the engine.
- If the energy storage system SOC is below the minimum allowable value, the engine has to provide additional power to replenish the battery via the M/G.

The strategy is prevalent for energy management in hybrid drivetrains. Anyhow, it shows the disadvantages that the efficiency of the whole drivetrain is not optimized, and improvement in emissions is not directly taken into account. Nevertheless, the control strategies of the Toyota Prius and Honda Insight are developed based on the power follower approach.

Modified Power Follower (Base Line) Strategy

This is a flexible rule-based energy management strategy to enhance the baseline control strategy. The main targets of this approach are to upgrade emissions and energy usage. This is done by implementing of a cost function that represents total emissions and fuel consumption at all adequate operating points. The control strategy utilizes a time averaged velocity to find instantaneous energy consumption and emission goals. (Johnson, Wipke & Rausen 2000)

According to Johnson, Wipke & Rausen (2000) the rule base for the suggested control strategy is as follows:

- Step 1) Determine the region of working points (distribution of engine and motor torques) represented by the region of the adoptable motor torque for the present torque demand.
- Step 2) Compute the discrete parameters for improvement for every working point.
- Compute the energy of the fuel that would be used by the ICE.
- Compute the actual fuel energy that would be used by electro-mechanical energy conversion for a time lag, e.g., a second.
- Compute overall energy that would be used by the car.
- Compute all emissions that would be emitted by the ICE.
- Step 3) Regularize the discrete parameters for each possible working point.
- Step 4) Implement user rating K_{user} to outcomes from Step 3).
- Step 5) Implement goal performance weighting K_{target} = (max of time averaged vehicle performance)/(performance aim) to outcomes from Step 4).

- Step 6) Calculate total impact parameter, which is a composition of outcomes from Steps 3) to 5), for each of the working points.

The ultimate operating point is the working point with the smallest impact factor. Although this strategy has improved the problems associated with the former approach, repeating the above steps for all candidates operating points is not desirable for online implementation. (Salmasi 2007, p. 2395)

State Machine-Based Strategy

The working mode of the automobile is defined by the state machine. These modes can be called "engine" (engine propelling the vehicle), "boost" (engine and motor, both propelling the vehicle) or "charging" (engine propelling the vehicle and charging the battery). The change-over between working modes will be determined on the basis of alterations in vehicle operating condition, the driver demand, or a system or a subsystem fault. Furthermore, it was presumed that dynamic control algorithms generate output commands to each subsystem, for example the required torque from the engine. The adoption of a automobile controller via state machines facilitates fault flexible supervisory control of the total system. Anyhow, the improvement of the performance aims like fuel efficiency or emissions is not guaranteed. Moreover, it is not clear how the proclaimed dynamic controllers are designed. Thus, this approach does not add value to conventional deterministic rule-based methods from an energy management point of view. Accordingly, switching to fuzzy rule-based methods (FRB) seems to be a sensible decision. These methods will be explained in the next section. (Phillips, Jankovic & Bailey 2000)

3.2.4.1.2 Fuzzy Rule-Based Methods

Fuzzy logic points out to be the most logical approach when looking into a hybrid drivetrain as a multidomain, nonlinear, and time-varying plant. Actually, instead of using deterministic rules, the decision-making property of fuzzy logic can be applied to realize a real-time and suboptimal power split. That is, the fuzzy logic controller is an extension of the conventional rule-based controller. (Salmasi 2007, p. 2395)

As stated by Salmasi (2007, p. 2395) the main advantages of fuzzy rule-based methods are the following:

1) robustness, since they are tolerant to imprecise measurements and component variations
2) adaptation, since the fuzzy rules can be easily tuned, if necessary

Conventional Fuzzy Strategy

A suggested fuzzy logic-based control strategy is to minimize NOx emissions while sustaining the battery charge and achieving the requested torque from the driver. The input for proposed fuzzy logic controllers is the acceleration pedal stroke Acc and the electrical motor speed ω_{rpm}. In the suggested drivetrain, the induction machine is directly coupled to the ICE shaft, which denoted that the rotational speed of the ICE is identical to the EM rotor speed. The output is determined to be the normalized proportional relation of EM torque command to rated EM torque at rotational speed, which is denoted by K. To design the FRB, a dynamo test had been accomplished, where power converters' torques and overall NOx emissions were detected. Based on the test results, at low velocities, the diesel engine offers comparatively low torque with high pollutant emission. Hence it would be reasonable to utilize only electric motors at low velocities to provide enough torque, which is proportional to the accelerator stroke. On the other side, the diesel engine has comparatively high torque and little pollutant emission when the velocity is high. In case the diesel engine revolution velocity is medium, depending on the accelerator stroke, the electric motor should provide enough torque to assist the diesel engine to satisfy driver acceleration intention or to act like a G to load the energy storage system. At higher velocities, the electric motor is principally used as a G, unless the acceleration command is too high. A sample rule for fuzzy strategies could be: "When Acc is high, and ω_{rpm} is medium, K is Positive-Small". (Lee & Sul 1998)

The recommended hybrid drive and controller can decrease NOx emissions by about 20% when matched with only a diesel ICE supplying driving power to the drivetrain. The central issue with this proposal would be that it does not guarantee charge sustenance of the energy storage system. To overcome this challenge, the authors suggested a more superior controller on the same bases in which the energy management system had two fuzzy logic controllers: driver's intention predictor (DIP) and power balance controller (PBC). The inputs to the DIP block are the accelerator stroke and the rate delta-Acc, while PBC blocks are fed with the sensed vehicle velocity v_{veh} and diesel ICE revolution speed. The DIP generates the torque reference responding to the fast acceleration or deceleration of the car, without consideration of the energy storage system level, and the PBC generates the torque reference responsible for keeping the battery loading level balanced. The weighted outputs are added to generate the reference electric motor torque. As mentioned at the beginning, both strategies are created to decrease NOx emissions, but they take neither emissions nor ICE efficiency into account. (Lee at al. 2000)

Fuzzy Adaptive Strategy

It is a noted fact that optimization of fuel efficiency and emissions are two goals that are in competition. This means that every optimal solution is always only a compromise between efficiency and various emissions. A good working point can be calculated by optimization of a criterion with the contenting factors emissions and weighted fuel (efficiency). When adjusting the corresponding weights, the relative importance between efficiency and different emissions can be modified based on requirements in different working conditions. This means for example that in areas with high air pollution, working points with high emissions are not allowed. In another driving situation, if the necessary torque by the driver is high, as high efficiency occurs close to high-torque regions, it is given the highest preference. In the proposed adaptive FLC, there are four competing factors in the definition of the optimum. This is to say the emissions of HC, CO, NOx, and the fuel efficiency. (National Renewable Energy Laboratory 2003)

Fuzzy Predictive Strategy

A global optimum solution can be reached by minimization of an adequate cost function over a drive cycle. In other words it is necessary to obtain the entire trip information prior to the start. The challenge is to accomplish real-time control tasks, and in the meantime to account for situations in the future along a planned route. GPS can support the system by providing vital information about sticking points that will be reached when driving. For example a steep grade or heavy traffic. If a driver is on a highway and entering a city where it is expected to be confronted with heavy traffic, it is a clever decision to load the energy storage system before, to make sure it is possible to use the EM later in the city mode. In this way it is possible to shift suboptimal solutions of real-time algorithms to near-optimal solutions, with predictive control. (Ichikawa et al. 2004)

3.2.4.2 Optimization-Based Control Strategies

Hereby, the ideal reference torques for power converters and ideal gear ratios are computed by minimization of a cost function normally describing the emissions or fuel economy. If the idealization is conducted over a fixed driving cycle, a global optimum solution can be found. Therefore it is necessary to use information about future and past power demands. Needless to say, this approach cannot be used directly for real-time energy management, but it might be fundamental for designing rules for online implementation or comparison for evaluating the quality of other control strategies. On the other hand, by determination of an instantaneous cost function, a real-time optimization-based control strategy can be found. This function has to depend only upon the system variables at the current time. The instantaneous cost function should include an equivalent fuel consumption to guarantee the self-sustainability of the electrical path. Certainly, the solution of such a hitch is not globally ideal, but it can be applied to real-time implementation. Lately, drivability is considered into real-time minimization-based control strategies. The aim is to achieve smooth gear changes and to minimize exorbitant driveline vibrations. (Pisu, Koprubasi & Rizzoni 2005)

3.2.4.2.1 Global Optimization

Performance goals by optimization of a cost function that represents efficiency and emissions over a drive cycle, can be achieved by many reported solutions. All these approaches are not adaptive because of their computational complexity and preview nature. Otherwise, it is possible to use them as a good design tool for other control strategies to adjust, assess and analyze them. Simulated annealing, game theory, linear programming, optimal control theory, dynamic and stochastic programming, and genetic algorithms are utilized to solve the aforementioned problem. In the following, the four latter approaches are discussed in detail. (Salmasi 2007, p. 2398-2399).

Linear Programming

Tate and Boyd implemented the adaptability of convex optimization to HEV powertrains. They are real pioneers in getting down to the energy management challenge with optimization tools. They framed the hitch of improving the fuel economy as a nonlinear convex optimization problem that is in the end estimated by a large linear program. The series HEV configuration was utilized for the challenge. (Tate and Boyd 1998)

Control Theory Approach

In this case the optimal control theory is directly implemented to find a global optimal solution for the energy management problem in parallel torque-addition arrangements. A parallel torque addition-type powertrain is utilized in which a reduction gear is situated between the ICE and electric motor. The torque at the wheel $T_w(t)$ and the vehicle velocity $\omega_w(t)$ are related to electric motor and engine torque and velocities. (Salmasi 2007, p. 2399)

Dynamic Programming (DP)

Dynamic Programming seems to be a sensible approach for ideal power split in HEV, because it is a capable instrument to resolve a general dynamic optimization problem, easily handling the constrictions and nonlinearities of the task while achieving a globally best result. DP techniques were implemented to resolve optimal power management problems of HEV trucks by minimizing a cost function over a driving cycle. They used the results of the DP solution to improve a simple intuition based algorithm. To reduce the computational burden of the DP, only three state variables (energy storage system SOC, transmission gear number, vehicle speed) were included to the state vector x to implement a dynamic model. (Lin et al. 2003)

Stochastic DP

This strategy treads the problem from a stochastically by constituting the energy management as stochastic dynamic optimization-problem with infinite-horizon. Over a averaged family of driving cycles at random, the power management strategy is maximized. Infinite-horizon optimization problems are framed and resolved by applying stochastic DP to achieve a time-constant control strategy. In this method, the driver's power demand P_{dem} is generated based on a stationary Markov chain and is expected to adopt a limited batch of values. (Lin, Peng & Grizzle 2004)

3.2.4.2.2 Real-Time Optimization

Since global optimization techniques provide only casual solutions, they are not directly application for real-time development. To guarantee electrical self-sustainability, additionally to a measure for fuel consumption also a cost function used in instantaneous optimization has to be developed, to take variations of the stored electrical energy into account. (Salmasi 2007, p. 2401)

Real-Time Control Based on Equivalent Fuel Consumption

The implementation of the equivalent fuel consumption cleared the way for utilization of optimal control theory for real-time power management in HEVs. The equivalent fuel consumption is determined as the extra fuel consumption that is necessary to load the energy storage system in the near future. (Sciarretta, Back & Guzzella 2004)

Decoupling Control

The control strategy ensures admissible drivability of the automobile, additionally to driver power demand and battery SOC. Although there are many measures for drivability, the most popular ones are to achieve smooth gear changes and to minimize exorbitant driveline vibrations. Decoupling control strategies are based on the automobile's dynamic model, including an electric motor which directly drives the rear wheels and an integrated starter alternator (ISA). The ISA is linked to an engine, while a torque converter is amongst the IC-ISA and an automatic transmission which drives the vehicle's front wheels. (Barbarisi et al. 2005)

Robust Control Approach

The robust control approach solves the power split challenge in PHEVs. The aim is to define an output feedback controller that optimizes the fuel economy with respect to a family of possible torque/power input profiles. (Pisu et al. 2003)

Optimal Predictive Control

The cost function represents the equivalent fuel consumption over a preview or look-ahead window. It was introduced to find a real-time prognostic ideal control law. The optimal control theory is suggested to tackle such problems. The approach uses the preview driving pattern and terrain information and hence gives low fuel consumption to the instantaneous one. (Salman, Chang & Chen 2005)

3.2.5 Energy Storage System

HEV require a energy storage system which has a turn-around efficiency greater than 90% to be effective. In fact, any system which does not store energy in the same form as it will be consumed or delivered is ill suited as an energy storage system because there will be one or more conversion steps to access the energy. A battery must go through a chemical to electrical conversion in order for its energy to be accessed, an ultra-capacitor does not. This is why many investigators have explored and continue to explore means of incorporating ultra-capacitors into the propulsion system since an ultracapacitor can be sized to deliver 95% efficiency in each direction, or a round trip efficiency of 90%. (Miller 2004)

3.2.5.1 Battery

Electrochemical devices that transform chemical energy into electric energy during discharging and transform electrical energy into potential chemical energy during charging, are called electrochemical batteries. A battery is assembled of several cells stacked together. Each cell is an independent and complete unit that possesses all the electrochemical properties. Generally, a battery cell is composed of three elements: The two electrodes (positive and negative), soused into electrolyte as shown in Figure 23. Battery manufacturers normally specify the battery with coulometric capacity (ampere-hours), which is defined as the amount of ampere-hours obtained when discharging the battery from a fully loaded state until the terminal voltage drops to its cut-off voltage. The generally offers a changing number of ampere-hours at different discharging current rates. Normally, the capacity will become smaller with a large discharge current rate. Battery producers typically specify a battery with a number of ampere-hours along with a current rate. For instance, a battery labelled as 100 Ah at C/5 rate has a 100 Ah capacity at a 5-h discharge rate (discharging current = 100/5 = 20). One more fundamental specific value of a battery is the state of charge (SOC). It is defined as the ratio of remaining capacity to fully charged capacity. Hence, a fully loaded battery has an SOC of 100% and fully discharged battery has an SOC of 0%. Specific energy is defined as the energy capacity in relation to the battery weight (Wh/kg). Theoretically, specific energy is the maximum energy that can be gained per unit total mass of cell reactants. Specific power is defined as the highest power that the battery can offer in short time in relation to the battery weight. Specific power is fundamental when reducing the battery weight, especially in high-power demand applications, such as hybrid vehicles. The specific power of a chemical battery depends in first line on the battery's internal resistance. Lithium is known as the lightest metal. It provides valuable electrochemical attributes. It makes a high thermodynamic voltage possible, that leads to a very high specific power and specific energy. Hence the thesis concentrates on lithium-based batteries, although also cadmium-based batteries are possible candidates for HEVs. (Ehsani, Gao and Emadi 2010)

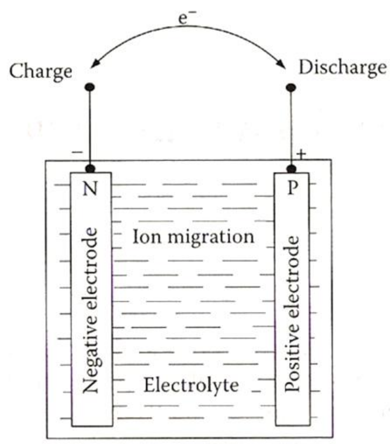


Figure 23: Typical electrochemical battery cell (Ehsani, Gao & Emadi 2010, p. 376)

Modern Li-Ion batteries consist of many subsystems. Figure 24 shows that some eight to twelve individual Li-Ion cells are assembled in a stack with a basic single-cell control system. Multiple stacks are then linked to create a complete battery pack with cooling, a solid housing for crash protection, and a master control device that manages the total system and the interaction with the rest of the automobile. (Roland Berger Strategy Consultants 2009)

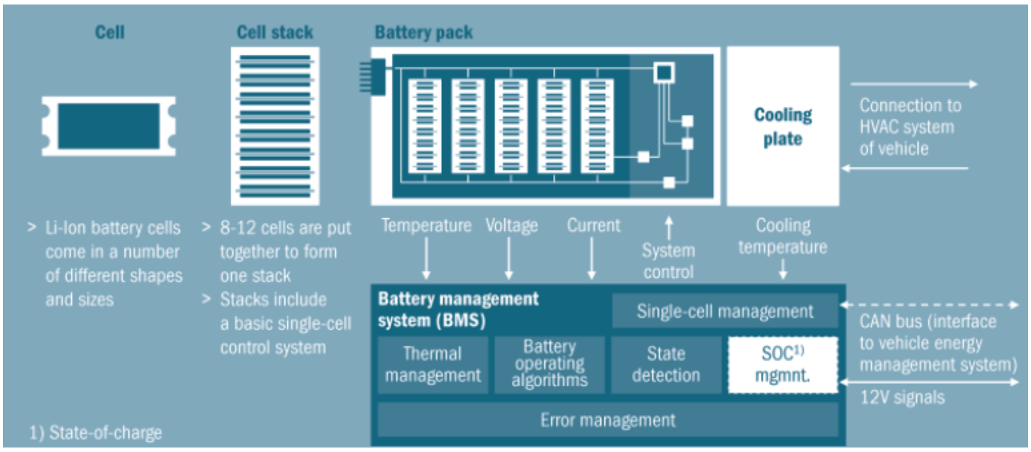


Figure 24: Li-Ion battery pack structure (Roland Berger Strategy Consultants 2009, p. 45)

The Li-Ion battery uses a liquid organic solution or a solid polymer for the electrolyte, a lithiated transition metal intercalation oxide ($Li_{1-x}M_yO_z$) for the positive electrode and a lithiated carbon intercalation material (Li_xC) for the negative electrode. Lithium ions are swinging through the electrolyte between the positive and negative electrodes during discharge and charge. On discharge, a lithium ion that is emitted by the negative electrode, moves inside the electrolyte, and is taken up by the positive electrode. On charge the process is reversed. Possible positive electrode materials include $Li_{1-x}CoO_2$, $Li_{1-x}NiO_2$, and $Li_{1-x}Mn_2O_4$, which have the advantages of reversibility for the lithium intercalation reaction, high voltage and stability in air. The $Li_xC/Li_{1-x}NiO_2$ type, loosely written as $C/LiNiO_2$ or simply called the nickel based Li-I battery, has a nominal voltage of 4 V, a specific power of 260 W/kg, an energy density of 200 Wh/L and a specific energy of 120 Wh/kg. The cobalt-based type has higher specific energy and energy density, but with a higher cost and significant increase of the self-discharge rate. The manganese-based battery has the lowest cost and the specific energy and energy density lies amongst nickel-based and cobalt-based types. It is foreseen that the development of the Li-Ion battery will ultimately move to the manganese-based type because of the low cost, abundance, and environmental friendliness of the manganese-based materials. (Ehsani, Gao & Emadi 2010)

Plastic Li-Ion technology has the potential to significantly impact vehicle integration issues that currently inhibit the application of HEV powertrains. Li-Ion provides packaging flexibility, reduced mass and allows low maintenance. It is promoted as an emerging technology having the potential to meet all energy and power needs, manufacturer cost targets and packaging requirements of the vehicle integrator and also the manufacturer. This technology is sometimes referred to as lithium polymer (LiPo). As with conventional Li-Ion, the LiPo is a "rocking chair" electro-chemistry because the lithium ions move back and forth through the electrolyte without undergoing chemical change. At the same time the lithium molecules move back and forth across the electrolyte, the electrons are released to do the same in the external circuit. Since the electrode material in a LiPo structure undergoes a reversible change during oxidation, no chemical reorganisation need take place so there should be little degradation of the cell. Hence the LiPo has the potential of a long operating life. However, LiPo is a thin film technology, so its durability in automotive harsh environments could be problematic. LiPo has a power to energy ratio (P/E = 12 and higher) well into the range of hybrid applicability. Lithium polymer is capable of high pulse power because the cell structure used is composed of a number of bicells in parallel instead of plates. These bicells rely on thin film technology to create a tight contact with the electrolyte with minimum free electrolyte. The electrodes are immersed in a polymer matrix akin to a sponge that retains the liquid electrolyte. Variations in the electrode thickness then have direct bearing on cell power and energy characteristics. Thin electrodes are high power, while thicker electrodes, with more volume of micropores, have higher energy. The bicell laminations can be made to any length or width. Prismatic cell construction is readily obtained, so that very thin, flat geometries can be fabricated that make installation easier. The cell electrode described forms the basic structure of the electronic double layer capacitor: The ultracapacitor. (Miller 2004, p. 149-150)

3.2.5.2 Ultracapacitor

In comparison to a battery a ultracapacitor is characterized by a high specific power but a low specific energy. Its specific energy is in the range of a few watt-hours per kilogram. The specific power reaches up to 3 kW/kg, much higher than any type of battery. By reason of the lower specific energy density as well as the dependence of terminal voltage on SOC, it is difficult to use ultracapacitors alone as an energy storage for HEVs. Nevertheless, there are a number of advantages that can result from using the ultracapacitor as an auxiliary power source. One promising application is the so-called battery and ultracapacitor hybrid energy storage system for HEVs. (Chan & Chau 2001)

Specific energy and specific power requirements can be decoupled, thus affording an opportunity to design a battery that is optimized for specific energy and cycle life with little attention being paid to specific power. By reason of the load levelling effect of the ultracapacitor, the high current discharging from the battery and the high current charging to the battery by regenerative braking are minimized so that available energy, endurance, and life of the battery can be significantly increased. (Ehsani, Gao & Emadi 2010, p. 391)

Double-layer capacitors are the major approach to achieve the ultracapacitor concept. The basic principle of a double-layer capacitor can be seen in Figure 25. When two carbon rods are immersed into a thin sulphuric acid solution, separated from each other and applied with increasing voltage from zero to 1.5 V, almost nothing happens up to 1 V; then at a little over 1.2 V, a small bubble appears on the surface of both electrodes. Bubbles at a voltage above 1 V indicate the electrical decomposition of water. Below the decomposition voltage, while the current does not flow, an electric double layer occurs at the boundary of electrode and electrolyte. The electrons are charged across the double layer and for a capacitor. (Ehsani, Gao & Emadi 2010, p. 391-392)

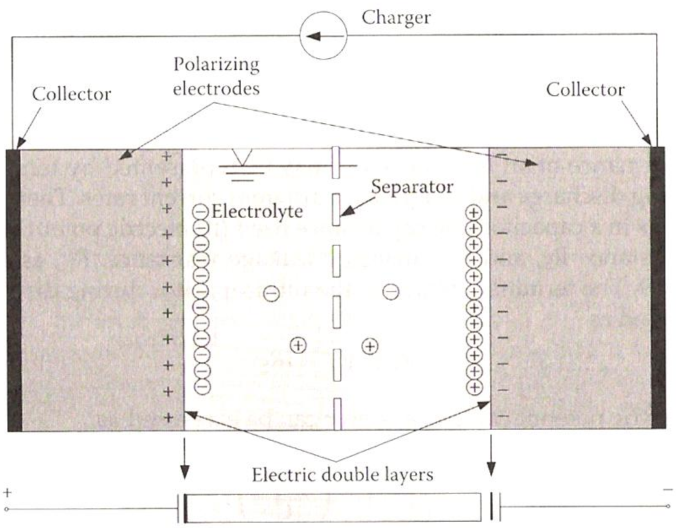


Figure 25: Basic principles of a typical electric double-layer capacitor (Ehsani, Gao & Emadi 2010, p. 391)

3.2.5.3 Hybridization of Energy Storages

The hybridization of energy storage system involves the combining of two or more energy storages together so that the advantages of each can be brought out and the disadvantages can be compensated by others. For example, the hybridization of a chemical battery with an ultracapacitor can overcome problems such as the low specific power of chemical batteries and low specific energy of ultracapacitors, thus achieving high specific power and high specific energy. Basically, hybridized energy storage systems consist of two basic energy storages, one with high specific power and one with high specific energy. Figure 26 illustrates the basic operation of this system. In high-power demand operation, such as acceleration and hill climbing, both basic energy storages deliver their power to the load as shown in Figure 26a. On the other hand, in low-power demand operation, such as constant-speed cruising operation, the high specific energy storage will deliver its power to the load and charge the high specific power storage to recover its charge lost during high-power demand operation, as shown in Figure 26b. In regenerative braking operation, the peak power will be absorbed by the high specific power storage, and only a limited part is absorbed by the high specific energy storage. In this way, the whole system would be much smaller in weight and size than if any one of them alone was the energy storage. (Ehsani, Gao & Emadi 2010, p. 404)

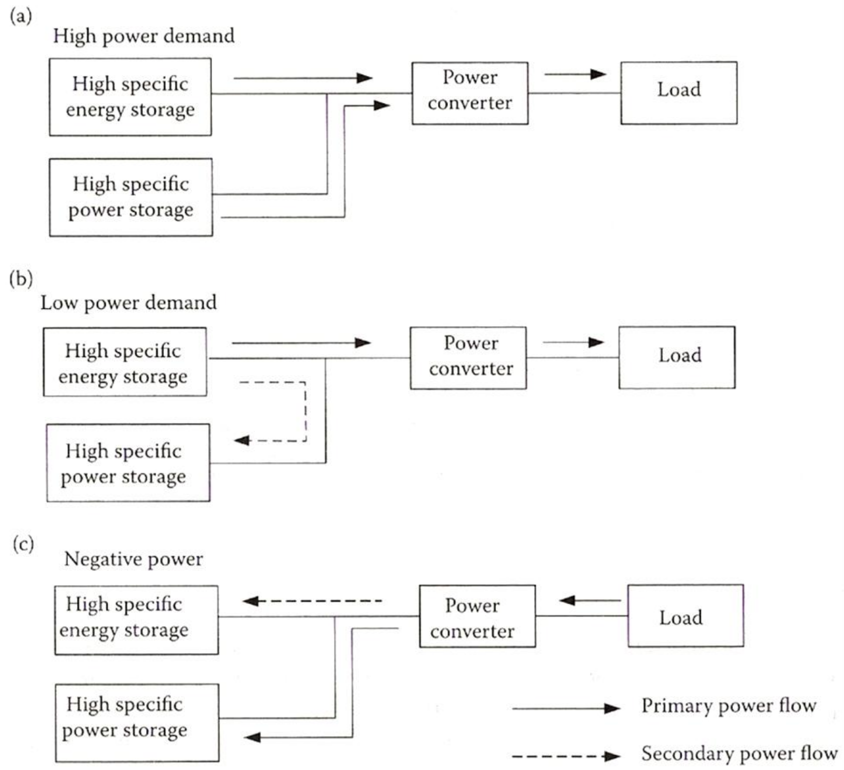


Figure 26: Concept of hybrid energy storage operation. (a) Hybrid powering, (b) Power split, (c) Hybrid charging (Ehsani, Gao & Emadi 2010, p. 405)

Based on the different available energy storage technologies, there are many feasible hybridization schemes for HEVs which are typically battery and battery hybrids, and battery and ultracapacitor hybrids. The latter is more natural because the ultracapacitor allows a much higher power than batteries, and it collaborates with different batteries to form the battery and ultracapacitor hybrids. During the hybridization, the simplest way is to directly and parallel connect the ultracapacitors to the batteries. In this configuration, the ultracapacitor simply acts a current filter, which can significantly level the peak current of the batteries and reduce the battery voltage drop as shown in Figure 27. The major disadvantages of this configuration are that the power flow cannot be actively controlled and the ultracapacitor energy cannot be fully used. (Ehsani, Gao & Emadi 2010, pp. 404-405)

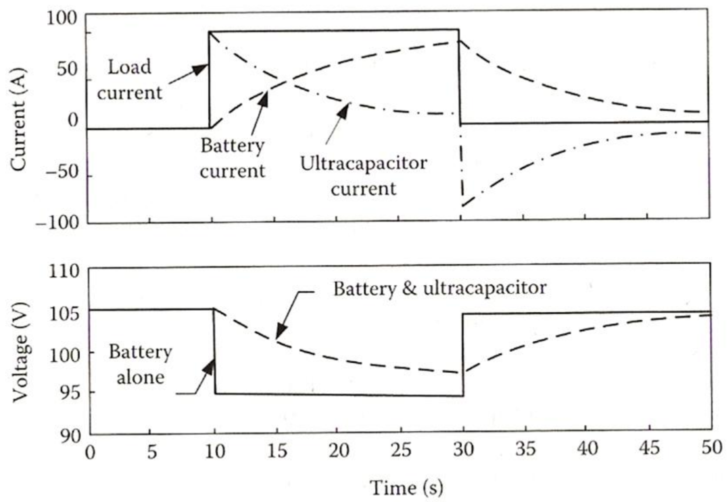


Figure 27: Variation of battery and ultracapacitor currents and voltages currents and voltages with a step current output change (Ehsani, Gao & Emadi 2010, p. 406)

Figure 28 shows a layout in which a two-quadrant DC/DC converter is situated between the batteries and ultracapacitors. This design allows to have different voltages for the battery and the ultracapacitor. In addition the power flow between them can be actively controlled and the energy in the ultracapacitors can be fully used. (Ehsani, Gao & Emadi 2010, p. 405)

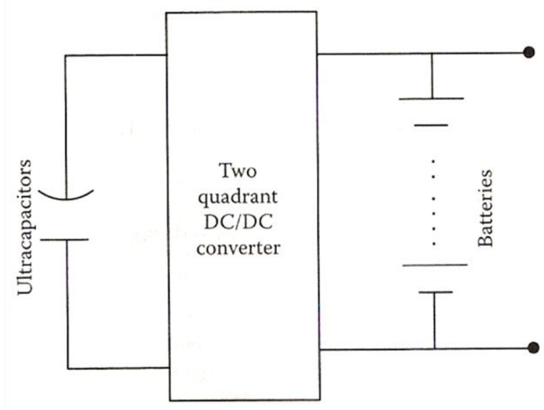


Figure 28: Actively controlled hybrid battery/ultracapacitor energy storage (Ehsani, Gao & Emadi 2010, p. 407)

The most favourable configuration of a HEV energy storage system with battery and ultracapacitor is that the total energy and power capacities just meet the energy and power needs of the automobile without much margins. (Gao & Ehsani 2006)

3.3 Aspects of Hybrid Electric Vehicles

3.3.1 Overview of Hybrid Systems

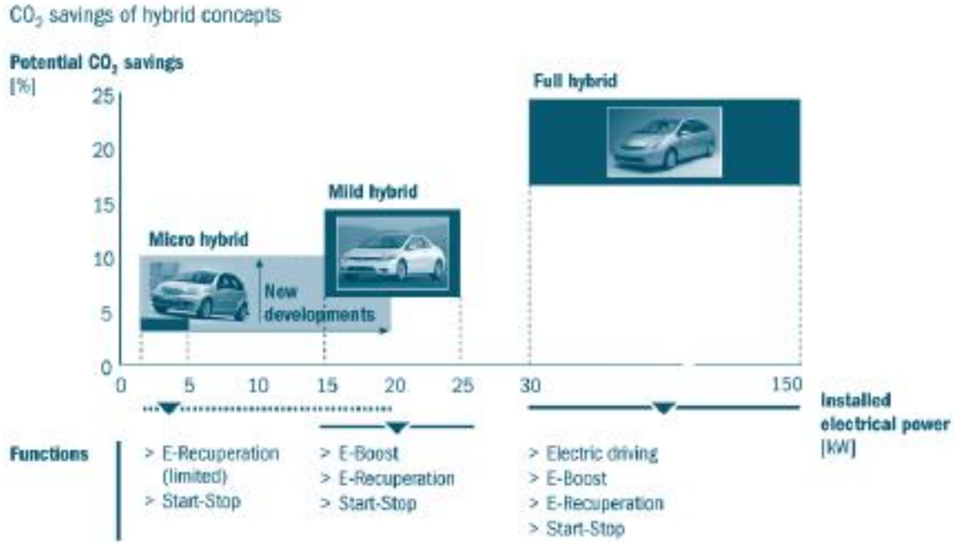


Figure 29: CO_2 savings of hybrid concepts (Roland Berger Strategy Consultants 2007, p. 24)

Full hybrids today allow CO_2 emission reductions of about 20 percent as can be observed in Figure 29. However, the potential reductions always depend on the driving profile. Another possibility is the mild HEV that only offers electric boost functionality. It is fitted with a smaller electric motor (15-25 kW) and a smaller energy storage system. The smaller EM only enables an electric boost in acceleration situations and no autonomous driving. Hence, the potential for CO_2 emission reduction is lower but still roughly 15 percent. Lastly, there is the micro HEV which only concentrates on regenerative braking and start-stop functionality. It is not equipped with an electric motor but has a more powerful starter and alternator (2-5 kW). In this case CO_2 emission reductions in the range of 3-4 percent are feasible. In the midterm, micro hybrids will change, moving away from the start-stop systems used today to systems with comparable possibilities as that offered by mild hybrids. Their installed electrical power will reach up to 20 kW. Hence there will be a fluent change to mild hybrids from an installed electrical power view. In addition to the start-stop function that is already well established, micro hybrids will also feature enhanced energy recuperation and enhanced acceleration support. The enhanced functions are enabled without the disadvantages of electrical machines installed somewhere in the gearbox or between engine and gearbox as in most mild hybrids. These system designs increase the centrifugal mass of the powertrain which lifts fuel consumption and reduces the engine's sporty characteristics. Furthermore the new micro hybrids can be installed in current vehicle concepts and engines without major design changes because their electrical machine is still connected to the engine's crankshaft. Only one function will be missing – solo electrical driving. Hybrids (considering micro hybrid, mild hybrid and full hybrid) will exceed a saturation rate of 50 percent by 2015. Full hybrids will most likely remain a niche product. (Roland Berger Strategy Consultants 2007, p. 25)

3.3.2 Architectures of HEV

In fact, there is one mechanical energy and one electrical energy flowing in the drivetrain. A accurate definition for HEV architecture may be to take the power coupling or decoupling features such as an electrical coupling drivetrain, a mechanical coupling drivetrain, and a mechanical-electrical coupling drivetrain. (Ehsani, Gao & Emadi 2010, pp. 126-127)

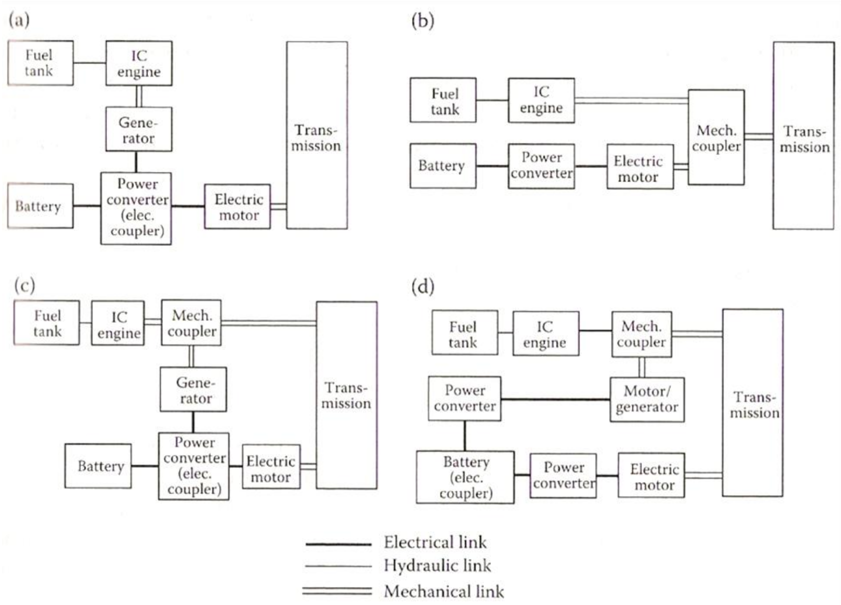


Figure 30: Classification of HEVs. (a) Series (electrically coupling), (b) Parallel (mechanical coupling), (c) Series parallel (mechanical and electrical coupling), (d) Complex (mechanical and electrical coupling) (Ehsani, Gao & Emadi 2010, p. 127)

Figure 30a functionally demonstrates the so-called series hybrid drivetrain configuration. This design adds two electrical powers together in the power converter. The power converter controls the power flows by acting as electric power coupler. There is an flow from the generator and energy storage system to the EM, and on the other side from the EM to the energy storage system. The ICE, the fuel tank, and the generator present the primary energy supply and the batteries function as the energy puffer.
Figure 30b shows the so-called parallel hybrid drivetrain configuration. The highlight of the design is that two mechanical powers are added together to each other in a mechanical coupler. The ICE is the prime power plant, energy storage system and EM present the energy puffer. The ICE and the electric motor are the only possibility to control the power flows.
Figure 30c demonstrates the so-called series parallel hybrid drivetrain architecture. Its designated characteristic is that two power couplers are implemented. In other words, there is one mechanical and one electrical power coupler. In fact, this architecture joins parallel and series drivetrain. Hence it shows major features of both and a big number of operation modes in comparison to those of the series or parallel structure alone. Having said that, it is proportionally more complex and may be more expensive.
Figure 30d illustrates the so-called complex hybrid architecture. It is related to the series parallel structure and only varies is in a way that the electric coupling function is moved from the power converter to the energy storage system and one more power converter is added between the M/G and the energy storage system. (Ehsani, Gao & Emadi 2010, pp. 127-128)

3.3.2.1 Series Architecture (Electric Coupling)

To obtain a series architecture two electrical power plants have to feed a single electrical power plant (EM) that propels the vehicle. The most often used configuration can be observed in Figure 31. The unilateral energy converter (power plant) is an ICE coupled to a M/G and the unilateral energy source is a fuel tank. Through a controllable electronic converter (rectifier) the output of the M/G is linked with a power DC bus. A battery pack linked with the power DC bus through a bilateral, controllable power electronic converter (DC/DC converter) is the bilateral energy source. The power bus is linked with the controller of the EM as well. Traction motors can be controlled in reverse and forward motion, and as motors or as generators. The drivetrain might make a battery charger necessary to load the energy storage system from a power grid by plug-in. (Ehsani, Gao & Emadi 2010)

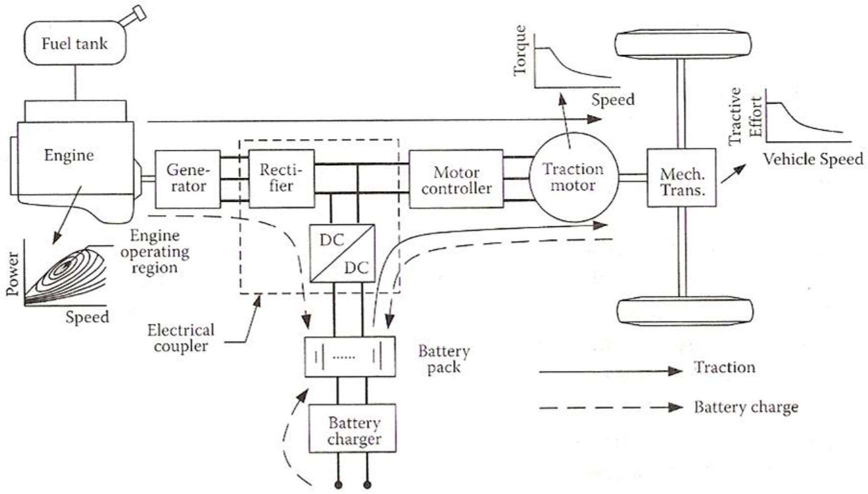


Figure 31: Configuration of a series hybrid electric drivetrain (Ehsani, Gao & Emadi 2010, p. 128)

The serial architecture in combination with ICEs is currently not a viable option since it is not as efficient as sole combustion engines that drive the drive gear directly. Therefore the series configuration only makes sense in combination with a fuel cell or in a pure EV, for example in combination with e-corners. These technologies still need at least 20 years before they will become a real alternative. (Roland Berger Strategy Consultants 2007, p. 26)

Ehsani, Gao and Emadi (2010, pp. 129-130) state the following series HEV advantages:

1. Between the ICE and the driven wheels there is no mechanical connection. Consequently, the ICE could be potentially run at every point on the torque-speed (power) map. This distinguished advantage, with a sophisticated power flow control, provides the engine with opportunities to operate it always in the region with highest efficiency. This can be seen in Figure 31. The emissions and efficiency of the ICE in this narrow region may be further improved by some special design and control technologies, which is much easier than in the whole operating domain. In addition, it is possible to spend the vehicle high speed engines since the engine is mechanically decoupled from the driven wheels. This can be done where it is complicated to directly propel the wheels through a mechanical link. In this case power plants and gas turbines that have slow dynamic responses can be used.

2. Since EMs have a torque-speed profile that is very close to the ideal for traction, the drivetrain may not need multigear transmission. Therefore, the structure of the drivetrain can be greatly simplified and is therefore cheaper. Furthermore, two EMs can be implemented, in doing so each can power a single wheel, and the mechanical differential can be removed. Such an arrangement also has the following advantages of decoupling the speed of two wheels, a similar function of a mechanical differential, and an additional function of antislip similar to the conventional traction control. Furthermore, four in-the-wheel motors may be used, each one driving a wheel. In such a layout, the speed and torque of each wheel can be independently controlled. Consequently the drivability of the vehicle can be significantly enhanced. This is very important for off-road vehicles which usually operate on difficult terrain, like ice, snow, and soft ground.

3. Compared to others, the control strategy of this configuration is simple, due to its fully mechanical decoupling between the engine and wheels.

As series HEV disadvantages Ehsani, Gao and Emadi (2010, p. 130) identified:

1. The produced energy of the ICE changes its form twice to reach the driven wheels. There is a electrical to mechanical change in the traction motor as well as a mechanical to electrical change in the generator. In dependence of the inefficiency of the traction motor and the generator this may cause significant losses.

2. Additional cost and weight is added by the generator. Since the traction motor is the single owner source to propel the car, it must be sized to produce enough power for optimal vehicle performance in terms of acceleration and gradeability.

3.3.2.2 Parallel Architecture (Mechanical Coupling)

Parallel hybrid architectures allow a direct powertrain from the ICE to the drive gear, mechanically coupled via an automatic clutch while the electric M/G is directly linked to the gearbox. Such an layout can be seen in Figure 32. The clutch is open during electric driving and during energy recuperation, so that the engine is totally separated from the powertrain. Only one electric M/G is necessary. The operating point optimization, however, is limited. (Roland Berger Strategy Consultants 2007, p. 27)

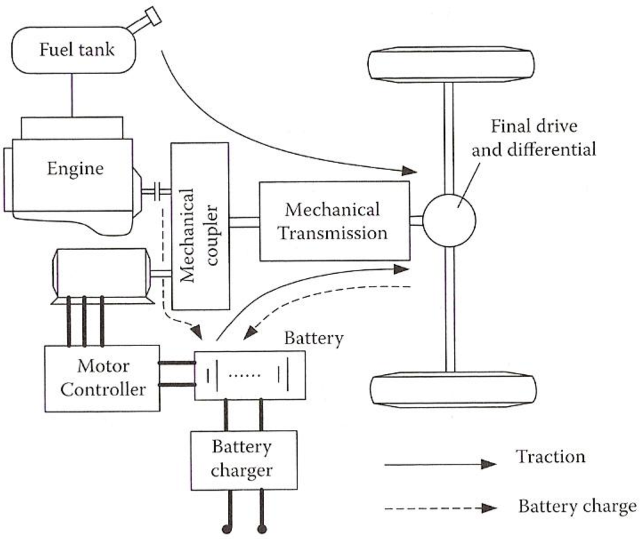


Figure 32: Parallel HEV drivetrain configuration (Ehsani, Gao & Emadi 2010, p. 131)

Normally, mechanical coupling consist of speed coupling and torque coupling. In torque coupling, the torque of EM and ICE are added together and delivered as total torque to the driven wheels by the mechanical coupler. The engine and motor torque can be independently controlled. Though, the speeds of the engine, motor, and car are linked together with a fixed relationship and cannot be independently controlled because of the power conversation constraint. Similarly in speed coupling, the velocities of the ICE and EM can be added together and all the torques are linked together and cannot be independently controlled. The details of these two kinds of mechanical coupler are described hereafter. (Ehsani, Gao & Emadi 2010, p. 131)

3.3.2.2.1 Drivetrain Configurations with Torque Coupling

Figure 33 demonstrates the concept of a mechanical torque coupling, which is a three-port, two-degree-of-freedom mechanical device. Port 1 is a unilateral input and ports 2 and 3 are bidirectional input or output, but both are not input at the same time. To explain in detail, input means the energy flow into the device and output means the energy flow out of the device. In a HEV application, port 1 is linked to an ICE directly or through a mechanical transmission. Port 2 is linked to the shaft of an EM directly or by a mechanical transmission. Port 3 is linked to the driven wheels by a mechanical linkage. If the losses are ignored and in steady state, the power input to the torque coupler is always identical to the power output from it. (Ehsani, Gao & Emadi 2010)

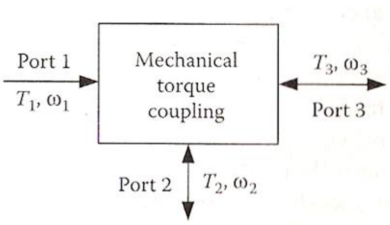


Figure 33: Torque-coupling device (Ehsani, Gao & Emadi 2010, p. 132)

To constitute HEV drivetrains with many different configurations, torque couplers can be utilized. Based on the torque coupler used, a two- or one-shaft architecture may be created. In each, transmission may be positioned unequal with differing gears. This results in various tractive characteristics. (Ehsani, Gao & Emadi 2010, p. 133)

In a two-shaft configuration, two transmissions are build in. The first is positioned between the EM and the torque coupler and the second between the ICE and the torque coupler. Each transmission can be multigear or single-gear. Obviously various tractive effort profiles can be produced with two multigear-transmissions. Since two multigear-transmissions offer many chances for the ICE as well as the electric traction system (EM and energy storage system) to run in the region with highest efficiency, the total efficiency and performance of the drivetrain can be predominant to other configurations. It offers more flexibility in the EM traits and the design of the ICE as well. On the other hand two multigear-transmissions can handicap the drivetrain and increase the burden of the control system for choosing the proper gear in each transmission. (Gao, Rahman and Ehsani 1997)

The single-shaft design is the most compact and simplest configuration of the torque-coupling parallel hybrid. In this case the torque coupler task is taken over by the rotor of the EM. The electric motor can be situated either among the ICE and transmission as shown in Figure 34, referred to as pretransmission, or among the transmission and final drive, referred to as post-transmission. (Ehsani, Gao and Emadi 2010)

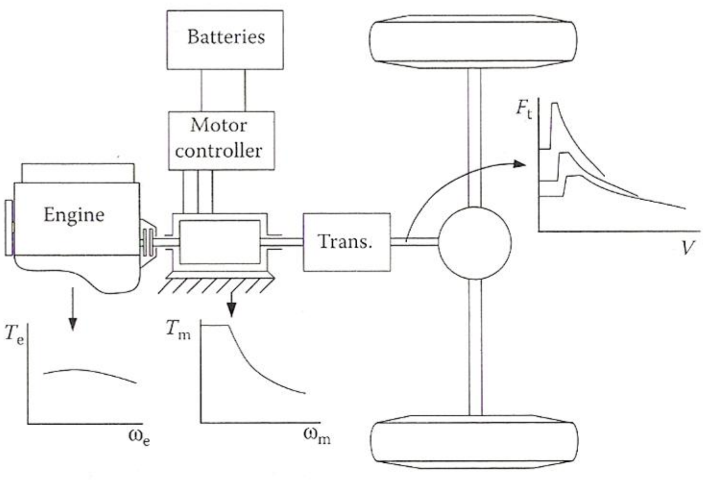


Figure 34: Pretransmission single-shaft torque combination parallel hybrid electric drivetrain (Ehsani, Gao & Emadi 2010, p. 136)

3.3.2.2.2 Through-the-Road Hybrid

The separated-axle configuration is one more torque-coupling parallel hybrid drivetrain. In this case the first axle is powered by the ICE and the second by the EM as shown in Figure 35. Road and vehicle chassis add the tractive efforts together which are made available by both powertrains. The working methods are related to the two-shaft design. Each transmission for the ICE and EM can be multigear or single-gear. The design has analogue tractive effort characteristics to the one before. In addition the separated-axle architecture provides a few advantages of traditional vehicles. The ICE and transmission are kept unmodified but an electrical traction system is added on the second axle. The vehicle offers also four-wheel drive, that helps to reduce the tractive effort on each single wheel and to improve the traction if it is slithery. On the other side the eventual differential gear system and the EM take plenty of space and hence the usable luggage space and passenger space may be reduced. This challenging issue can be tackled if the transmission behind the EM is single-gear and the single EM is substituted by two small-sized EM which can be positioned inside both driven wheels. In this configuration it is not possible to charge the energy storage system from the ICE when the car is idling. (Ehsani, Gao & Emadi 2010)

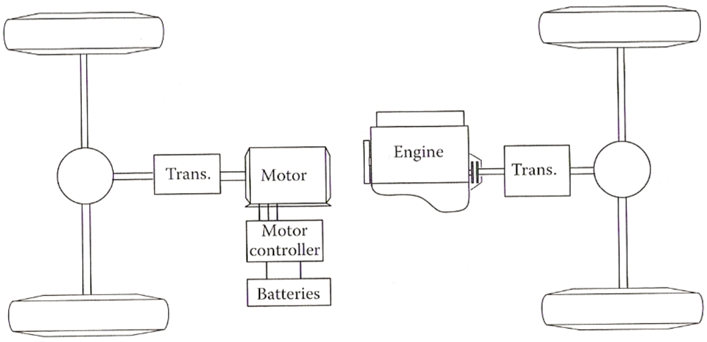


Figure 35: Separated axle torque combination parallel hybrid electric drivetrain (Ehsani, Gao & Emadi 2010, p. 138)

3.3.2.2.3 Drivetrain Configurations with Speed Coupling

The power which is gained by the two power plants may be coupled together by summing up their speeds. Equal to the mechanical torque coupler, the speed coupler is also a three-port, two-degree-of-freedom mechanical device. Port 1 may be linked to an ICE with unilateral energy flow. Ports 2 and 3 may be linked to an EM and to the final drive, both with bidirectional energy flow. Further device which can be applied as speed coupler is an EM with a floating stator. The stator, which is usually connected to a fixed frame in a conventional EM, is disconnected to form a double rotor machine with inner and outer rotor. The air gap, inner rotor and outer rotor define the three ports. Electric power is transformed into mechanical power through the air gap, as shown in Figure 36. Traditionally the EM velocity is the relative velocity of inner rotor with respect to outer rotor. The torques acting on both rotors are always the same by reason of the action and reaction effect. (Ehsani, Gao & Emadi 2010)

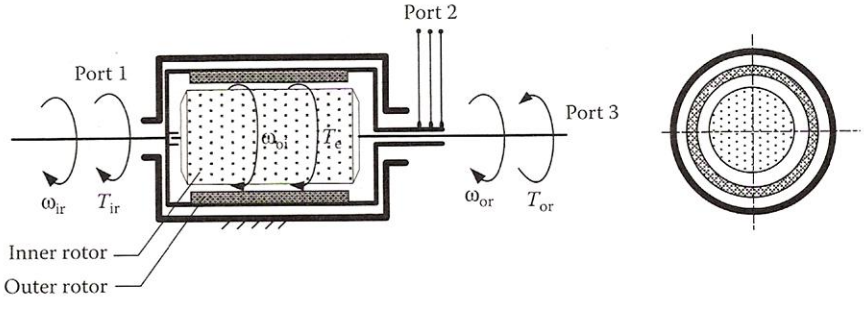


Figure 36: Electric variable transmission used as speed coupler (Ehsani, Gao & Emadi 2010, p. 141)

According to Ehsani, Gao & Emadi (2010) parallel HEV offer the following advantages:

The distinguished feature of this architecture is that two mechanical powers from the ICE and EM are added by a mechanical coupler. All the possible operation modes mentioned in the series hybrid drivetrain are still effective.

Compared to the series hybrid drivetrain the parallel one has the following advantages:

1. Engine and the EM forthright allocate torque to the driven wheels. No energy is converted to another form, thus energy efficiency is higher.

2. It is compact since the traction motor is very small compared to series and it is not necessary to have an extra generator.

As parallel HEV disadvantages Ehsani, Gao & Emadi (2010) mentioned:

1. The major disadvantage is that it is not possible to fix the ICE working points in a narrow torque and speed region because of the mechanical coupling among the ICE and the driven wheels.

2. The complex structure and control may also be a disadvantage.

3.3.2.3 Series Parallel Architecture (Torque and Speed Coupling)

3.3.2.3.1 With Optional Coupling Mode

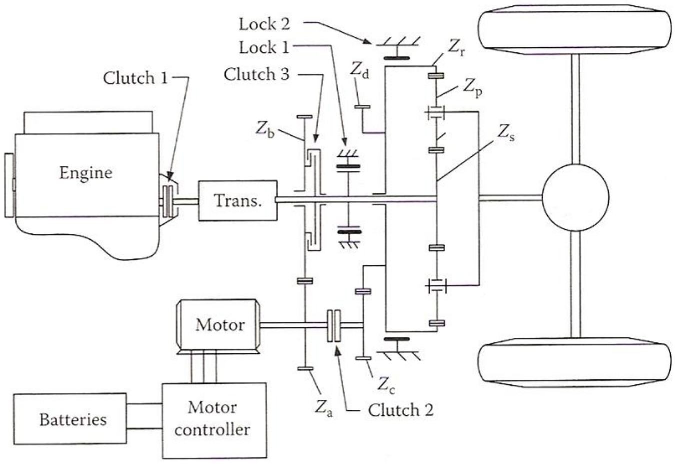


Figure 37: Alternative torque and speed hybrid electric drivetrain with a planetary gear (Ehsani, Gao & Emadi 2010, p. 145)

Hybrid drivetrains with the possibility to choose speed- and torque-coupling states optionally can be constructed by joining speed and torque coupling. Such a drivetrain is shown in Figure 37. Firstly it is necessary to choose the operation mode for the torque coupling. While clutch 1 and clutch 3 are coupled and clutch 2 is decoupled, lock 2 will lock the vehicle frame and the ring gear of the planetary unit. The power of the ICE and the EM are accumulated together by accumulating their torques together by means of gear Z_a, Z_b and clutch 3 to the sun gear shaft. In this case, the planetary gear unit functions only as a speed reducer. The gear ratio from the sun gear to carrier, defined as ω_1/ω_3, equals $(1+i_g)$. This is a usual parallel hybrid drivetrain with torque coupling. After choosing the speed-coupling mode as the current operation mode, clutch 1 and clutch 2 are coupled, while clutch 3 is decoupled. Lock 1 and lock 2 disengage the ring gear and sun gear. The velocity of the carrier which is linked to the driven wheel, is a combination of ICE velocity and EM velocity. The torques of the ICE, the

EM, and on the driven wheels are retained in a determined correlation. With the option to choose the power-coupling mode (torque or speed coupling), the power plant has many options for its working region as well as its working manner and hence to optimize the performance. If the car is driving slow, the torque combination mode can be adequate for hill climbing or high acceleration. Though, at higher velocity, the speed combination mode should be applied so that the ICE velocity is kept in its optimal region. The planetary gear unit and the traction motor in Figure 37 can be replaced by a electrical variable transmission to form kindred drivetrains like shown in Figure 38. The drivetrain operates in the torque coupling mode when the lock is activated to fix the outer rotor of the electrical variable transmission to the car frame and clutch 1 is closed to engage the output shaft of the transmission to the inner rotor shaft of the electrical variable transmission. Otherwise the drivetrain operates in the speed coupling mode when clutch 1 is decoupled, clutch 2 is coupled and the lock is disconnected. (Ehsani, Gao & Emadi 2010)

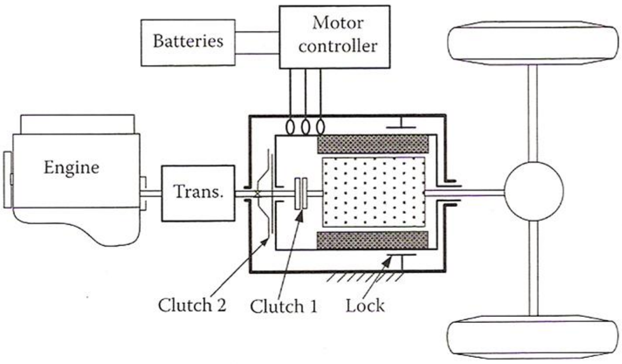


Figure 38: Alternative torque and speed-coupling hybrid electric drivetrain with a electrical variable transmission (Ehsani, Gao & Emadi 2010, p. 146)

The distinguishable characteristic of the above HEV drivetrains is that the drivetrain can optionally choose the best coupling mode in various driving situations in order to obtain the best driving performance and efficiency. However, they cannot run on both coupling modes at the same time, since only two power plants are available. (Ehsani, Gao & Emadi 2010, p. 145)

3.3.2.3.2 With Both Coupling Modes

A hybrid drivetrain with both speed- and torque-coupling modes at the same time can be realized just by adding another power plant. A well known example is the Toyota Prius. Figure 39 illustrates its drivetrain schematically. The drivetrain uses a set of fixed axle gears as the torque-coupling device and a planetary gear unit as the speed-coupling device. The planetary gear set is composed of sun gear at the centre of the diagram, a set of pinion gears (planets) arranged around the sun and held by the carrier and the ring gear. Bearings support the three sets of gears. (Toyota Motor Company 2010)

An ICE is connected to the carrier of the planetary gear unit, and to constitute the speed-coupling configuration a small M/G (few kilowatts) is connected to the sun gear of a planetary gear unit. The ring gear is connected to the driven wheels via the axle fixed gear unit (torque coupler). To constitute the torque-coupling configuration, a traction motor is linked to the fixed axle gear unit. (Ehsani, Gao & Emadi 2010)

The mechanical power is transmitted from the ICE to the driveline via the planetary gear set through the ring gear to the final drive and to the wheel. The electrical path is split off via the M/G1, or starter-alternator (S/A), which is working as generator so that reaction torque is developed against the carrier to effect the mechanical path. Electric power from the S/A is then routed to the dc bus and taken by the main M/G for propulsion or sent to the energy storage system. M/G is the main traction motor utilized for regenerative braking and for propulsion. (Miller 2004)

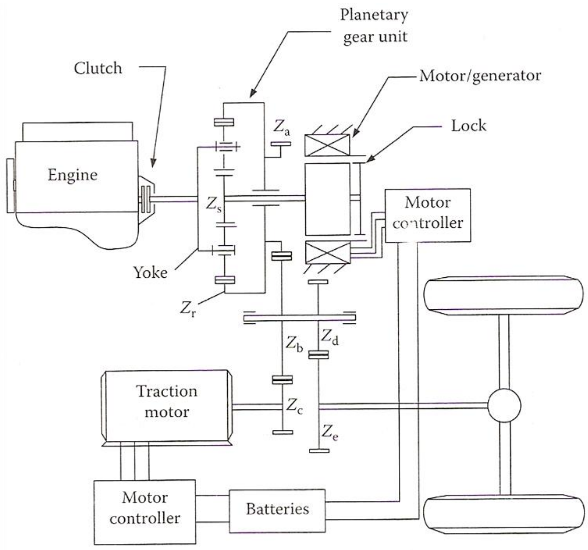


Figure 39: Integrated speed- and torque-coupling hybrid electric drivetrain (Ehsani, Gao & Emadi 2010, p. 147)

The torque, acting on the sun gear, supplied by the M/G has opposite direction to ICE torque and same direction as load torque on the ring gear. With low vehicle velocity (small ω_r) and a not very low engine speed (larger than its idle speed), the M/G has to rotate in the positive direction, which is the same direction as engine speed. In this condition, the M/G runs with a negative power, that is, generating. The ICE power is split into parts: The first part goes to the M/G and the other to vehicle load through the ring gear. This is how the drivetrain gets its name of power split hybrid drivetrain. However at high vehicle velocity, while trying to maintain the engine speed below a given speed, for high engine operating efficiency, the M/G may be operated in negative speed. That means it rotates in the contrary way to engine speed. In this case, the M/G delivers positive power to the planetary gear unit, that is, motoring. It becomes clear through the above analysis that the major function of a M/G is to control engine speed, that is, decouple engine speed from wheel speed. (Ehsani, Gao & Emadi 2010, p. 147)

This balancing act can be described very well when utilizing a static diagram of power split operation at a static operating point as shown in Figure 40. It is clear to see that the speed of the S/A is very high in relation to engine speed and vehicle speed during acceleration. While cruising, however, it behaves just the opposite. The speed of the carrier C is associated with the engine speed. The speeds of the sun gear S and ring gear R are always in a certain ratio to the velocity of the carriers C.

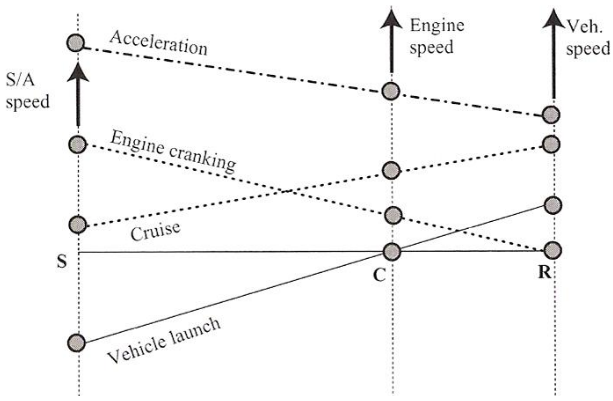


Figure 40: Power split "stick" diagram of speed constraints (Miller 2004, p. 70)

Power split propulsion systems do not contain driveline clutches, only indirect mechanical paths between the ICE and the driven wheels. Figure 41 shows the basic characteristics of power split systems.

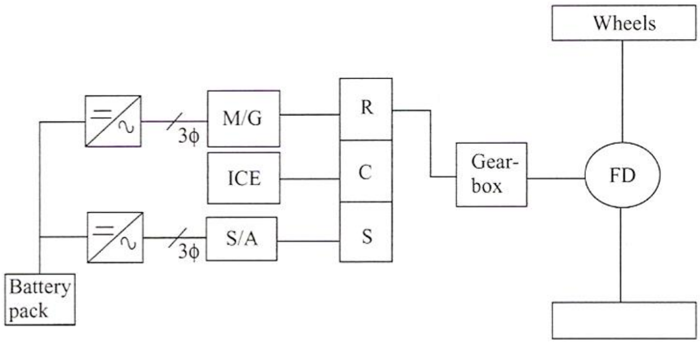


Figure 41: Power split functional architecture (Miller 2004, p. 69)

The traction motor adds additional torque to the torque output from the ring gear with a torque-coupling mode via gears Z_c, Z_b, Z_d, and Z_e, by which the ICE torque is decoupled from the automobile load. The small motor and the planetary gear unit in Figure 39 can be replaced by an individual electrical variable transmission, as shown in Figure 42. The drivetrain shows analogue characteristics to the one shown in Figure 39. (Ehsani, Gao & Emadi 2010, p. 147)

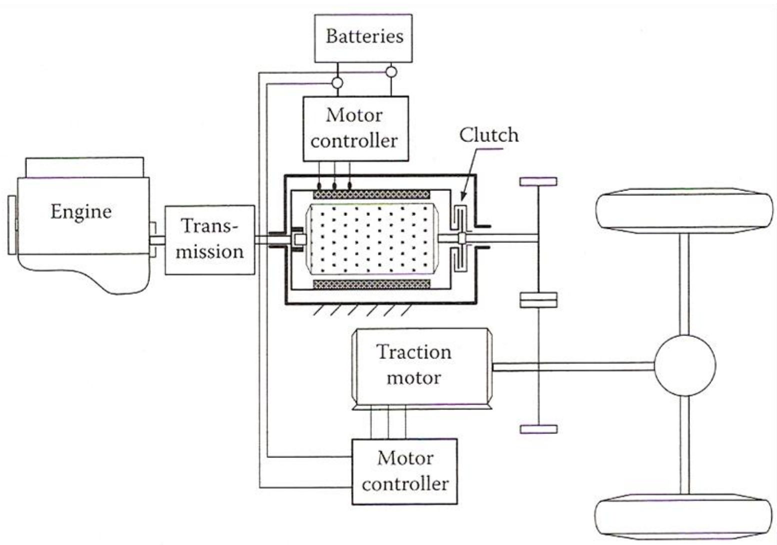


Figure 42: Hybrid electric drivetrain with speed and torque coupling of a electrical variable transmission and double shaft (Ehsani, Gao & Emadi 2010, p. 148)

Another possible variation of the drivetrain is the single-shaft design which can be seen in Figure 42. It is a more compact design of the drivetrain since the traction motor and the electrical variable transmission are integrated together. The construction and control may be more complex than the separated structure as a result of the correlated magnetic field in the double air gaps. (Ehsani, Gao & Emadi 2010)

Depending on the driving situation the EM can drive the car solely, support the ICE or recoup energy when the vehicle decelerates. This is the main advantage of a power split HEV. Furthermore the operating point can be optimized by applying the ICE torque partly to charge the energy storage system, in dependence of the ICE load level. (Roland Berger Strategy Consultants 2007, p. 27)

4. CASE STUDIES

The thesis will address those three configurations, whose description will cover most of the future hybrid vehicles.

4.1 MILD HYBRID COMPACT CAR

4.1.1 OVERVIEW

It is well known that full HEVs with parallel, series or series parallel architectures can optimize fuel economy to a great extent by operating the ICE optimally and using effective regenerative braking. (Gao, Chen & Ehsani 1999)

Otherwise, a high electric power demand desires a voluminous and heavy energy storage system. This leads to problems for packing the drivetrain under the bonnet and allows less loading capacity. In addition it increases the energy losses into the rolling tires. Full hybrid drivetrains have architectures completely different from traditional drivetrains. It needs big investments of money and time to change completely from a traditional drivetrain to a full hybrid. Hence it makes sense to find a compromise by developing an intermediate product that is easier to remodel from the current automobiles, and yet is more efficient than full HEV. One possibility is to put a small EM behind the ICE to set up a mild or soft HEV. The small EM can work as an engine starter as well as an electrical generator. Supplementary it can add power to the drivetrain when high power is required and it can transform part of the braking energy into electric energy. The small motor can possibly substitute the clutch or the torque converter, which is inefficient when working with a high slip ratio. A mild hybrid electric drivetrain does not necessitate high-power energy storage systems since the EM has a small power rating. A 42-V electrical system could already fulfil the request. Other subsystems of the traditional automobile like engine, transmission (gearbox), and brake, do not need many design changes. (Ehsani, Gao & Emadi 2010)

4.1.2 STUDY

4.1.2.1 Configuration

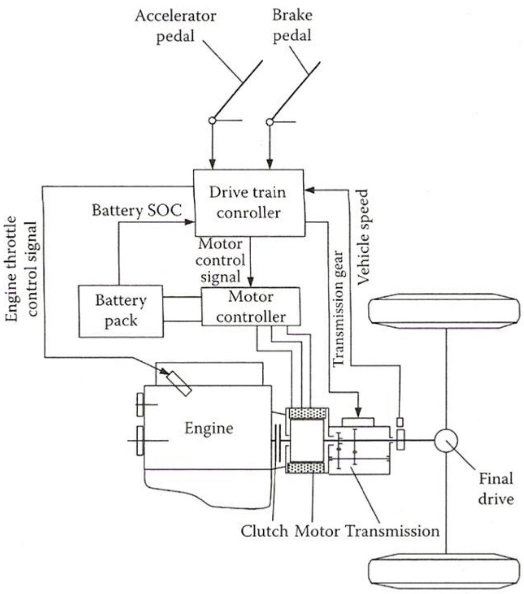


Figure 43: Configuration of the parallel connected mild hybrid electric drivetrain (Ehsani, Gao & Emadi 2010, p. 356)

The parallel mild HEV drivetrain can be seen in Figure 43. A small EM, which can function as engine starter, generator, and traction motor, is placed between the engine and the automatically shifted multigear transmission. The clutch is utilized to disconnect the gearbox from the ICE when required, for example during gear shifting and low vehicle speed. The power rating of the electric motor may be in the range of about 10% of the engine power rating. The electric motor can be smoothly controlled to run at any speed and torque. Therefore, isolation between the electric motor and transmission is not necessary. The operation of the drivetrain and each individual component is controlled by the drivetrain controller and component controllers. (Ehsani, Gao & Emadi 2010, p. 355)

4.1.2.2 Control Strategies and Operating Modes

The following operating modes dependent on the working of the ICE and EM are possible (Ehsani, Gao & Emadi 2010, pp. 355-356):

Engine alone traction mode - The electric motor is de-energized, and the automobile is powered by the ICE only. The mode should be applied when the SOC of the energy storage system is in the high region, and the combustion engine alone can handle the power demand.

Motor-alone traction mode - The engine is shut down, the clutch is disengaged (open). The vehicle is powered by the EM alone. This operating mode may be used at low driving velocity, for example below 10 km/h.

Battery charge mode - In this mode, the M/G operates as generator and is powered by the combustion engine, to charge the energy storage system.

Regenerative braking mode - The ICE is shut off, the clutch is disengaged. The EM is producing a braking torque to the drivetrain. Part of the automobiles kinetic energy is transformed into electric energy and charges the energy storage system. A significant amount of energy is dissipated by braking. Cikanek and Bailey (1995) remark that braking a 1500-kg vehicle from 100 km/h to zero speed dissipates about 0.16 kWh of energy in a few tens of meters. If this amount of energy is dissipated by coasting and only by drag forces (rolling resistance and aerodynamic drag) without braking, the vehicle will travel about 2 km

Hybrid traction mode - In this mode, both the combustion engine and EM provide traction power to the drivetrain.

The operating mode to be used in real operation depends on the power demand, that is commanded via accelerator or brake pedal, the SOC of the energy storage system, and the driving speed. The control strategy is the preset control logic in the drivetrain controller. The drivetrain controller receives the real-time signals from the driver and each individual component (refer to Figure 43) and then commands the operation of each component, according to the preset control logic. A proposed control logic is illustrated in Table 2:

Table 2: Illustration of the control logic (Ehsani, Gao & Emadi 2010, p. 357)

Driving Condition	Control Operation
Standstill	Both engine and motor are shut down
Low speed (<10 km/h)	Electric motor-alone traction
Braking	Regenerative braking
High-power demand (higher than power that can be produced by ICE)	Hybrid traction
Middle and low power demand	Battery charge mode or engine-alone traction mode, depending on the battery SOC

4.1.2.3 Drivetrain Design

The design of the mild HEV is very similar to the design of the conventional drivetrain, because both are very close. The following is an example of the systematic design of a 1500-kg passenger car drivetrain. The major characteristics of the automobile can be seen in Table 3. Referring to the similar conventional drivetrain the engine is designed to have a peak power of 108 kW. In addition a small motor with 7-kW rating power is used, which can operate as an engine starter and alternator and assist regenerative braking. Figure 44 shows the torque and power characteristics versus speed of this motor. (Ehsani, Gao & Emadi 2010, pp. 357-358).

Table 3: Major parameters of the mild hybrid electric drivetrain (Ehsani Gao & Emadi 2010, p. 357)

Vehicle Mass	1500 kg
Rolling resistance coefficient	0.01
Aerodynamic drag coefficient	0.28
Front area	2.25 m^2

The batteries in this design example are lead-acid batteries which are popularly applied in automobiles, due to their mature technology and low cost. They have relatively high power density, when matched with different types of usual batteries. Hence they are considered to be the good selection for mild HEVs, in which power density is more important than energy density. (Gao & Ehsani 2002)

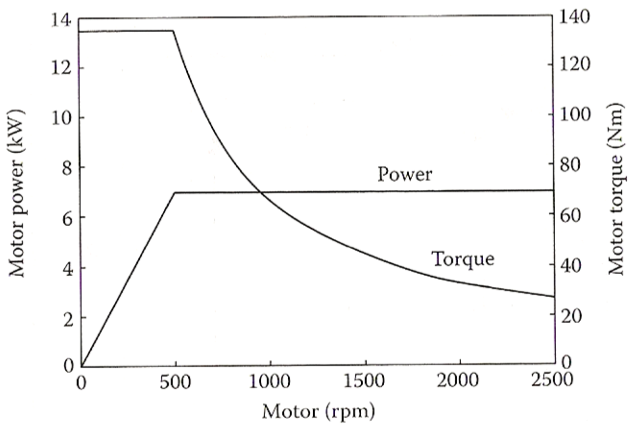


Figure 44: Power and torque of electric motor versus motor speed (Ehsani, Gao & Emadi 2010, p. 359)

Figure 45a shows the terminal voltages and currents of 36 V and 12 V batteries with a current capacity of 100 Ah versus load power (discharge power). It indicates that for the 36 V battery, the maximum power that the battery can supply is about 8.5 kW. Though, for 12 V below 3 kW. Figure 45b indicates the discharge efficiency of the 36 V battery with over 70% at a power of less than 7 kW. For 12 V voltage, it is less than 2.5 kW. Thus, for the mild hybrid electric drivetrain proposed in this chapter, a 42 V electric system (36 V battery) can support the operation of the electric motor (rated power of 7 kW). (Ehsani, Gao & Emadi 2010, p. 360)

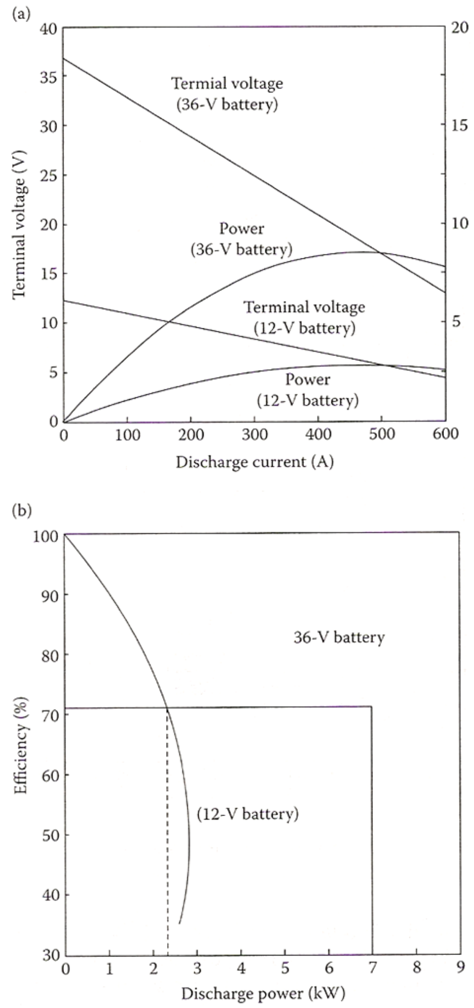


Figure 45: Battery performance with 36 V and 12 V rated voltages: (a) battery power and terminal voltage versus discharge current and (b) battery discharge efficiency (Ehsani, Gao & Emadi 2010, p. 361)

4.1.3 Result

Since there are only a few differences from the traditional drivetrain (engine, transmission, etc.), the mild HEV drivetrain is expected to have similar acceleration and gradeability performance. It was indicated that a mild hybrid electric drivetrain in an urban cycle with a small motor cannot momentous improve ICE operating efficiency, because most of the time the engine still runs in a low load region. However, because of the elimination of engine idling and of the inefficient torque converter and utilization of regenerative braking, fuel consumption in urban driving is significantly reduced. The simulation shows that for the 1500-kg passenger car mentioned above, the fuel consumption is 7.01 l per 100 km. The simulated fuel consumption for a similar conventional vehicle is 10.7 l per 100 km. With mild hybrid technology fuel consumption can be reduced by more than 30%. The motor efficiency map and operating points indicate that the electric motor operates as a generator more than a traction motor, to support the electric load of auxiliaries and maintain the battery SOC balanced. The simulation results of the same vehicle on an highway drive cycle show higher speeds for both engine and motor, due to higher vehicle speed. The fuel consumption is 7.63 l per 100 km. The fuel economy has not improved compared to conventional cars. The reason is that the highway vehicle has less energy losses in engine idling, braking, and transmission than during urban driving, and thus not much room exists for fuel economy improvement using mild hybrid technology. (Ehsani, Gao & Emadi 2010, pp. 360-365)

4.2 Series Parallel Full Hybrid Compact Car

4.2.1 Overview

The torque/speed coupling hybrid drivetrain provides advantages over the series (electrical coupling) and parallel (single torque or speed coupling) drivetrains. The torque and speed couplings in this drivetrain release the ICE from the driven wheels in the torque and velocity constraints. Hence, the current engine torque and revolution speed can be independent of the load torque and velocity of the vehicle. Therefore, the ICE can work in its high-efficiency region in a similar way as that of the series (electrical coupling) drivetrain. Otherwise, the ICE power is partly directly transferred to the driven wheels without experiencing multiform conversion. The characteristic is more equal to the parallel (torque or speed coupling) drivetrain. The series-parallel HEV can be assembled of speed-coupling devices such as planetary gears and transmotors. (Husani 2003)

4.2.2 Study

The best-known torque-coupling devices are basically gear set, sprocket-chain set, or pulley-belt set. Though, speed-coupling devices are more extensive. Hence the working traits of planetary gear functioning as a speed-coupling device are discussed in detail as follows. The structure of a mechanical planetary unit can be seen in Figure 46. It is composed of a sun gear labelled s, several planetary gears labelled p (usually three or four for force balance), a ring gear labelled r, and a carrier labelled y, that is mounted to the centres of the planetary gears. (Nedungadi 1999)

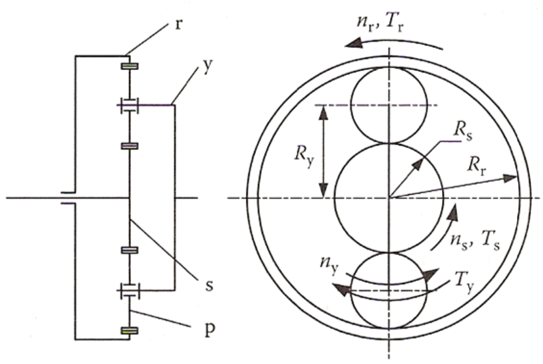


Figure 46: Planetary gear unit used as a speed coupling (Ehsani, Gao & Emadi 2010, p. 310)

It is indicated that the torques acting on ring gear and sun gear always have the same sign. In other words, they are always turning in equal directions. However, the torque acting on the carrier, is always in the opposite direction of ring gear and sun gear. The torque acting on the carrier is balanced by torques acting on the sun gear and ring gear. When one element among the sun gear, ring gear, and carrier is locked to the vehicle frame, that is, one degree of freedom of the unit is constrained, the unit becomes a single-gear transmission (one input and one output). In composing a hybrid drivetrain with the planetary gear unit as a speed coupling, there are many options as shown in Figure 47. To reduce the torque capacity requirement, therefore reducing the M/G physical size and weight, connecting the M/G to the sun gear of the planetary gear unit may be the appropriate choice. The engine can be either linked to carrier or to ring gear as shown in Figure 47a and b. (Ehsani, Gao & Emadi 2010, pp. 310-311)

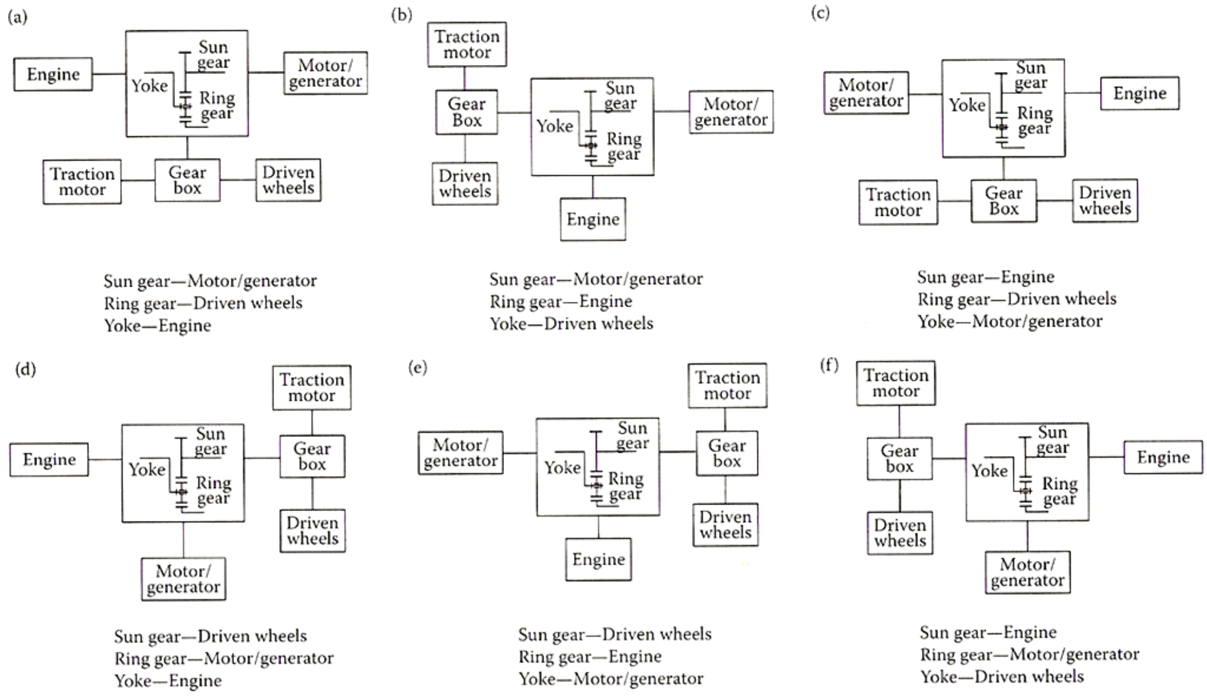


Figure 47: Possible configurations of the torque- and speed-coupling hybrid drivetrain (Ehsani, Gao, & Emadi, 2010, p. 312)

4.2.2.1 Drivetrain Configuration

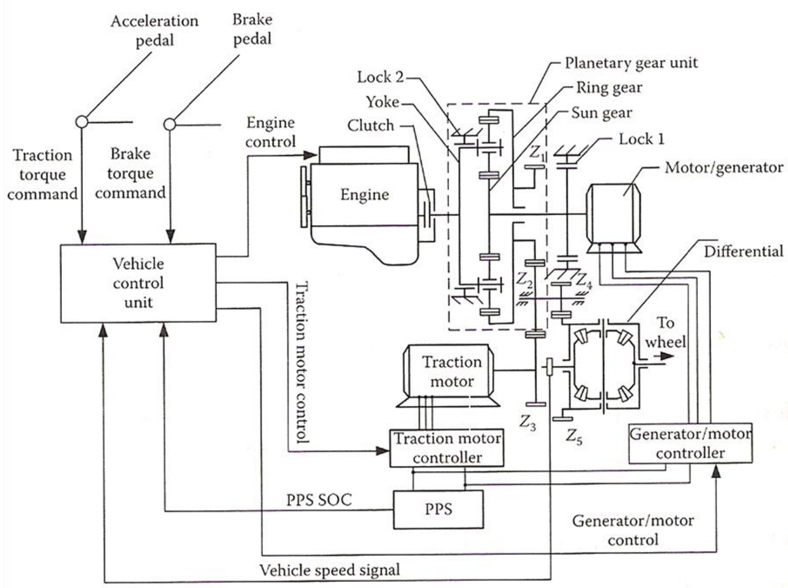


Figure 48: Drivetrain configuration (Ehsani, Gao & Emadi 2010, p. 314)

Figure 48 shows very detailed the configuration of a series parallel HEV (torque/speed coupling). The planetary gear unit constitutes the speed coupling that connects an ICE and a M/G together. The engine and M/G are linked to carrier and sun gear, alternatively. The ring gear is linked to the drive wheels through gears of Z_1, Z_2, Z_4, Z_5, and a differential. A traction motor is linked to the driven wheels via gears of Z_3, Z_2, Z_4, Z_5, and the differential, which couples the output torques of the ring gear and the traction motor together. In this configuration, one clutch and two locks are used. The clutch serves for connecting or disconnecting the engine to or from the carrier of the planetary gear unit. Lock 1 locks or releases the shaft and the sun gear of the M/G to or from the stationary frame of the vehicle. Lock 2 is used to lock or release the carrier to or from the stationary frame of the vehicle. By controlling the clutch, locks, engine, M/G, and the traction motor, many operation modes are available to be used. (Ehsani, Gao & Emadi 2010, pp. 313-314)

Ehsani, Gao and Emadi (2010, pp. 314-319) described these modes as follows:

1. Speed coupling mode:
In this mode, the traction motor is de-energized. There are three sub-modes:

1.1 Engine-alone traction:
The clutch is engaged to connect the engine to the carrier, lock 1 is used to lock the sun gear to the automobile stationary frame, and the M/G is de-energized. Lock 2 releases the carrier from the vehicle stationary frame. The energy flow route is shown in Figure 49. In this case, the engine alone delivers its torque to the driven wheels.

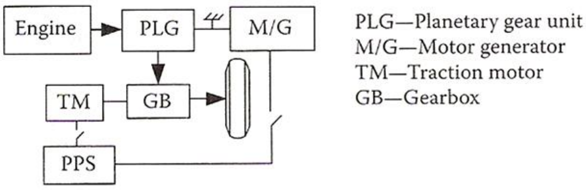


Figure 49: The traction flow route is from the engine alone (Ehsani, Gao & Emadi 2010, p. 314)

1.2 M/G-alone traction:
In this mode, the ICE is switched off. The clutch is engaged or decoupled and lock 1 releases the sun gear and the shaft of the M/G from the stationary frame; lock 2 locks the carrier to the stationary frame. In this case, the automobile is powered by the M/G only. The energy flow route is shown in Figure 50.

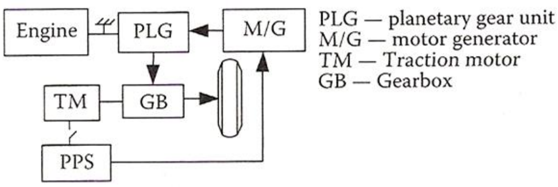


Figure 50: Energy flow route in the mode of motor/generator traction (Ehsani, Gao & Emadi 2010, p. 315)

1.3 Engine and M/G with speed-coupling traction:
In this mode, the clutch is engaged. Locks 1 and 2 are released from the stationary frame. At a given vehicle speed, the engine speed can be adjusted by the M/G speed. The torques of ICE, M/G as well as load torque on the driven wheels always hold a defined relation. This implies that a change in one torque will cause a change in the other two torques, causing the operating points of the engine and M/G to change. The energy flow routes are Figure 51.

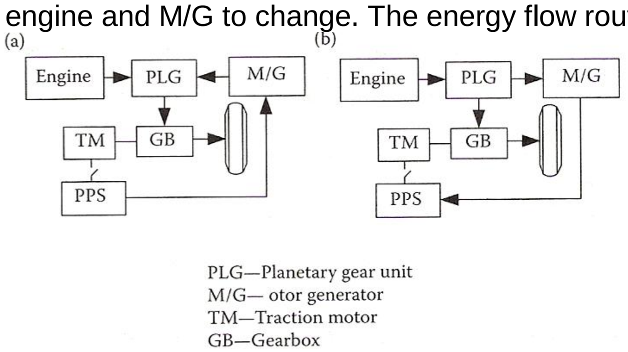


Figure 51: Energy flow route in speed-coupling mode: (a) M/G motoring and (b) M/G generating (Ehsani, Gao & Emadi 2010, p. 317)

2. Torque-coupling mode:
When the traction motor is energized, its torque can be added to the torque output of the ring gear to constitute the torque-coupling mode. Corresponding to the three modes (1.1), (1,2), and (1.3), when traction motor is controlled to operate in motoring and generating, six basic operation modes are constituted.

2.1 Engine alone in mode (1.1) plus traction motor motoring:
This mode is the same as the general parallel hybrid traction mode. The energy flow route is shown in Figure 52.

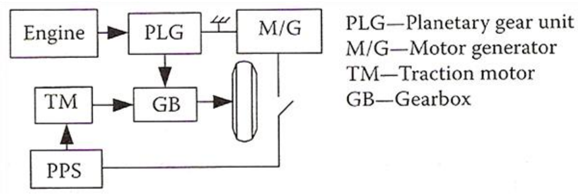


Figure 52: Energy flow route in parallel traction mode (Ehsani, Gao & Emadi 2010, p. 317)

2.2 Engine alone in mode (1.1) plus traction motor generating:
This mode is the same as the peaking power source (PPS) charging from the engine mode in the general hybrid drivetrain. The energy flow route is shown in Figure 53.

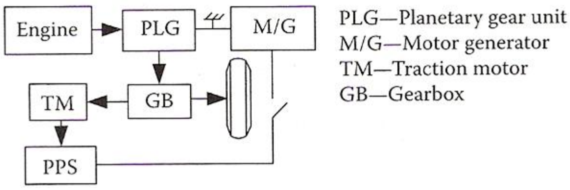


Figure 53: Energy flow route in parallel peaking power source charging (Ehsani, Gao & Emadi 2010, p. 317)

2.3 M/G-alone mode (1.2) plus traction motor motoring:
This mode is similar to mode (2.1), but the engine is replaced by the M/G. The energy flow route is shown in Figure 54.

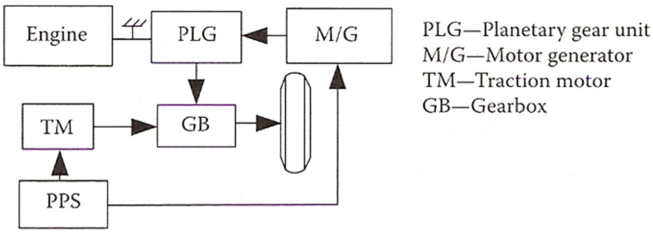


Figure 54: Energy flow route in the mode of two motor traction in parallel (Ehsani, Gao & Emadi 2010, p. 318)

2.4 M/G alone in mode (1.2) plus traction motor generating:
This mode is similar to mode (2.2) but the engine is replaced by the M/G. This mode may never be used because part of the M/G energy circles from the PPS and finally to the PPS through the M/G and traction motor as shown in Figure 55.

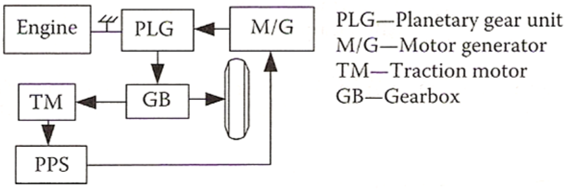


Figure 55: Energy flow route in the mode of M/G traction and PPS charging (Ehsani, Gao & Emadi 2010, p. 318)

2.5 Speed-coupling traction in mode (1.3) plus traction motor motoring:
In this case the full functions of speed and torque coupling are used. There are two operating states of the M/G as shown in Figure 56: Motoring and generating. The operating states of the M/G in motoring (Figure 56a) may be used at high driving velocities. In this case, the engine speed may be limited to somewhat lower than its medium speed to avoid too high an engine speed where its operating efficiency may be low. The M/G contributes its speed to the drivetrain for supporting the high vehicle speed as shown in Figure 56a. Similarly, the operating states in Figure 56b may be used in the case of low vehicle speed. In this case, the engine can run at speeds somewhat lower than its medium speed to avoid too low speed operations, where its operating efficiency may be low. The M/G absorbs part of the engine speed.

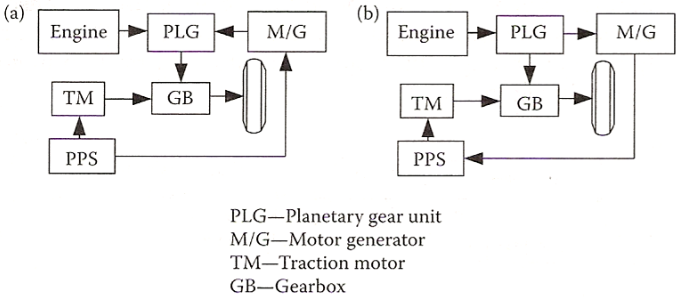


Figure 56: Energy flow route: (a) Traction motor motoring and (b) Traction motor generating (Ehsani, Gao & Emadi 2010, p. 318)

2.6 Speed-coupling traction in mode (1.3) plus traction motor generating:
Similar to mode (2.5), the engine and M/G operate in speed-coupling mode, but the traction motor operates in generating mode as shown in Figure 57.

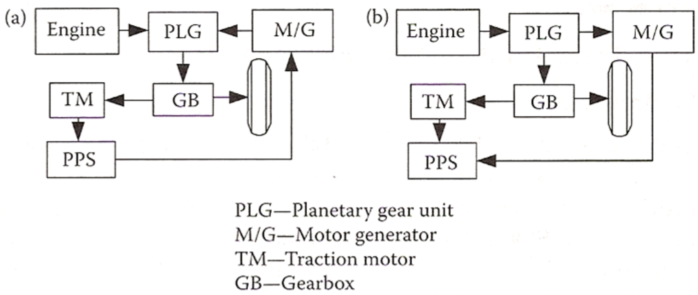


Figure 57: Energy flow route: (a) M/G motoring and (b) M/G generating (Ehsani, Gao & Emadi 2010, p. 319)

3. Regenerative braking:
If the automobile is braking, the traction motor, the M/G, or both can produce braking torque and recapture the braking energy partly in order to charge the PPS. The ICE is shut down with the clutch opened. The possible energy flow is shown in Figure 58.

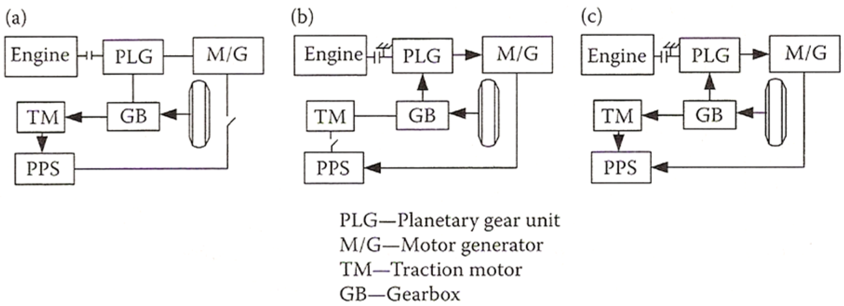


Figure 58: Energy flow in regenerative braking: (a) Traction motor alone, (b) M/G alone and (c) Both traction motor and M/G (Ehsani, Gao & Emadi 2010, p. 319)

All these operating modes are possible to utilize. In real control scheme design, of course not all of them are really used. It depends on the operating characteristics of the major components, the drivetrain design, driving conditions, and others.

4.2.2.2 Traction Torque Control Approach

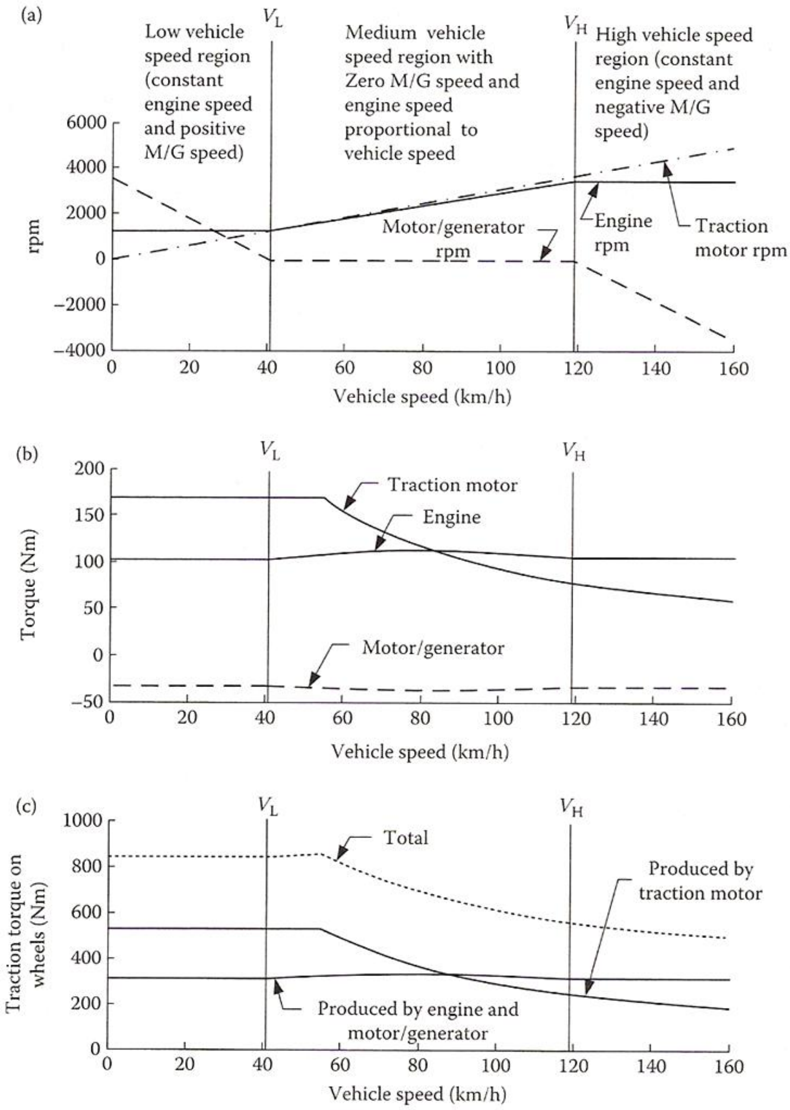


Figure 59: Torques and speeds of the engine, traction motor, M/G, and driven wheels with full engine throttle opening and full loading of the traction motor along vehicle speed (Ehsani, Gao & Emadi 2010, p. 322)

The total required traction torque on the driven wheels, that is commanded by the accelerator pedal, can be provided by the torque outputs from the ring gear, and the traction motor. As mentioned above, the torque output of the ring can be obtained by controlling the ICE throttle or injection and the M/G torque to run the engine with high efficiency. The contributions of ring gear and traction motor torque to the total depend on the control strategy of the drivetrain, which will be discussed next. Figure 59 illustrates the simulation results of an example drivetrain with full engine throttle opening and full traction motor load (maximum torque vs. motor speed). In the simulation, the engine rpm is controlled such that, at low driving velocity, the engine runs at constant revolution (1200 rpm in this example) and the M/G operates with positive speeds. At medium vehicle speeds, the M/G is locked to the vehicle frame and the engine velocity linearly increases with vehicle speed (pure parallel or pure torque-coupling operation). At high driving velocities, the engine again runs with a constant speed (3500 rpm in this example and the M/G operates with negative speed (rotating in the opposite direction of the engine). With the pervious engine speed control, the engine working speeds are constrained in the medium range in which the engine efficiency may be higher. It is known that the M/G is de-energized in the medium vehicle speed range for using the high engine torque and closing the energy flow through the M/G, which may cause more energy loss. (Ehsani, Gao, & Emadi, 2010, pp. 321-323)

4.2.2.3 Engine Speed Control Strategy

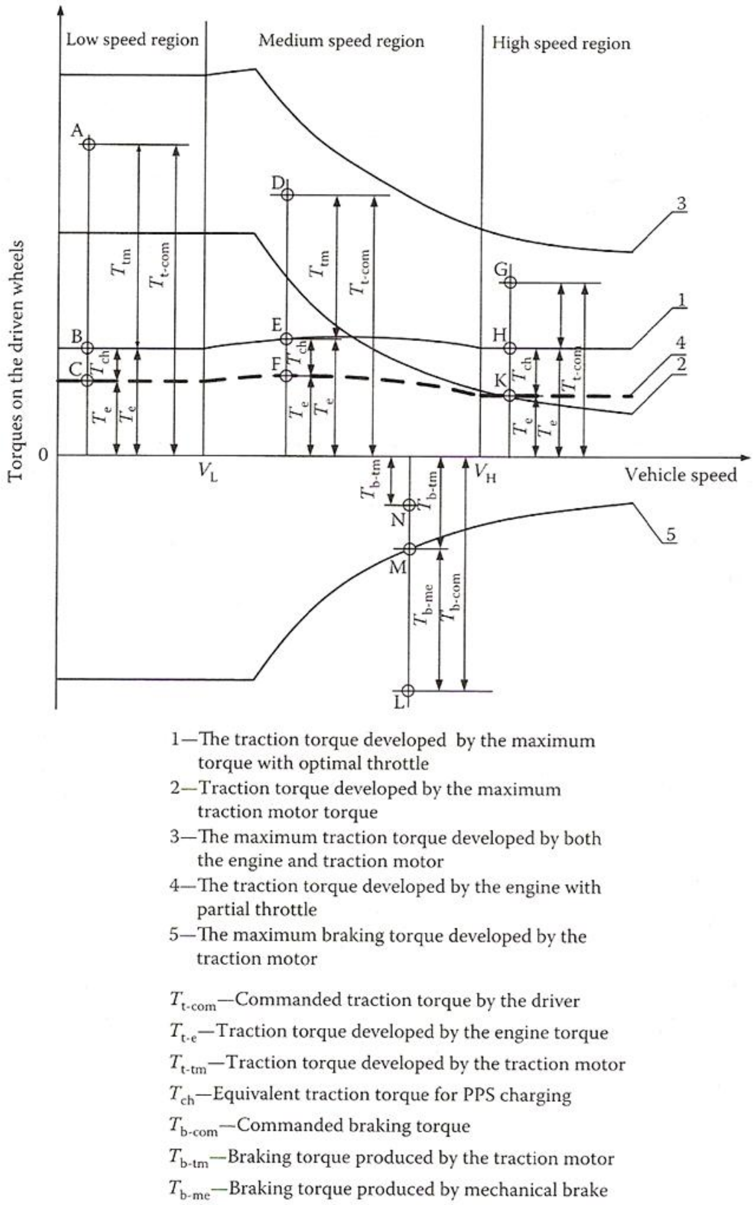


Figure 60: Schematic illustration of the max. SOC control strategy (Ehsani, Gao & Emadi 2010, p. 324)

The vehicle speed range is divided into three regions, low, medium, and high as shown in Figure 59 and Figure 60. If the driving velocity is below a given speed V_L, the speed coupling mode is used to avoid too low ICE velocity. The vehicle speed V_L of the low speed region is defined by the lowest ICE velocity that is possible with zero M/G speed (lock 1 is used to lock the sun gear to the stationary frame). The torque produced by the M/G, applied to the sun gear of the planetary unit, has the direction opposite to its speed. Therefore, in this case, the M/G incorporates the ICE power partly to charge the energy storage system. When the driving velocity is above the low velocity region V_L but below the high speed region V_H, the M/G is de-energized and the sun gear (the shaft of the M/G) is locked to the stationary frame of the vehicle. The drivetrain operates in the torque coupling mode. The ICE velocity is proportional to the vehicle velocity. When the driving speed is in the high velocity region V_H, the engine speed is kept constant and the M/G starts working again with a negative speed to compensate for the engine speed. In the medium velocity region, all the ICE power is delivered to the driven wheels. (Ehsani, Gao & Emadi 2010)

4.2.2.4 Traction Torque Control Strategy

Figure 60 shows the supply of the entire traction torque directed by accelerator pedal to the engine (M/G) and the traction motor, similar to the torque (power) control in the HEV. It also shows the complete braking torque directed to the traction motor and the mechanical braking system.

4.2.2.4.1 Low Vehicle Speed Region

If the driving velocity is in the low speed region V_L, the ICE is working at a specified velocity. Point A represents the traction torque directed by the driver, which is higher than the torque that the ICE can deliver with the optimal engine throttle as shown in Figure 58. In this case, the ICE alone cannot handle the directed torque and needs to be supported by the traction motor. Obviously, the ICE has to be directed with its ideal throttle as shown by point B in Figure 60 if it is no direct injection engine. However, the torque that the traction motor can produce depends on the SOC of the energy storage system. When the energy level of the energy storage system is lower than a specified value SOC_L (30% for example), the energy storage system should not be further discharged. In this case, the highest power of the traction motor is the power produced by the M/G. Then the planetary gear unit, the M/G, and the traction motor together function as an EVT, because no energy goes into or comes out of the PPS. When the SOC is higher than the bottom line, SOC_L, that is, the PPS has sufficient energy to support the traction motor, it is necessary to control the traction motor to deliver its torque to meet the commanded traction torque as shown in Figure 60. In this event the energy storage system supplies power to the traction motor. When the commanded torque is smaller than the engine torque produced with optimal throttle as shown by point B in Figure 60. (Ehsani, Gao & Emadi 2010, p. 326)

Therefore, Ehsani, Gao & Emadi (2010, pp. 326-327) mention various options in choosing the engine and traction motor operations:

- If the SOC of the energy storage is lower than SOC_L, the engine may be working with optimal throttle (point B in Figure 60). The PPS is charged by the M/G.
- If the SOC of the energy storage is between the SOC_L and SOC_H (SOC_L < SOC < SOC_H), the engine and the M/G may be controlled so that the ICE produces the torque that meets the commanded traction torque. The traction motor is idling (de-energized). The energy storage system is charged only by the M/G.
- If the SOC of the PPS is higher than SOC_H, the engine is shut down and the traction motor alone produces its torque to meet the traction torque demand

4.2.2.4.2 Medium Vehicle Speed Region

If the driving velocity is in the medium speed region as shown in Figure 59 and Figure 60, only the torque-coupling (traditionally parallel) mode is employed, that is, lock 1 locks the sun gear (shaft of M/G) to the stationary vehicle frame. In this mode, the ICE speed is proportional to the driving speed. The engine and traction motor control strategy, based on the commanded traction torque and energy level of the PPS, is equal to that discussed for the parallel architecture compact car. (Ehsani, Gao & Emadi 2010, p. 327)

4.2.2.4.3 High Vehicle Speed Region

If the car is driving in the high speed region V_H, the ICE velocity is controlled at its top. In this case the M/G works in the motoring mode, taking energy from the energy storage system and delivering it to the drivetrain. The torques of the engine and traction motor are controlled based on the commanded traction torque and energy level of the energy storage system. When the commanded traction torque (point G in Figure 60), is larger as the torque that the ICE can deliver with its optimal throttle at the maximum speed and the SOC of the PPS is lower than SOC_L, that is, the energy storage system cannot be discharged any more to support the motoring operation of the M/G and traction motor, the ICE has to be forced to run with a speed higher than the specified one to develop larger power. In this case, there are two options: One is to use the engine-alone mode with only torque coupling, which is equal as in the medium vehicle speed range. The other possibility is to control the ICE to operate with a speed somewhat higher than the speed that corresponds to the vehicle speed in the torque-coupling mode. If the energy level of the energy storage system is at its medium and high level, that is, $SOC > SOC_L$, the engine is controlled at its specified speed, with the optimal engine throttle (point H in Figure 60). The traction motor produces its torque, together with the engine torque, to meet the commanded traction torque. In case the commanded traction torque is smaller than the engine torque with optimal throttle as shown by point K in Figure 60, and the energy level of the energy storage system is below SOC_L, the engine is operated at point K and the traction motor works in its generating duty to charge the PPS. If the SOC is in the medium region ($SOC_L < SOC < SOC_H$), the traction motor may be de-energized and the engine alone propels the vehicle (point K). If the energy level of the energy storage system is at a higher level ($SOC > SOC_H$), the engine may be shut down and the traction motor alone propels the vehicle. It has to be mentioned that the control strategies discussed above are only for guidance in a real control strategy design. More complicated and subtle approaches may be employed, such as fuzzy logic, dynamic programming, and so on. (Ehsani, Gao & Emadi 2010, pp. 327-328)

4.2.2.5 Regenerative Braking Control

In this case both mechanical braking and regenerative braking by the traction motor are adopted similar to the parallel drivetrain control, when the commanded braking torque is larger than the highest torque which the ICE can deliver in generating mode. Otherwise only regenerative braking is adopted (Ehsani, Gao & Emadi 2010, p. 328)

For the simulation a 1500-kg passenger automobile in urban and highway driving cycles had been chosen. The parameters of the car can be seen in Table 4:

Table 4: Major parameters of the series-parallel hybrid electric drivetrain (Ehsani, Gao & Emadi 2010, p. 329)

Vehicle mass	1500 kg
Engine power	28 kW
Traction motor power	40 kW
Generator motor power	15 kW
Tire rolling resistance coefficient	0.01
Aerodynamic drag coefficient	0.3
Front area	2.2 m^2

4.2.3 RESULT

When driving in series parallel mode it can be seen that the M/G always works in the generating mode (negative power) as a result of the low driving speeds. Through the regenerative braking and charging from the engine by the M/G, the energy storage system energy level can be easily kept high, which ensures that the energy storage is always able to supply sufficient power to the drivetrain for acceleration. It is also indicated that the engine, most of the time, runs in its high-efficiency area. Engine-alone traction with light load and high SOC of the energy storage system causes some engine operating points away from its high-efficiency area. The fuel usage of the automobile in an urban driving cycle obtained from the simulation is 5.88 l per 100 km. On the hand, the results while driving in an highway cycle show that the M/G power is zero, except in the short time of cycle start. This indicates that the drivetrain, most of the time, worked with a pure torque coupling (the sun gear and its M/G are locked to the vehicle frame). The simulation indicated that the fuel consumption of the vehicle in an highway driving cycle is 4.96 L/100 km. (Ehsani, Gao & Emadi 2010, pp. 329-330)

4.3 PLUG-IN HYBRID SEDAN

4.3.1 OVERVIEW

Charging the energy in the energy storage device from the utility grid, to displace part of the petroleum fuel, is the major feature of the plug-in hybrid electric vehicles (PHEVs). The amount of fuel displaced by utility electricity depends principally on the amount of electrical energy per recharge. In other words, the energy capacity of the energy storage, the total driving distance between recharges (usually daily driving distance) and the driving cycle features and control strategies. To achieve optimal design especially for the energy storage system it is very useful to understand the daily driving distance in a typical environment. (Ehsani, Gao & Emadi 2010, pp. 333-334).

The daily driving distance distribution and the cumulative frequency derived from the 1995 National Personal Transportation Survey data. The cumulative frequency or utility factor in reference represents the percentages of the total driving time (days) during which the daily driving distances are less than or equal to the said distance on the horizontal axis. Figure 61 reveals the fact that about half of the daily driving distance is less than 64 km. If a vehicle is designed to have 64 km of pure EV range, that vehicle will have half of its total driving distance from the pure EV mode. Even if the daily travelling distance is beyond this 60 km pure EV range, a large amount of the petroleum fuel can be displaced by electricity, due to pure EV mode taking a large portion of the daily travel. Research also shows that even if the pure EV range is less than 64 km, such as 32 km, still a lot of petroleum could be displaced in normal daily driving. (Markel & Simpson 2006, p. 3)

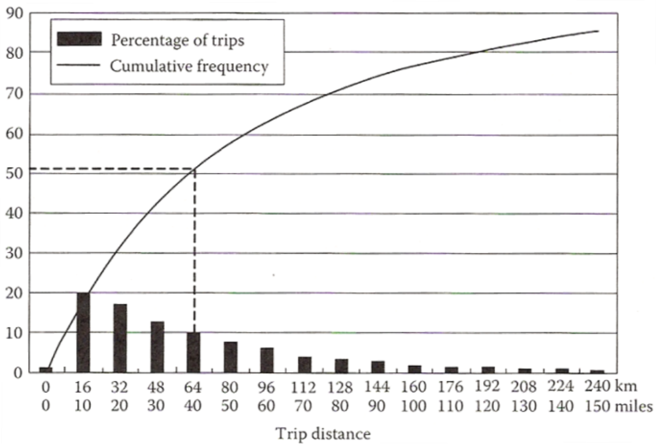


Figure 61: Daily driving distance distribution and cumulative factor (Markel & Simpson 2006, p. 3)

4.3.2 STUDY

4.3.2.1 Energy Management Strategy

Markel (2006, p. 5) introduced some definitions about PHEV:

Charge-Depleting (CD) Mode: When driving, the SOC of the battery is fluctuating, but on average it is decreasing.

Charge-Sustaining (CS) Mode: When driving, the SOC of the battery is fluctuating, but on average it is kept at a particular level.

All Electric Range (AER): The total amount of electrically driven kilometres (ICE off) when fully loaded before the ICE switches on first time.

Electric Vehicle Kilometres (EVKM): The cumulative amount of electrically driven kilometres (ICE off) when fully loaded before the automobile reaches CS mode.

Charge-Depleting Range (CDR): The total amount of driven kilometres when fully loaded before the automobile reaches CS mode. It should be noted that EVKM dictates pure electric driving. However, CDR may include engine propulsion, but the on-average SOC of the energy storage decreases till the sustaining level.

PHExx: A plug-in hybrid electric vehicle with available energy storage equivalent to xx kilometres of propulsion energy on a reference driving cycle, where xx stands for the kilometre number. For example, PHEV32 can displace gasoline energy equivalent to 32 kilometres of moving on the reference driving cycle with off-board electricity. It should be noted that PHEV32, for example, means not that the automobile will reach 32 km of CDR, EVM or AER, on the driving cycle. In addition the working characteristic depends on nature of the driving cycle, the powertrain control strategy, and the power rating of components.

4.3.2.2 AER-Focused Control Strategy

The concept is to use the energy of the battery augmentative in the AER. It is feasible to provide the driver the choice to manually select between a CS mode and a full EV operating mode. This design could be interesting for cars which may be driven in regions where combustion engine use is restricted. This design provides flexibility for the driver to constitute the times that the car is driven in pure EV mode. For instance, in a trip which includes cities where pure EV operation is necessary, the driver can select the pure EV operating mode just before entering the zone in order to have adequate range. On other roads, the automobile may be driven in pure EV mode or CS mode, depending on the energy status of the battery and the power demand. In normal conditions, where the trip does not include obligatory pure EV mode, the driver could select the pure EV mode prior to starting to fully use the energy of the battery to displace the fuel, until the energy of the energy storage reaches its specified level at which the CS mode will start automatically. This approach for energy management clearly differentiates the whole trip into pure EV and CS operation. When a series hybrid configuration is used, the power rating design of the motor, ICE, and energy storage system are nearly the same as in the CS hybrid. The motor power ensures the acceleration and gradeability performance, the engine/generator power maintains the automobile driving at a steady velocity on flat or mild grades. The energy storage power is larger (or at least not smaller) than the EM power minus the engine/generator power. The energy storage system has to be configured in a way that it can fulfil the needs of pure EV range. When parallel or series parallel configuration is used, the EM power should be able to fulfil the peaking power requirements of the reference driving cycle. If not, the car would be tardy when driving. The vehicle parameters used in this computation are listed in Table 5. It is indicated that the peaking traction power on the driven wheels is 25 kW. Though, there are power losses from the energy storage to the driven wheels. The motor output power should be configured in a way that accounts for the power losses from the EM shaft to the driven wheels so that the power requirements are met. Assuming that the efficiency from the motor shaft to the driven wheels is 90%, then the motor shaft power rating is about 28 kW. This necessary EM power is also related to the driving velocity at which this peak power occurs. The motor must be able to produce the peak power at this driving velocity. Comparably, the peaking power of the battery system should include the losses in the EM, the power electronics, and the transmission. Assuming that the efficiencies of the motor and power electronics are 0.85 and 0.95, respectively, then the power capacity of the energy storage system is about 34.7 kW. (Ehsani, Gao & Emadi 2010)

Table 5: Major parameters of the plug-in hybrid electric drivetrain (Ehsani, Gao & Emadi 2010, p. 337)

Vehicle mass	1700 kg
Rolling resistance coefficient	0.01
Aerodynamic drag coefficient	0.3
Front area	2.2 m^2
Rotational inertia factor	1.05

If the energy storage is fully charged, the total energy is 10 kWh. The simulation was proved several times. The pure EV mode was started at the beginning of the simulation, until the energy level reached about 30%, after that the CS mode was started. The control strategy in the CS mode employed the constrained engine on-off control strategy. 400 W of constant auxiliary power was added at the terminal of the energy storage system. In case that the travelling distance is less than four driving cycles (42.5 km), it can be seen that the vehicle can completely displace the petroleum fuel with electricity in the pure EV mode. The total electric energy consumed is about 7.1 and 15.5 kWh per 100 km. With the increasing total travelling distance the percentage of the fuel displacement decreases since the CS modes take larger percentages of the trip. For nine sequential driving cycles (96 km), the fuel and electrical energy consumptions are about 3.2 l per 100 km, and 7.42 kWh per 100 km. (Ehsani, Gao & Emadi 2010, p. 339)

4.3.2.3 Blended Control Strategy

Different than the AER focused control strategy, in which a pure EV range is designed, the blended control strategy uses both the ICE and the EM for traction, with CD mode, until the SOC of the energy storage reaches the specified low threshold, beyond which the vehicle will operate in the CS mode. In the CD mode, both the ICE and the EM may work at the same time. The range before entering the CS mode is longer than in the pure EV mode. Control strategies are needed to control the ICE and the EM to meet the load demand. Many control strategies are possible. The following is the one in which the engine and motor alternately propel the vehicle with no energy storage system loading from the ICE. The ICE is constrained to operate in its optimal fuel economy region. The details are shown in Figure 62. (Ehsani, Gao & Emadi 2010, pp. 341-343)

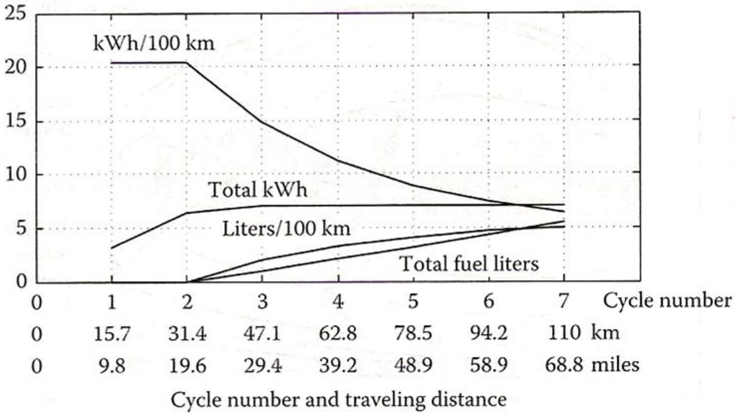


Figure 62: Fuel and electric energy consumption versus the number of driving cycle and travelling distance with AER mode in metric unit (Ehsani, Gao & Emadi 2010, p. 343)

The engine operating area is shown schematically in Figure 63. When the requested ICE torque is larger than the upper torque boundary, the engine is controlled to run on this boundary and the remaining torque is supplied by the EM. When the requested engine torque falls below the upper boundary, the ICE alone propels the car. When the requested engine torque is below the lower torque boundary, the engine is shut down and the EM only propels the automobile. Then, the ICE operation is constrained within its optimal region. Due to the absence of battery charging from the engine, the battery energy level will continuously fall to its specified lower level. Then the drivetrain goes into CS mode. It has to be mentioned that the pure EV range is mostly determined by the capacity of the energy storage and its SOC level, at which the CS mode started. The range in the CD mode is also related to the drivetrain control strategy, especially the specified engine operating region. When the ICE lower torque boundary is moved downward, that is, the engine operating area is enlarged, the CD mode range is increased. However, the fuel displacement is reduced when the travel distance between charging is shorter than the full CD mode range, and the SOC of the energy storage does not hit its lower limit, leaving useable energy in the energy storage system. (Ehsani, Gao & Emadi 2010, pp. 344-346)

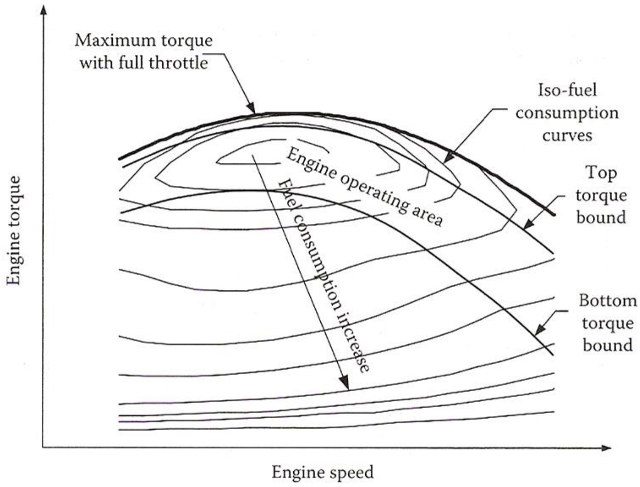


Figure 63: Operation area of the engine in the CD mode (Ehsani, Gao & Emadi 2010, p. 344)

4.3.3 Result

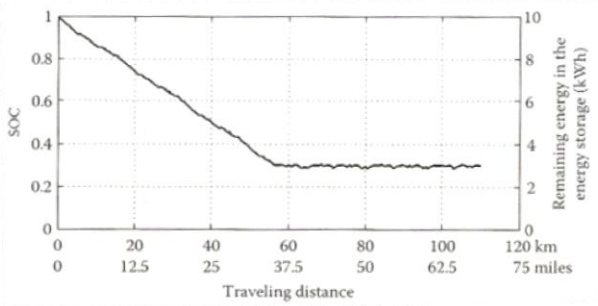


Figure 64: SOC and the remaining energy in the energy storage versus travelling distance in driving cycle with CD mode (Ehsani, Gao & Emadi 2010, p. 348)

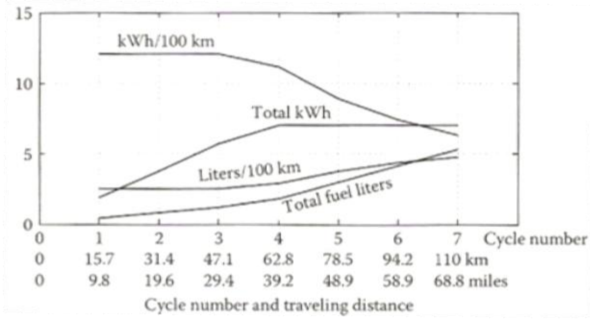


Figure 65: Fuel and electric energy consumption versus the number of driving cycle and travelling distance with CD mode in metric unit (Ehsani, Gao & Emadi 2010, p. 349)

The energy storage system is a very fundamental component in the PHEV. It is closely related to vehicle performance, fuel consumption, fuel displacement, initial cost and operation cost. The most important parameters in the energy storage design are the storage energy and power capacities. In the example shown above in Figure 64 and Figure 65, the useable energy is about 7 kWh and the SOC operating window is 0.7 (from 1 to 0.3). The total energy capacity of the battery is about 10 kWh. It is necessary to say that the depth of discharge (DOD) of batteries is closely related to battery life. Figure 66 illustrates the battery cycle life with the DOD. If one deep discharge per day is assumed, a total of 4000+ deep charges would be required for a 10-15 year lifetime. With the characteristics shown in Figure 66, a 70% DOD, for NiMH, and a 50% DOD, for Li-Ion batteries, may be proper designs. The power requirement of the energy storage system is completely determined by the electric motor power rating. This power should be designed to work at low SOC levels, such as 30%, since the energy storage always works at this low SOC level in the CS mode. (Ehsani, Gao & Emadi 2010, pp. 346-351)

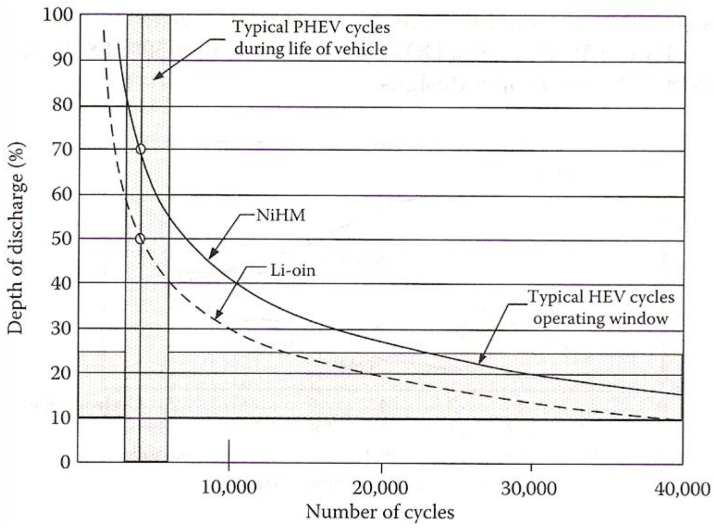


Figure 66: Varta energy storage system cycle life characteristic (Markel & Simpson 2005, p. 4)

A good scale unit for the suitability of an energy storage system is the energy/power ratio. The size of the battery can be minimized when its energy/power ratio is alike the necessary one. In the simulated automobile, the complete energy needed is roughly 10 kWh and the necessary power is approximately 60 kW, which is defined at 30% of the energy storage SOC, yielding an ratio $R_{e/p}$ (total energy to power at operating SOC) of 0.167 h at 30% battery SOC. A typical energy/power ratio versus the specific power of energy storage technologies can be seen in Figure 67. In case that 0.2 h of energy/power ratio is adopted in the design, Cobasys´ NiMH battery will feature a total weight of 129 kg (60/0.465), that can carry a total energy of 12 kWh (0.2 x 60). For comparison, a Li-Ion battery from Saft that can carry the equal amount of 12 kWh, shows a weight of roughly 56 kg (60/1.08). (Ehsani, Gao & Emadi 2010, p. 351)

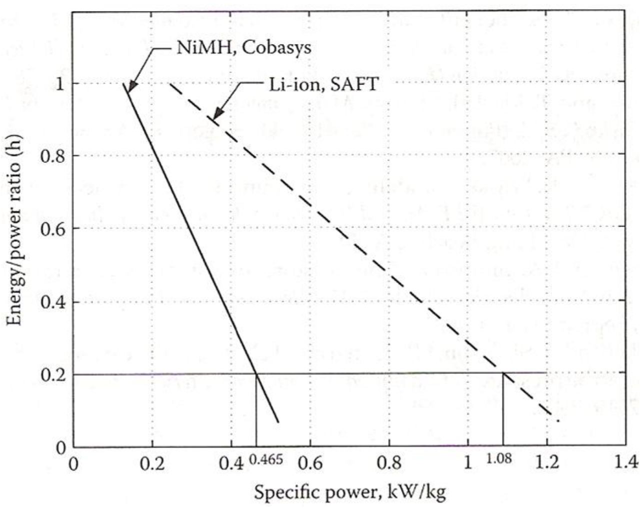


Figure 67: Typical energy/power ratios versus specific power (Ehsani, Gao & Emadi 2010, p. 351)

5. Strategic Orientation

5.1 The Present

Automobile manufacturers at present launch micro-hybrids and mild hybrids in all car segments. These cars provide extensive capability to boost efficiency as well as low component costs. By virtue of the unattractive cost-benefit ratio, full HEV is a niche technology.

Japan´s JADA dealer association publicised that in 2009 Toyota´s Prius was number one on Japan´s annual sales ranking of all cars, including minivehicles. Sales increased by roughly 300 percent to more than 208,000 cars. The Honda Insight was number two in hybrid sales. In Japan about 10 percent of all new cars are hybrids. In Europe, start-stop systems or micro-hybrids with brake energy recuperation are going to break in the mass market. (Schmitt 2010)

Internal combustion engines are the dominating source of motion. To improve the efficiency in partial load an optimized overall powertrain calibration and improved thermodynamics in the combustion is necessary. To reduce the mechanical friction has also big influence on overall powertrain and engine efficiency in each load stage. Relating technologies to each of the previous mentioned levers are already in series production or in development. The CO_2 reduction potential for these technologies are shown in Table 6:

Table 6: CO_2 reduction potential (Roland Berger Strategy Consultants 2009)

	Technology	Reduction Potential in %
Thermodynamic Improvements	Optimized Cooling	3
	Variable Valve Timing and Lift	6 - 8
	Gasoline Direct Injection	10 - 13
	Camless Valve Train	15
	Advanced Diesel Direct Injection	3 - 5
	HCCI	3 - 14
Reduction of Friction	Electric Power Steering	2 - 3
	Low Friction Engine	3 - 5
	Low Friction Gearbox	4 - 5
	Start-Stop System + Regenerative Braking	4 - 7
	Cylinder Deactivation	6 - 12
	Electric Water Pumps + Optimized Cooling	2 - 4
	Strong Downsizing	8 - 15
Powertrain Calibration/ Hybridisation	Optimized Gearbox Ratios	1 - 3
	Dual Clutch Transmission	4 - 5
	Micro Hybrid	2 - 5
	Mild Hybrid	8 - 12
	Full Hybrid	15 - 25

5.1.1 Power Electronics

The power electronics represent one of the most complex power processing elements in the vehicle. Therefore it constitutes the highest cost components of the HEV propulsion system together with the energy storage system. The research in first line focuses on developing more compact and cost efficient traction inverter layouts. Chargers vary momentously in terms of their system specifications, weight and cost. Currently small chargers allow minimum weights of 2.5 kg, while large ones with more than 4.5 kW power will add about 11 kg to the total car weight. Hence, depending on the maximum power levels that are necessary for charging the vehicle, chargers can add notable weight and volume to the powertrain system. Efforts are currently underway to combine the charging capabilities of the traction inverter with the energy storage charger in a single component, thus saving both costs and packaging space. Depending on the voltages and exact system specification, the weight of the DC/DC converter can vary from approximately 2 to 4 kg. (Roland Berger Strategy Consultants 2009, pp. 41-43)

5.1.2 ICE

Downsized GDI engines are currently becoming standard in established car markets like Europe, North America and Japan. Start-stop systems are launched as a standard feature by different brands since it offers relatively high efficiency but adds only a little additional cost. Since simply a more powerful starter and a few additional electronics are needed, start-stop systems are expected by many OEMs to reach a market share of 50 percent even in the B-segment by 2020.

All car manufacturers define ICE requirements on basis of the SOP (start of production). Automobile requirements are usually defined over a time frame of less than one decade, from 2010 to 2020 for instance. While most producers intend to use the basic ICE concept for such a long time, these concepts are often not flexible enough to make unexpected alterations and changes possible later. Due to this inflexibility, life cycles of six to eight years are normal. Hence automobile manufacturers offer an increasing number of engine types, and many development projects run parallel. Needless to say that this leads to additional development costs and more complexity of the technology portfolio that no OEM can afford, since to meet the demand for lower fuel consumption and emissions is costly. According to a powertrain manufacturing executive from a large automobile manufacturer with high vertical integration there are no base ICE components which cannot be sourced from suppliers and then simply assembled. The manufacturers, however, are not keen on outsourcing base engine development from manufacturing, or even arranging them separately. While there will always be a share of high-end and highly innovative ICEs that are manufactured and developed internally, mass produced volumes need to be developed and manufactured with partners to drive down costs. (Roland Berger Strategy Consultants 2007)

5.1.3 Transmission

Basic innovations in vehicle transmissions are no longer expected. Rather is a gradual evolution given. It is characterized by systems thinking environment ⇔ transport ⇔ vehicle ⇔ engine/transmission and the use of electronics for measurement, control and surveillance operations. Vehicle transmission is developed quickly and market-oriented. The development of the vehicle transmission is always adapted with the planning horizon for new vehicles. Parallel to the development of a vehicle also the associated transmission is newly developed or enhanced. (Naunheimer, Bertsche & Lechner 2007)

For manual gearboxes a larger gear ratio to reduce the engine speed is successfully launched in a few new cars such as Volkswagen's "blue motion" models. For automatic gearboxes the shift strategy and a higher amount of gears are a possibility to optimize the operating point of the ICE.

5.1.4 Electric Motor

The investments of OEMs and suppliers in developing special EMs for automobile applications are just at the beginning. By reason of their high power density, compact PMSMs are the favourite choice for PHEVs in a parallel or power split HEV architecture with strong powertrain package constraints. Thus, export restrictions on rare earths recently announced in China have put up a major barrier for using permanent magnets. Electric motor producers outside China therefore need to focus on developing alternative solutions to avoid high costs and losing the market to Chinese players. (Roland Berger Strategy Consultants 2009, p. 40)

5.1.5 Control Strategy

Owing to the complexity of the hybrid's powertrain, the energy management strategy plays a crucial role in the functionality and performance of the vehicle. In addition, it has been very exciting for control engineers to deal with such a nonlinear multidomain time-varying system. Nevertheless, there is still much room for advanced control strategies for HEVs.

5.1.6 Energy Storage System

5.1.6.1 Li-Ion batteries

Since Li-Ion batteries have been implemented very successful for consumer electronic goods like laptops and mobile phones, the door to further developments could be opened. These batteries are powerful enough to make PHEVs a potential alternative to today's standard ICE vehicles, but Li-Ion batteries have not completely solved the problems. The energy density of gasoline is with more than 9,000 Wh per litre still more than 40 times that of Li-Ion batteries. Hence the research continues for the next generation of batteries for EVs. Until alternative technologies are developed in the coming decade, it is assumed that Li-Ion batteries will be the key technology for PHEVs. Other non-chemical energy storage devices like super-capacitors currently do not meet the requirements for longer-distance electric driving since it can only reach very high specific power levels for a few seconds, but cannot hold a lot of energy. The majority of modern Li-Ion batteries produced for consumer electronic goods use CoO_2 or MnO_2 (cobalt-oxide or manganese-oxide) cathodes. These cathodes have a proven production process technology. However, the material has a number of drawbacks for vehicle applications. This includes the problem of limited cycle times, which is the number of charging processes before the battery loses a significant amount of its energy capacity, and thermal instability in case of malfunction. Therefore, producers are making a lot of effort to develop an alternative chemical make-up that will meet the requirements of vehicle applications. The first Li-Ion batteries on the market, such as those used in the Mitsubishi iMiEV introduced in Japan in July 2009, already seem to meet the necessary lifetime and safety requirements of car producers. Two-thirds of the material costs of modern Li-Ion batteries are caused by the electrodes and the separator material. Like the battery manufacturers, the major suppliers of raw materials are also currently building up their electrode and separator production capacities to meet the demand expected in the coming two to three years. Production lines have been put in place for several million cells per annum. It has to be mentioned that Western suppliers currently purchase most of the production equipment they use for the production of Li-Ion batteries from high-cost countries like the US and Japan. As a result of the high quality requirements, they have few alternatives. Thus, Chinese competitors have started using equipment developed locally or in-house for less critical production steps. They have also substituted some of the automated steps with manual tasks, because of the low cost of labour in China. (Roland Berger Strategy Consultants 2009, p. 43-49)

Many energy storage system producers, like Varta, Sony, Panasonic, GS Hitachi and Saft, are involved in the development of the Li-Ion batteries. The materials used by them can be seen in Figure 68. Saft offers medium and large-sized batteries. They are available in near-prismatic and cylindrical form. The energy-power trade-offs are from 65 Wh/kg when fully discharged in 15 seconds to 150 W/kg when fully discharged in 2 hours. (Saft 2010)

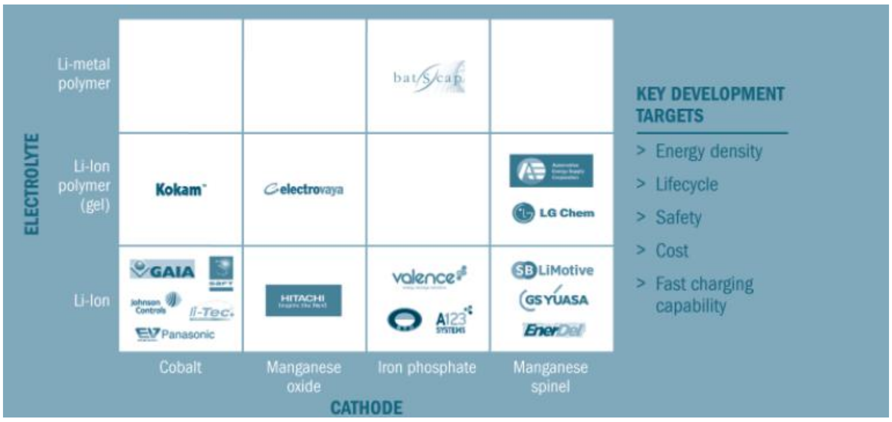


Figure 68: Main battery suppliers pursuing varied technologies (Roland Berger Strategy Consultants 2009, p. 46)

5.1.6.2 Ultracapacitor Technologies

According to the goals set by the U.S. Department of Energy for the inclusion of ultracapacitors in HEVs, the near-term specific energy and specific power should be better than 5 Wh/kg and 500 W/kg, respectively, while the advanced performance values should be over 15 Wh/kg and 1600 W/kg. So far, none of the available ultracapacitors can fully satisfy these goals. Nevertheless, some companies are actively engaged in the research and development of ultracapacitors for HEV applications. Maxwell Technologies (2010) has claimed that its power Boostcap ultracapacitor cells (2600 F at 2.5 V) and integrated modules (145 F at 42 V and 435 F at 14 V) are in production. (U.S. Department of Energy 2009)

5.2 Future Developments

5.2.1 Powertrain Components

In recent decades there have been many discussions about the need for automotive powertrain electrification. The strategy of the car manufacturers was to introduce new technologies piece by piece, always financing the change with returns from the general business. However, now there is the time for big changes since the crises melts away the economic base. In addition OECD governments put pressure on OEMs to developed a carbon-free road transportation. This pressure is driven by the global warming and oil dependence. The G8 countries committed to limit the increase in global warming to 2°C. This requires significant efforts from the automotive industry. It is not enough only to improve the existing internal combustion technology. Despite the fact that emissions from diesel and gasoline ICE can be reduced by up to 30% and 40% until 2020, a 10 g/km CO_2 gap to the EU objective of 95 g/km can be identified in Figure 69 because of two factors: Customers expect a certain level of vehicle performance and size. In addition there is a limit of physics. A similar graphics for the US fleet emission targets by 2016 can be seen in the appendix. (Roland Berger Strategy Consultants 2009)

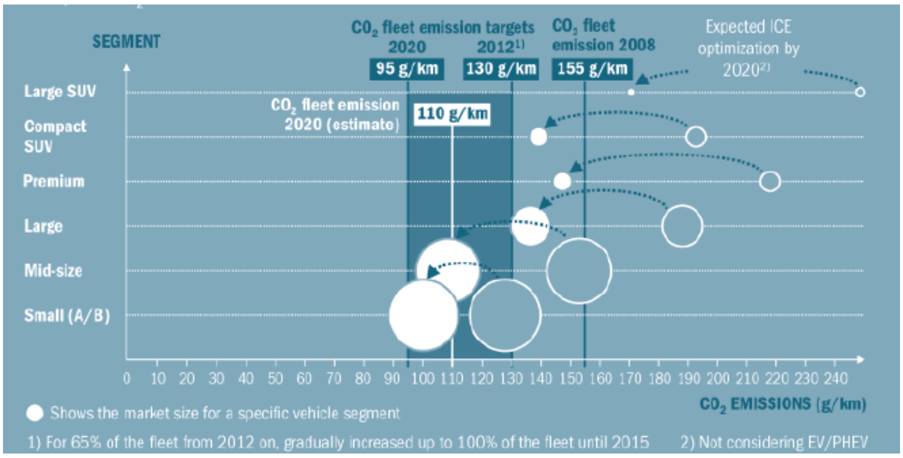


Figure 69: Expected ICE CO_2 emission to EU targets gap (Roland Berger Strategy Consultants 2009, p. 28)

Hence, more serious efforts in powertrain electrification are necessary. Near zero-emission automobiles will be offered, the question is just when. Major challenges remain for key electrical components and batteries regarding infrastructure, regulations and cost. This issue will determine how quick the market will develop. The electrification of the automotive powertrain will deform the actual mobility value chain. This drives new partnerships, consolidation and hence opens up new profit pools and revenues for new and already existing manufacturers. Since industrial policies and governments are necessary to support market development and afford investments, they are a important factor in technology development and market pervasion. The US government leads with a financial support of nearly € 20 billion. China follows with € 1 billion. Japanese companies are in a good position yet, only the EU members need to strengthen their players. (Roland Berger Strategy Consultants 2009)

5.2.1.1 Power Electronics

The market for power electronics will be between € 4.6 billion to 9.3 billion by 2020. Power electronics for automotive applications are still in their initial phase. There is still a lot of space to improve them concerning their production costs, integration, weight, size and performance. In the long term, it is expected that the further development leads to especially for the car industry made traction inverters, which are the heaviest part of the power electronics, that weigh well under 10 kg and cost far less than € 500 each. Ultimately the DC/DC converter will render a "normal" lead acid starter battery unnecessary, as it can supply appropriate power to start the engine and operate the vehicle's internal grid. (Roland Berger Strategy Consultants 2009)

5.2.1.2 ICE

The additional saving potential of HCCI is small compared to advanced diesel combustion and second-generation GDI. The difficult combustion process is very challenging since it requires a highly advanced control system. The process is even more difficult to control in a multi-cylinder engine because specific conditions in different cylinders are needed (air intake temperature and volume). This will make it arguable if HCCI gasoline or diesel engines will be produced in large-scale before 2020. In the smaller and volume vehicle segments, much less new technology will be used since buyers pay less for efficiency-boosting technologies. Hence mild hybrids and fully variable valve trains will have only limited fitment rates. Technologies like advanced direct injection systems, downsizing concepts and start-stop will provide most of the CO_2 emission reductions. (Roland Berger Strategy Consultants 2009)

5.2.1.2.1 Gasoline

The best-in-class gasoline engines of the future will be downsized, with fewer cylinders and much less displacement. They will feature a variable valve train and direct injection. A micro or mild-hybrid powertrain will support them. Full hybrid powertrains will persist a niche technology, especially in markets with a high share of diesel since it is a cost-intensive way to improve fuel efficiency. The relative increase of costs will be higher for gasoline engines since they use a large portfolio of new technologies. Three- and four-cylinder gasoline engines will cover most of customer needs. In the very small automobile segment even two-cylinder engines will be introduced. Six-cylinder engines will be dominant above 250 hp. The flagship powertrain will be formed by V8 engines, produced simply for image and marketing purposes. (Roland Berger Strategy Consultants 2009)

5.2.1.2.1 Diesel

Diesel powertrains seem to provide less potential to reduce CO_2 emission. In 2020 the best-in-class diesel engines can be 30% more efficient compared to today´s standard diesel engines. Diesel ICEs will still be the more expensive engine type. Figure 70 shows that three and four-cylinder engines will form the standard motorization for diesel-powered vehicles in the volume segments. Similar to gasoline powertrains, six-cylinder engines with a much lower fitment rate will answer higher performance needs above 250 hp in 2020. The key powertrain technologies by segment for the US market can be seen in the appendix. (Roland Berger Strategy Consultants 2009)

		Small (A-/B-segment)	Mid-size (C-segment)	Large (D-segment)	Compact SUV (D-segment)	Premium (E-/F-segment)	Large SUV (E-segment)
GASOLINE	Power (hp)	80	120	150	180	350	250
	Cylinders	3	3	4	4	6	4
	Injection	1st-gen. GDI	2nd-generation GDI			HCCI (partial load)	
	Valve train	VVT			VVT + VVL + cylinder deactivation (6-cylinder)		
	Turbo		Single-stage charging			Multi-stage charging	
	Hybrid	Micro-hybrid				Mild hybrid	
	Gearbox	MT or AMT 5	MT or DCT 6/7			AT 8	
	Saving pot.	**30%**	**35%**	**30%**	**35%**	**40%**	**40%**
DIESEL	Power (hp)	Niche application	120	150	170	300	230
	Cylinders		3	4	4	6	4
	Injection		Advanced DDI (≤ 2,000 bar)		Advanced DDI (> 2,000 bar)		
	Turbo		Single-stage turbocharging			Multi-stage turbocharging	
	Hybrid		Micro-hybrid			Mild hybrid	
	Gearbox		MT or DCT 6/7			AT 8	
	Saving pot.		**25%**	**20%**	**20%**	**30%**	**30%**

Figure 70: Key powertrain technologies in Europe by segment in 2020
(Roland Berger Strategy Consultants 2009, p. 28)

Further modularization is necessary from a component perspective to offer suppliers higher economies of scale. Hence a definition of concepts common across the industry will be essential to further reduce costs. Standards have to be determined by OEMs in close cooperation with suppliers. Only a minority of OEM engineering executives is confident about the hypothesis that engine sharing and common solutions will increase dramatically in the mid-term. Thus, this will be a significant driver enabling OEMs to reduce costs. The importance of reducing costs will increase, especially as low-cost ICEs, that fulfil relatively high emission standards for both toxic gases and CO_2, will be required on a broader scale. (Roland Berger Strategy Consultants 2007, p. 71)

5.2.1.3 Transmission

According to a press release of the Car Training Institute about 30 percent of experts at the CTI Symposium "Innovative Automotive Transmissions and Drive Trains" see the future of continuously variable transmissions (CVT) pessimistic. On the other hand dual-clutch transmission (DCT) and automatic transmission (AT) will take an important role in the drivetrain. When asked about the long-term prospects of the DCTs in comparison to the ATs almost 40 percent are convinced that both gear types will prevail equivalent. Though, 37 percent see a superiority of dual clutch transmissions due to the potential for fuel savings. (Car Training Institute 2009)

5.2.1.4 Electric Motor

Most past developments in the field of electric motors have focused on other applications and not taken the specific requirements of the automotive industry into account. This will no doubt change as PHEVs become more common on the market. It is estimated that there will exist a € 3.6 billion to 9.2 billion market for electric machines by 2020. Incumbent manufacturers and the current leaders are confronted with a huge menace from new Chinese companies. These Chinese manufacturers have excellent accession to rare earths used for the E-machine production that rely on permanent magnets. European manufacturers hence need to lift their assiduity when developing different technical solutions in order not to lose the business. On challenge is the lack of high-speed performance for PMSMs in serial layout PHEVs, when a high automobile top-speed is necessary. In these cars, current-excited synchronous EM and induction motors are expected to be the dominant application. Increasing R&D budgets will lead to further advances in the specific power of all motor types. In addition a higher market penetration rate will decrease the cost of a standard 50 kW electric motor (permanent power) well under € 1,000. Hence the production of such EM will become highly competitive compared to combustion engines. (Roland Berger Strategy Consultants 2007)

5.2.1.5 Control Strategy

Some issues that should be addressed in the future according to Salmasi (2007, p. 2402), are listed below:

1. The durability of the energy sources: If someone has purchased an HEV the person has to pay much more to repair or change the battery cells, fuel cell, or ultracapacitor in the car than the saved 70% per gallon. Therefore, it is necessary to design a control strategy which weighs seriously on the durability extensions of the energy sources in the overall cost function.

2. Increasing number of components in drivetrain: There can be more components in a hybrid HEV powertrain in addition to the conventional ones such as ultracapacitor, S/A, continuous variable transmission, and multiple auxiliary loads in the car, which necessitates the development of new power split systems.

3. Increasing number of control targets: In addition to conventional objectives like fuel/efficiency optimization, or charge sustaining, some other targets can be taken into account, like vibration control of the automobile.

4. Complex structures: The main literature in this field is devoted to parallel structures. Development of control strategies for more complex structures can be exhausting. One example is the approach called agent control which is described below.

In case of rule based control the software follows a formula for the allocation of resources based on predetermined decisions, suggesting that there is a simple process of cause and effect - that is, that the occurrence of event X leads to the probable outcome Y. Whenever an unanticipated event arises at any stage in the order process, however, it will generate an exception. Many variables - such as quantity, deadline, failures - could give rise to exceptions when the system lacks the necessary information to make a decision based on its rules. To add a new scenario into a rules-based system to accommodate similar exceptions the planner must generate and program in new rules.

To solve this problem and create a more evident and responsive supply chain, all different controllers could be incorporated into a single system. This would allow the entire control system to react as a unified whole to any new event that may arise.

In essence, multi-agent technology derives its value from its highly granular approach to the IT aspect of forecasting. It allows all the individual controller - or agents - that make up an application to interact intelligently with other objects in a wider system. Each agent is subject to its own needs, constraints, attributes and preferences. Each link between the controller constantly communicates, negotiates and trades with the other agents, which are also seeking to maximise the benefit of their relationships and improve the overall performance of the system. Any agent can perceive events as they arise and then assess their impact, plan a response and act appropriately in a coordinated fashion. Furthermore, they will be aware of the need to request help from their control partners should an event give rise to a situation they feel they cannot adequately handle on their own. Problem solving becomes far quicker and easier when separate modules in a control network interact to allow agents to cooperate and exchange information.

5.2.1.6 Energy Storage System

By 2020 the high-power and high-energy batteries will be a € 10.6 billion to 29.8 billion market. To meet battery requirements will be the key barrier to succeed. European companies like 3M, BASF and Phostec Lithium (Süd-Chemie) are in a good situation for active battery materials. Japanese and Korean manufacturers are bestriding cell manufacturing. On the other hand Chinese manufacturers leverage extensive government support, get inimitably access to arbitrative raw materials and hence fast closing the gap. A massive R&D is needed, therefore quick consolidation is presumable. By 2020 it is expected that less than ten producers will dominate cell manufacturing. To allow the usual 150,000 km driving range of automobiles, built-in batteries must be able to withstand more than 1,000 charging cycles without losing too much capacity. The batteries must also pass crash and malfunction tests. Currently the development concentrates on improving energy density, reducing production costs and speeding up the charging time. A key to improve energy storage systems is the chemical composition of the electrodes, especially the cathode, electrolyte and separator material. The research looks into utilizing various chemical components in combination with lithium. One more field of investigations is the surface structure of the individual components at a nano level. The hope is that it will be possible to find a way to improve the travelling behaviour of the Li-Ions and so optimize cycle and charging times. Since a high number of cells is needed in car batteries, much effort is made to improve battery management systems. These systems monitor the battery performance on a continuous basis, right down to the cell level. Concerning the driving range, it is expect to see continuous improvement in energy density over the coming years which can be seen in Figure 71. For HEVs it should reach up to 180 Wh/kg on a battery system level by 2020. (Roland Berger Strategy Consultants 2009)

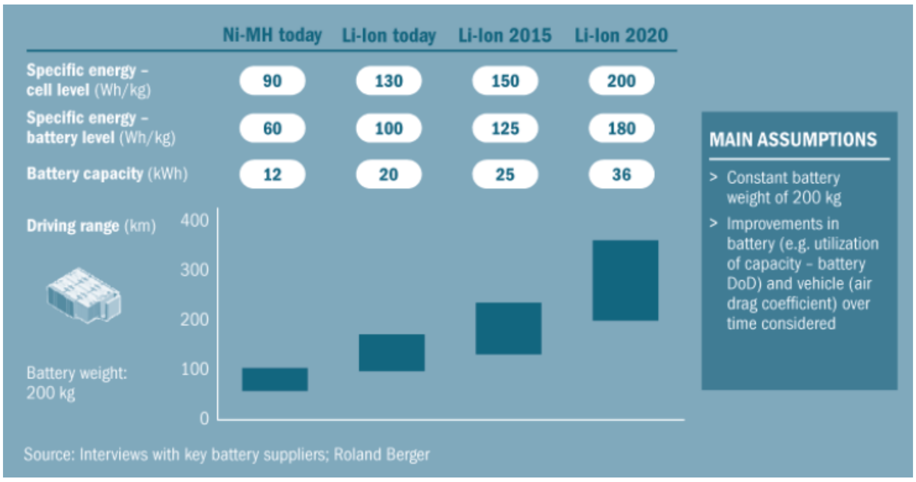


Figure 71: Capacity of a 200 kg Li-Ion battery (kWh) and electric driving range (km) (Roland Berger Strategy Consultants 2009, p. 47)

5.2.2 Value Chain Expansion Opportunities

Since it is also possible that OEMs operate services such as battery exchange stations in the future, a higher level integration will be considered. The upcoming modifications in drivetrain design will thoroughly arouse automobile manufacturers. Figure 72 shows will lead to new business areas, but also bring up grave danger for both new and established companies. Individual players can only be successful when they understand the market dynamics of their particular section of the value chain very well.

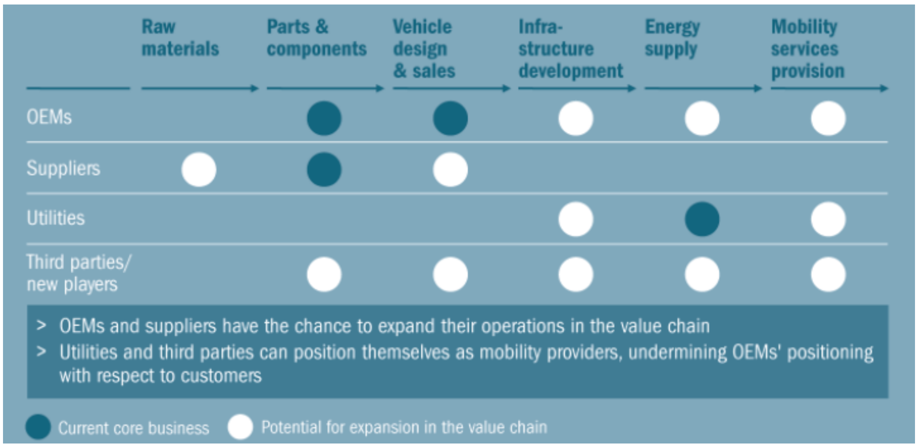


Figure 72: Value chain expansion opportunities for suppliers and OEMs (Roland Berger Strategy Consultants 2009, p.80)

5.2.2.1 Automobile Manufacturers

The conventional approach of selling automobiles can and will also be applied for electric mobility. Car manufacturers will sell HEVs and PHEVs including the energy storage system, and one or more partners will provide access to electricity, infrastructure, and services. Buy-ers will create their own package, and avail from competition at each step along the value chain. It is doubtless that there is also a possibility that the car manufacturers will reduce the value they add by offering the electric vehicle without the energy storage system, and partners will provide the battery, electricity and services to the customer. New players, like Better Place, are already targeting this new business model and position the companies as partner for the automobile manufacturer. In the coming years, OEMs are likely to become deeply involved in many of the processes to understand the fundamentals within critical systems better. The car makers will also need this involvement to make decisions about in-house competencies that are critical in the future for sustainable product differentiation. After this phase, when the market matures and competitive landscapes become clearer, car manufacturers might think about scaling back their involvement, reducing it to their core areas. These considerations apply in particular to the battery. Most automobile producers, like Toyota, VW and Daimler, have already entered into strategic cooperations with energy storage producers, either through long-term agreements or even joint ventures. The Chinese company BYD, for example, is one producer deeply involved in battery production, and is actually a leading supplier of Li-Ion batteries for cell phones. The company develops and produces LiFePO4 batteries in-house. It covers most of the value chain down to raw materials production. (Roland Berger Strategy Consultants 2009, pp. 89-90)

5.2.2.2 Infrastructure, Energy and Additional Services

Electrical power itself will become a € 2 billion to 10 billion market until 2020. Under an optimistic scenario, up to 20 percent of EV and PHEV (Plug-in Hybrid Electric Vehicles) are expected on the streets of the EU27 by 2020. Worldwide, the proportion would be eight to ten percent. This forecast is based on fuel cost of € 2.20 per litre. Hence all over the world enterprises try to get in the right position. This will become a great challenge because of smart companies like Better Place. The newcomer invests significantly in new technology and in additional services to add value for the customer. For the auto manufacturers a defined strategy is necessary in order not to lose the business and being marginalized because of a slow shift in the value generation from car sale to mobility services supply. (Roland Berger Strategy Consultants 2009)

Recently the vbw-Unternehmermagazin mentioned that Siemens wants to make more profit with environmental technology in the coming years. CEO Peter Löscher said that Siemens will provide charging stations for electric cars and link them to power plants. The company will build nuclear power plants together with Russia's Rosatom. (vbw-Unternehmermagazin 2010)

5.3 Hypotheses

Obviously, the end of the oil age effects on the mobility of people. However, the economy must continue to ensure individual mobility at a reasonable price. As the oil maximum delivery volume has been exceeded in 2008, motorists must expect a higher price for fuel in the future. This will result in the wish of people to become more independent on oil. Since the current main power source of automobiles, the ICE, is fuelled mainly by fossil fuels, some hypotheses have been developed. For example is expected that the internal combustion engine will be of decreasing importance already in 2020. On the other hand, electric motors and energy storage systems will gain in importance. In addition a higher modularisation of powertrain components is expected. An overview of the hypotheses, that will be explained on the following pages, can be seen in Table 7. Therefore a PHEV mid-size vehicle was taken as example since it is very likely to achieve a high market share by 2020. The cost values for each component have been found by the Roland Berger Strategy Consultants (2009, p. 52). These costs helped to compute the values of contribution per component in relation to the total powertrain costs. Since the cost of the control strategy cannot be clearly quantified, they are not included in the percentage of the total costs.

Table 7: Matrix of hypotheses for mid-size vehicles

	PE	ICE	T	EM	C-S	ESS	Info
Differentiation now	No	Yes	Yes	No	No	No	p. 86
Differentiation 2020	Yes	No	No	Yes	No	Yes	p. 86
Classification now	IP	IP	IP	IP	IP	IP	p. 87
Classification 2020	IP	Com	Com	Com	IP	IP	p. 87
Modular Design Possible	Yes	Yes	Yes	Yes	No	Yes	p. 87
Pressure	High	Med	Med	High	High	High	p. 88
Maturity Level	Low	High	Med	Low	Low	Low	p. 88
Cost Conventional now (EUR)	0	1,800	500	0	n.a.	100	p. 88
Cost PHEV now (EUR)	3,500	1,500	400	2,100	n.a.	6,000	p. 88
Cost PHEV 2020 (EUR)	2,000	500	200	800	n.a.	2,500	p. 88
Value of Contribution now	0%	75%	21%	0%	n.a.	4%	p. 90
Value of Contribution 2020	33%	8%	3%	13%	n.a.	42%	p. 90

5.3.1 Differentiation

Hypothesis: If it comes to a hybridization rate above 50% of new passenger cars by 2020, then internal combustion engines will be less important for the differentiation of the brand.

In reality there is only a little differentiation potential left that can be obtained by automobile manufacturers for volume base engines (4-cylinder). Anyhow, still most automobile manufacturers consider engine manufacturing to be core competence. The mechanical processing of major components leads to high tied-up investments. On the other side, personnel costs to manufacture crankcases and cylinder heads still account for 20-25 percent of total costs in western Europe. As a result, suppliers move their production sites to countries with lower wage levels, for instance Belarus. Since parts like crankshaft, crank case, camshaft, conrod and cylinder head can be purchased from powertrain suppliers in good quality, the component plants of OEMs face increasing competition from these low-cost suppliers. The price battle with component plants of suppliers forces car manufacturer to produce in cheap countries and further turn the screw on product costs. This results in a higher capacity need from engineering to reduce production costs of engines already in series production. On the other hand, many engine plants of OEMs are rather small and do not realize real economies of scale. Examples showed that OEMs do not need to manufacture all those components to guarantee brand distinctiveness. Luxury manufacturers like Aston Martin use Ford base engines, the MINI brand now uses base engines engineered and manufactured together with PSA, and transmissions are mostly purchased from third parties. Porsche obviously had no disadvantage although its vehicles are equipped with an automated transmission from DaimlerChrysler, and neither had the BMW 5-Series car, which uses ZF as well as GM as an automatic transmission source. Especially premium and "near-premium" manufacturers continue to consider engine development as an OEMs core competence. However, most manufacturers have shown that they can use base engines from other partners and still launch a vehicle that clearly incorporates the brand DNA within its driving characteristics. Given the fact that developing and preparing production for a family of new engines produced in two locations in large numbers can easily require investments of € 800 to € 1 billion, partnerships obviously make sense. (Roland Berger Strategy Consultants 2009, pp. 58-74)

5.3.2 Classification of Components

Hypothesis: If it comes to such a high hybridization rate by 2020, then internal combustion engines will be only a commodity. In other words, ICEs will be bought from a small number of suppliers or other OEMs and do not constitute intellectual property of the OEM.

It is expected that some components which now are still considered as intellectual property, in future will only be regarded as commodity. As a commodity they will simply be purchased like other parts of the vehicle. They do not represent important internal company knowledge. This may include electric motors, transmissions and ICEs. Such commodities have only to be cheap and meet certain requirements. Due to the large volume prices will be reduced greatly.

Through the power electronics and control strategy, the efficiency of the vehicle is strongly affected, thus it must remain intellectual property. As many car manufacturers already received cooperation with battery manufacturers, or even buy them, energy storage systems could be considered as future IP for OEMs.

5.3.3 Modular Design

Hypothesis: If there is such a strong electrification of the drivetrain, the gradual market launch of modular designed powertrain components is expected by reason of higher flexibility and cost advantages.

Modules can be adapted to specific vehicle requirements. Thus, they are useful for all vehicle classes, from compact car to SUV or for all drive types such as pure electric and hybrid and fuel cell applications. The flexibility end efficiency of this concept will reduce time to market and development costs of the customers. Modular systems make many drive designs for different customer requests possible.

One example for modular design is the sandwich-floor architecture by the Daimler. It forms the basement for a big choice of models with electric drive systems. In addition the company is developing another platform for the future compact class that uses optimized ICEs as power unit. The range of products can be developed very efficient and flexible by the clever networking of the two designs. The developed models called BlueZero are adapted from the sandwich-floor platform that Mercedes launched primary for the A-Class and then for the B-Class. It was always a target to implement new powertrain concepts. Both BlueZero vehicles offer five seats and front wheel drive, which is common in this class. The modular system contains multiple flexible powertrain components that can be combined. For example an EM with 100 kW (70 kW continuous output), that achieves a maximum torque of 320 Nm. In addition a liquid-cooled Li-ion battery with a maximum capacity of 35 kWh. Both vehicles reach 100 km/h after standstill in fewer than 11 seconds. The maximum velocity is restricted electronically to 150 km/h to reach optimum energy efficiency and driving range. One advantage of the construction is that many powertrain parts are situated near the centre of gravity, and that the centre of gravity is low. Therefore the handling of the vehicle is agile and extremely reliable. It also has to be mentioned that the powertrain is well protected inside the automobile underfloor and that the construction is space saving as well as weight saving. Most drivetrain parts are housed among the two axles and this leads to high crash safety. With modular design some disadvantages of conventional HEV can be avoided, since they place bulky and heavy energy storage systems in the rear-seat area or the trunk. (Daimler 2010)

Requirements for the HEV powertrain modules such as electric motor and necessary technologies should only be defined once the powertrain criteria catalogues are complete. It has to be ensured that all requirements are fulfilled and necessary improvements can be made to all components, for example the base engine characteristics. The powertrain and technology portfolio should be a base for the definition of further concept standards across powertrain platforms. This can be for instance the angle cylinder banks and other geometric measures of the base engine which are influencing necessary flexibility of production equipment and manufacturing costs. Also common engine functions across different engines as well as vehicle packaging standards including alternative powertrain concepts: transverse/longitudinally mountings, assembly of auxiliaries. (Roland Berger Strategy Consultants 2007)

5.3.4 PRESSURE

Hypothesis: With increasing hybridization energy storage systems and electric motors are under highest pressure to develop them further.

Some powertrain components are subjected to greater pressure than others. This is true especially for components that are specific for vehicles in the future. In addition to those that are necessary for differentiation from other manufacturers. Some new powertrain components like the electric motor cause greatest uncertainty since it is not clear which concepts and materials will prevail. Therefore different variants have to be considered which leads to additional development costs. Furthermore, it is assumed that there is pressure on components that have already proportionally high costs, such as the energy storage system. For them it will be necessary to quickly reduce the cost and weight. The assumed indicators for increasing pressure on components will be described on the following pages.

5.3.4.1 Maturity Level

For powertrain components which are in a more mature stage of the life cycle, suppliers either need to come up with totally new technical solutions that offer a significant higher performance than current technologies. Otherwise they need to come up with extensive cost improvements to deliver current performance via improved product designs, reduced overhead costs and low-cost manufacturing and sourcing. One example is the shift from solenoid to piezo actuators in injection technology. Most of these mature components are not under high pressure. On the other hand, for technologies still in the earlier phases of the life cycle, suppliers need to create entry hurdles for competitors. This can be done for example by a much higher functional integration. That usually reduces product costs, but also increases technical product complexity, hence helping to avoid a break-up of the system and picking of components by their customers. For this kind of components the pressure is higher. (Roland Berger Strategy Consultants 2007, p. 79)

5.3.4.2 Cost

The financial burden for OEMs will increase. Although it is presumed that the majority of the above mentioned technologies are standard in 2020 and that producers benefit from the economies of scale, the average cost per vehicle is going to increase as can be observed in Figure 73. End-customers may be willing to pay partially for the additional cost, since 30% fuel savings and less tax payments due to lower CO_2 emissions can be provided. Though, only in Europe OEMs will have to absorb about € 12 billion additional costs each year for components, although the profit pool will be limited. In the US customers are even less willing to pay higher sticker price. This will be very challenging for the automotive industry there since the key players are in a invalid financial situation and will have to cope with annual extra costs of USD 10-15 billion. (Roland Berger Strategy Consultants 2009)

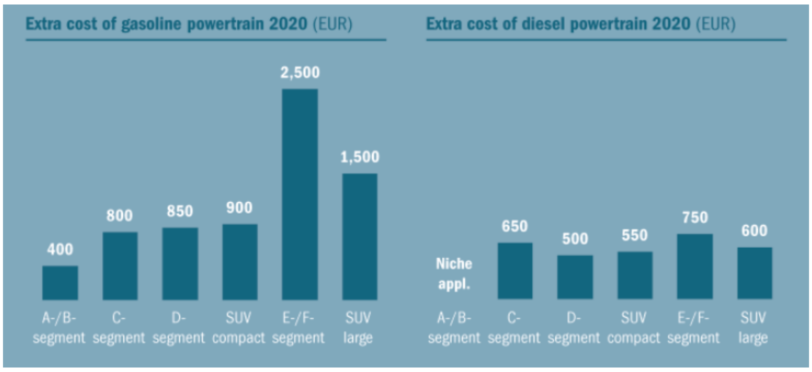


Figure 73: Additional powertrain costs in 2020 (Roland Berger Strategy Consultants 2009, p. 32)

When comparing the technology that can optimize the combustion engine powertrain with the cost of hybrid technology, Figure 74 indicates that the CO_2 reductions reached with hybrids come at an exorbitantly high cost. Currently full hybrids are therefore only a feasible option to significantly reduce CO_2 for very large and heavy cars. With lower prices of hybrid technology, especially energy storage systems, the situation might change. Optimizing ICEs should always be the first option when trying to reduce fuel consumption and CO_2 emissions. Start-stop systems should be a first step since it can be introduced very quick. Only after taking these steps it makes sense to switch to full hybridization for large cars. It is essential to optimize the total powertrain to find a acceptable cost-benefit ratio for fully hybridized automobiles. (Roland Berger Strategy Consultants 2007)

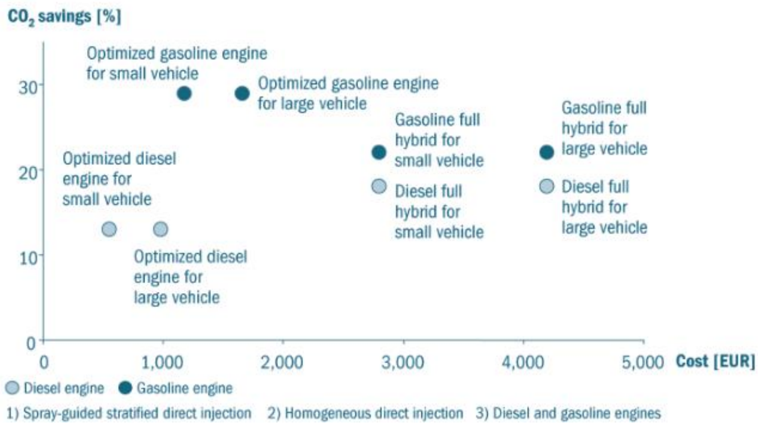


Figure 74: Cost/Impact relation of selected "technology packages"
(Roland Berger Strategy Consultants 2007, p. 46)

The potential for reducing ICE production costs is huge. Savings of 20 percent per base engine by doubling the volume are possible on average. Partnership models or engine carry-over from third parties could form the blueprint for future business models in the volume car segment. Battery costs will mainly be driven by the materials required and their purchasing price. An additional driver is the cost of installed production machinery. In the coming years, it is expected to see the cost of batteries falling substantially from its current level of around € 400-500 per kWh for high-energy cells. The target of approximately € 200 per kWh (on cell level) may be achievable by 2020. There is a good chance that a state-of-the-art PHEV with a very small ICE, could reach battery pack weighing not much more than 100 kg by 2020. This would make overall vehicle weight comparable with today's ICE-powered competitors. It would also provide an electric driving range of about 150 km, and superior driving characteristics. All this could be possible with battery costs of not more than € 5,000. (Roland Berger Strategy Consultants 2009)

5.3.4.3 Value of Contribution

It is assumed that the percentage of costs on the entire powertrain is also evidence, which components are under considerable strain to reduce costs and to improve the technology. Figure 75 allows a quick overview of the estimated value of contributions in percent for a conventional car in 2010 and a PHEV in 2020 as well as the classification of the components. The calculation of the cost values can be found in Table 7. As mentioned before, costs for the control strategy are not considered and included. The classification distinguishes between commodities and intellectual property. Commodities are easily interchangeable. Intellectual property, however, is specific. Commodities therefore in contrast to intellectual property generate less value.

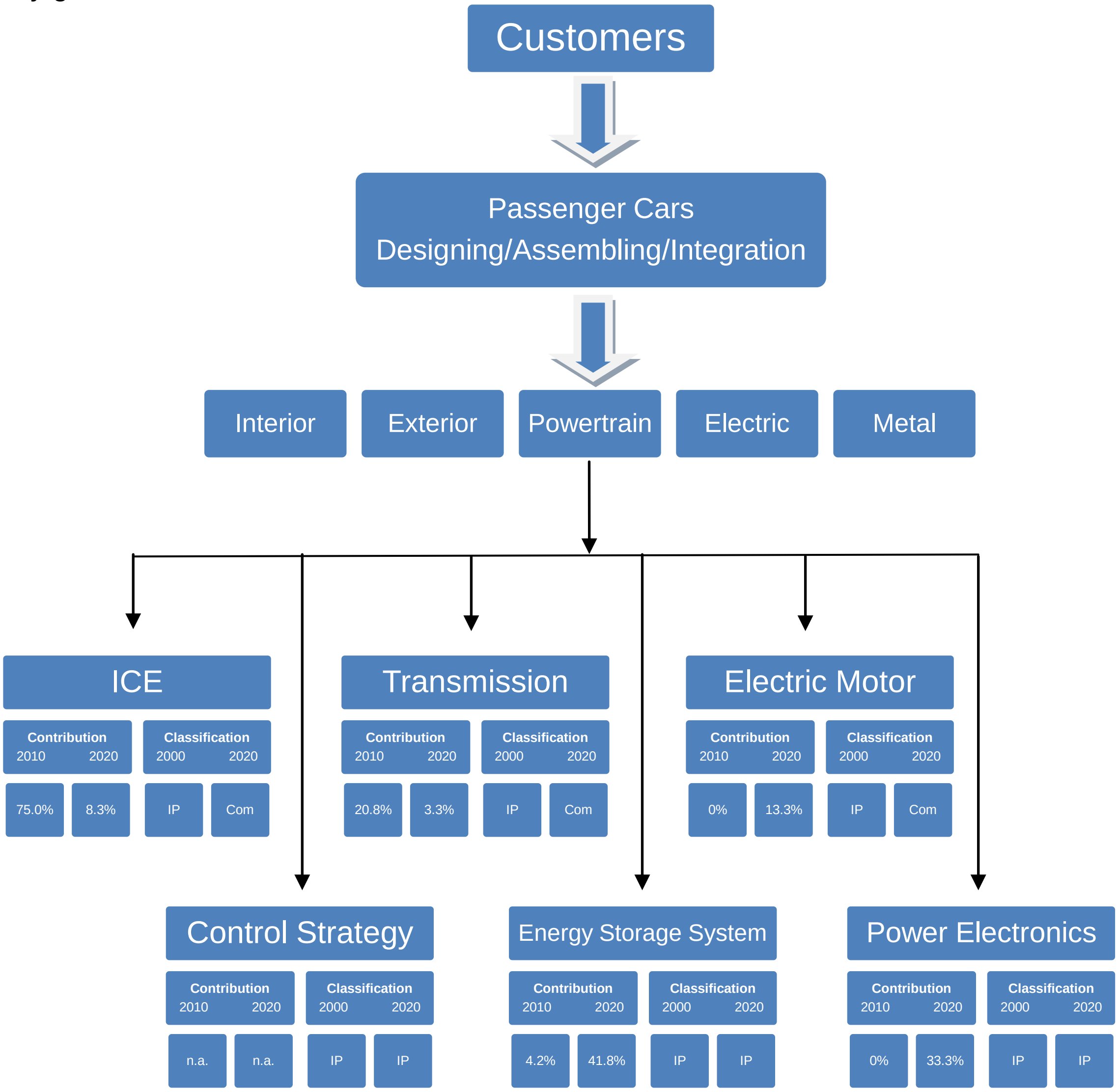
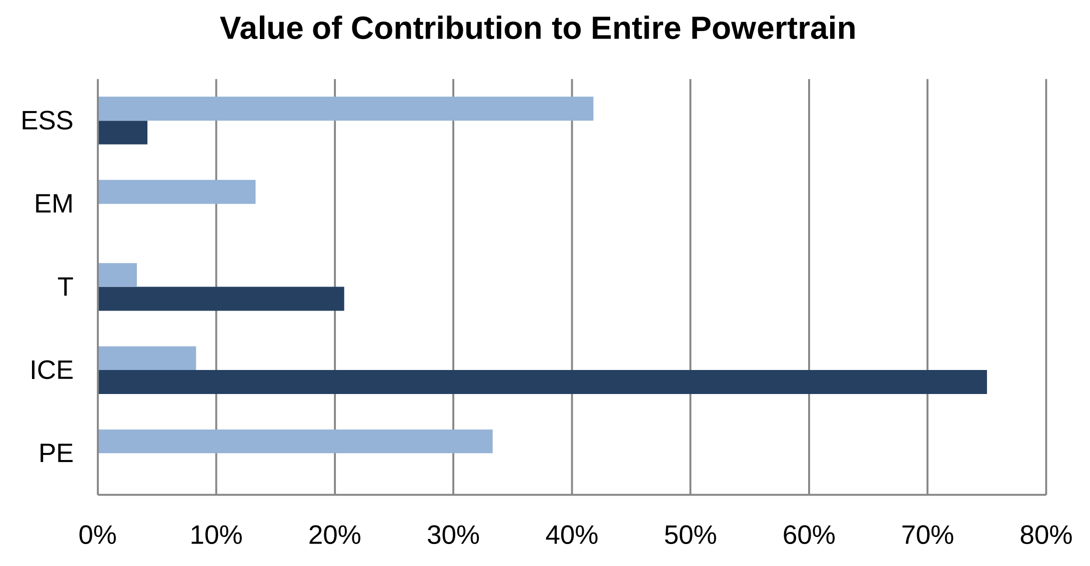


Figure 75: Value generation and classification of powertrain elements

Figure 76 on the next page shows a clearly laid out diagram of the value of contribution.



	PE	ICE	T	EM	ESS
2020	33,30%	8,30%	3,30%	13,30%	41,80%
2010	0%	75,00%	20,80%	0%	4,20%

Figure 76: Diagram value of contribution to entire powertrain

5.3.5 Financial Winner and Loser

Hypothesis: The ICE will generate less value in the value chain of the future.

It is expected that the high pressure components will generate the largest supplier profits in the future. Figure 77 shows the assessment of trends:

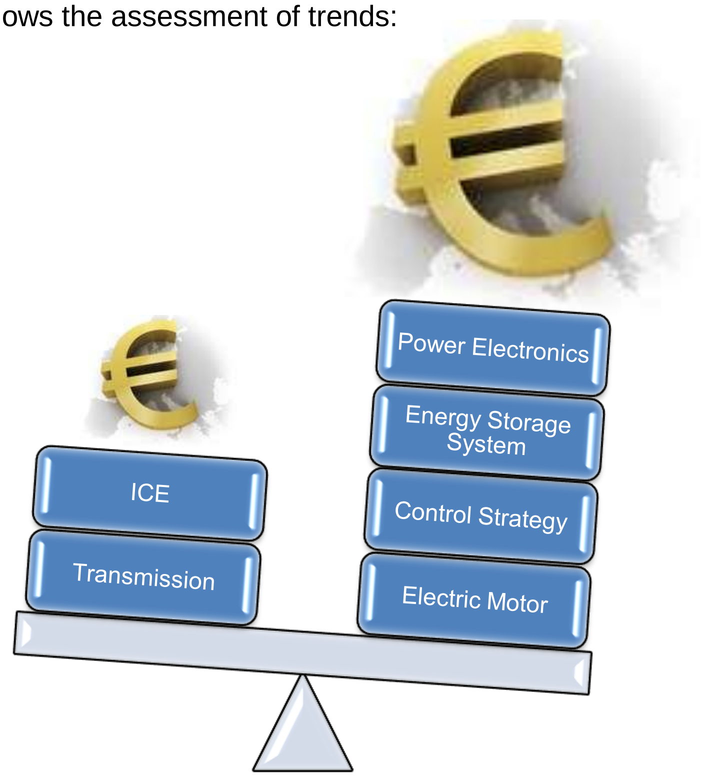


Figure 77: Trends in future value generation

5.4 Validation of Hypotheses

To verify the hypotheses by multiple sources, several independent experts were interviewed. These are eleven anonymous men from different countries who work in an international environment and have an average work experience of about 15 years but a minimum of 10 years. They are senior engineers and managers employed in India, USA, Austria, Japan, Germany, Korea and China and work in the field of powertrain testing and development.

Since there are questions that concern the future, the time frame of 10 years has been set. So the arrival of the allegations is expected in 2020. The results were evaluated statistically. At the beginning an email questionnaire was developed for data collection, which can be found in the appendices. One criteria of the survey was that it should allow an assessment of the hypotheses using as few answers as possible, all without doing the interview personally. It had to be only a few questions, since otherwise many interviewees would have rejected the answer in advance. Also unclear answers that cannot be interpreted should be avoided. Subsequently, the respondents were selected. The objective was to interview people from different countries working abroad in the automotive industry. They are known from former work experience and internships as well as independent persons proposed by supervisors. The collected data was compared to the theory, namely the hypotheses. The answers were finally prepared by using Microsoft Excel. Specific responses are quoted.

5.4.1 Differentiation

Question: Do you think it is necessary that below-mentioned components are self-developed and self-produced for differentiating the brand from other OEMs by 2020?
a) Power Electronics
b) Internal Combustion Engine
c) Transmission
d) Electric Motor
e) Control Strategy
f) Energy Storage System

It was tried to fathom whether the respondents consider it necessary that the individual powertrain components have to be developed and produced by the car manufacturers themselves in order to differentiate itself from other OEMs. In doing so it was clearly highlighted that the own power electronics (PE), the own internal combustion engine (ICE), the own control strategy (C-S) and the own energy storage system (ESS) deemed to be necessary for the differentiation of the brand. Thus, the respondents disagree with the hypothesis that the internal combustion engine will be less important to distinguish the brand. It is also surprising that the control strategy shows the highest percentage. This means, that almost all expect no outsourcing for the development of the control strategy. Further information can be found in Figure 78.

5.4.1.1 Power Electronics

The majority of experts believe that a self-developed power electronics is not brand specific. One respondent from Austria agrees with them:

"Most of the developments done by suppliers for OEMs will be sold to the customers as an OEM technology. Nevertheless, only a few OEMs will develop the own electric system (IP), the other OEMs will buy it from suppliers / other OEMs. For sure, some OEMs will use their technology for differentiation - not the P-E alone but the whole system architecture, e.g. Toyota"

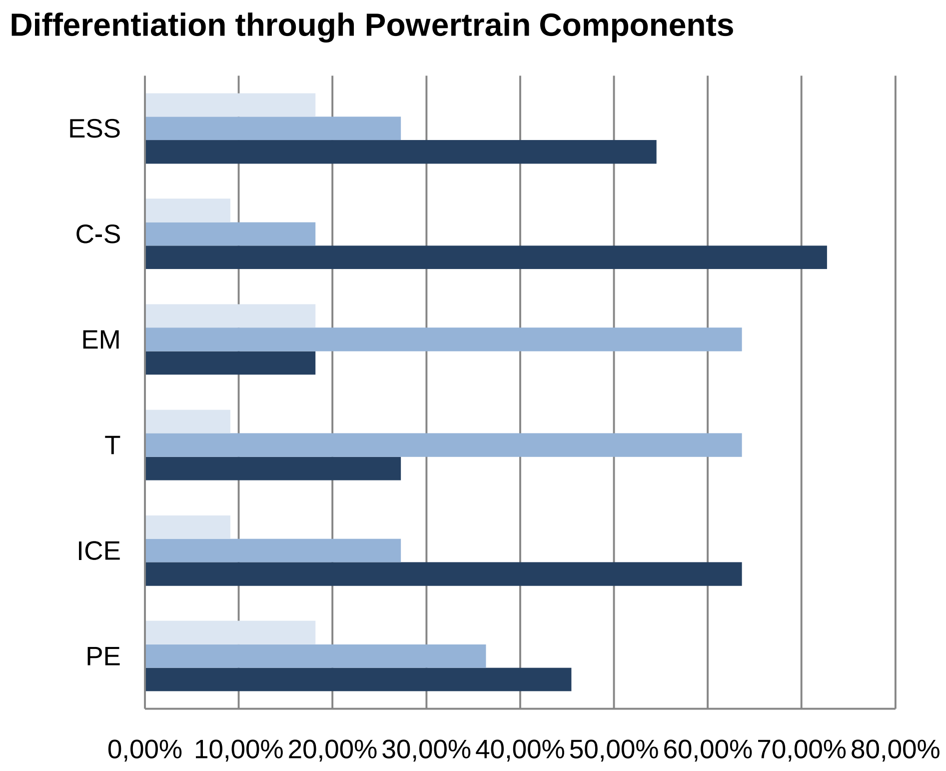
5.4.1.2 ICE

The replies about the need for self-produced shows an explicit trend, that can be seen in Figure 78. It contradicts the hypothesis that engines will be less important for the differentiation.

"I think in the mindset of the people engines are the heart of the vehicle and they will always be produced and developed by the OEM (may with help of engineering companies). There is a slight trend that companies exchange engines but that will take longer than 2020 before people understand that the engine is just another part of the vehicle."

A colleague from Germany agrees:

"Established OEMs will not give up their core competence in development of IC engines. There is a high degree of value creation in the IC development and production at the OEMs. Maybe new companies like BYD will buy a IC engine for a range extender."



	PE	ICE	T	EM	C-S	ESS
Brand Specific No answer	18,19%	9,10%	9,10%	18,19%	9,10%	18,19%
Brand Specific No	36,36%	27,27%	63,63%	63,63%	18,18%	27,27%
Brand Specific Yes	45,45%	63,63%	27,27%	18,18%	72,72%	54,54%

Figure 78: Powertrain components that lead to differentiation from other OEMs

5.4.1.3 Transmission

A high percentage of respondents believe that self-developed transmissions are not necessary for the differentiation.

"Major OEMs have already sourced the transmission development out to suppliers like GETRAG, ZF or LUK. It has no big influence at the final customers decision behaviour."

5.4.1.4 Electric Motor

Two third of answers say that self-produced electric motors will be useless for the differentiation of the OEM. An interviewee from North America represents the opinions.

"A motor would have to be something very special to provide real differentiation for an OEM. Existing motor technology is being adapted and improved for the automotive powertrain application, but it is essentially a mature technology. For the most part, it will be treated as a commodity."

5.4.1.5 Control Strategy

The control strategy pointed out to have highest importance to be self-developed as one colleague remarks.

"Absolutely YES. Next to power electronics, controls strategy is in the top 3 powertrain component. With the control strategy, the OEM might even have the biggest "knob" to adjust their competitive success and differentiation to others in the industry."

5.4.1.6 Energy Storage System

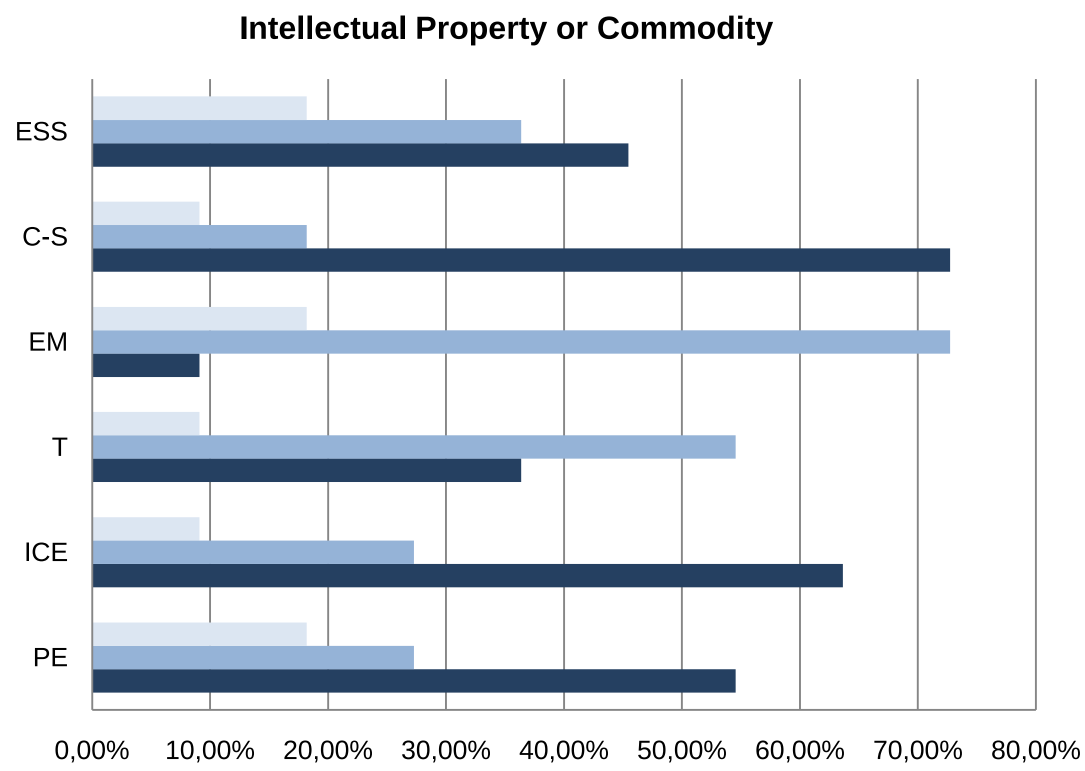
A high percentage of interviewees believe that the energy storage system is necessary to differentiate the own brand from other OEMs. But in their opinion it is useless for the car manufacturers to develop and produce them.

"The specific technology used in an energy storage system can be a differentiator, and it is critical that an OEM is well versed in the technologies being developed. But, it is not critical that the OEM develop and product the energy storage system."

5.4.2 Classification of Components

Question: Which of the below mentioned components will be intellectual property, which a commodity (supply part) by 2020?
a) Power Electronics
b) Internal Combustion Engine
c) Transmission
d) Electric Motor
e) Control Strategy
f) Energy Storage System

An attempt was made to determine whether the components in 2020 will be purchased only or constitute intellectual property of the vehicle manufacturer. The same results could be found as before. The four components Power Electronics, combustion engine, control strategy and the energy storage system are expected to constitute intellectual property that is not given out of hand. Hence, the respondents do not confirm the assumption that only a few manufacturers will produce their own motors and sell them to all other OEMs, where they are assembled. Detailed information can be found in Figure 79.



	PE	ICE	T	EM	C-S	ESS
No answer	18,19%	9,10%	9,10%	18,19%	9,10%	18,19%
Com	27,27%	27,27%	54,54%	72,72%	18,18%	36,36%
IP	54,54%	63,63%	36,36%	9,09%	72,72%	45,45%

Figure 79: Expected classification of powertrain components to intellectual property or commodity in 2020

5.4.2.1 Power Electronics

Most respondents believe that the power electronics will constitute intellectual property of the automobile manufacturer in 2020.

"Self developed PE might not be necessary. Compare it to ECU/TCU/xCU of today. The consumer (ideally) don't feels if his vehicle uses BOSCH, Denso, Magneti Marelli, etc. control unit HW. The software itself (control strategies) will have certain IP parts."

5.4.2.2 ICE

Two third of experts believe that engines will still be intellectual property of OEMs. But most hesitate to give a clear answer.

"As the trend to electrification continues, for certain market segments (range extender) the visibility of the ICE to the consumer will shrink. Therefore it could become a commodity. For upper market segments the 'image' of self-developed (prestige) engines will likely continue."

"In the context of an electrified powertrain, the combustion engine can be a differentiator, but not nearly as strong a differentiator as it is in a combustion-only powertrain. Truly unique engine concepts, such as those being considered in some range extender applications, could be useful for differentiating an OEM, but it isn't critical that the IP be owned by that OEM. The downside to not owning the IP is the threat of competitors using the same technology."

5.4.2.3 Transmission

Many experts are not sure if transmissions will be intellectual property. However, they tend to say it will become a commodity.

"If the electrification is a unique integration of electric motors into the transmission, it would be useful IP. If the transmission is more of a standalone component, it becomes a commodity."

5.4.2.4 Electric Motor

A very high percentage of interviewees expect electric motors to be a commodity in the future.

"In order to understand the technology and ensure a steady supply chain some OEM's might enter the field of e-motor production. In the long run this will likely become a commodity - and produced from suppliers."

5.4.2.5 Control Strategy

Nearly 90% of respondents say that the control strategy is of high value and hence has to be intellectual property.

"Control strategy done by a system integrator or OEM will be the key know how for new drivetrain concepts. At the moment and in near future all the important development and research work is done by themselves. It will be protected by Intellectual Property."

5.4.2.6 Energy Storage System

The answers do not show a clear trend if the energy storage system will be intellectual property in the future.

"Initially many different versions and combinations will be around before the favoured version becomes dominant. So initially It will be IP and brand differentiation."

5.4.3 Modular Design

Question: Do you believe that the whole powertrain of vehicles will consist of modular components that can be easily replaced (for example in sandwich-floor platform) by 2020?

It was asked whether it is expected in the future that the whole powertrain of vehicles will consist of modular components that can be easily replaced. The answer does not show a clear picture. About 55% believe that the increased modularization will be realized as can be seen in Figure 80.

Those who said no, believe that it will take longer than ten years, but it will happen. However, one interviewee is confident that modularization will find a way in the car industry very quick:

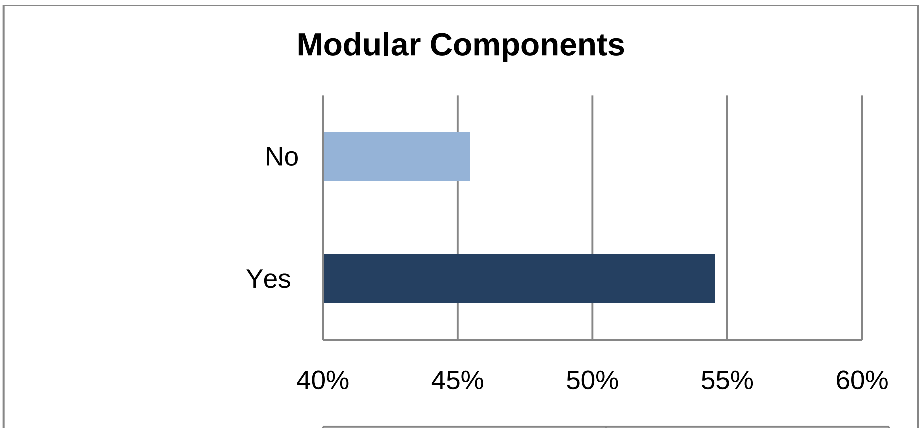
"YES - I believe so. I believe that in the future vehicles will be sold like washing machines today. The consumer will by a vehicle based on energy ratings and will care less about performance. Note: today washing machines are all pretty much the same and built from modular components. They differentiate themselves via intelligent electronics, creative design features (colour, shape...). I expect that to happen to the auto industry in 10 years - even here in North America."

Another respondent from Germany agrees with him:

"Yes definitely. AUDI and VW show the advantages of having a construction kit system. They are able to design, develop and produce cars in shorter times as their competitors."

A colleague agrees with the previous answer in a way that he also believes modularization is necessary to allow derivatives of cars. Modularization makes derivatives cheaper. In other words, one platform is used to build cars with different shape. One example is Audi with the A5 coupe and the A5 sportback.

"For high volume vehicles, there will be enough cost savings and functional improvement available from specifically designed powertrains that the OEMs will go through the effort of doing new or at least heavily modifying existing designs. An OEM could do a range of specialty vehicles based on a standard powertrain architecture, but that would be for lower volume, niche vehicles."



	Yes	No
Modular Components	55%	45%

Figure 80: Percentage of respondents who expect a modularization of the powertrain components

5.4.4 PRESSURE

Question: Which powertrain components are under highest pressure to develop them further?

Asked which powertrain components are under highest pressure to develop them further, the answers show a clear trend. Almost all agree that energy storage systems are under most pressure to quickly shrink them and increase them in efficiency. The number of entries can be seen in Figure 81.

"Energy storage is the one component that needs the most development in the near future. Active energy generation from solar technology built into the vehicle surface (paint or glass layers) is promising and need commercialization. Active energy generation from micro-organisms (already used in the US military in combat jackets on solders) is also promising for the auto industry."

On the other hand also the ICE is important since it is the biggest lever to reduce CO_2 emission on a grand scale.

"Still the engine as it is still the heart of the PWT and still the major propulsion technology followed by software to ensure the connection of all systems in the vehicle."

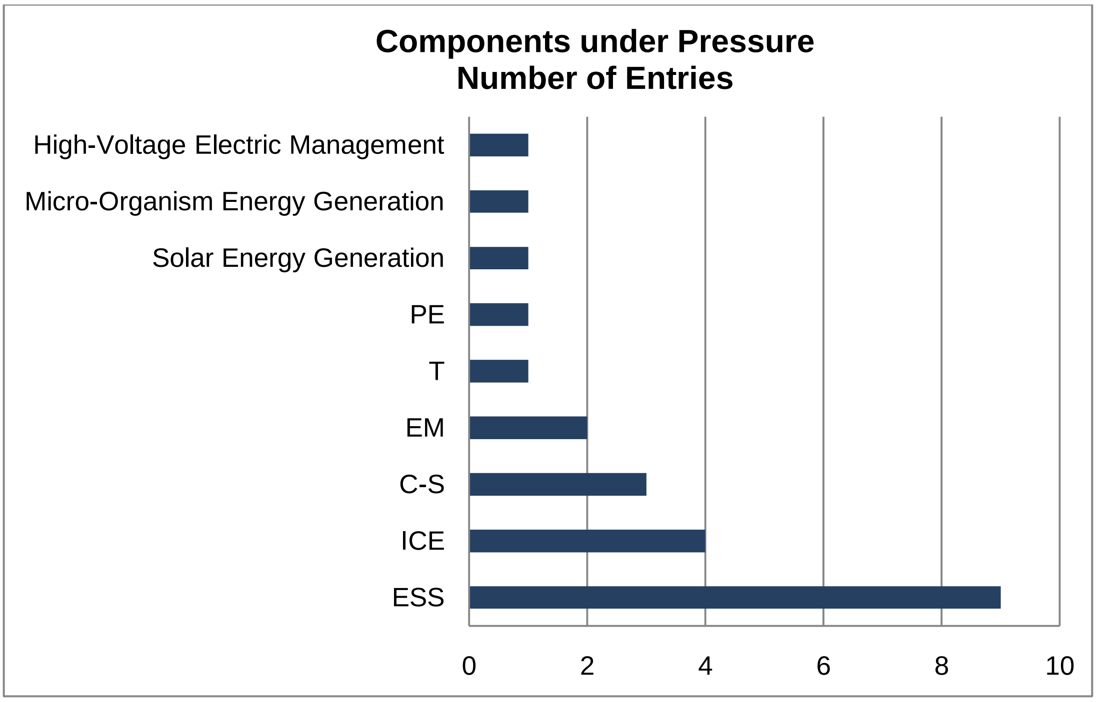


Figure 81: Number of entries for components under high pressure to develop further

5.4.5 FINANCIAL WINNER AND LOSER

Question: *Where will the financial winners and losers be in the supply industry in the area of the Powertrain by 2020? We mean by powertrain: Power Electronics, engine, gearbox, electric motor, control strategy and energy storage system.*

When asked what powertrain components in the next few years allow to generate most value in the value chain, the answer also points to a clear picture. The number of entries shows that those who offer intelligent solutions for energy storage systems, control strategies, electric motors (EM) and power electronics, will be the financial winners of this revolution in the auto industry. On the other hand, the informants expect the combustion engine to be the clear financial loser in the value chain. That means, the ICE will still be a very important component of the powertrain, but it will not allow to generate as much value as today for suppliers and developer. At least this confirms the hypothesis of the decreasing importance of ICEs. Also for transmission (T) concepts it is expected that suppliers no longer generate as much value as today. Figure 82 shows the details.

One colleague from the United States is not sure how the prices of the components will develop and believes that winners and losers depend on the price.

"Engine will lose, and the rest will win varying degrees with energy storage systems and control strategy leading the way. If costs can be reduced and capability increased I see an increasing need for electrification; however, if the additional price remains as with the diesel engine the customer will stay with the IC engine. This is cheap available technology which customers are currently happy with. Therefore, the engine will remain the most profitable component."

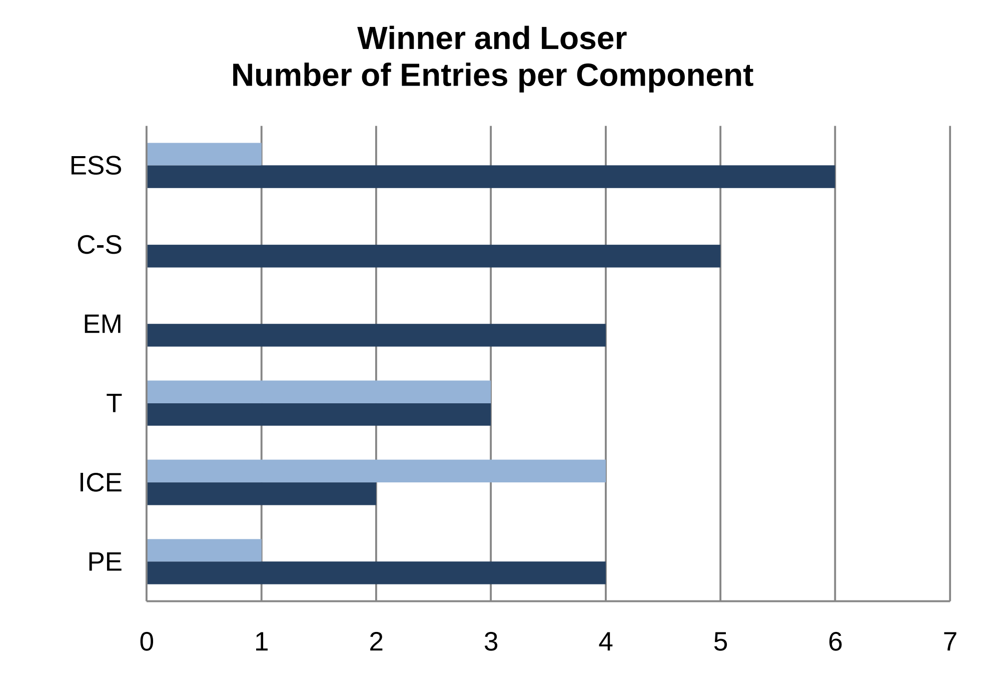
Another respondent expects that a few companies will be the winners and not producers of specific components.

"I anticipate that what are many companies today will boil down to a handful of truly successful suppliers over the next 10 years. If a company were to develop a major technical break-

through in this area, they would be poised to dominate the market for years to come. Historically we've see this as the case if a major breakthrough is achieved (consider Ford and the assembly line). Without a major breakthrough, it becomes a battle of marketing and profitability."

This was confirmed by another interviewee:

"System suppliers with the overall knowledge about the complete system will be the winners if they understand to wisely sell their knowledge. Single topic suppliers will remain but not grow anymore."



	PE	ICE	T	EM	C-S	ESS
Loser	1	4	3	0	0	1
Winner	4	2	3	4	5	6

Figure 82: Powertrain components divided by financial winners and losers in the supply chain

5.4.6 MAJOR CHANGES IN SUPPLIER INDUSTRY

Question: The powertrain of the vehicle has always been an important competence of the vehicle manufacturer. What major changes in the car components industry do you expect with the electrification of the drivetrain (hybridization)?

In a additional question it was asked which changes we have to expect in the supplier industry over the next years. The answers showed many different opinions. One respondent who is employed in North America believes that companies which are still very small today, will count to the important ones soon.

"I expect a series of new components manufacturers (often start-up companies) to become major players in this industry. For example Transonic Combustion or A123 in their respective areas (if not prematurely acquired by a Bosch or Delphi or Conti) are going to be future lead names."

One colleague from China agrees with him and estimates a modularization of components.

"Suppliers who cannot embrace this change will shrink or vanish. I assume the standardization and modularization of drivetrain components will continue, so less base development programs might be done. New entrants will certainly appear (Batteries, Power Electronics suppliers). They will try to get on the value chain and replace 'traditional' suppliers. In/Outsourcing trend unclear, might change over time as components become 'commodity' (e.g. GM started own e-motor production)."

5.5 Results of Validation

Contrary to assumptions, it pointed out partly that even people who are at the controls of development and strategy finding do not know exactly which way the automotive industry will take in the next decade as can be seen in Table 8.

The hypotheses that combustion engines will lose importance to differentiate the own brand from other car manufacturers has been clearly contradicted. The answers for the question if engines will still be intellectual property of OEMs show a similar trend. Both hypotheses are not confirmed by the asked people.

Even less clear is the picture in the survey for increased modularization 2020. About half of respondents say that we will see a quick modularization of powertrain components, but the other half is not sure. However, almost all of them believe in a modularisation, but it will take more time.

The hypothesis that it is of highest importance to develop energy storage systems and electric motors further was clearly confirmed. Electric motors have emphasized to be number four in the ranking behind the control strategy and internal combustion engines.

The last assumption that the cash flow for the development of internal combustion engines will lessen, could be clearly confirmed. The ICE got the highest number of entries to be the financial loser in the next decade.

Table 8: Hypotheses versus results of the validation

Hypothesis	Result of Validation
ICE less important for differentiation of the brand.	About two third of respondents believe that engines will still be brand specific .
Engines will not be intellectual property of the OEM.	Only 27% of informants believe that ICEs become a commodity. That is to say, a part which is bought from a small number of producers.
The whole powertrain will consist of modular components.	About 55% believe that the increased modularization will be realized by 2020.
Energy storage systems and electric motors are under highest pressure to develop them further.	80% of respondents agree that the ESS is under highest pressure to improve it.
The ICE will generate less value in the value chain.	The engine got highest number of entries to generate less value, which confirms that it is expected to be the financial loser.

6. GENERAL DISCUSSION

Today's mobility value chain will strongly be affected by the market success of HEVs in the near future. The new automobiles will require the already mentioned technically innovative components and systems. This will influence key parts of the component and vehicle creation value chain. Supplementary, the fundamentally new organization of the fuel and charging side will have a huge effect on the downstream side of the mobility value chain. This potentially opens doors for new business models. The changes will create various possibilities for new players to take over certain parts of the value chain. Incumbents will get the opportunity to strengthen their current position. The change is driven by necessary CO_2 reduction. Whereby the EU has set the most challenging aims. The average CO_2 emissions of car manufacturers yearly sales in 2012 should not be above 130 g/km (that means 65% of the fleet, going to increase incrementally to 100% by 2015). Later in 2020 the aim is expected to be 95 g/km. It would stand for an averaged fuel consumption of 3.6 litres of diesel and 4 litres of gasoline per 100 km. Average CO_2 emissions of E-segment vehicles (German C-segment) will fall to about 140 g/km on average. (Roland Berger Strategy Consultants 2009)

6.1 MATERIALS FOR LI-ION BATTERIES

At the moment most battery suppliers concentrate on Li-Ion batteries since the technology will probably determine the production ramp-up for the next decade. Hence, all suppliers will need an amount of lithium or lithium carbonate as raw material for sure, although some alternative chemical compositions exist for the anode, cathode and electrolyte. (Roland Berger Strategy Consultants 2009, p. 71)

For this reason, the description about energy storage systems in Chapter 3 concentrates especially on lithium batteries. Otherwise it is necessary to say that Li-Ion batteries do not offer very high specific power. For that reason ultracapacitors are necessary. A hybrid energy storage system is very useful since it combines the high specific power of the ultracapacitor with the high specific energy of the battery. Ultracapacitors need carbon and a sulphuric solution for manufacturing.

Lithium is currently used in a variety of industries, including glass/ceramics, pharmaceuticals, lubricants, synthetic rubber, air-conditioning systems, alloys and batteries. Due to the U.S. Geological Survey the global reserves are approximately 11 million tons (lithium carbonate equivalent), with around 75% found in Chile and Bolivia, 10% in China and 15% elsewhere. Some 25% of current annual production is used for batteries, mainly for consumer products. (U.S. Geological Survey 2009)

Power and energy cells for HEVs and PHEVs will mainly influence the future increases in lithium demand. Since big reserves are existing, experts are not expecting a shortage on the supply side of lithium, in face of these increases. Indeed, temporary price increases that have been noted in the past are possible. Li-Ion battery cathodes consist basically of lithium-based composites like lithium metal phosphates. The research will concentrate on these materials in the next years since they offer advantages in terms of material costs and safety. However, it has to be mentioned that the composites need to be manufactured with a high level of purity and homogeneity, which makes excellent production technology and process expertise necessary. Due to this fact, the field will probably be dominated by established players from the chemical industry like Süd-Chemie (Phostec Lithium) in Germany and 3M in the United States, although new players have big chances. For battery cell manufacturers, it will be crucial either to control the making of cathode material composites in-house or to establish stable relationships with key players in the field. Patent issues will further increase the complexity of this critical part of the component-making value chain. (Roland Berger Strategy Consultants 2009, p. 71)

6.2 Raw Materials for Electric Motors and other HEV Components

By virtue of the Mineral Commodity Summaries published by the US Geological Survey, China controls 93% of rare earth production and its reserves account for 31% of the total worldwide This shows that earth elements which are necessary for permanent magnet electric motors are strongly concentrated in China. Since there is an increasing demand for this raw material, China imposed export restrictions on rare earths lately, resulting in higher prices and stronger dominance of Chinese players. To avoid higher raw material costs, EM manufacturers will probably promote the development of PMSM using alternative substances or less rare earth material. They will probably also concentrate on the development of electric motors featuring induced electromagnetic fields. This will open up the field for new players such as Brusa AG in Switzerland. (Roland Berger Strategy Consultants 2009, p. 72)

China will use the abundant natural resources for sure to become a global player in the electric motor production as mentioned in chapter 5. The People's Republic in recent years has shown in other areas that it wants to gain influence. For the producers of electric motors in Europe it could mean however that they cannot compete. They are therefore likely to rely on other technologies. The induction motor, which has been described in chapter 3 is already widely used in the industry, seems to be a reasonable alternative because of its affordability.

6.3 Parts and Components

Due to the hybridization of automobiles, parts like energy storage, electric motors, AC/DC and DC/DC converters and power electronics will show much higher growth rates than other areas in the automotive industry. The hybridization will also lead to an adaption of other components like air-conditioning units, water pumps, brakes and steering systems in order to make the overall vehicle system as efficient as possible. This presents opportunities for both established and new players to access new revenue streams and obtain larger profit margins. For this reason, automobile manufacturers and suppliers need to review their core activities and product portfolios. (Roland Berger Strategy Consultants 2009, pp. 72-73)

Especially suppliers of the total powertrain, who can implement the hybrid architectures discussed in Chapter 4, will have success. This is also supported by some interviews with the experts in Chapter 5. Only provider of complete solutions are suitable for necessary strategic collaborations with OEMs, that are discussed in Chapter 2.

6.4 Shake-Up of the Established Supplier Base

Currently also established suppliers of powertrain parts must analyze their product portfolio, technology basis and competitive edge. Carelessness to do so could lead to a loss of future business as the powertrain environment changes and develops. Toyota and Honda introduced hybrid vehicles in the late 1990s. This has enabled their key component suppliers in Japan to build up a considerable knowledge base. Now these suppliers use the experience to further develop their products for use in HEVs and PHEVs on a global basis. At the same time, key European suppliers such as Bosch and Continental are increasing research and effort to compensate Asian dominance. Except those in Asia, existing players essentially have to start from zero when it comes to the development of the new electrified components and systems. Hence, it is much easier for new players to gain market share than it was previously the case in the highly mature automotive component market. A number of new players such as A123, Litec and Tesla are already offering innovative technologies in specific components, trying to gain a share of the attractive revenues in this section of the value chain. This is a challenge for them since strong reactions are expected from incumbents, and huge investments are necessary in this field. Battery cells have a number of different potential chemical compositions. Moreover, safety requirements often conflict with performance requirements. The R&D expenses and production investments involved are also enormous. It will only be possible for the strongest players to achieve the required economies of scale. This will probably result in a first supplier concentration process, similar to that found in the semiconductor industry. Other key components like EMs and power electronics also demand large up-front investments and rely on companies that can realize economies of scale. Consequently innovative new players are more likely to enter on the software side and in specialized market niches. (Roland Berger Strategy Consultants 2009, pp. 73-74)

When asked about the biggest changes in the supply industry, many surveyed in chapter five responded that they expect many new suppliers. Obviously, they have the potential to rise to important companies through shrewd solutions quickly and to generate huge profits. Just think of the Internet and Google. The search engine operator was founded at the late 1990s founded, today everybody knows and uses it. In addition, the company has even endured the last two years of the economic crisis with making high profits. Also suppliers for hybrid components can quickly gain a high status.

6.5 Strategic Partnerships

In order to secure access to technological know-how automobile manufacturers should try to identify strategic partners with the expertise and solid financial backing. Existing joint ventures between LiTech and Daimler or Evonik in Germany, are good examples of such attempts. Established suppliers such as Bosch and Continental are also trying to support their in-house development activities with joint ventures with leading independent players. This is particularly the case in the area of energy storage systems. Another example that has to be mentioned is the newly formed SB LiMotive, which is a 50-50 joint venture between Samsung and Bosch. Changing technologies for other components, like air conditioning and cooling, will create additional opportunities for suppliers, while compensating for losses in the traditional components business. (Roland Berger Strategy Consultants 2009, pp. 74-75)

It is necessary to keep a value-creation logic in full view in order to obtain successful strategic partnerships in the powertrain area. Therefore, four basic rules can be mentioned. First, strategic partnerships must always derive from the powertrain strategy and result in a "win-win" situation for all partners involved. Second, to ensure long-term gains, the evolution of partnerships is more important than the initial deal. Third, strategic partnering should follow portfolio thinking. Multiple partnerships must be managed as a portfolio, synchronized with each other, and aligned with the overall powertrain strategy. Fourth, there has to be an open-minded culture that allows and fosters learning across all parties. (Roland Berger Strategy Consultants 2007, p. 74)

These rules are described in more detail in Chapter 2. Ultimately, the need for strategic partners will also result in fewer suppliers. Small scale enterprises will find difficulties since OEMs will choose capable suppliers, the bigger companies, for cooperation in first line. The big companies will buy up many small, which themselves are not viable.

6.6 Infrastructure and Energy Provision

The fuel production and the refuelling infrastructure (i.e. gas stations) is bestrode by a few global oil companies, such as Exxon, Shell and BP. With pure EVs and PHEVs used mainly in the electric driving mode, the fuel base will change to electrical energy. Here, production is in the hands of a large number of mostly smaller regional players. They include state-owned companies such as EDF in France, the State Grid Corporation of China (SGCC), and the China National Offshore Oil Corporation (CNOOC) plus independent players such as Southern California Edison in the United States and E.ON in Germany. The electrical energy is distributed by a large number of regional grid operators. Many of these companies are subsidiaries of leading utilities, or are state-owned. Though, this does not mean that the last kilometre to the car customer will also be controlled by the grid operators. Here, again, the race remains wide open. In case that the "charging everywhere" model becomes reality, with charging stations at home, at work and in parking lots, companies will require a good knowledge of future customers, their mobility needs and driving patterns. Understanding the owners of parking lots and their needs is also essential. With their expertise in charging technology and grid management, utilities companies are currently well-positioned in this section of the value chain. However, there is much room for new players to move in if they can act quickly, secure strong financial backing and come up with innovative business models that allow local stakeholders to participate in future revenue streams. The decade will be pivotal for companies hoping to acquire a leading position in this area. To build a solid basis for future business, companies must make significant up-front investments and be prepared to put up with a slow customer growth rate in the initial years. The most determined and creative companies will win this challenge. (Roland Berger Strategy Consultants 2009, pp. 78-79)

According to ERTRAC leads a estimated energy consumption of hundred Wh/km per EV which is driving 10.000 km annually, to a energy consumption of about one TWh for one million cars. This is only a small proportion of the annual electricity output of the European countries. For instance in Germany it is less than one percent. In other words, the impact would be much less than the expected global increase in electricity generation from renewable sources. (European Road Transport Research Advisory Council (ERTRAC) 2009)

6.7 Mobility Service Providers

The already mentioned modifications in the industry will offer many opportunities for innovative companies. This includes mobility service providers, since their products cover several steps of the new mobility value chain. Leasing models for cars could become popular due to the fact that customer are insecure about the new technology and ongoing improvements in energy storage systems. Combined with new approaches of refuelling on an almost daily basis in a number of different locations, this enables companies to provide end-customer mobility on a monthly payment basis. The providers of this kind of service can come from a number of different backgrounds. They may be completely new to the business but have a strong understanding of the key business dynamics like Better Place. Alternatively, they may already be active in one section of the existing mobility value chain, as is the case with car manufacturers and utility companies. (Roland Berger Strategy Consultants 2009, p. 79)

It is unlikely that large oil companies like Exxon, BP or Shell will leave their entire infrastructure for gas stations to other companies. They will also try to earn money with the mobility and the energy supply of people in the future. Therefore, it makes sense that they cooperate with mobility service providers like Better Place, since the company must provide opportunities for the battery exchange.

6.8 OEMs' Degree of Vertical Integration

Conventionally OEMs treat the powertrain as a critical part of their in-house development and production base and the powertrain is how they differentiate their vehicles from those of their competitors. Now, with the arrival of new electric technologies, companies need to redefine their core competences. This is particularly important as electrical components have not traditionally been a focus area for OEMs. If they want to stay ahead of the competitors in terms of technology, the development and manufacturing of new components will be pivotal for OEMs. To some extent this is happening already. Forerunners such as Toyota have built new R&D centres focused purely on electric and HEV powertrains. Other players such as Daimler are following their example. In powertrain production, OEMs current focus is on core mechanical components, such as the crankcase and cylinder head, as well as final assembly. Here, a complete rethink of the in-house production setup is needed. Within the next decade, OEMs must build up and develop their in-house competence in electric powertrains. Initially, they should concentrate mainly on product and process design. Component manufacturing, integration and assembly can be considered at a later stage, but only if the scale effects justify the efforts. (Roland Berger Strategy Consultants 2009, p. 73)

Not all of the above mentioned statements are clearly confirmed in the survey in Chapter 5. For example, according to the interviewees it is not necessary to acquire competence in the field of electric motor production.

6.9 Financial Burden and Increased Complexity for Incumbent OEMs

Car manufacturers are aware that they must prepare their business for the new powertrain era. It is necessary to follow a number of paths in parallel, improving current ICE technology and investigating various options for the hybridization. This leads to major investments and substantial risks. On the other hand manufacturers face challenges not only in R&D and manufacturing, but also in sales and distribution. It is essential that they give their buyers orientation to use established brands, guiding them through the propulsion technologies of the future. Dealer and service networks must also prepare for the broader product portfolio of the coming years. Some OEMs have already determined a clear path for the future. Toyota and the Renault-Nissan Group are two exceptions since the former is building on its success with hybrids and developing hybridization from this basis step by step in R&D, manufacturing, and in its brand positioning. The Renault-Nissan Group concentrates mainly on EVs as the vehicle choice of the future. This leaves a number of areas where new players can enter the mobility value chain by focusing on one of the emerging niches and pushing ahead fast with developments. A number of Chinese players see EVs and PHEVs as a way of closing the gap to leading established global automotive players. The Chinese government is strongly supporting their efforts. Chinese OEMs can challenge established OEMs especially on the cost side. They enjoy lower raw material costs for Li-Ion batteries and key components for EMs, like rare earths for permanent magnets. They can also keep manufacturing costs down by using domestically produced manufacturing equipment and leveraging their lower labour costs. In addition Chinese universities are also focusing on hybridization and postgraduates are increasingly being employed by leading players in the sector. (Roland Berger Strategy Consultants 2009, p. 76)

As described in Chapter 5 OEMs in Europe are expected to defray € 15 billion annually in addition, and the U.S. suppliers about 10-15 billion dollars annually due to the hybridization. Hence, it can be assumed that there will be a further reduction of independent producers of everyday vehicles. Certainly survive less than ten, that buy up all the other lucrative brands. Only those who can divide the additional cost on a large number of vehicles will continue to make profits.

6.10 Opportunities for New Players

Two types of new competitors emerging in vehicle manufacturing can be foreseen. Firstly, there will be completely new companies. Secondly, there will be companies that wish to exploit the opportunity to become OEMs and that are already active in other parts of the value chain. Tesla is an example of the first type of new competitor. In the past, OEMs were large, publicly listed companies with an extensive history and tradition behind them. Tesla, by contrast, is a start-up company funded by its founders and venture capital and with a clear vision of the future. If this vision will be enough to succeed in the future remains to be seen. Pininfarina is an example of the second type since it is already active in other parts of the value chain and an established contract manufacturer. In 2008 the company unveiled its new City EV, which builds on the company's wide experience in automotive design and production, leveraging their brand name, which is well known in the industry. With solid financing behind them, these two players may represent a major challenge to established OEMs. (Roland Berger Strategy Consultants 2009, p. 77)

7. CONCLUSIONS

7.1 THE NEW VALUE CHAIN

Both vehicle suppliers and vehicle manufacturers currently feel uncertainty. There are countless opportunities how vehicles could develop with further hybridization. This realignment of the automotive industry has great influence on the supply chain. The rearrangement also provides companies potential to generate profits, which are currently not represented in the automotive industry. In particular power supply companies have numerous opportunities to get a piece of the action. Thus, the supply chain in the automotive industry will change radically. Established and new producers of powertrain components can quickly gain market share, if they focus on the proper technique. In addition, the technique must be adopted by as many OEMs as possible to achieve a breakthrough. Therefore, strategic alliances are of the utmost importance. Apparently, the still uncertain vehicle manufacturers will be persuaded to set on a technique by the suppliers of their confidence. Certainly, the internet supports better cooperation. Supply platforms should therefore be improved.

7.2 THE NEW POWERTRAIN

Some developments are already foreseeable. The engine displacement will be downsized while performance and driveability remain at least equal and in addition the fuel consumption is reduced significantly especially at part load. Many automobile manufacturers also want to develop HCCI for mass production. The development objectives for automatic and manual transmission are more gears, further spreading of the gear transmission ratio and less friction. An increase in market share for automatic transmissions is useful if they offer a reduction in fuel consumption such as the dual-clutch transmission.

Mild hybrid vehicles are rapidly gaining influence as many existing components can be reused. Start-stop automatic will switch off the engine at standstill in almost all new cars soon. When coasting or braking, the generator wins back energy and feeds it into the energy storage system. If the driver needs extra power, for example to accelerate, the electric motor provides a gain in torque. With a stronger hybridization plug-in vehicles make sense, since the battery technology is still at the beginning and does not allow ranges that are as high as in conventional cars today. Thus, people are able to drive to work all-electric, if they charge the battery overnight. They can also travel further distances with the help of the combustion engine.

7.3 HYPOTHESES

The survey revealed an interesting picture. The hypotheses could not be clearly confirmed. This demonstrates the great uncertainty that exists just across the automotive sector. Although the respondents do not agree on the hypothesis that ICEs will be less important for the differentiation of the brand in the future, the Roland Berger Strategy Consultants believe the same. In chapter 5 it was mentioned that the sharing of base engines will allow huge cost savings. Since money rules the world, the chances are high that more and more car manufacturers are buying the engines from a few OEMs by 2020. In this case it would be also confirmed that ICEs do not constitute intellectual property anymore.

The Roland Berger Strategy Consultants also believe in a stronger modularisation of components. This trend is confirmed by Daimler, which have developed a sandwich-platform strategy. The replies of the respondents indicate that they also expect a modularization. However, many believe this will take much longer than ten years.

The hypothesis that energy storage systems are under highest pressure to develop them further was clearly confirmed. Also, that the battery system will allow the highest value generation in the future. The Roland Berger Strategy Consultants expect big steps in the development of battery systems as well. Hence, there is no doubt appropriate.

7.4 Prospects

This work will allow anyone a quick overview who is interested in the future development of the automotive industry in the area of the powertrain. On the internet a lot of information can be found, unfortunately only few pages bring the situation to the point. Hence, a comprehensive work was necessary that describes the economic sector on the basis of the value chain as well as the technical components. No technicians can disregard economic considerations nowadays. Conversely, also managers of supplier companies have to understand the technique they sell. The work can be read by anyone quickly and provides an orientation which measures are appropriate and which may only waste money.

If more time would have been available for the work, then the pure electric vehicle should be included in the formulation. This should be done by reason that almost all the OEMs are planning their own electric car or have it already introduced. Electric cars will belong to the normal cityscape at the end of the decade, although they now have a market share close to 0 percent.

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9. APPENDICES

9.1 APPENDIX A US CO_2 FLEET EMISSIONS - 2008 AND FORECAST FOR 2016

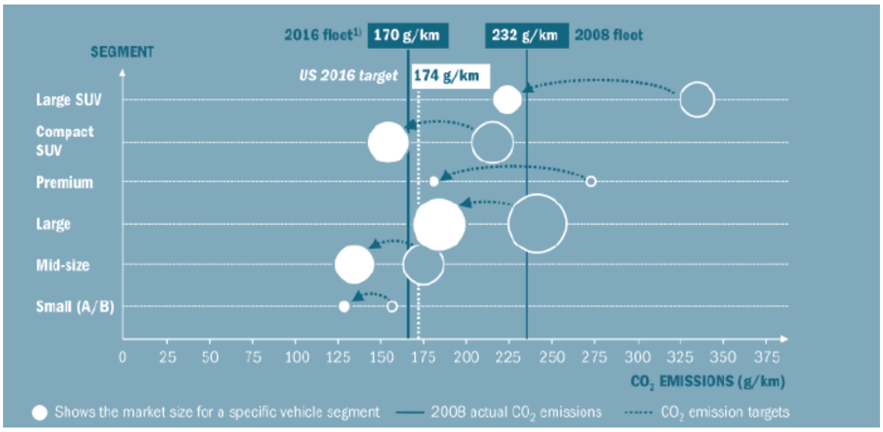

Figure 83: Expected ICE CO_2 emission to US targets gap (Roland Berger Strategy Consultants 2009, p. 30)

9.2 APPENDIX B US KEY POWERTRAIN TECHNOLOGIES BY SEGMENT 2020

GASOLINE	Small (A-/B-segment)	Mid-size (C-segment)	Large (D-segment)	Compact SUV (D-segment)	Large SUV/ pickup	Premium (E-/F-segment)
Power (hp)	80	150	250	280	320	350
Cylinders	3	4	4	4	6	6
Injection	1st-generation GDI					HCCI (partial load)
Valve train	VVT		VVT + VVL		VVT + cyl. deactivation	VVT + VVL + cyl. deactivation
Turbo		Single-stage charging				Multi-stage charging
Hybrid	Micro-hybrid					Mild hybrid
Gearbox	AMT 5	DCT 6/7 or AT 8			AT 6	AT 8
Saving pot.	30%	25%	30%	30%	30%	40%

Figure 84: Powertrain Technologies in North America by Segment in 2020 (Roland Berger Strategy Consultants 2009, p. 29)

9.3 Appendix C Full Questionnaire

1.)
The powertrain of the vehicle has always been an important competence of the vehicle manufacturer. What major changes in the car components industry do you expect with the electrification of the drivetrain (hybridization)?

2.)
P-E: Do you think that in the future a self-developed and produced power electronics is necessary for differentiating the brand from other OEMs? Will it be intellectual property or a commodity (supply part) by 2020?

ICE: Do you think that in the future a self-developed and produced internal combustion engine is necessary for differentiating the brand from other OEMs? Will it be intellectual property or a commodity (supply part) by 2020?

T: Do you think that in the future a self-developed and produced transmission is necessary for differentiating the brand from other OEMs? Will it be intellectual property or a commodity (supply part) by 2020?

EM: Do you think that in the future a self-developed and produced electric motor is necessary for differentiating the brand from other OEMs? Will it be intellectual property or a commodity (supply part) by 2020?

CS: Do you think that in the future a self-developed control strategy is necessary for differentiating the brand from other OEMs? Will it be intellectual property or external developed by 2020?

ESS: Do you think that in the future a self-developed and produced energy storage system is necessary for differentiating the brand from other OEMs? Will it be intellectual property or a commodity (supply part) by 2020?

3.)
Where will the financial winners and losers be in the supply industry in the area of the Powertrain by 2020? We mean by powertrain: Power Electronics, engine, gearbox, electric motor, control strategy and energy storage system.

4.)
Do you believe that the whole powertrain of vehicles will consist of modular components that can be easily replaced (for example in sandwich-floor platform) by 2020?

5.)
Which powertrain components are under highest pressure to develop them further?