Integration of environmental technology in modularised production systems in the automotive industry

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1.1. Introduction

Modern vehicle production is characterised by a modular design and manufacturing of core technologies fitted in cars (Pandremenos et al 2009, Persson 2006b, Sturgeon and Lester 2003). The purpose of this paper is to explore how the use of modularised production systems in the automotive industry can be combined with the integration environmental technologies.

The integration of environmentally sound technologies in the automotive industry is closely linked to the economic and technical configuration of the existing production system (Wells 2004). Sunk costs in production equipment at the vehicle assembly plants, designed for manufacturing of vehicles based on steel bodies and internal combustion engines, creates high entry barriers for technologies that are not easily adapted to the mass production paradigm of the conventional automotive industry (Andrews et al 2006). The high entry barriers have for decades hindered the integration of alternatives to the conventional fossil fuel powered combustion engine (Orsato and Wells 2007). This has for example been the case for the light weight body materials such as aluminium, magnesium and carbon fibre that potentially could decrease the weight of the vehicles and thereby reduce fuel consumption (Christensen et al 2003) and for alternative alternative drivetrain solutions such as the battery electric or the fuel cell based.

The implementation of platform production based on modularised technologies has enabled vehicles manufacturers to increase scale in the manufacturing which is usually considered as an entry barrier for novel technology. The success of alternative drivetrain solutions is consequently reliant on whether they can be designed and produced as modules which can be produced in the conventional production system. This paper therefore aims at exploring the potential modularisation of alternative drive trains.

1.2. The environmental challenge facing the automotive industry

The automotive industry is facing a huge future challenge to reduce the environmental impact from cars. The European automotive industry is pressured by consumers who demand fuel efficient cars; the European Union legislation on fuel efficiency of newly registered cars and by national and local authorities who set up incentives for car-users to purchase cleaner and more fuel efficient cars.

The conventional mass-market vehicles that are offered to consumers are typically based on steel bodies and fitted with an internal combustion engines designed for fossil fuel consumption. The conventional combustion engine and the steel body are closely interlinked. The steel body has a high up-from weight. The high body weight cascades weight onto other systems in the car such as the suspension, crash components, fuel systems and breaking systems that need to be robust and consequently heavy in order to fit the heavy vehicle system (Lovins and Cramer 2004). The final result is a heavy car that requires a powerful propulsion system in order to meet consumer demand for peak power and acceleration. The conventional combustion engine is perfect match for that system, not because the combustion engine is efficient (in fact it is hugely inefficient), but because of the availability of cheap fossil fuel with a very high energy content (Åhman 2001).

The combination of these two technologies provides consumers with heavy cars that consume a substantial amount of fossil fuel which eventually cause climate changes and emits pollutants that lead to air quality problems in urban areas (European Environmental Agency 2007). The environmental problems are further amplified by the trend in vehicle design towards larger and heavier cars (Kågeson 2005).

The awareness of the environmental impact form car use combined with the expectation of fossil fuel supply shortage and growing scientific evidence of climate changes caused by CO2 emission (IPCC 2007) have forced vehicles manufacturers to consider how alternative technologies to the conventional combustion engine can be designed and integrated in the current production system.

A variety of different proto-type vehicles have been presented by vehicles manufacturers at auto-shows but only a small number of vehicles equipped with alternative technologies have been placed on the roads. Huge sums of money have been invested in the development of for example fuel cell powered vehicles (Hoed 2007), but the market penetration have so far been insignificant.

Researchers (Lovins and Cramer 2004, Hoed 2004) and NGO's (Kågeson 2005) therefore argue that the automotive industry has failed to renew the technological base on which new cars are developed and produced, especially within the areas of environmental performance of the cars. Lovins and Cramer (2004) argue that

> *"[A]utomaking is exhibiting all the signs of a classic overmature industry: hypercompetition over shrinking niches for convergent products in saturated core markets, global overcapacity and consolidation, cutthroat commodity pricing, modest to negative margins, stagnant basic innovation (until the mid-1990s), and limited attractiveness for recruiting top talent or strategic investment. In short, automaking, like airlines, is a great but challenged industry, ripe for fundamental change." (Lovins and Cramer 2004)*

The critique raised by Lovins and Cramer relate to the reluctance in the automotive industry to incorporate new technologies, such as alternative drive trains like fuel cell and hybrid technology, and slow implementation of alternative materials to the conventional steel body.

Research (Hoed 2007) indicates that adaptation of disruptive technologies is complicated by the economic and institutional configuration of the automotive production system.

1.3. The structure of the automotive industry

The development, deployment and diffusion of environmental technologies in the automotive industry are largely dependent on current configuration of the production system. The large scale production in the automotive industry, with economic break-even points approaching 250.000 units per car model (Orsato & Wells 2007), has enabled car manufacturers to incrementally reduce production costs and supply consumers with relatively cheep cars (compared to, for example, hand made custom cars) (Womack et al, 1990). However the mass-production system of the automotive industry also favours continued production of cars based on a steel body and a conventional combustion as large-scale investments in production equipment makes it difficult to implement new technologies that require changes to the established production processes. Andrews et al. (2006) estimates that the price of a modern vehicle assembly plant including a press shop, a welding plant, a painting shop and an assembly shop is somewhere between 390 and 665 million £. The majority of this investment is related to production equipment associated with the manufacturing (stamping, welding and painting) of the steel body. The combustion engine is usually manufactured at a separate factory also associated with very high unit numbers. Production average capacity at British engine plants was in 2005 just below 500.000 engines per year (Rhys et al. 2005). This production system has created a lock-in situation in which it is economically unattractive and technically unattainable for the vehicle manufacturers to experiment with alternative body materials and drivetrain options (Wells and Nieuwenhuis 2003).

The high volume production furthermore makes the industry vulnerable to changes in the consumer demand for cars. IHS Global Insight estimates, in a report prepared for the European Union, DG Enterprise and Industry, that the economic crisis in the autumn 2008 and followed fall in car sales in the Europe (EU 27) will cause a decrease in capacity utilisation at European vehicle assembly plants from just above 80% down to 65% during 2009 – keeping in mind that the typical profitability zone is above 80% (IHS Global Insight 2009). These figures also illustrates that the profitability of the mass production system in the automotive industry highly sensitive capacity utilisation at the assembly plants. This is a feature of the system that also adds to the lack of innovation and experimentation in the area environmental technology.

Not only that, the organisation of design, purchasing and operation also favours mass-production of cars in high unit numbers. Two commonly used interlinked production principles are especially important for the mass-production regime. *Modular production* which makes it possible for the vehicle manufacturers to reuse outsourced technologies across models and brands and the *platform production* which makes it possible increase scale in component production across models and brands. These production principles have strong implications for the organisation of the value chains and for the product design.

1.3.1. Outsourcing component design and manufacturing to suppliers

A distinct feature of the automotive production system is the high degree of component production undertaken by suppliers. Today around 75% of vehicle production (IHS Global Insight 2009) and about 50% of automotive R&D is carried out by suppliers (European Commission 2004). Vehicle manufacturers focus their activities towards a few core activities including vehicle assembly, design of complete vehicles, manufacturing of core technologies, marketing and distribution (Economist Intelligence Unit 2000) and encourage suppliers to conduct a larger share of the R&D activities (UNIDO 2003). Suppliers have achieved increasing influence on the development and production of environmental technology for modern mass-market vehicles.

The outsourcing of manufacturing and R&D activities from vehicles manufacturers to their suppliers has increased need the coordination in the value chains. Some vehicles manufacturers have tried to improve the coordination and reduce the complexity of the supply base by reducing the number of tier 1 suppliers. Chrysler, for example, had in 1986 around 3000 suppliers in the US. This number had in 1996 this had been reduced to around 950 and by 2000, this had been further reduced to around 600 (Economist Intelligence Unit 2000). The reduction in tier 1 suppliers has pushed small and medium sized suppliers upstream in the automotive value chain and created large and powerful tier 1 suppliers that operate as system integrators in the value chains.

Introduction of the modular production technique is another trend in the automotive industry, implemented parallel to outsourcing of manufacturing activities. Modularisation has been applied in order to improve the coordination of activities across companies in automotive value chain (Pandremenos et al 2009). Vehicle manufacturers aim at modularising design and manufacturing when oursourcing activities to suppliers so that components eventually can be utilised across a number of different brands and models in order to increase scale in the component manufacturing (UNIDO 2003). Components are therefore integrated into complete functional units which are developed, manufactured and pre-assembled by suppliers before they are delivered to the final vehicles assembly plants (Persson 2006b).

This way of organising activities in the automotive value chain has left responsibility for pre-assembling, logistics and coordination of upstream suppliers to large tier 1 suppliers, also referred to as system integrators (Mondragon et al 2009) or turn-key suppliers (Sturgeon and Lester 2003).

1.4. Modularisation

The modularisation of the production entails a new way of organising activities across companies. Previously, vehicle manufacturers purchased a large amount of different parts and components from a huge supply base. The components were manufactured by suppliers on the basis of detailed drawings made by the vehicles manufacturers (Womack et al 1990). The components were then assembled in to vehicles at final assembly plants (Womack et al 1990). Today a large share of these components is integrated into families of related component, called systems and modules, by the tier 1 suppliers and supplied to the vehicles manufacturers as complete functional units (Pandremenos et al 2009, Sturgeon & Lester 2003). According to Sturgeon and Lester (2003) the most important modules in the automotive industry are: suspension, doors, headliners (including components such as grip handles, lighting, wiring, sunroof, sun visors, and trim preassembled), ventilation (including heating and air-con units), seats, dashboards and finally engines (including engines, transmission and axels).

The vehicles manufacturers have, to a large extend, outsourced not only the production and assembly of these modules and systems but also responsibility for their design and development (often conducted in collaboration with the vehicles manufacturer and tier 2 and 3 suppliers) and the responsibility for the upstream logistics. This development has created a modular structure of the automotive value chain (Sturgeon & Lester 2003).

The modularisation can, from a technical perspective, be defined as the partition of a product (in this case the cars) into subsystems that constitutes complete functional units which can be designed and manufactured independently (Persson 2006b). Modularisation thus is concerned with the allocation of tasks and activities between companies in the value chain. Modularisation is likewise closely linked to the outsourcing of activities from vehicles manufacturers to suppliers (Lester and Sturgeon 2003). Initially, this takes place in relation to outsourcing of simple manufacturing tasks, but is in its more mature form related to the modular production system that includes full production and design of complete functional units by suppliers, as well as coordination of activities among lower tiered suppliers.

Persson (2006a) presents three main reasons for introducing modular production: 1) the partition of a product into independent and interchangeable functional units allows the manufacturers to economically increase product variety by enabling large scale production of relatively customised products, 2) the modularisation also increase the strategic flexibility as it enables the manufacturers to respond to changing market requirement by re-using modules across models or model generations and 3) the modularisation reduces task complexity as it enables different parts (modules) of a given product to be developed and produced in parallel tracks, as long as the standard interface between the various modules is maintained.

The modularisation occurs in different phases of vehicle life-cycle. Morris and Donnelly (2006) distinguish between two types of modularisation; *modularisation in design* where modularisation is focussed on boundaries between sub-systems of integrated components in design features and tasks, and *modularisation in manufacturing* where modularisation is related to the interchangeability and degree of sharing of functional sub-systems of integrated components across vehicle models. *Modularisation in design* appears in situations where the vehicle manufacturer has outsourced the full responsibility for the design of a given module and therefore only possesses functional knowledge about the module, which includes knowledge about functions, applications and use of a given module (Morris & Donnelly 2006). The supplier on the other hand possesses the substantive knowledge about design and manufacturing. In most cases however, the vehicle manufacturer will chose to maintain Insight into the substantive knowledge about design and manufacturing in order reduce dependency on a single supplier (Morris & Donnelly 2006). Mondragon et al (2009), for example, found that vehicles manufacturers preferred a more open and transparent collaboration between suppliers and vehicle manufacturers when analysing design of complex electronic vehicle architectures. Batchelor (2006) adds *modularity in use* to these two types of modularity (respectively modularity in design and modularity in production). *Modularity in use* comprises the product boundaries and interchangeability of elements relevant to customers on the end-market. This type of modularity is usually related to use or maintenance of the products and only requires functional knowledge about the product.

These three types of modularity together represent the functional, the process and the physical decomposition of the product. Each type of modularity is primarily related to a specific phase in the product lifecycle. However the three types of modularity interfere with one another as the degree of modularity in manufacturing, for example, obviously depends on how the product is designed. Batchelor (2006) argues that the choice of *approach* to modularity therefore depends on which strategic driver is considered to be important under the given circumstances.

This three-legged modularity typology is primarily related to the *technical* configuration of vehicle design, manufacturing and use and will henceforth be referred to as the *technical modularity*. It is mainly concerned with the technical design, manufacturing and use (related to repair and maintenance) of the vehicles. The mastering of these three types of modularity is closely related to elements of system engineering, which furthermore underpins the technical character of the typology. The issue of modularity however pertains to more than just the technical when viewed from a value chain perspective. Technical modularity is related to the concept of value chain modularity developed in the Global Value Chain approach (Sturgeon 2003) but differs in the sense that modularity, in the GVC perspective, is foremost concerned with structure of a value chain defined by the distribution of power between companies (and stakeholders) in the value chain. The technical modularity is in that respect a material condition, without which the modular value chain is most unlikely to occur.

1.4.1. Value chain modularisation

The modularisation of the automotive production chain has two interlinked dimensions: 1) The technical modularisation which is related to the technical modularisation of design, manufacturing and use, and 2) the value chain modularisation that concerns the power to coordinate, manage, control and organise activities in the value chain.

The vehicle manufacturers have historically been the dominant company in automotive value chain but the emergence of global tier 1 system integrators, supported by the outsourcing of manufacturing and design activities from vehicles manufacturers to tier 1 suppliers, has created a modularisation of the value chain structure. The modular type of value chain organisation is also a feature of other industries such as the aerospace industry and by companies in the power tooling industry (Persson 2006b). For example the design and production of cell phones is divided into subsystems such as LCD display, printed wiring board, chip, battery, cabinet etc.: each part designed independently and integrated into a complete cell phone using standardised interfaces between the different units (Andersen et al 2006).

The systems and modules are often assembled in close proximity to the final vehicle assembly plants in order to simultaneously reduce the risk of supply shortage disruption of production at the assembly plant and eliminate the need for expensive inventory at the assembly plants (Sako 2005). It is therefore common that vehicles manufacturers, as a consequence of the modular production, create supplier parks in proximity to the assembly plants where strategically important suppliers are expected to locate production facilities (Sako 2005). The modularisation of the vehicle designs enhance the need for proximity between the tier 1 pre-assembly plants and the vehicle assembly plants as the modules when assembled often become more complicated to handle and transport. The modules also accumulate value in each process step and therefore become more expensive to keep on stock. This factor also makes it more profitable to pre-assemble the modules as close to the vehicle assembly plants as possible.

The system integrators are expected by the vehicles manufacturers to engage in R&D activities and R&D competences have consequently been pushed upstream in the supply chain from the vehicle manufacturers to the system integrators. This development has to some extent shifted the bargaining power in the value chains between tier 1 suppliers and vehicles. Sofka and Zimmermann (2005) argue that one consequence of the outsourcing of module design and manufacturing is that competitors gain the opportunity to source vital technology and components in equal sophistication and quality from the system integrators . Models produced by competing vehicle manufacturers may thereby include identical technology and components. Examples of this phenomenon are the Mitsubishi Colt and the Smart ForFour, or the Porsche Cayenne and the VW Touareg (Sofka & Zimmermann 2005).

1.4.2. Different strategies to modularisation

The trend towards modularisation in the automotive industry includes a number of variants as vehicles manufacturers have implemented the production principle slightly different and with deviating intensity. Some have chosen to outsource the full production of a given module along with responsibility for upstream logistics and R&D in a black-box setting where the vehicles manufacturers are excluded from detailed knowledge about manufacturing and design of the given module. Whereas other vehicles manufacturers prefer to maintain control over design in-house or even conduct a shadow module design in order to maintain strategic control over core elements of the product development (Morris & Donnelly 2006). Batchelor (2006) argues that the Japanese vehicle manufacturers historically have been more devoted to a business model were design tasks have been outsourced to dedicated suppliers in black-box settings whereas their European and US counterparts especially in the 1990s have been have more focussed on achieving modularity in the manufacturing of the vehicles rather than achieving modularity in the design phases through outsourcing (Batchelor 2006).

In an analysis of the North American vehicle manufacturers Sturgeon and Lester (2003) found that GM and Ford, even though having outsourced large shares of the manufacturing activities, still use fairly traditional market oriented sourcing strategies. The Chrysler division in the DaimlerChrysler Group by contrast used a more consultative and relational supply chain structure (Sturgeon & Lester 2003). The Japanese vehicles manufacturers have historically had a stronger vertical integration with their tier 1 suppliers and the value chains are therefore better described as *relational* or *captive* whereas the structure of the American automotive value chains has been more *modularised* influenced by large system integrators such as Viesteon, Delphi, Johnson Controls and TRW.

1.5. Alternative drive trains

The vehicles manufacturers are, as argued above, expected to develop and market vehicles drive train solutions that are more energy efficient than the conventional fossil fuel based combustion engine.

A number of alternatives to the conventional combustion engine have been presented by vehicles manufacturers – most of which on a proto-type basis only. This following section introduce on three most promising alternatives: a) the fuel cell system, b) the hybrid drivetrain, and c) the battery electric drivetrain. It includes first of all a discussion about the differences between the various options in terms of energy efficiency and secondly a discussion that relates to the technical similarities between the various systems.

1.5.1. The technical differences between the systems

In a comparison between hydrogen fuelled PEM fuel cell based drive-train, hybrid electric drive-trains, battery electric drive train (lead/acid, NiMH or lithium battery) and internal combustion engines, Åhman (2001) found that there is a potential to double energy efficiency when using electric drive-trains compared to ICE's. Åhman (2001) found that the worst efficiency rates were provided by internal combustion engine vehicles when considering a scenario in which electricity used for battery charging and hydrogen production where generated from fossil fuels. This was mainly due to the fact that most of the energy from the fuel used in a combustion engine is turned into heat and wasted during combustion. Åhman (2001) furthermore found that a scenario where renewable sources (biomass or wind and solar or hydro power) were used to generate electricity, would make the overall efficiency of the battery electric car far better than the fuel cell driven car due to high energy loss hydrogen production and distribution (electrolysis of water into hydrogen and oxygen or by using biomass to produce hydrogen) combined with low efficiency in the fuel cell. Åhman (2001) found that 23% of the energy was lost when producing and distributing hydrogen and further 64% lost due to low efficiency in the fuel cell. The study further found that the battery electric vehicle turned out as twice as energy efficient as the fuel cell vehicle when using renewable energy to generate electricity.

A similar study by Bossel et al (2005) of the well-to-wheel efficiency of fuel cells found that the efficiency would fall below 20% if the hydrogen used in the PEMFC vehicles was produced from electrical energy generated in coal fired power plants. The poor fuel efficiency rates for hydrogen fuelled PEMFC's is confirmed by Hammerschlag & Mazza (2005) who calculated that the high losses in electrolysis, hydrogen compression and in the fuel cell, would make the hydrogen fuelled fuel cell an unattractive alternative to battery electric vehicles.

1.5.2. The similarities between the systems

The difference in performance between various alternative technologies is obviously very interesting, as it point towards the best available technology. It has therefore been assessed in numerous studies. However the technical similarities between various technologies are even more interesting due to the fact that a large number of the components used in the various drive-train solutions are actually shared. Drive trains such as the hybrid drive train, the fuel cell drive train, the battery electric drive train and the stop-start device are all based on some kind of electric application. This means that components and systems such as batteries, electric motors, inverters, generators and brake energy regeneration system are shared between these drive train options. The similarities between systems consequently make it interesting to analyse how the alternative technologies can be combined so that innovation activities is pooled and maximized across the various options. This could potentially prevent a dead end in the innovation path similar to the one the battery electric vehicle experienced in the nineties. Instead of a separate innovation path for each of the alternative drive train options a more flexible and open-ended innovation path is available to the vehicle manufacturers which eventually will enable the vehicles manufacturers to exploit spill-over's between the innovation paths of each of the alternative drivetrains.

The fuel cell vehicle basically is an electric vehicle where the battery is replaced (or combined) with a fuel cell system including a tank and a converter. The fuel cell system is thereby closely linked to the battery electric vehicle. The battery electric vehicle is also linked to the gasoline hybrid vehicle and the diesel hybrid vehicle as they share components such as electric motors, batteries and brake energy recovery components. The most critical component in the battery electric vehicle and the hybrid vehicle is the battery, of course more so for the battery electric vehicle as it is solely dependent on the battery. However a decrease in weight, recharge time or price would improve both types of drive-trains. A replacement of the nickel-metal battery, which currently is the preferred battery solution by vehicles manufacturers, with the more energy intensive lithium-ion battery could be a promising future scenario for drive trains solutions that necessitate a battery module, due to its higher energy intensity. Vehicle manufacturers such as Tesla and Fisker Coachbuild are by now ready with electric vehicles based on the lithium battery. Tesla Motors has created a division within the company that aims at selling the lithium battery technology to other niche car manufacturers (Tesla Motors 2007). The Tesla battery pack has thereafter been sold to the Norwegian electric car manufacturer Th!nk.

The introduction of a plug-in hybrid that enables the battery to be recharged directly from the electric grid would technically link the hybrid vehicle even closer to the battery electric vehicle as the plug-in option would enable hybrid vehicles to completely by-pass the combustion engine when driving shorter trips without compromising the consumer demand for vehicles with longer reach than can be provided with a pure battery electric drive train. The downside to the hybrid system is the costs of having to apply vehicles with two drivetrain options (gasoline/diesel and electric).

The hybrid vehicle is also closely technically related to the stop-start system which is offered as an option in some vehicle models produced by vehicles manufacturers such as BMW, Citroën, Fiat, Daihatsu and Mercedes. The stop-start system is an electrical application which can be applied to a gasoline or diesel combustion engine. The stop-start system turns off the engine when the vehicle is about to stop and immediately turns it back on when a gear is engaged or, if the car has an automatic transmission, when the driver release the brake. The engine thereby saves fuel and avoids noise and emissions during the stop. The hybrid system and the stop start system shares components such as starter/generator, batteries and brake energy recovery components.

1.6. Modular design of alternative drive train solutions

As the technological development progress, the balance between the benefit and loss when applying the various drive-trains may tip unexpected. A strategy that supports a wider spectrum of different interchangeable technologies therefore entails obvious benefits to the vehicles manufacturers. Such a strategy also bypasses the well-known problem of “picking the winner”. Modular design and production of alternative drivetrains is a promising way of accomplishing such a strategy. The following section illustrates four examples on how such a strategy can be implemented practice.

Example 1: Mitsubishi has developed a strategy where the modularisation of related components for electric drive trains enables the company to develop components for three drive systems simultaneously. Mitsubishi has developed an in-wheel assembled electric engine that can be applied to a battery electric vehicle, a hybrid electric vehicle or a fuel cell electric vehicle. The relation between the components is illustrated in the figure below. The figure illustrates the relation between components shared by the three types of drive trains.

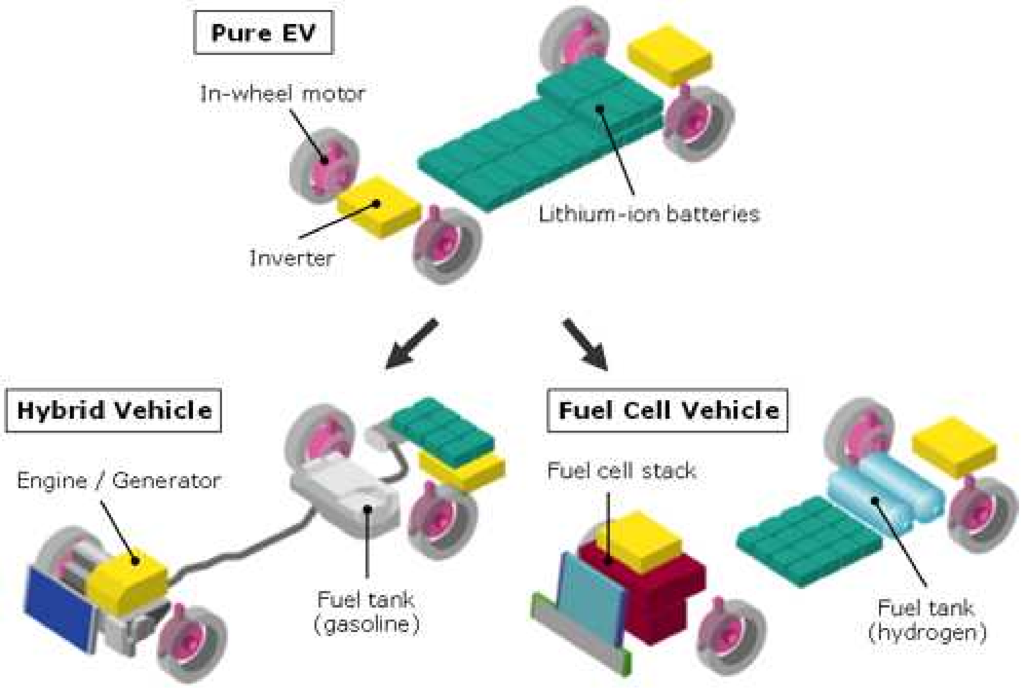


Figure: Mitsubishi Motors 2005a

The concept, which is called Mitsubishi In-wheel motor Electric Vehicle (MIEV) is based on two critical components; the lithium-ion battery and the in-wheel electric motor. Mitsubishi has launched a number of prototype vehicles based on the lithium-ion battery including Mitsubishi HEV in 1996, the FTO-EV in 1998, the Eclipse EV in 2000, the Colt EV 2005 and the Lancer Evolution MIEV 2005. The lithium-ion battery offers high specific energy, specific power and long life time compared to lead-acid or nickel-metal batteries (Mitsubishi Motors 2005a). The lithium battery therefore has a high power to weight ratio. The battery system is manufactured and supplied by GS Yuasa Corporation. The in-wheel electric motor developed by Mitsubishi enables torque and braking force on each wheel to be regulated individually. The in-wheel motor also renders complex and heavy components such as transmissions, drive shafts and differential gears unnecessary. The in-wheel motor finally releases space in the vehicle to fit in batteries or fuel cell stacks (Mitsubishi 2005a). The in-wheel motor is manufactured by the supplier Toyo Denki Seizo K.K. and has a maximum output on 50KW and has build in brakes (Mitsubishi Motors 2005b).

The Mitsubishi MiEV is scheduled to go on sale in summer 2009 in Japan and in 2010 in Europe. Mitsubishi has furthermore made an agreement with PSA which allows Peugeot to market the MiEV vehicle with a Peugeot badge in Europe (Mitsubishi 2009).

The Mitsubishi MiEV concept illustrates how the technical flexibility between alternative drivetrain options can be utilised in a design strategy for multiple engine system configurations.

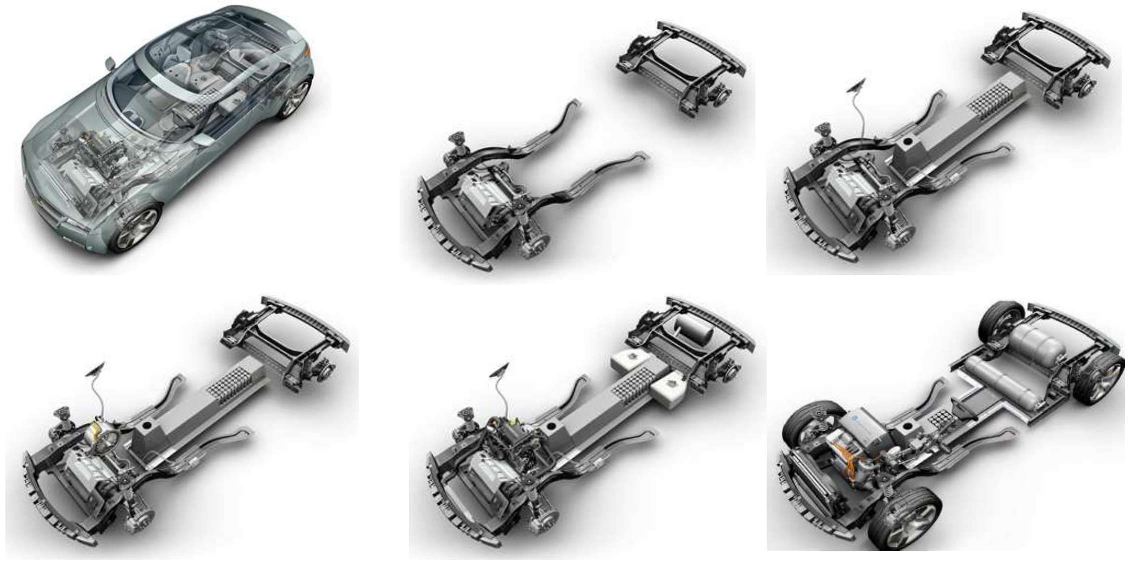
Example 2: General Motors has also experimented with a modularised vehicle concept called GM Hy-wire. The GM Hy-wire is build on the AUTOnomy concept and the vehicle is based on a 11 inch thick skateboard-like aluminium frame that contains a full fuel cell system with drive-by- wire technology. The fuel cell system produce 94 KW and the vehicle has a range of 128,75 kilometers (80 miles) while the total weight of the system is 1900 kg (GMability 2007). The GM Hy-wire is propelled by four in-wheel electric motors in the same style as the Mitsubishi MIEV. The system is modular in the sense that skateboard-like lower body can be applied to various upper body vehicles applications facilitated by the drive-by-wire technology. However the system is not modular in the sense that it allows different components and technologies to be interchanged as the technology inside the skateboard-like lower body is fixed. The concept does therefore not allow the same flexibility in terms of changing components and technologies as the Mitsubishi MIEV concept.

The GM Hy-wire illustrates an early example of a car that offers maximum flexibility to the top of the vehicle. It illustrates how the fuel cell drive train skateboard module can be utilised across multiple vehicle model configurations.

Example 3: The Chevy Volt is a concept model developed by GM and planned for production in 2010 in the US and 2011 in Europe (Barkenbus 2009). The vehicle will be manufactured at GM's Hamtramck-Detroit plant. The vehicle architecture will be based on Delta II platform also shared by Cheverolet Cruze and 2011 the Saab 9-3.

What makes the Chevy Volt stand out from other mass produced cars is its electric drivetrain. The drivetrain is developed on a platform named Voltec, formerly called the E-Flex platform, that facilitates the flexible choice between three different propulsion options: a pure battery electric option, a combined electric / combustion engine option and a combined electric / fuel cell option. The Voltec drivetrain platform is designed as a series hybrid where the wheels exclusively are driven by electric motors (AutoblogGreen 2006). The batteries can be charged from the grid or charged by internal combustion engine or a fuel cell while driving. GM has therefore chosen to refer to the drivetrain as an “extended range electric vehicle” rather than a hybrid, which is usually associated with cars that have two parallel drive trains. The system is consequently to be distinguished from the parallel hybrid system, used in vehicles like Saturn Vue and Aura, Chevy Tahoe and Toyota Prius, where the combustion engine is mechanically connected to the wheels parallel with the electric motor. The Voltec platform is intended to be used by other GM vehicles in the future as well. GM has presented a Cadillac Converj Concept vehicle also build on the Voltec drivetrain platform (GM 2009).

The Voltec platform is a flexible platform designed to allow interchangeability between three modularised subsystems. The figure below illustrates the combination of drivetrain modules.



Picture: Autoblog Green 2007

The frame and the front end across the three versions. It includes an electric motor with controls, charging and inverter mounted on top of if. The lithium ion battery, which will be supplied by Compact Power Incorporated, owned by LG Chem, is placed in the middle of the car to maximise stability while driving (Green Car Congress 2009). The battery can be charged either by an external connection to the electric grid or by en internal range extender (ICE or Fuel cell) (AutoblogGreen 2007). The version with an ICE has a small 1L turbocharged three cylinder gasoline engine fitted on top of the electric motor in the front end of the vehicle. The ICE will run a constant speed and begin recharging when battery load drops (AutoblogGreen 2007). The fuel cell version will use a slightly smaller battery but is otherwise identically to the ICE version (Yang 2008). Both versions will have the fuel (gasoline, bioethanol or hydrogen) stored in the rear end of the car.

The Chevy Volt illustrates how modularised drivetrain options can be combined to ensure a high degree of technological flexibility and thereby enable vehicles manufacturers to keep the doors open if unexpected discoveries should be made within other drivetrain options.

Example 4: The Th!nk hydrogen vehicle is based on the two seated electric city car originally developed by Ford and now produced by the independent Norwegian company TH!NK Global. The hydrogen version is technically similar to a conventional series hybrid drive train but uses a PEM fuel cell as opposed to a conventional combustion engine to recharge the batteries. The vehicle is propelled by an electric motor which is powered by a battery pack that can be recharged either from the electric grid or by the fuel cell. The pure electric version of the car has a range of 185 km but the hydrogen version extends the range of the car to approximately 300km as the hydrogen tank carries an additional energy to the battery capacity (Th!nk 2005). The TH!NK vehicle is technically modular in the sense that development and production of fuel cell application is outsourced from the Norwegian vehicle manufacturer TH!NK Global to the company H2 Logic. The substantive knowledge about the development and production of the application is possessed by H2 Logic whereas TH!NK Global only possesses functional knowledge about the fuel cell system (Christensen 2008). H2 Logic has based the fuel cell system for the TH!NK hydrogen vehicle on knowledge and know-how which has been accumulated from development of fuel cell systems for other vehicles such as the H2 Truck (Christensen 2008).

The TH!NK Global Hydrogen Vehicle is an example of how the technical modularity and value chain modularity enables new technological solutions to be designed and manufactured.

1.7. Discussion

The analysis of energy efficiency clearly indicates that the conventional combustion engine is a poor choice if the aim is to reduce energy consumption. The comparison furthermore indicates that the battery electric vehicles are more energy efficient the fuel cell option. Proponents of hydrogen vision argue that an energy system based on hydrogen and renewable energy sources such as wind, hydro power and solar energy entails huge advantages compared to conventional energy systems based on fossil fuels (Hawken et al 1999). The central idea is to use electricity from the renewable energy sources like windmill farms, photovoltaic and hydro power to produce hydrogen from water using electrolysis. When implementing hydrogen in established energy systems that have a significant proportion of wind power, the surplus electricity, generated in periods where the weather conditions makes it possible to produce more electricity than consumed, can be used to produce hydrogen from water using electrolysis processes. The hydrogen vision or the hydrogen economy is however somehow simplified as the energy system does not quite work like assumed above. Hydrogen is today mostly produced from natural gas and as such not is linked to any renewable energy source and excess wind does not generate enough electricity to fuel the transport sector. The high price of the fuel cells combined with the required fuelling infrastructure investments furthermore makes fuel cell technology less likely to be integrated in mass market vehicles in the near future.

Battery electric drivetrain have gained new momentum with novel battery technology (e.g. lithium ion battery technology) initially developed for portable devices and now being fitted into cars. Hybrid drivetrains are the most likely to lead the electrification of mass produced cars. The Japanese vehicles manufacturers Honda and Toyota have so far been the market leaders in hybrid technology. The vast majority of hybrid cars are assembled in Japan but vehicle assembly volumes of hybrid car are in the US expected to rise from only a couple of thousands in 2007 to more than 700.000 before 2014 (PricewaterHouseCoopers 2007).

The essential question regarding the future of the alternative drive train solutions is weather they can be fitted in to the conventional production system or necessitates a complete transformation of the current production system? Lovins and Cramer (2004) argue that the full potential of alternative drivetrains is unexploited unless the complete vehicle system is re-invented. They furthermore suggest that vehicle design should begin with a blank sheet and a complete vehicle system in order to maximize spill over's between subsystems instead of designing components and subsystems independently as it is the case in the modularised production system. Lovins and Cramer (2004) have a strong case but implementation of their design strategy requires a complete transformation of the established production system. Huge sunk costs in production equipment designed for production of steel based cars fitted with combustion engines

(Andrews et al 2006), makes such a transformation seem less likely to occur. A modular strategy to design and production of environmental technology seems to be a more realistic approach.

The four cases presented above illustrates that such an approach is possible. Mainly due to the fact that the electrification of the alternative drivetrain options creates a number of potential spill over's between the various solutions. The modular design of alternative drivetrains principle makes it possible to decompose the system into subsystems and units that can be designed and produces independently. The critical aspect is to ensure standardised interfaces between the modules in order to allow interchangeability of systems that in turn create flexibility for the vehicles manufacturers.

The modular design strategy is closely linked to the *modularity in production* in which functional units can be manufactured independently. The modular production system also makes it possible to outsource production and design activities to suppliers. This system has for other parts of the vehicle created system integrators (Sturgeon and Lester 2003) that coordinates production, logistics and design. The question is weather such a system is likely to occur for the drive train as well? Mondragon et al (2009) analysed technologically advanced brake-by-wire and steer-by-wire systems and found that these were developed in horizontally organised networks with a high degree of transparency between the stakeholders. Their findings thereby contest the idea of vertically disintegrated modular value chain in which a system integrator plays a vital role. The case of the Th!nk hydrogen car tells a different story but that vehicle is again developed outside the conventional mass market vehicle production system. The case of the Chevy Volt and the GM Hy-wire vehicles illustrates that modularisation is possible but only from a technical point of view as the design is still controlled by the vehicles manufacturers and not outsourced to system integrators.

The central component of all the alternative drivetrain technologies is the battery. The battery is essential for a number of reasons including price of the system, weight and vehicle performance. The battery is also the main technical bottleneck for alternative drivetrains. The battery is usually designed and manufactured by suppliers in close collaboration with the vehicles manufacturers.

1.8. Conclusion

Modularisation opens a window of opportunity for the alternative drive trains as it could potentially enable a rapid up-scaling of the production and at the same time ensure technical flexibility.

The technical modularisation of production of alternative drive trains enables vehicle manufacturers to choose a flexible development path that allows multiple solutions to be developed simultaneously and thereby allow for strategic change during development stages if the technological development takes an unexpected turn. Vehicle manufacturers that chose to concentrate activities around developing the hybrid drive trains may therefore be able to re-use components and systems such as batteries, high voltage wiring, electric motors and brake regeneration system if, for example, the development of the battery electric vehicle or the fuel cell vehicle progress faster than expected. The technical linkages between the alternative drive trains additionally allow vehicle manufacturers to benefit from technological discoveries made in competing drive trains.

The Mitsubishi concept vehicle illustrates how components for alternative drive trains can be modularised in order to enhance flexibility and ensure an open ended development path. The concept vehicle illustrates how components for battery electric vehicles, hybrid vehicles and fuel cell vehicles are related. The stop-start engine is not included in the Mitsubishi concept vehicle but could easily be integrated as it shares components with the other three systems.

The development of the plug-in hybrid vehicle with the capacity to connect to the electric grid would further link the hybrid to the battery electric vehicle. The grid connection capability is important because it significantly increases the energy-efficiency of the vehicle. Production and sale of hybrids is predicted to increase in the near future as some of biggest vehicles manufacturers have announced that they are planning to market vehicles propelled by hybrid drive trains.

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