Designing a Hybrid Car at BMW

A Case Study for The Mechanical Design Process

Introduction

In an effort to reduce CO₂ emissions and develop a distinctive electric driving experience, BMW initiated a program to develop a hybrid version of their 5-Series, high-end car. They needed to develop a concept that on the one hand realized the fuel economy potential of hybrid technology, and on the other, offered typical powertrain characteristics and drivability. Further, they wanted an architecture that would allow them flexibility to evolve more sophisticated systems, scaling from a mild-hybrid to plug-in-hybrid.

This case study focuses on the development of drivetrain for the ActiveHybrid 5, Fig. 1. BMW’s entry into the luxury hybrid market was the model Active Hybrid 6 equipped with a power split drivetrain.

This case study describes one of the tools to explore the many hybrid architectures and some of the reasoning behind the choices made for the ActiveHybrid 5. It focuses on the use of Design Decision Matrices (DSMs) and similar tools to manage the functions and components that make up a hybrid system.

**The Problem:** Develop an architecture for the ActiveHybrid 5 line of drive trains.

**The Method:** Engineers at BMW use Multiple Domain Matrix (MDM), Function Design Structure Matrices (F-DSM), Design Mapping Matrices (DMM) and Component Design Structure Matrices (C-DSM) to explore the space of hybrid architectures.

**Advantages/disadvantages:** The methods allowed the designers to derive and evaluate architectures in order to develop a new concept that best achieved the goals for the new Active Hybrid 5. It helped them to frame a solution space; study available competitors’ architectures; derive, analyze and evaluate specific solutions; and funnel the whole solution space, detailing promising concepts further.
**Background**

Traditional automobile architectures are changing. Automobile architecture, like building architecture, refers to basic ways that the functions are fulfilled by physical components and assemblies. Traditionally, automobiles have been built with an internal combustion engine (ICE) to provide power to a transmission that converts the power and delivers it to a differential that distributes the power to the wheels. The mix of functions (verbs) and components (nouns) in the previous sentence describes the traditional powertrain architecture which has remained virtually unchanged since early in the twentieth century.

BMW began to experiment with electric cars in the 1960s resulting in the BMW 1602 electric demonstrator built to move dignitaries at the 1972 Munich Olympic Games. They have undertaken periodic electric car experiments since that time and moved to serious hybrid car research and development in the 1990s. Their goal was to not only be responsive to customer interests, but to reduce CO₂ emissions and increase efficiency.

BMW began a fleet wide Efficient Dynamics strategy in 2007 to incorporate improvements in aerodynamics, rolling resistance, light weight construction, intelligent control systems and improved combustion engine technology. Part of this strategy was the addition of hybrid models with electric motors and batteries added to the traditional powertrain components. The hybrid functions and components opened up the possibility for many new architectural options and added significant complexity to the systems.

BMW was responding not only to customer demands, but also increased government standards both in the US and the EU. Cars are responsible for around 17% of emissions of CO₂ in the US and 12% in the EU. In 2007 the BMW CO₂ fleet emissions average was 158.7g/km (255 g/mile) improving to 132g/km (212 g/mile) by 2012. The EU has specified that the fleet average to be achieved by all new cars is 130 grams of CO₂ per kilometer (g/km) (209 g/mile) by 2015, 95g/km (152 g/mile) by 2020. For BMW, these targets represent reductions of 18% by 2020. In the US, the EPA will require 144g/mile (89g/km) for cars and 203g/mile (126 g/km) for light trucks by model year 2025.

As part of their Efficient Dynamics strategy, and to optimize their learning how to best evolve their current fleet using electric hybrid technology, engineering design teams within the company operated semi-independently in realizing a production family of models. Each team could explore a range of architectures. This case study focuses on the effort on the BMW 5-Series hybrid team.
Automobile architectures

For automobiles there are four broad classes of architectures:

1. ICE - Internal Combustions Engine, the traditional powertrain
2. HEV - Hybrid Electric Vehicles, where the ICE is supplemented by an electric motor and batteries. This is the focus of this case study.
3. PHEV - Plug-in Hybrid Electric Vehicles, the batteries can also be charged by plugging into the grid.
4. BEV - Battery Electric Vehicles, all electric with no ICE.

HEVs were first commercially available as an alternative to the conventional ICE powertrain in 1898 when Dr. Ferdinand Porsche developed the 'Lohner-Porsche' featuring electric hub motors. It was in production from 1900-1905.

In modern times, initial HEVs featured small electric systems that interact with the ICE. In these systems, battery charging only occurs through the ICE or regenerative braking (converting the momentum of the car to electricity by using the motor as a generator). Primary amongst these HEVs, the Toyota Prius, introduced in Japan in 1997 and worldwide in 1999, has sold over 4 million units. Prius’ were later updated to be also available as a PHEV where the batteries can be recharged from the grid. The Prius PHEV has an all-electric EPA estimated range of 13 km (11 mi). The Chevy Volt and its European cousin, the Ampera are PHEVs. As of mid 2013 they have combined global sales of over 50,000 units since their introduction in 2010.

The best selling high end BEV is the Tesla Model S. Tesla’s Roadster, introduced in 2008 and discontinued in 2012, sold about 3000 units in its lifetime. The Model S, introduced in 2012, has sold 10,000 cars by mid 2013.

The different types of architectures are compared in Table 1 using a decision matrix with HEV as the datum.

Table 1: Comparison of classes of automobile architecture

<table>
<thead>
<tr>
<th>Criteria</th>
<th>ICE</th>
<th>HEV (Reference)</th>
<th>PHEV</th>
<th>BEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Driving Range</td>
<td>NA</td>
<td>0</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Total Range</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>--</td>
</tr>
<tr>
<td>Operating costs</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Tank to Wheel Emissions</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Tank to Wheel Efficiency</td>
<td>-</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refueling Duration: Electric</td>
<td>NA</td>
<td>NA</td>
<td>-</td>
<td>--</td>
</tr>
<tr>
<td>Gasoline/Diesel</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>Vehicle Weight</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Manufacturing Costs</td>
<td>++</td>
<td>0</td>
<td>-</td>
<td>--</td>
</tr>
<tr>
<td>Commercial Risk (Battery-Tech. Maturity, Service Costs)</td>
<td>++</td>
<td>0</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Ecological Image/ Possible Perks</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Political Support</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>++</td>
</tr>
</tbody>
</table>

++ Very Advantageous; + Some Advantages; 0 Average; - Some Disadvantages; - - Many Disadvantages
HEV Major Architectures

There are many ways to configure an HEV. The 5-Series design team first defined the different modes of operation needed for a hybrid system. In the definitions below, there is an ICE, a high voltage battery for storing propulsive energy and at least one electric motor connected through a controller to the high voltage batteries. This list will be refined later in the case study.

To begin, the design team first itemized the basic HEV modes of operation:

**ICE engine Start-Stop** – The engine start-stop function is a basic function found in all hybrid vehicle concepts. As soon as the hybrid control system senses that the vehicle will come to a complete stop, for example at a traffic light, the engine will shut off to prevent idling. The ICE must be restarted quickly and smoothly by means of an electrical motor or starter-generator as soon as there is a power requirement.

**Regenerative Braking** – The term “regenerative braking” refers to capturing the braking energy that would normally be lost to friction and heat in conventional car brakes. Brake energy recuperation is achieved by using the electric traction motor as a generator that serves slow the vehicle and supply that energy to the batteries.

**Power Boost** – When the automobile requires acceleration power beyond what the ICE can deliver, the electric motor(s) provide additional torque to the wheels known as boosting. Power boosting situations also include driving on inclines or towing use cases. In this mode, the battery charge is depleted and delivered through the electric motors as an additional source power.

**Load level Increase** – Load level increase or generative mode allows the ICE to deliver some of its excess power to generate electricity for storage in the high voltage batteries. Also, since running at a more optimal setting, this increases the efficiency of the ICE itself.

**Electric Driving** – Electric driving is achieved by using electric energy stored in the high voltage battery to power an electric motor connected to the wheels. During the electric driving mode, the combustion engine is decoupled from the powertrain and in most cases shut down. Optionally, the ICE can be used to generate electricity while decoupled from the wheels.

**External Battery Charging** – External battery charging (i.e. plugging into the wall or a charging station) differentiates plug-in hybrid (PHEV) concepts from all other hybrid vehicle (HEV) concepts.

There are many architectures that can provide these modes of operation. To explore these, the engineers first defined a set of icons representing the components as shown in Fig. 2. These will be used as the potential architectures are described.
These components can be used to design many thousands of different systems. Useful architectures can be organized in a tree structure (Fig. 3) with the six branches described in detail below.

Figure 2: The components used in an HEV

Figure 3: Major HEV architecture classification

A “parallel HEV” maintains a mechanical linkage between the internal combustion engine and the wheels, the electric motor supports the ICE (which is still the primary method of propulsion). Thus, the ICE and the electric motor run “in parallel.” Parallel hybrids offer the broadest range of architectural configurations. There are over 4000 different configurations of major components in parallel HEV using the methods discussed in the next section.
The simplest HEV uses the parallel – single clutch architecture, Figs. 4(a) and 4(b). Here, if there is no power to the electric motor, the car’s drive train operates in a traditional manner. Add power to the electric motor from the batteries and then both the ICE and electric motor power the wheels. Fig 4(a) is typical of mild hybrid systems such as the Honda Insight and the BMW Active Hybrid 7 that are designed to start and assist the ICE, but are not designed for electric only driving. Systems such as shown in Fig 4(b) can open the clutch to operate as an electric car, but require a separate electric motor system to start the ICE. One advantage of this configuration is the possibility to uncouple both transmission and ICE and thus reduce drag torque to maximize energy recovery during regenerative braking.

The parallel – double clutch, Fig 4(c), is similar to the prior example, except there is a second clutch between the electric motor and the transmission. By uncoupling the transmission, the ICE can drive the motor as a generator to recharge the battery. In some double clutch designs, the electric motor can also serve as a starter for the ICE. This is the system that ended up being used in the ActiveHybrid 5. More details on it will be developed in the next section.

The parallel – motor post transmission, Fig 4(d) uses the electric motor to directly power the drive train without use of the transmission. This configuration facilitates keeping existing motor-transmission conventional placement intact and adding the electric motor component outside of already established modules.

A “series HEV” completely severs the mechanical link between the ICE and the wheels. Rather, the engine serves only to produce electricity.
The pure "series" configuration, Fig. 5(a) is where the ICE and an electric motor/generator system are in series with each other. Here, all the power produced by the ICE is converted to electricity and the car is essentially an electric car. Fisker’s Karma brought this architecture to mass production in 2012 and coined the term Electric Range Extended Vehicle (EREV) to emphasize it always drives the wheels electrically.

The "power split" architecture made popular by the Toyota Prius, Fig. 5(b), uses a planetary gear to channel the ICE produced energy between driving the wheels mechanically and generating electricity. In the diagram, the ICE is connected to the planetary’s planet carrier, “C”; a motor/generator is connected to the sun, “S”; and the second motor/generator connected to the drive shaft to the ring gear, “R”. Here a varying part of the ICE power is transferred mechanically to the wheels with the rest converted to electricity and transferred electrically. This architecture enables the car to operate the ICE at optimal efficiency. The driver may recognize driving conditions in which the ICE has a constant engine speed, but the car continues to accelerate.

Some vehicles use systems that are a mix between series and parallel architectures and are referred to as “combined”. In Fig 5(c) the system can be run as a pure series or a parallel HEV by simply adding a coupling component. While there are no commercially produced combined hybrids, there are several concept cars that have combined hybrid architectures. The series mode is used for the long distance electric driving and the parallel mode is used for when the battery is depleted.

Finally, other variations of hybrids exist. Fig 5(d) shows a diagram of a two-mode power split hybrid used in the BMW Active Hybrid X6. The combination of four clutches, three planet gears and two electric motors allow for various control strategies for a variety of power delivery combinations to the drive train. This hybrid drive also allows for uncoupled electric motor use for charging the batteries, brake energy recuperation and uncoupled starting of the ICE.
BMW Series 5 Down-Select

Based on their knowledge of the Active Hybrid 7 series and other HEV systems, the engineers needed to choose an architecture and refine it. Their major considerations were:

- **Needed electric only driving pattern**
  HEVs can be designed so that: 1) the vehicle is only assisted by the electric motor but not for pure electric driving (known as a ‘mild hybrid’ – such as the Honda Insight), 2) the vehicle can drive electric for short distances of a few miles for inner-city speeds and accelerations (known as a ‘full hybrid’ – such as the Ford Escape), or for managing typical distances such as the daily commute to work by pure electric drive (in this case a ‘Plug-in hybrid’ is required – such as the Chevrolet Volt). The team decided to take the middle ground and design a system that can run a few miles on pure electric and be categorized as a full hybrid, but not require external charging.

- **Ability to integrate in existing systems**
  The 6-cylinder N55 turbocharged direct injection straight-6 DOHC ICE with the 8-speed automatic transmission is the basis of the ActiveHybrid 5. The aim was to make all necessary adaptations in this well known package for integration of the electric motor. The engineers decided to stick closely to the mature and reliable transmission and fit the electrical motor in the space of the conventional torque converter within the transmission.

- **Easy ICE start-up capability**
  The design team placed extra emphasis on a smooth transition between electric driving and combined ‘engine plus motor’ modes of operation to ensure optimal electric vehicle performance. Excellent comfort and response characteristics during start of the combustion engine were also an area of focus. To achieve this, a belt driven starter unit connects to the combustion engine powered separately by a 12V battery with the main function of ICE start up. This ensures that the vehicle can start from rest in pure electric driving mode, and then comfortably start-up and couple in the ICE when power demands require it.

- **Platform for future development**
  The lithium-ion battery (developed and produced in-house), the power electronics and the electric motor result in an electric powertrain system which is connected via the electronics of the combustion engine to give one harmonious unit. This can serve as a basis for future development.

The Active Hybrid 5 design team chose a parallel, double clutch system (Fig 4(c)) as the one that best met the requirements. It was shown to be the most affordable solution.
with the greatest customer benefits. It is comparably cost effective to produce, since it has the least modification to the existing system and has just one electric motor that could integrate within the transmission module of the vehicle, in line with the engine. Further, it is a good platform for future development with its modular architecture.

A more detailed diagram of the system is in Fig. 6. Here:

- \( K_0 \) = Separating clutch between the ICE and transmission (AT) and the integrated electric motor (EM)
- IAE = Integrated start-up element
- EME = High-voltage power electronics with integrated control unit
- DC/DC = Voltage converter 317V – 12V
- SGR = 12V Starter unit in the belt drive
- EPS = Electric power-steering pump
- ELUP = Electric pump for brake servo

![Figure 6: Layout of the Series-5 Hybrid](image)

The design of the Active Hybrid 5 had to decouple several conventional subsystems normally tied directly to the ICE through belt systems to make them operate electrically since the combustion engine does not power the drive train during electric driving. The pump for the brake servo, the power-steering and air conditioning systems are examples of these architecture deviations from conventional ICE cars that are normally tied by belt systems that run directly from an ‘always on’ ICE. By creating electrically driven subcomponents, the functionality of these systems continue to remain on-line when the ICE is shut off completely but the vehicle continues to run in electric mode.

Note that the system has a high voltage and low voltage system. The high voltage batteries (an Lithium-Ion Battery) power the motor, the control unit and the air
conditioning system that is needed by both the batteries and the interior cockpit. The control unit (labeled as EME in Fig. 6) also has a DC/DC converter to interface with the conventional low voltage components and electronics.

The double clutch configuration allows the car to decouple the ICE from the electric motor by leaving the K0 clutch open when driving in electric only mode or during brake energy recuperation. It also allows for the electric motor to decouple from the transmission and be used as a generator for the high voltage system (317v) using engine power when the car is stationary and the controller senses the battery is depleted.

When battery power is available, an electric start from rest is always preferred by the hybrid control unit, delivering the highest traction motor torque almost instantaneously to the wheels. This is achieved by leaving the K0 clutch open and closing the integrated starting element (IAE) clutch. In this coupling configuration the electric motor and high voltage battery powers the vehicle.

When additional power beyond that of the electric motor is required, the belt driven starter generator (SGR) starts the combustion engine (the belt is depicted in the diagram as the thick line on the left connecting the ICE and the SGR). This SGR is found standard in all 5 series and delivers the motor start-stop function, along with some minor recharging of the 12V system - like in most so called 'micro' hybrids. Keeping the same engine and SGR package from the conventional 5-Series was selected over adding a second electric motor. This decision was key for capitalizing on production economies of scale.

Fig. 7 shows the transmission with the electric motor.

![Figure 7: The 8P70H transmission with the Electric Motor.](image)

In the next section we further explore how the engineers detailed this configuration.
The Multiple Domain Matrix

The goal of this section is to demonstrate one of the tools used to explore the functional and component relationships – the architecture of the system. What is presented here is a greatly simplified version of what was considered at BMW.

During the development of the Active Hybrid 5, engineers studied existing HEV architectures. The Active Hybrid X6 was BMW’s first hybrid car to go into production (2008) featuring a highly capable, yet very complex ‘two-mode’ power split hybrid architecture developed in cooperation with GM and Mercedes Benz, Fig. 5(d). The X6 saw small production volumes and its development formed the basis for further hybrid development.

The Active Hybrid X6 was followed by the Active Hybrid 7 series that entered production in 2009 and was fully designed at BMW. The Active Hybrid 7 series architecture moved away from the complexity of the X6, focusing primarily on the basic hybrid system functionality of a mild hybrid Fig 4(a).

In developing the Active Hybrid 5, developers wanted the simplicity of the Active Hybrid 7, but with the powertrain flexibility offered by the Active Hybrid X6. The development team turned to the Multiple Domain Matrix (MDM) tool to help map the fundamental relationships amongst and between hybrid functions and components. The tool helped in analysis of architectures in a standardized way, in what already was a large field of design possibilities. The MDM is built from a Functional Design Structural Matrix (F-DSM), a Design Mapping Matrix (DMM) and a Component Design Structure Matrix (C-DSM).

The first step is to fully understand the relationships among the functions using a Functional Design Structural Matrix (F-DSM). The detailed functions for a single clutch parallel architecture hybrid are shown in Fig. 8. The architecture can be visualized in Fig. 4a. Each function was entered into the rows and columns of a Design Structure Matrix (DSM) and the inputs and output dependencies where noted with a “1” as shown in Fig. 9.

<table>
<thead>
<tr>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Store Fuel</td>
</tr>
<tr>
<td>2 Store Electric Energy</td>
</tr>
<tr>
<td>3 Convert Fuel into Mechanical Energy</td>
</tr>
<tr>
<td>4 Convert Mechanical into Electrical Energy</td>
</tr>
<tr>
<td>5 Convert Electrical into Mechanical Energy</td>
</tr>
<tr>
<td>6 Deliver (Recover) torque to (from) wheels</td>
</tr>
<tr>
<td>7 Convert Moment transferred (mechanical)</td>
</tr>
<tr>
<td>8 Equate Rotation</td>
</tr>
<tr>
<td>9 Couple/Uncouple Moment</td>
</tr>
<tr>
<td>10 Release Energy as Heat to the Environment</td>
</tr>
<tr>
<td>11 Transfer Heat (to Cooling system)</td>
</tr>
<tr>
<td>12 Transfer Moment to (from) the road</td>
</tr>
<tr>
<td>13 Slow or Stop Vehicle (recovering energy)</td>
</tr>
<tr>
<td>14 Slow or Stop Vehicle (using friction)</td>
</tr>
<tr>
<td>15 Control Energy Flow</td>
</tr>
<tr>
<td>16 Consume El. Energy for Auto Accessory OPS</td>
</tr>
<tr>
<td>17 Consume Mech. Energy for Engine Accessory</td>
</tr>
</tbody>
</table>

Figure 8 Functions identified for components of an Integrated Motor Assist HEV.
Figure 9 Functions identified for the Active Hybrid 7 series architecture.

To make the best use of the functional DSM in designing architecture, it can be expanded into a DMM (Design Mapping Matrix). This allows the development of the components and their relationship with the functions. The “components” may be systems or individual parts.

The DMM maps components to functions. In some cases this may be 1-to-1 and the DMM will result in a square matrix, but this is not usually the case as some functions require many components and some components provide many functions. Fig. 11 is a DMM for the active hybrid 7 series. The functions head the columns, and the components the rows.
Note that the 'E Motor/Generator1, component # 21, serves multiple functions. It can ‘convert mechanical to electrical energy’ when in generative mode, ‘convert electrical into mechanical energy’ when working as a motor, and can be used to ‘slow or stop the vehicle’. Additionally, the motor releases heat to a cooling system. Looking at the cooling function in column 11 we see that components 19, 20, 21 and 28 all require cooling.

Finally, the engineers used a Components Design Structure Matrix (C-DSM) to determine the final configuration of components shown in Fig. 12. The C-DSM has the components in both the rows and the columns. It is used to help understand the physical connection between components. Since there is no sense of one component preceding another, the C-DSM is symmetrical. For example, the Fuel Tank must be physically connected to the internal combustion engine and vise-versa. The location of the “1”s gives a good indication of potential component architecture.
The F-DSM, the DMM and the C-DSM can all be put together as a platform for making architecture decisions often called the Multiple Domain Matrix (MDM). Fig.13 shows all the pieces together, with the DMM updated to the DSM reordering. It has been assumed here that function #9, Sense Torque Need, is part of the controller. It is easy now to manage the architecture, add additional functions or components, and group functions within components.

For example, the function “convert fuel in mechanical energy” (performed by the ICE) is depicted in the middle node as taking inputs from the function “store fuel” (function of the fuel tank) to provide an output to the function “convert mechanical energy to electrical energy” (performed by the electric motor). The usage of fuel by the ICE can only occur in one direction. Other components such as the electric motor display a bi-directional energy flow in converting from mechanical energy to electrical energy and vice versa.

The value of the MDM vehicle architecture representation between the components and functions domain lies in the systematic determination of differences and similarities of various structural configurations.
Conclusions

There are many hybrid drive architectures that can be used in a high performance car of today. DSM and MDM diagrams enabled exploration of this solution space. The methods used and the resulting system both offer platforms for future developments and architecture evolution.

Links


C. Luttermann et.al, The Full-Hybrid Powertrain of the New BMW Active Hybrid 5, Aachen colloquium China, BMW Group, 2011


Author
This case study was written by David G. Ullman, Emeritus Professor of Mechanical Design from Oregon State University and author of The Mechanical Engineering Process, 5th edition, McGraw Hill. He has been a designer of transportation and medical systems and holds five patents. More details on Professor Ullman can be found at www.davidullman.com. In writing this case study he was assisted by Carlos Gorbea and Andreas Kain.