TECHNISCHE UNIVERSITÄT MÜNCHEN
Lehrstuhl für Produktentwicklung

Vehicle Architecture and Lifecycle Cost Analysis In a New Age of Architectural Competition

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Vollständiger Abdruck der von der Fakultät für Maschinenwesen der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktor-Ingenieurs

genehmigten Dissertation

Vorsitzender: Univ.-Prof. Kristina Shea, PhD

Prüfer der Dissertation:
1. Univ.-Prof. Dr.-Ing. Udo Lindemann
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Massachusetts Institute of Technology/USA

Die Dissertation wurde am 08.02.2011 bei der Technischen Universität München eingereicht und durch die Fakultät für Maschinenwesen am 08.07.2011 angenommen.

Bibliografische Information der Deutschen Nationalbibliothek
Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über
http://dnb.d-nb.de abrufbar.

ISBN 978-3-8439-0458-2

Sternstr. 18, 80538 München
Tel.: 089/66060798
www.dr.hut-verlag.de

1. Auflage 2012

EDITOR'S FOREWORD

Automotive product development is experiencing an exciting moment in its history. As this work goes to print, several major automakers have launched their first mass produced plug-in hybrid and electric vehicles. These car concepts have been under intense development over the last decade, the hybrid market has become more competed and innovation has become a key differentiating factor amongst manufacturers. The risks coupled with innovation can partially be mitigated by a robust and adaptable product development process. Both process and cycle adaptability can translate into increased product flexibility without losing sight of the initial design goals and above all, the customer.

More functionality, additional components, and more interfaces make the complexity of modern automotive design a true challenge to manage. Despite breakthroughs in making vehicle structures lighter, the hunger for product features has steadily added components and driven the overall vehicle weight to new highs in modern cars. Most of the hybrid electric drives discussed in this work add significant weight and cost in components. Careful study of these additions is necessary to determine whether they add or detract value to the end customer.

The field of complexity management in product development has found emphasis in our Institute of Product Development over the last years. As the challenges of improving multidisciplinary product development evolve, this work adds new insights on how to address complexity issues by means of modeling and life cycle use case analysis.

One of the most prominent contributions to research and industry provided in this book is the indication that a new age of architectural competition has begun. Product architecture has gained equal or greater importance to that of traditional evolutionary development of component technology. Tools such as system dynamics modeling of vehicle architecture market adoption or the matrix based configuration of hybrid and electric cars are useful aids to analyzing and generating options for future product development.

Finally, this work demonstrates how lifecycle cost models can be introduced early on in the development process to aid with architecture decision making. Cost comparisons between various electrification scenarios to a reference conventional vehicle help in filtering out dominated solutions in a systematic way. The results from this study indicate that the automotive industry has not come near exploring the thousands of possible hybrid and electric vehicle configurations possible for production. The take away is simple; there is ample opportunity for further architectural innovation.

Garching, May 2012

Prof. Dr.-Ing. Udo Lindemann

Institute of Product Development
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ACKNOWLEDGEMENTS

This work was written during my tenure as both a doctoral researcher at BMW Group AG from September 2006 until September 2009 and as a scientific research assistant at the Institute of Product Development at the Technische Universität München (TUM) from November 2006 until June 2011.

I am greatly thankful for the mentorship provided by my doctoral advisor, Prof. Dr.-Ing. Udo Lindemann. He not only was an avid listener of my ideas, but one that would pose challenging observations that continually refined my work throughout the years. I am particularly grateful for his candid inclusion of me as a regular doctoral candidate in his research institute with access to international conferences, teaching opportunities, courses and self-development, despite my external work commitment to the BMW research and innovation center.

I want to thank Professor Olivier L. de Weck for having encouraged me to continue my academic path to a doctoral degree in Germany while still an MBA student at MIT. I am honored for his assuming the role as my second thesis advisor and grateful for his intense review and insightful comments that helped shape this improved final publication. I also want to thank Prof. Kristina Shea for accepting to chair the examination board and for the organizational handling of the dissertation process.

I want to give special thanks to Dr. Ernst Fricke who served as my mentor at BMW and introduced me to the world of automotive systems engineering. It was he who placed me in contact with Prof. Lindemann at the TUM and helped develop my early academic papers. I want to thank all my colleagues from BMW's Future Vehicle Architecture group (EG-22 Zukünftige Gesamtfahrzeugarchitektur), especially the future hybrids team for the successful and positive collaboration in the many projects and research. At BMW I had the pleasure to interact with a great mix of highly professional industry veterans as well as a young team of hybrid vehicle engineers. I cannot name all, but I want to thank my friends and colleagues Uwe Seitz, Michael Reger, Thomas Busch, Alfred Dick, Andreas Rucker, Andreas Egger, Dr. Jens Kohl, Juergen Kammerer, Markus Lehmann, Johann Maidl, Dr. Andreas Penka, Soenke Richter, Dennis Simon, Dirk Weiler, Phillip Wilde, Andreas Wilde, Dr. Luc Felgen, Vahid Salehi-Douzloo, and Dr. Michael Boeckl.

Special mention and thanks go to my student assistants. At BMW, I had the pleasure to team up with the MIT Germany program that provided me with the talents of Gavin Cotter and Tina Srivastava, brilliant assistants who greatly aided in my research. The close relationship between TUM and BMW facilitated Tobias Spielmanleitner, Johannes Labutis and Markus Steinhauer to become key student contributors to this work for which I am very grateful.

I want to thank all my colleagues at the Institute of Product Development that largely contributed to my research results. Andreas Kain was the first reviewer of my work and was instrumental in helping me polish my writing. David Hellenbrand introduced me to his ideas on compatibility matrices. Frank Deubzer, Dr. Maik Maurer, Dr. Matthias Kreimeyer and

Wieland Biedermann were helpful in discussions relating to Multiple Domain Matrices. I want to thank Frank Hoisl, Stefan Langer, Manuela Paravan, Dr. Markus Petermann, Dr. Thomas Meiwald, Delia Illie, Christoph Ertelt, Martin Graebsch, Dr. Birgit Dick, Bergen Helms, Katharina Helten, Stefan Wölkl, Robert Orawski, Fatos Elezi, Torsten Metzler, Dr. Markus Mörtl, Clemens Hepperle, Sebastian Kortler, Florian Behnke, Arne Herberg, Alexander Reik, Sebastian Schenkl, Bernd Schröer, Dr. Julia Roelofsen, Dr. Stefanie Zirkler, Dr. Wolfgang Lauer, Dr. Andreas Gaag, Dr. Michael Filious, Thomas Gmeiner, Charalampos Daniilidis, Amir Hooshmand, Rune Jorgensen, Maximilian Kissel, Dr. Thomas Anton, Dr. Josef Ponn all who made my time at the TUM special in many ways. For those I left out, I apologize but please know that your interaction was always well received and I am extremely grateful to have shared my doctoral studies with you. It was this group that triggered many discussions and provided important feedback that helped me finish this work to earn my doctoral title.

Throughout my academic experience at the TUM, I came in contact with two academic organizations, the Design Society and the American Society of Mechanical Engineers. I participated in several conferences through the generous sponsorship of the Institute of Product Development, the BMW Group and the TUM Graduate School. These conferences brought me in contact with the leading minds in the field of engineering including Tyson Browning and Steven Eppinger with whom I was able to contribute ideas from this thesis in their book *Design Structure Matrix Method and Application,* Cambridge, MA: MIT Press, 2012.

Another source of inspiration in my thoughts on complex systems was my work with the US Army Reserves. This included an enlightening academic experience at the Command and General Staff College- Intermediate Level Education schooling in 2008, along with command of Bravo Company, 457^{th} Civil Affairs Battalion from June 2007 until February 2012. I am grateful for the support my military friends and colleagues provided during this enriching academic experience. Special mention goes to the soldiers of B/457^{th} CA BN; LTC Christopher Varhola, PhD; LTC Lawrence Tubbs; MAJ (Ret.) Phil Margeta Cacace, PhD and especially LTC Anita Becker who generously volunteered to serve as editor of selected chapters.

Most importantly, this work would have not been possible without the continuous support from my wife Andrea Hermann, who always encouraged me in my work and offered patience and comprehension in stressful times. I want to also thank my son Rafael, whose birth was filled with joy and was a catalyst to complete this academic journey. Finally, I am very grateful to my German and Puerto Rican families. The extraordinary love, permanent support and prayers offered me the stamina to reach this goal in my life– thank you, I love you all!

Böblingen, May 2012 Carlos Enrique Gorbea Díaz

The following publications are part of the work presented in this thesis:

Gorbea, C.; Fricke, E.; Lindemann, U.: Pre-Selection of Hybrid Electric Vehicle Architectures during the Initial Design Phase. In: Lindemann, U. et al. (Eds.): 9th International DSM Conference, Munich, 16.-18.10.2008. Aachen: Shaker 2007, p. 225-234. ISBN: 978-3-8322-6641-7.

Gorbea, C.; Fricke, E.; Lindemann, U.: The Design of Future Cars in a New Age of Architectural Competition, ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE. Brooklyn, New York, 3-6 August 2008.

Gorbea, C.; Fricke, E.; Lindemann, U.: Life Cycle Cost Modeling of Hybrid Vehicles during Early Product Architecture Development, ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE. San Diego, CA, 30 August - 2 September 2009.

Gorbea, C.; Lindemann, U.; Fricke, E.: Innovation and Vehicle Architecture Development in a New Age of Architectural Competition, International Conference in Engineering Design. Palo Alto, CA, 24-27 August 2009.

Gorbea, C.; Spielmannleitner, T.; Lindemann, U.; Fricke, E.: Analysis of Hybrid Vehicle Architectures Using Multiple Domain Matrices. In: Kreimeyer, M. et al. (Eds.): 10th International DSM Conference, Stockholm, 11.-12.11.2008. Munich: Hansa 2008, p. 375-387. ISBN: 978-3-446-41825-7.

Gorbea, C.; Hellenbrand, D.; Srivastava, T.; Biedermann, W.; Lindemann, U.: Compatibility Matrix Methodology Applied to the Identification of Vehicle Architectures and Design Requirements. Design Society, 11th International Design Conference-DESIGN 2010, Dubrovnik, Croatia May 17-20, 2010.

Gorbea, C., Lindemann, U., de Weck, O. L.: System Dynamics Modeling of New Vehicle Architecture Adoption. Design Society, International Conference in Engineering Design. Technical University of Denmark, Copenhagen, 15-18 August 2011.

ABSTRACT

Vehicle Architecture and Lifecycle Cost Analysis in a New Age of Architectural Competition.

Today's automotive market is facing a new age of architectural competition where the dominance of the internal combustion engine car is being challenged for the first time in over a century. Two key focus areas are presented in this work. The first is a thorough understanding of vehicle architecture, using a novel application of matrix based working methodologies. The second considers the importance of assessing future lifecycle costs within the early phases of product planning. This work contributes various models that analyze: (1) adoption of new vehicle architectures, (2.) vehicle architecture structure identification, and (3.) Lifecycle cost modeling of hybrid and electric car concepts. These models along with research on architectural change are intended to support developers in making early product development decisions regarding future vehicle architectures.

Analyse der Fahrzeugarchitektur und Lebenszykluskosten in einem neuen Zeitalter architektonischen Wettbewerbs

Der heutige Automobilmarkt steht an der Schwelle einer neuen Ära architektonischen Wettbewerbs, wo die Vorherrschaft des Verbrennungsmotors das erste Mal in einem Jahrhundert in Frage gestellt wird. In dieser Arbeit werden zwei Hauptbereiche vorgestellt. Der erste betrifft das genaue Verständnis von Fahrzeugarchitektur, indem eine neuartige Anwendung einer Matrix-basierten Arbeitsmethode verwendet wird. Der zweite Bereich bezieht sich darauf, die zukünftigen Lebenszykluskosten bereits in der Frühphase der Produktplanung einzuschätzen. Diese Arbeit stellt verschiedene Modelle zur Analyse vor: (1) Akzeptanz neuer Fahrzeugarchitekturen, (2) Strukturidentifizierung neuer Fahrzeug-architekturen, und (3) Lebenszykluskostenmodelle hybrider und elektrischer Fahrzeugkonzepte. Diese Modelle in Verbindung mit Forschungsarbeit zum Architekturwandel zielen darauf ab, Entwickler bereits in der Frühphase bei Entscheidungen in der Produktentwicklung zu unterstützen.

CONTENTS

List of Abbreviations

AC	Alternating Current
ACEA	European Automobile Manufacturers Association (Association des Constructeurs Européens d'Automobiles)
ASM	Asynchronous Motors
AT-PZEV	Advanced Technology - Partial Zero Emission Vehicle (US state of California term for HEV and CNG vehicles)
AT-PZEV+	Advanced Technology - Partial Zero Emission Vehicle Plus (US state of California term for PHEV and hydrogen ICE vehicles)
BCG	Boston Consulting Group
BEV	Battery Electric Vehicle (Electric Car)
BEV100	Battery Electric Vehicle with 100 miles (160km) of electric range
BGR	German Federal Institute for Geosciences and Natural Resources (Bundesanstalt fuer Geowissenschaften und Rohstoffe)
BLDC	Brushless Direct Current Motors
BTL	Biomass to Liquid
CARB	California Air Resources Board
CI	Compression Ignition Engine - Diesel powered engine
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO2	Carbon Dioxide
COO	Costs of Ownership and Operation
ΔCOO	Delta Cost of Ownership - the difference in cost of ownership between a particular vehicle architecture and a reference vehicle
CVT	Continuously Variable Transmission
DC	Direct Current
DME	Di-Methyl Ether
DMM	Domain Mapping Matrix
DOD	Percentage "Depth of Discharge" for the High Voltage Battery
DOE	Degree of Electrification (Pel/Ptot) - see section 4.2.1 also referred to as Electrical Index
DOT	US Department of Transportation
DSM	Design Structure Matrix or Dependency Structure Matrix
ECcity	Electric Consumption City
EChighway	Electric Consumption Highway
ECU	Electronic Control Unit
ECVT	Electric Continuously Variable Transmission (using planet gears)
E-Drive	Electric Driving
EHPS	Electro-Hydraulic Power Steering
EIA	US Energy Information Agency

EM	Electric Motor
E-Motor	Electric Motor
EPA	US Environmental Protection Agency
EPS	Electric Power Steering
ERF	Electric Range Fraction - for a PHEV the electric range while in charge depleting mode
EU	European Union
EV	Electric Vehicle
FCcity	Fuel Consumption City
FCEV	Fuel Cell Electric Vehicle
FChighway	Fuel Consumption Highway
FEA	Finite Element Analysis - simulation methodology
FHTA	US Federal Highway and Transportation Administration
FMEA	Failure Mode and Effects Analysis - Quality Assurance methodology
FT	Fischer-Tropsch process for synthetic fuels (e.g. FT Gasoline)
FTP72	US City dynamometer testing cycle to test fuel consumption and emissions
GDP	Gross Domestic Product
GHG	Green House Gasses
GLG	Gerson Lehrman Group
GM	General Motors
H2ICV	Hydrogen Internal Combustion Vehicle (US state of California term for Hydrogen ICE cars)
HC	Hydrocarbon
HEV	Hybrid Electric Vehicle (Hybrid Car)
HFC	Hydrofluorocarbons
HiL	Hardware in the Loop - simulation methodology
HoQ	House of Quality - Methodology similar to QFD
HSM	Hybrid Synchronous Motors
HVB	High Voltage Battery
HWFET	US Highway Fuel Economy Test - test cycle to determine highway fuel consumption conducted using a dynamometer
ICE	Internal Combustion Engine
IEA	International Energy Agency
IPCC	International Panel on Climate Change (United Nations)
KMH	Kilometers Per Hour
LCC	Lifecycle Costs
Li-ion	Lithium Ion Battery
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MDM	Multiple Domain Matrix
ΔMDM	Delta Multiple Domain Matrix resulting from the subtraction by fields of two MDMs
∑MDM	Sum MDM or Sigma MDM - results from the summation by fields of two or more MDMs
MfC	Manufacturing Cost
MPG	Miles per Gallon (1 liter per 100km = 235.21MPG)
MPGe	Miles per Gallon equivalent

MPH	Miles Per Hour
MSA	Motor Start Automatic - Function in Microhybrids that prevents the ICE to idle for extended periods of time (also known as start and stop function)
MSRP	Manufacturer's Suggested Retail Price
NEDC	New European Driving Cycle - European dynamometer test cycle to determine fuel consumption and emission values
NHTS	US Nationwide Household Transportation Survey
NiMH	Nickel Metal Hydrate Battery
NOAA	US National Oceanographic and Atmospheric Administration
NOx	Nitrousoxides
NREL	National Renewable Energy Laboratory (US Department of Energy)
OC	Overhead Cost
OCV	Open Current Voltage
OEM	Original Equipment Manufacturer
OICA	International Organization of Motor Vehicle Manufacturers (Organisation Internationale des Constructeurs d'Automobiles)
P/E	Power to Energy Ratio
Pel	Electric system peak power (Electric motor peak power)
PERT/CPM	Program Evaluation Review Technique / Critical Path Method
PFC	perfluorocarbons
Pfuel	Price of Fuel
PHEV	Plug-in Hybrid Electric Vehicle
PHEV10	Plug-in Hybrid Electric Vehicle with 10 miles (16km) of electric range
PHEV20	Plug-in Hybrid Electric Vehicle with 20 miles (32km) of electric range
PHEV30	Plug-in Hybrid Electric Vehicle with 30 miles (48km) of electric range
PHEV40	Plug-in Hybrid Electric Vehicle with 40 miles (64km) of electric range
PPM	Parts per million
PPMV	Parts per million
PSAT	Powertrain Simulation Advanced Toolkit - Program
PSM	Permanent Magnet Synchronous Motors
Ptot	Total Power including electric and ICE peak power
PZEV	Partial Zero Emission Vehicle (US state of California term for Conventional Vehicles that meet low emissions standards)
QFD	Quality Function Deployment
R&D	Research and Development
RCD	Range charge depleting - for a sPHEV this is the distance traveled where the vehicle operates using only the Electric Motor in an all electric mode (ICE is off - battery system's charge is depleted)
RCS	Range charge sustaining - for a sPHEV this is the distance traveled where the vehicle operates using both the ICE and Electric Motor
RE	Range Extender (ICE and EM module for sPHEVs)
RPM	Revolutions Per Minute
SI	Spark Ignition Engine - Gasoline powered engine
SOC	State of Charge

sPHEV	Series Plug-in Hybrid Electric Vehicle
sPHEV50	Series Plug-in Hybrid Electric Vehicle with 50 miles (80km) of electric range
SULEV	Super Ultra Low Emission Vehicle - US state of California category for cars that require less than 0.062 g/km of HC+Nox, 0.006 g/km Particulate Matter and 1.3 g/km Carbon Monoxide (CO)
SUV	Sport Utility Vehicle
Sys Viz	Computer program for complex system visualization
TRIZ	cross-disciplinary generic methodology for product development
TTR	Through the Road
UDDS	Urban Dynamometer Driving Schedule - US test cycle to determine city fuel consumption using a dynamometer
UN	United Nations
US	United States of America
US06	US Regulatory Cycle used for fuel efficiency testing - US06 is a highway cycle conducted using a dynamometer
VAT	Value Added Tax
VDI	Association of German Engineers (Verein Deutscher Ingenieure)
VDT	Vehicle Distance Travelled Annually
WBCSD	World Business Council for Sustainable Development
WTW	Well to Wheels
ZEBRA	Molten Salt Batteries
ZEV	Zero Emission Vehicle (US State of California term that includes BEVs and FCEVs)

1 Introduction

Our automotive world is facing fundamental change in regard to basic car architecture and understanding this phenomenon is key to forecasting what types of architectures should be viable in the market year 2020 and beyond. Vehicle architecture, analogous to building architecture, refers to the interaction of form and function within the basic car structure and its subsystems. For example, the powertrain in the cars we drive today has seen significant changes in both form and function since the earliest cars were developed. Comparatively, the principles and architecture of the internal combustion engine (ICE) design that has dominated the market since the mid 1930s has remained relatively unchanged [UTTERBACK 1996, p.32]. Since then, only incremental changes were made to the ICE architecture to bring us the performance improvements drivers enjoy today. The evidence that conditions leading to so-called "architecture lock-in" are swiftly changing is the emergence of new vehicle architectures that can be seen in the market today, such as hybrid and electric cars..

The market for electric mobility is wide open for growth. At this early stage no single firm has the definitive solution for the right way to build a hybrid or electric car. Many issues are still pending, such as mastering design of the high-voltage battery and control systems at the heart of the electric powertrain design. Projecting beyond the system boundaries of cars today, the industry is researching possibilities that could enable integration of electric cars with the public electric grid management system. The interactions and requirements for a vehicle-to-grid interface are being developed now. Additionally, customers have not yet discovered their own sense of what they need or want from an electric or hybrid car in terms of features or functions. The conditions are at a very young stage of development as the first cars of these types come to market. All stakeholders in this process are intensely watching and learning as electric mobility takes to the road.

The motivation for the work presented here is to examine the factors that led to the changes the industry is presently experiencing and to examine in detail what architecture alternatives can be available for the future. Two key focus areas are presented in this work. The first is a thorough understanding of vehicle architecture using a novel application of matrix-based working methodologies. The second considers the importance of assessing future lifecycle costs within the early phases of product planning. Various working models are presented to address: (1) adoption of new vehicle architectures; (2) vehicle architecture structure identification; and, (3) lifecycle cost modeling of hybrid and electric car concepts. These models along with research on boundary conditions affecting architectural change are intended to help developers make early planning decisions for a market that has not yet been fully defined.

This introductory chapter presents the current situation in the automotive industry. Section 1.1 provides a general overview of several "catalysts" that are bringing about change to vehicle architecture. Section 1.2, presents a roadmap of "energy pathways" beginning with primary energy sources and moving to the various "vehicle architecture pathways." Finally, section 1.3 outlines the goals and structure of this work.

1.1 The Automotive Industry after More than a Century

The automotive industry is vital to our modern world. It amounts to more than 5% of the world's manufacturing capacity, with more than 9 million workers employed directly by auto manufacturers and tier 1 suppliers, and many millions more indirectly [OICA 2009]. More than 60 million vehicles (cars and trucks) are produced annually using nearly half of the world's annual output of rubber, 25% of its glass and 15% of its steel. This accounts for roughly 10% of GDP in the world's developed countries [ECONOMIST 2004].

This powerful industry is recovering from its worst economic crisis in history. Automakers in the traditional markets of North America, Japan and Europe are experiencing the effects of a recession that started in late 2008 and continued into 2010. The crisis is not merely financial. It is pushing the industry towards an innovation breakthrough in order to offer affordable mobility with reduced environmental impact or other negative externalities. The present situation provides opportunity for the creation of new hybrid and electric vehicle architectures.

Some important factors inducing this market change are highlighted below:

- Financial market cycles
- Shift in customer demand to cars with improved fuel economy
- Oil availability and price fluctuation
- Increased global competition in Asian growth markets
- Stricter government regulations throughout the industry's top markets

Financial market cycles - At the end of 2008, the global financial credit crisis effectively slammed the brakes on auto sales in Europe, Japan and the United States. According to Reuters figures, by the first quarter of 2009 the top three automakers, Toyota, General Motors and Volkswagen, reported sales figures of -46%, -47% and -11% from the previous year respectively. The industry as a whole was at a dire -43% in sales despite offering generous rebates and car discounts [PLUNKETT 2008]. Even in growth markets in China and India, where more vehicles were produced and sold by the end of 2009 than in Europe for the first time ever, growth has slowed during the recession period [GOMES 2009]. Globally, the trend for 2010 for the number of vehicles manufactured still remains 12% lower than in 2008 [OICA 2010].

> ***Catalyst for Change:*** *Financial market cycles such as the 2008 global financial crash translated into deep losses for the auto industry and generated a need to develop improved ways to produce and sell cars maintaining profitable margins. New technologies that generate sales or new segments are welcome in this market.*

Shift in customer demand - With sales dropping, major manufacturing firms filing for bankruptcy protection, and most other automakers looking for ways to conserve cash or procure government funding, the consumer's needs are also changing. In the US and European markets, financing is tight and demand for cars is shifting to smaller, more affordable, fuel-efficient cars [VASILASH 2008]. Using the US market as an example, Figure 1-1 shows how the customer demand of trucks versus cars has evolved from 1980 to 2009. Trucks (and Sport Utility vehicles - SUVs) clearly grew in popularity from 1990 to 2004 displacing a once 80% market share held by passenger cars.

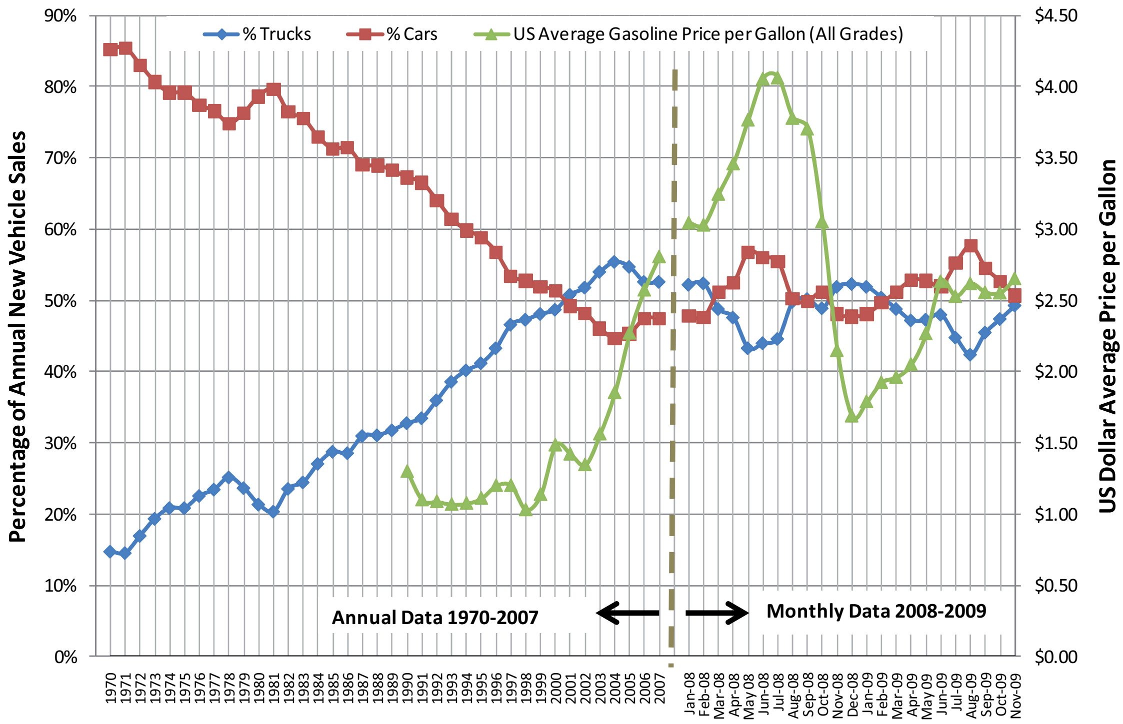

Figure 1-1 Percentage of annual new trucks and cars sales in the United States. Data from DoE Transportation Energy Data Book, Ed 26-2007, Table 4.6 [DAVIS et al. 2007] and [AUTODATA 2009] – Avg. price of gasoline taken from Energy Information Agency [EIA 2009b]

The rise of the SUV came at an alarming pace of 10% market share every five years. This seemingly constant trend had most automakers in the United States placing large product volumes to fill the SUV/truck market well into 2010. However, from 2004 to 2009 a sudden rise in oil prices reversed this trend; making gas-guzzling SUVs too expensive to own. The more fuel-efficient passenger cars subsequently gained demand, showing how quickly customer needs can change and how sensitive purchase decisions are in relation to fuel-price fluctuations.

Catalyst for Change: *Consumer demand in the US, Europe and Asia is shifting to smaller, affordable light-duty cars with better fuel economy.*

Oil price fluctuation – The oil price spike shown in Figure 1-1that peaked in June 2008 had similar effects in the European and Asian markets. The world price per barrel of oil topped an unprecedented $150 [IEO 2009] at that time. Even adjusting for inflation, the peak price per barrel in 2008 topped the "oil shocks" of the 1970s. The rapid price increase generated uncertainty in the market as to what the future price of fuel would be both in the short and long runs. Even though prices have eased considerably, the psychological effect felt by consumers remains and they worry that prices can suddenly affect their lifestyle. This inhibition has new-car buyers focusing on fuel consumption as one of the top purchase criteria within the premium vehicle segments. Not surprisingly, the top passenger car sales volumes in Europe for 2008 and 2009 went to small, fuel efficient cars consisting of 45% of sales [ACEA 2009a].

Catalyst for Change: *The world oil price fluctuation in the summer of 2008 and speculation that oil demand will outstrip supply and push petrol prices at the pump higher has consumers and manufacturers looking for alternatives to petrol-based cars.*

Increased competition – In the early 1980s, globalization brought the western auto industry new opportunities for sales in developing markets in Asia. Now after roughly three decades of increasing world trade, established auto markets in the United States, Japan and Europe are experiencing hard competition from once developing markets in Korea, China and India. In Europe, competition in the small-car segment has witnessed historically low base sale prices (as low as 5000 €) [ACEA 2009a].

In India, automaker Tata made history in 2008 announcing the sale of its "no-frills" two-seater car, called the "Nano," (see Figure 1-2) for a record retail price of roughly $2500, along

Figure 1-2 The record low priced $2500 Tata Nano [TATA MOTORS 2009]

with export plans to the US and Europe [Hagel et al. 2009]. The Nano, dubbed the "world's cheapest car" and the "people's car,," has to tackle some quality issues before expanding to the global market, but, there is no doubt that it has already gained the attention of other manufacturers as well as the international press. The Nano is already available in India and known for its innovative modular kit design and business model. The car is specifically designed for distribution "in "part kits" that can be assembled in rural areas through third-party authorized auto shops. This allows for opening new markets outside conventional city centers.

Asian import cars, notably from Korea, have made their way into the higher priced premium segments. European incumbents in these spaces are subsequently pushed into even higher cost segments within the entire vehicle-class market spectrum. Ultimately, a highly competitive premium market is now hard pressed for customers willing to pay luxury car prices. The key to survival in the premium segment now more than ever is differentiation through technological breakthroughs.

> ***Catalyst for Change:*** *Globalization has brought car manufacturing to every corner of the globe. Manufacturers in developing economies are now competing globally and the commoditizing of cars has grown stronger. Incumbent and niche OEMs are seeking differentiation through technology leading to breakthroughs in new car architectures.*

Government regulations – Governments have become key stakeholders in advocating for change in emissions generated by transportation. Globally, more than 806 million cars and light-duty trucks were driven in 2007; growth projections indicate this figure should surpass the one billion mark by 2020 [Plunkett 2008]. Given this increased vehicle availability, the magnitude of personal transportation contributions to oil consumption and green house gas (GHG) production is and will remain significant. For governments in leading automotive markets, sourcing transportation fuel has become a sustainability issue. Tradeoffs between supplying scarce fuel resources to power world economies versus personal mobility will be a relevant choice for world leaders in the near future.

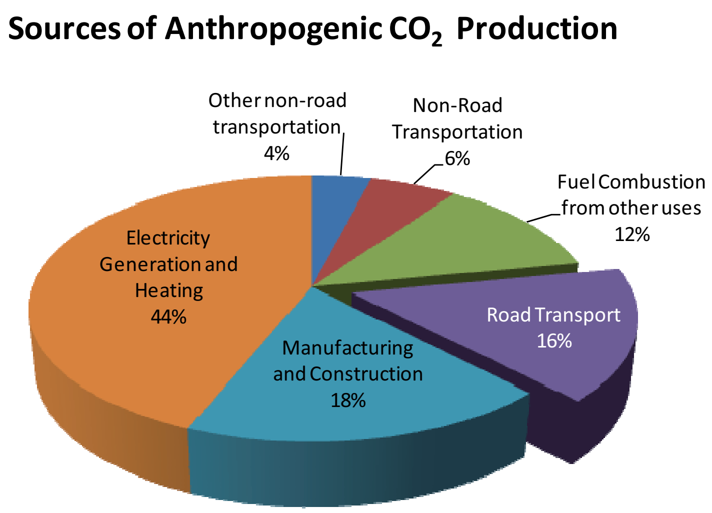

Figure 1-3 Worldwide breakdown of CO_2 emissions [according to OICA 2009]

Concerns of the environmental impacts of GHG emissions from transportation have gained importance. The need to reduce the advancing rate of global warming and the protection of local air purity are focal points for legislators. Although personal transportation makes up only 16% of CO_2 emissions worldwide (see Figure 1-3), governments view emission reduction in new car fleets as a path to reduced oil consumption for transportation and an individual commitment to environmental awareness. As a result, the auto industry has been mandated to reduce emissions of new car fleets significantly within the next decade.

> ***Catalyst for Change:*** *Worldwide concern for global warming has led governments in leading economies to heavily regulate automotive CO_2 emissions and seek to reduce oil consumption for transportation. Achieving the emission targets within these regulations can only be achieved through the implementation of new car architectures.*

Technological advances in the auto industry are well underway to ensure a brighter future. A number of architectural innovations such as hybrid and electric cars have made their way out of the labs and taken front stage at leading auto shows and trade fairs [WISSMANN 2007]. These new cars are referred to as *alternative fuel vehicles* as they provide substitute solutions to the conventional oil centric propulsion systems that currently dominate the market.

1.2 Vehicle Architecture Classification and Future Pathways

V*ehicle architecture* refers to the linkage of functions and components in a particular configuration to meet a desired set of functional goals or requirements. Understanding that the car is a complex system consisting of multiple component subsystems, three types of overarching vehicle architecture classifications exist based on the car's propulsion system dependence on external energy sources: monovalent, bivalent and multivalent architectures.

- **Monovalent Architectures** - Cars that exhibit a propulsion system dependent on one external energy source. Most cars today are monovalent cars that use an internal combustion engine with a one liquid fuel such as gasoline or diesel. Hybrid cars that exhibit a secondary internal fuel source in form of a high voltage battery are also referred to be monovalent, as the car remains dependant on one external fuel source.
- **Bivalent Architectures -** Cars that exhibit a propulsion system with two external energy sources. An example of a bivalent car, or fuel flexible car, is a plug-in hybrid electric car where two external energy sources are transferred and stored within the vehicle – electricity and fuel.
- **Multivalent Architectures -** Vehicle architectures that exhibit a propulsion system with more than two external energy sources. These cars are designed to obtain and store three or more sources of energy. An example of such a system is the Fiat Siena Tetra fuel designed to run on gasoline, E-20 to 25 blends, pure ethanol (E100) or as a bi-fuel with natural gas (CNG) [AGÊNCIA AUTOINFORME 2006].

Advances in vehicle architecture are expected to evolve through various lines of development, otherwise known as "pathways." The fuel pathways shown in Figure 1-4 present how energy is transformed from primary sources to a variety of energy carriers (fuels). In turn, architecture pathways carry onto monovalent, bivalent or multivalent powertrain configurations that are designed to use the various fuels available for propulsion.

Primary Energy Sources - Primary energy sources include fossil fuels, nuclear, biomass and renewable sources. At the moment, fossil fuels are used as an input source of energy for making all other energy carriers, whereas renewable energy and nuclear sources are used exclusively in the production of electricity. As governments look for ways to reduce their dependency on fossil fuels and reduce the CO_2 emissions footprint of cars, the electric transportation pathway is being favored. The biomass alternative has been effective in countries that have the land and resources available. Methanol and ethanol blends are created from biomass for standalone production or to mix with diesel fuel (such as in biodiesel). Biomass can also be used to produce compressed natural gas (CNG), liquefied petrol gas (LPG) or hydrogen. Countries like Brazil have been successful in developing a biomass infrastructure used to support an alternative vehicle auto industry.

Energy Carriers – Years of research and development have gone into developing "cleaner fuels" and experimenting with developing varying stoichiometric mixtures of hydrocarbons [HEYWOOD 1988, pp.64-69]. In addition to the ubiquitous gasoline and diesel fuels derived from crude oil widely available around the world, liquid fuel compositions of similar content can be developed using the Fischer-Tropsch (FT) chemical process [WALTZ 2008]. In the near future, this FT process can be used in creating diesel from natural gas ("gas-to-liquid") - FT gasoline or naphtha is another possibility. Although these FT fuels are not expected to become mainstream products, research might lead to use of other feedstocks, such as coal or biomass, to generate fuel blends at larger scales as substitutes for gasoline or diesel [WBCSD 2004, p.13].

Biofuels are blends of gasoline or diesel with alcohol-based liquid fuels produced from biomass. Examples of ethanol biofuels are designated by the letter““E”along with the percent of ethanol blended in. For instance, E85 is a blend of 85% ethanol and 15% conventional gasoline [INDERWILDI et al. 2009]. A known problem with biofuels is the competition for use of farm lands for fuel versus food production. New methods of producing “advanced” biofuels are being researched that decouple their production from that of food. Two such methods are the conversion of lignocellulosic material to fuel components via the use of enzymes and biomass gasification followed by a FT process, also known as biomass to liquid (BTL) [AHMED S. et al. 1999, SUDIRO et al. 2008]. The latter process can use a range of biomass feedstocks from agricultural or municipal waste. Successful scaling of these processes can reduce the price of biomass-sourced fuels to the levels of common gasoline and diesel fuel [YACOBUCCI et al. 2007].

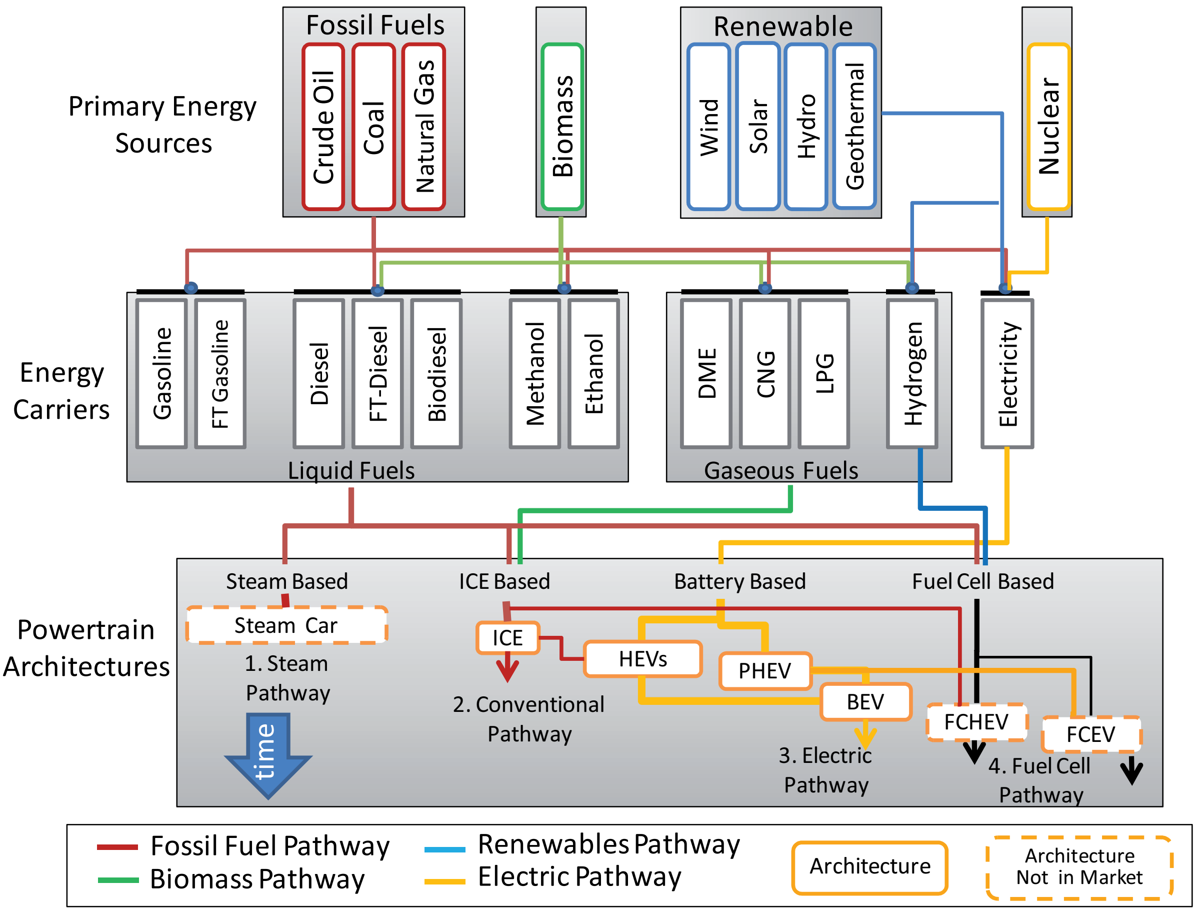

Figure 1-4 Energy to vehicle powertrain architecture pathways

Investment in adequate delivery infrastructure is the biggest barrier to mainstream adoption for most fuels that cannot be used as blend components such as compressed natural gas (CNG), dimethyl ether (DME), liquefied petroleum gas (LPG) and Hydrogen. Of these fuels, only LPG is expected to generate enough demand to attract a viable infrastructure. LPG is comparable to gasoline with the added benefit of producing lower conventional pollutants [WBCSD 2004, p.14]. LPG is expected to remain a niche product within major markets as use is limited but still growing and fueling points are relatively inexpensive to install.

Hydrogen has the benefit of offering zero tail pipe emissions. However, current production of hydrogen based on steam methane reforming of natural gas results in higher emissions than most other fuels when the entire production and delivery CO_2 emissions are considered [LEE et al. 2009, p.4243]. An alternative Hydrogen production method is from electrolysis. The energy required in separating hydrogen and oxygen in water molecules is larger than the amount of energy released in burning the produced hydrogen fuel [LEE et al. 2009, p.4249]. Electrolysis is also not a carbon neutral process and depends on the primary energy sources used in generating the electricity used. However, when hydrogen is produced with electricity stemming from nuclear or renewable energy sources the fuel takes on close to no CO_2 footprint [STUBINITZKY 2009, p.77].

Perhaps the most difficult problem hydrogen fuel faces is the inability to contain the fuel for large periods of time [ACEVES et al. 2006, p.2274]. The hydrogen molecule is small enough to find its way out of a solid fuel container after several weeks. Test cases with the Hydrogen 7 series vehicle from BMW have shown that if a car is filled with hydrogen and parked at rest for an extended period of time, a substantial amount of the fuel will dissipate and be lost [TALBOT 2007, p.82]. Technology advances in hydrogen production, distribution and storage will be necessary for successful broad commercialization.

Finally, electricity as an energy carrier has the advantage of having multiple sources of production from primary sources. Electricity enjoys the advantage of having a well established distribution infrastructure in most developed countries. Due to its wide availability and flexibility, it can directly compete with widely available fuel carriers such as gasoline and diesel for transportation purposes. The greatest limitations for using electricity for personal transportation is the lack of battery-based car architecture offerings with considerable energy

Table 1-1 Energy carrier comparisons – based on research findings presented in this section

Energy Carriers	Vehicle Technology Availability	Commenrcial Infrastructure	Safety	Refueling Time	Storage Capability	Energy Requirements to Produce	GHG Well to Tank Emissions
Gasoline	+	+	o	+	+	+	-
Diesel	+	+	o	+	+	+	-
FT - Gasoline	+	- - -	o	+	+	- - -	- -
FT - Diesel	+	- - -	o	+	+	- - -	- -
Bio Diesel	+	-	o	+	+	o	+
Methanol	o	o	o	+	+	-	+
Ethanol	o	o	o	+	+	-	+
DME	o	- -	o	o	-	o	-
CNG	o	- -	o	o	-	+	-
LPG	o	o	o	+	-	+	-
Hydrogen	- -	- -	- -	-	- -	-	- - / o
Electricity	-	+	o	- -	-	- / o	- - / +

Fully Capable	Capable	Some limitations	very limited
+	o	-	- -

density storage capability that can compete with petrol-based cars.

Table 1-1 provides a comparison summary of the energy carriers based on the author's qualitative assessment. Vehicle technology is commercially available for most fuels with the notable exception of hydrogen fuel cells and electric car technologies now in development. The commercial infrastructure for transportation is available only for the leading liquid fuels and, of course, electricity is widely available in most countries. Hydrogen is the only fuel with safety limitations as its highly reactive small molecule size is hard to contain. For refueling time and storage capability, liquid fuels are most practical with gaseous fuels and batteries showing considerable limitations. The energy used to produce each fuel and the "well to tank"[1] emissions are based on a joint industry study for Europe [CHOUDHURY et al. 2004, p.14]. In these last two categories the assessment particularly on electricity and hydrogen depend on whether the fuel is produced using renewable energy; the better assessments assume the use of renewable energy.

Powertrain Architectures – Four general powertrain architecture pathways are known to date. These include steam, internal combustion engine, battery, and fuel cell based architectures with multiple combinations thereof.

Steam based (pathway #1 in Figure 1-4) architectures, that once dominated the early automotive market from approximately 1790 to 1906, have not seen successful commercialization at a large scale ever since. Attempts have been made to combine the early steam concepts with other architectures such as a steam-hybrid electric car, or in using internal combustion engine exhaust gasses to generate steam [PHENIX 2006, p.22]. The BMW turbo-steamer project developed a proof of concept that could use the combustion engine exhaust gasses to generate steam and use the excess energy to boost the car's torque by 10%, but at a weight increase of 220 lbs. Arguably, the overall vehicle efficiency of steam, steam-electric and ICE-steam combinations lie below that of traditional cars today.

Gasoline-powered spark ignition (SI) engines and diesel-powered compression ignition (CI) (pathway #2 in Figure 1-4) internal combustion engine (ICE) types are well known alternatives. Other combustion engine alternatives for cars, such as turbine engines, have also been studied but have failed to meet the equivalent performance in fuel consumption to SI and CI engines [HARMON 1992, p.58]. The biggest opportunity in bettering ICE architecture performance in the future seems to be in the development of CO_2-neutral synthetic fuels [SUDIRO et al. 2008, p.13].

Battery electric powertrains (pathway #3 in Figure 1-4) are now gaining favor as environmental demands for the reduction of exhaust gasses in transportation have become a leading issue. Hybrid electric vehicles (HEVs) represent the first commercially available alternative to the conventional ICE. Initial hybrids feature small electric systems that assist the internal combustion engine in delivering power to the wheels. These first successful

[1] Well to Tank GHG emissions include the extraction, production, transportation and delivery of the fuel to the point of distribution to the tank of the car. The tail-pipe emissions produced by the car itself are referred to as "tank to wheel" emissions. The analysis of the entire GHG emissions for a fuel/vehicle architecture pathway is referred to as a "well to wheels" analysis.

hybrid models are expected to lead the way for larger battery electric architectures that feature external battery charging, as in the case of plug-in hybrid electric vehicles (PHEV). Battery electric vehicles (BEV) will gain importance for city driving and short commuting customer use cases [KING 2007, p.35]. The large advantage of the battery based architecture pathway is the ability to reduce tailpipe emissions and gained flexibility in selecting less CO_2 emission intensive production of electricity from primary energy sources. The greatest limitation to battery-based architecture is the battery itself. Improvement in battery life, energy density limitations and costs are key factors to making the battery-based pathway a success [LACHE et al. 2008, p.13].

Finally, the fuel cell architecture (pathway #4 in Figure 1-4) is considered to be several decades away from development [BROWN 2007, p.36]. The first commercial fuel cell vehicles are expected to combine a large battery electric system and a fuel cell range extender with the ability to chemically convert fuel into electricity to be used in powering electric motors. Fuel cell powertrains may feature hydrogen as a fuel or a variety of liquid fuel carriers such as methanol.

1.3 Research Thesis and Objectives

The last section established the breadth of research activities focused on improving the "pathways" from primary energy sources to vehicle architectures. This section outlines the areas of concentration and the research goals of this work.

Situation

- Many leading products with a standardized product architecture achieve dominance in their market only to lose their leading position due to the unforseen emergence of new product architectures
- The lifecycle costs of new product architectures are rarely understood early in the development phase, making it hard to determine the cost-benefit proposition of new products
- The case of automobiles can be used to analyze both emerging product architectures and lifecycle costs as they enter the market to compete with long established ICE product architecture

Research Thesis

- Early analysis of changing conditions, product architecture and lifecycle cost estimation during the initial stages of new vehicle product development can reveal architectural innovations that can lead to improvements and emerging market opportunities

Research Objectives

- Taking hybrid electric vehicle architectures as an example, explore the research thesis by means of:
  - An analysis of conditions affecting vehicle architectural change (Chapters 2-3)
  - Vehicle architecture analysis using a methodical approach (Chapters 4-5)
  - Estimation of life cycle costs for new vehicle architectures (Chapter 6)
  - Methodical pre-selection of vehicle architectures considering the points above (Chapter 7)

Figure 1-5 Situation, research thesis and objectives

Central to the situation, thesis and objectives highlighted above in Figure 1-5 is the definition of vehicle architecture and the role of architectural competition in the automotive industry. Also important to this work is the exploration of lifecycle costs of product architecture alternatives. These costs are rarely understood at the earliest design stages where key design decisions are required.

The numbers of functions encompassed in a car have steadily increased as cars have evolved [NEGELE, HERBERT et al. 1999]. Developing the right car for a customer base today is a systems engineering problem that entails several lines of development for the many vehicle subsystems. The intent of this work is to provide methodologies that can help systems engineers analyze vehicle architecture and incorporate lifecycle cost estimates to vehicle architecture decisions during the earliest planning stages.

Emphasis is placed in analyzing the spectrum of architectures within the "electric pathway" stemming from the conventional ICE powertrains to the various levels of electrification, including HEVs, PHEVs and BEVs.

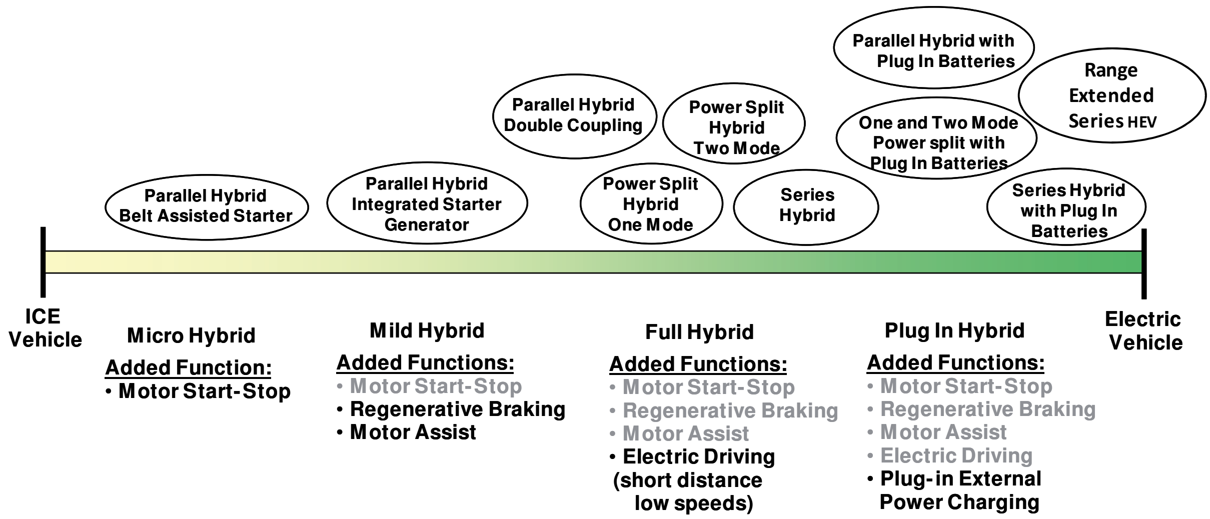

Figure 1-6 The spectrum of vehicle architectures for the electric pathway is the focus of this work

Figure 1-6 shows selected hybrid architectures within the ICE to BEV spectrum ordered by the degree of electrification based on established concept categories of micro, mild, full and plug-in hybrids. These categories are defined by the added functions that the hybrid car architectures offer. The architecture bubbles cover a wide area in the spectrum due to varying functional capabilities of product offerings within a category. For example, a number of micro-hybrids that exhibit the motor start-stop function along with limited regenerative braking are already available in the market today. The placement of such an architecture in the spectrum presented above would lie somewhere between a micro- and a mild-hybrid. A more thorough discussion of vehicle architecture functional classification is found in section 4.2.1.

1.4 Thesis Structure Overview

A brief introduction to each chapter is provided in this section. The structure of this work is presented in Figure 1-7 as a useful guide for the reader. Each chapter topic is presented with a task and purpose that supports the research goals outlined in section 1.3.

Chapter 2 introduces the term "vehicle architecture" building on multiple referenced definitions of product and system architecture. The chapter serves as a literature review of technology and innovation s-curve theory and applies its principles to vehicle architecture in a novel way to explain the term “architectural competition.” The s-curve framework is central in determining how transitions in powertrain architectures occur and what implications or hypotheses can be stated.

Chapter 3 describes the factors and boundary conditions to the vehicle architectural change already introduced. The purpose of this section is a detailed discussion to understand the complexity involved in transitioning from conventional internal combustion engine cars to new hybrid and electric vehicle architectures. At the end of chapter 3 an original system dynamics model for the adoption of new vehicle architectures is presented.

Chapter 4 provides a literature review on system architecture fundamentals and methodologies. The purpose is to develop an understanding of established system architecture principles and present the wide typology of hybrid vehicle architecture structures. The chapter culminates by presenting a methodology for pre-selection of hybrid vehicle architectures used in the final chapter’s “evaluation case study.”

Chapter 5 starts with a literature review on matrix based methods including the design structure matrix (DSM) and the multiple domain matrix (MDM). A novel application is developed for the analysis of dependencies within vehicle architecture’s function and components. Research contributions in this chapter include the use of “sigma (or sum) MDMs” and “delta MDMs” to collect information necessary for a case-based synthesis of new architectures using “compatibility matrices.”

Chapter 6 explains lifecycle costs theory and presents a model for estimating costs differences of new architectures compared to a reference ICE architecture. The model uses various established methodologies in the field of cost engineering to estimate the manufacturer and user costs in a variety of scenarios. The purpose of this chapter is to show how lifecycle costs estimates can be generated early on in the development process despite the uncertainty that is inherent in this development phase.

Chapter 7 rounds up the research contributions from chapters 5-7 in a practical evaluation case study based on the pre-selection of a future urban vehicle architectures. The example uses the tools developed in chapters 4-6, including matrix-based tools, lifecycle cost estimation and optimization.

Chapter 8 presents this work’s contributions to both research and industry. The research outlook section identifies related promising areas of study requiring further development.

Finally, Chapter 9 provides an appendix with useful data generated and used in this work.

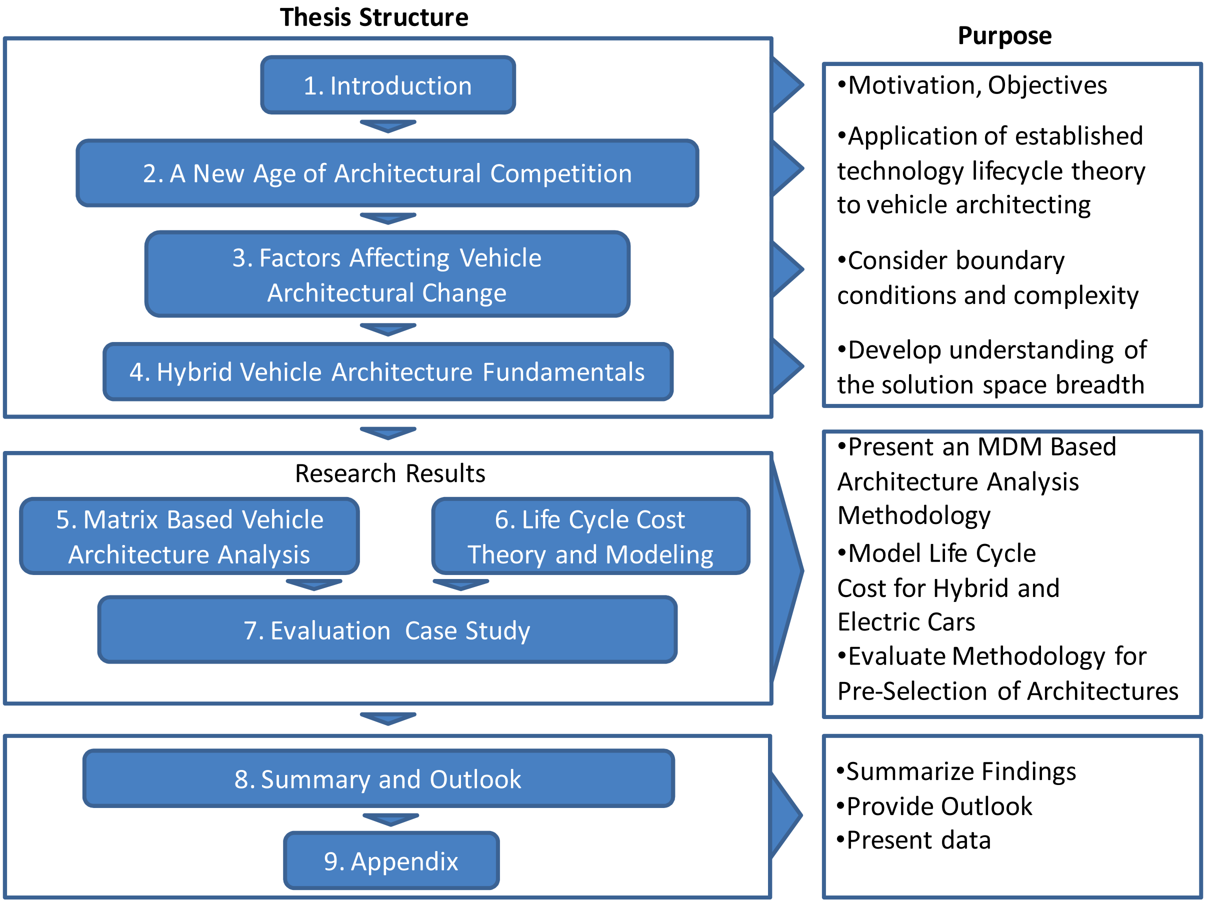

Figure 1-7 Thesis structural overview

2 A New Age of Architectural Competition

Yesterday's automotive innovations have become today's innovation challenge and some of tomorrow's more progressive ideas. This chapter presents how complex system architecture lifecycles, such as those of cars, follow an S-curve shaped path much like that of individual technological innovations. By applying technology innovation lifecycle theory to vehicle architecture, it is shown that today's automotive industry has started a new chapter of "architectural competition" with similarities to its early history from 1885-1915 when steam, electric and internal combustion engine cars were competing to dominate the automotive market.

Taking a historical perspective, firms that organize their development activities to focus on bringing about architectural innovation are better placed in succeeding in the future market until a new dominant vehicle architecture(s) emerges. Depicting architectural performance over time helps identify periods of architecture competition and dominance where historical agents to change can be identified.

The research contributions in this chapter include an empirical Lifecycle S-curve for vehicle architectures and a discussion on what implications architectural competition presents to the future automotive industry.

2.1 Literature Review

The present conditions in the automotive industry share striking similarities with the era of architectural innovation of the early 1900's. As an initial step in determining which car architectures will be best suited for the future, it is important to understand the history that has brought us up to this point. Then as is now, firms that develop methodical ways to achieve architectural innovation will have the greatest competitive advantage in the future market.

First, some basic definitions in section 2.1.1 will develop a clear understanding of what is meant by the terms vehicle architecture, architectural competition, incremental innovation and architectural innovation. The definitions are followed by an introduction to innovation lifecycle theory in section 2.2, including a historic representation of vehicle architecture performance. These results are then used to develop an understanding of the current challenges facing automakers as they look to compete on architecture in section 2.3.

2.1.1 Vehicle Architecture

Product architecture is defined by as "the scheme by which a function of a product is allocated to its physical components" [ULRICH, K. T. 1995, p.420]. Pahl and Beitz define a **function** to be a set of abstract "verb noun" sub-functions interconnected by flows of energy, materials and signals [PAHL et al. 2006, p.43]. Components are thus elements of a greater system architecture that must be integrated to form a complete product. A component in this sense can be both a separable physical part or a sub-assembly of multiple parts[VDI 2004, p.10].

The fundamental definition of product architecture can applied to systems. Crawley defines **system architecture** as an "abstract description of entities within a system and the relationships within those entities" [CRAWLEY et al. 2004, p.2]. This more generalized definition of entities and relationships is applied to complex systems that are made up of multiple sub-systems.

In studying complex systems, Lindemann presents the interplay between functions and objects – that are analogous to components. He describes "functions" to be an abstract description of a system that formally documents the effect or use of objects, or relationships between these objects [LINDEMANN, UDO 2007, p.329]. The architecture of a system is important in that it has a direct influence on its behaviour. By understanding system architecture, valuable information on how the system works and evolves with time can be inferred.

Vehicle Architecture - Understanding today's car to be a complex system, meaning one with multiple component subsystems, **vehicle architecture** refers to the linking of vehicle sub-systems in a particular configuration to achieve a set of desired functions the vehicle is to

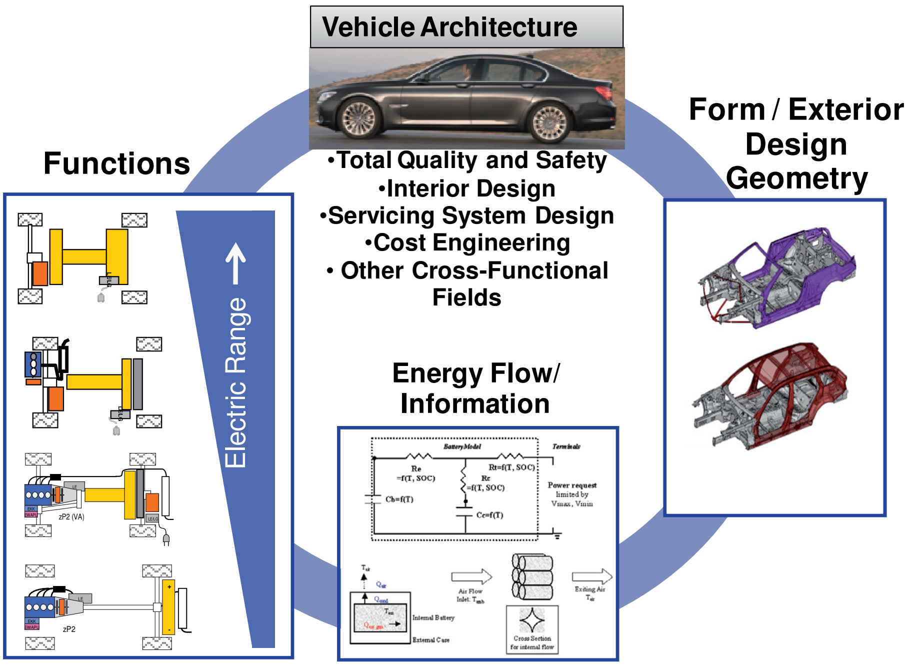

Figure 2-1 Three views of vehicle architecture encompassing cross-functional design fields

perform as a whole. Three views of vehicle architecture are presented in Figure 2-1 below: the functional view, the geometric view and the information and the energy flow/information view. These three broad categories encompass a multitude of cross functional design fields that encompass the overall vehicle system. A closer look at these areas is discussed below.

The *functional view* stems from customer, legal and market requirements that are translated into functions the vehicle must perform. For example, customer requirements for a hybrid or electric vehicle architecture can involve varying levels of electric range to support the function “drive electric.” The functional view of vehicle architecting addresses the dimensioning of components based on functional requirements collected through the various cross functional fields such as quality standards, vehicle structural framework, interior design, cost engineering, crash safety, and others. The various architecture depictions in Figure 2-1 illustrate various scaling and configuration alternatives for the electric motor, battery, and the combustion engine components to fulfil various electric range requirements.

The *geometric view* of vehicle architecture ensures that the component subsystems can be integrated within the vehicle’s special constraints stemming from the exterior, interior design and structural packaging. The geometric view ensures that both form and functional goals can be achieved within the framework of all other cross-functional fields. Computer automated design tools allow system architects to view the integration of the many component sub-systems in a digital mock up that becomes a living document that is updated until a particular concept is discarded or developed further in subsequent design stages within the product development process.

Finally, the *information and energy flow view* of vehicle architecture provides the linkage between components or sub-system elements. This last view entails the energy, material and signalling links within the vehicle featuring electronic controls, mass transfer and heat transfer systems that allow the entire design to work as a whole. Within this view system architects bring together information from many cross-functional fields and ensure the synchronization of efforts in a timely manner.

The three views of vehicle architecting occur simultaneously during the design process and are iterated through as a concept matures in its definition. During the pre-development stages of a vehicle, the most significant technical specifications are defined in what is referred to as the general **vehicle concept**.

The vehicle concept encompasses a preliminary analysis of overall technical goal definitions. Concurrent to the vehicle concept, the **vehicle design**, defined as all aesthetic and form of the car’s exterior visible parts are developed to match the vehicle concept. The order and placement of component sub-systems according to the vehicle concept and its design constraints results in the so called car **package**. The simultaneous development of the vehicle concept, design and package are critical for completing a consistent vehicle architecture for mass production (series development) as seen in Figure 2-2 [HEISSING 2008].

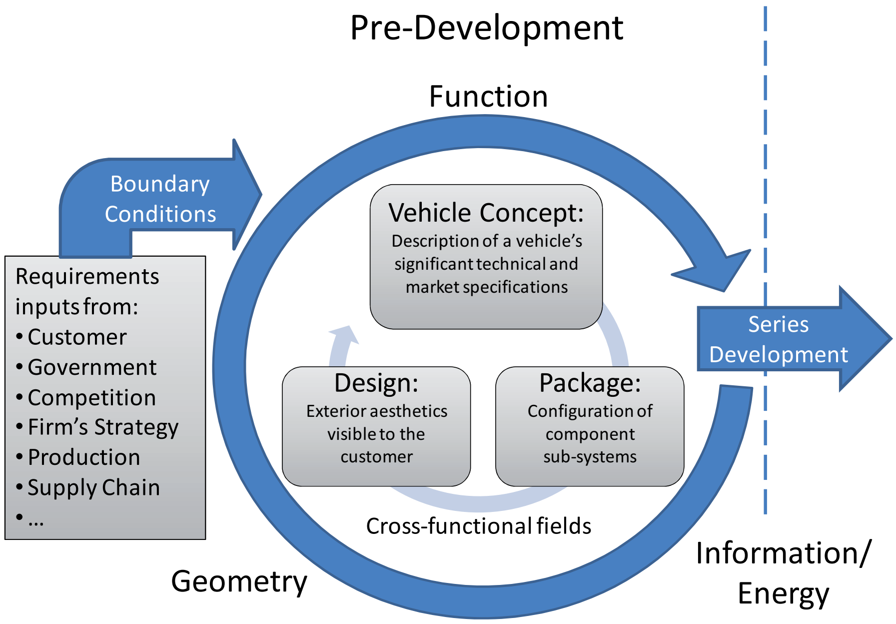

Figure 2-2 The total vehicle architecture cycle during the pre-development stage [Adapted from HEISSING 2008]

The total vehicle architecture takes input information from design boundary conditions and iterates simultaneously through the generation of vehicle concepts, design and packages and the three main architecture views during the pre-development phases. The concurrent analysis of the inner and outer cycles shown in Figure 2-2 supports the selection of vehicle architectures that are mature for further development. The number of factors and cross-functional fields involved in this early stage requires coordination from a system architect or engineer that can determine how much complexity can be effectively handled for the purpose of generating a good start to the formal series development process. The pre-development work is simplified by modeling tools that can analyze the effects of design changes across various disciplines.

2.1.2 Architectural Competition

Architectural competition refers to differentiating a product from others in the market based on product architecture. During the early years of modern automotive history (1890-1915), cars used to compete primarily on architecture. For example, electric cars were marketed to female drivers for their ease of use and minimal maintenance, whereas internal combustion engine (ICE) and steam cars where attractive to male drivers seeking power and speed.

The advertisements in Figure 2-3 are early evidence of architectural competition in the automotive market. Customers during the early 1900s had to decide which car architecture best met their mobility needs. The electric car advertisement on the left presents a car fit for aristocrats claiming electric range is no longer an issue and showing a female driver at the wheel in the countryside. The advertisement on the right dating from 1904 is more technical in nature boasting a 100 miles on one filling of tanks – referring to both the fuel tank and the

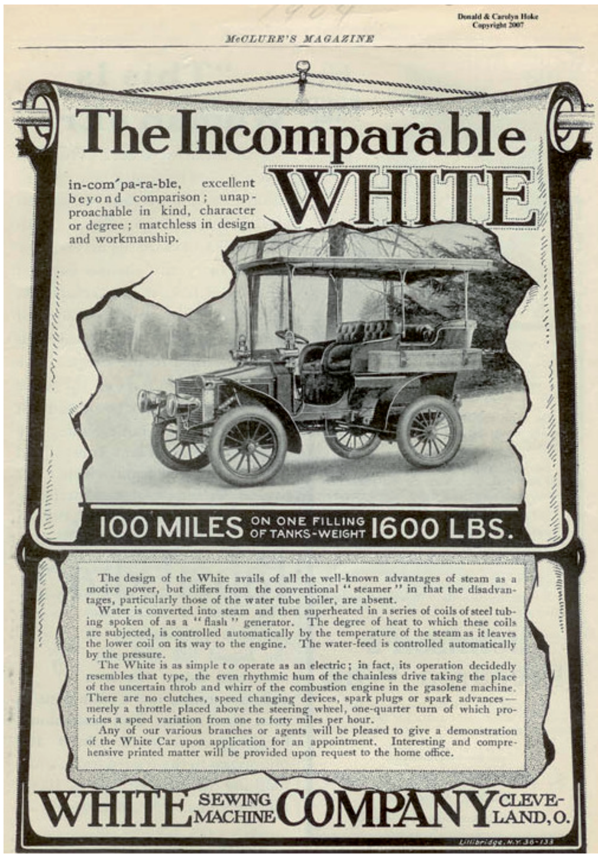

Figure 2-3 Early vehicle advertising for an electric car[FARBER 2009] (left) and a steam car [HOKE 2008] (right) in 1904 during the first age of automotive architectural competition

water tank in the steam car.

The two vehicles support similar functionality at an aggregate system level, namely to provide transportation capability, however they exhibit very different vehicle architectures. The mapping of functions and components for the steam powertrain architecture had several decades of evolutionary development from steam engine locomotives, which then translated to a new product system in cars. The electric car featured some similar components to the steam car, along with new components configured differently in both form and function.

What factors triggered architectural competition and dominance in the past? During the early modern automotive time period (1885-1915), steam was clearly the dominant architecture with its origins dating back to the late 1780s. The shift towards architectural competition was triggered primarily by a series of new technological breakthroughs that sought to improve one of the main weaknesses of steam power; the dependence on water availability. The first uses for the resulting internal combustion engine and the electric motor at the time, focused on solutions for the rail and electric power generation markets, before they entered into the nascent automotive industry.

As competition grew amongst steam, electric and internal combustion engine cars, price and quality advantages became more acute. Steam cars exhibited high pricing and offered the ability to quickly accelerate achieving 0-65 km/hr (0-40 mi/hr) in less than 10 seconds. This is due to the fact that the highest power and torque in a steam engine occurs when the vehicle starts from rest. However, early steam models could not go more than two miles without replenishing their water tank and took more than 20 minutes to start the boiler to build up enough pressure to drive.

The early electric car exhibited comparable pricing to a steam car and required an electric power source – found mostly in major cities at the time. It was limited in range to less than 64km (40 miles) per charge and no more than 32 km/hr (20 mi/hr) in velocity provided by the low energy density of early lead acid batteries at roughly 15-20Wh/kg - compared to 12,200 Wh/kg contained in gasoline fuel. However, its key advantages remained that it was simple to drive with no complicated shifting mechanisms and provided essentially no maintenance or uncomfortable emissions.

Early performance of the ICE car was on par with electric cars but inferior to that of steam cars. Steam proponents would often call it "internal explosion engine" to communicate a negative feeling that the ICE car was less safe than the proven steam car. Although starting the engine was achieved in less than a couple of minutes with the ICE, many motorists suffered from injuries in starting the vehicle with the external hand crank – a real safety issue.

The dominance of the internal combustion engine came only after two key events: first, the dramatic decrease in price achieved through assembly line production of ICE cars and second, the development of the electric starter. The price and quality improvements to the ICE car made it affordable to the masses and comparably a better solution to all other architectures in the market by 1920.

Steam cars built from 1920-1930 remained a high end market product. Significant improvements were introduced to compete with ICE cars such as the integration of a condenser to recycle the use of water and a spark ignition starter that could provide the car enough starting pressure within one minute. However, the systems added tremendous weight and increased the overall price of the already low production volumes. The steam car that had dominated since the 1780s eventually disappeared completely from the market by 1930.

Presently, new architectures are appearing in the automotive market; most notably a revival of electric and hybrid electric vehicles. Will the future of the ICE car mirror that of the steam car? Automotive original equipment manufacturers (OEMs) will have to develop an understanding of architectural competition and develop strategies to address the present and future markets – their corporate life might depend on it. Electric cars were a looser in 1910, but can become a winner again now thanks to technological advances.

2.1.3 Typology of Innovations

The following definitions pertain to Henderson and Clark's typology framework on innovation (radical, incremental, architectural and modular) [HENDERSON et al. 1990] which will be applied in this chapter to the automotive industry. The consideration of the product as a system of components is the basis for the framework presented in Figure 2-4.

Product development requires two fundamental forms of knowledge. The first is

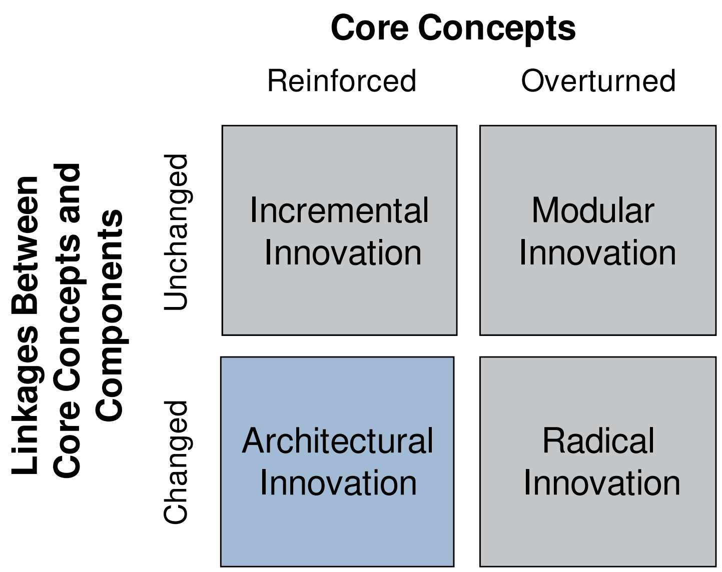

Figure 2-4 Typology framework on innovation [HENDERSON et al. 1990]

knowledge of the design core concepts and how they are applied to a particular component. This type of knowledge is represented by the horizontal axis. The second form of knowledge is more structural and entails the way components link together to make a whole that achieves the core concepts. This second type of knowledge, sometimes referred to as architectural knowledge, is depicted along the vertical axis of the framework.

Incremental Innovation – also known as evolutionary innovation refers to the use of a current product as a starting point for the next generation car product that holds the same architecture. Incremental innovation focuses on optimizing sub-systems by incorporating new technology [CHRISTENSEN 1997]. In this model of innovation the knowledge of how the system works is maintained and reinforced throughout many years of the same product families. A performance improvement is achieved through the incorporation of new technologies that improve a particular component but maintain similar linkages to others.

Radical Innovation – is the extreme opposite from incremental innovation. Here the new technology exhibits a revolutionary way of achieving the established product's core goal using new conceptual principles. Radical innovations in the automotive industry have been witnessed mostly at the sub-component level. For example the replacement of a car's tape deck mounted in the cars instrument panel to a compact disk player in the back of the car solves the function to play music using completely new core principles and new linkages to new component sub systems. Today, another radical innovation, the digital .MP3 player, has replaced the compact disk player representing a follow-on cycle.

Modular Innovation – relates to technological innovations where the linkages between core concepts and components remain unchanged but offer an innovative way to arrive at the product's goals. For example the change from roll up windows to power windows essentially maintain the same linkages between core concepts and components but allow for an electronic motor to replace the rolling up and down of the window.

Architectural Innovation - is the reconfiguration of an established system in a new way [HENDERSON et al. 1990]. The system in this case is the car as a whole and the reconfiguration refers to how sub-systems, made up of vehicle components, are linked with each other to perform the car's basic functions. For example, the market introduction of the hybrid electric car in the late 1990s is considered an architectural innovation, as it presented a new way to propel the car by using both an electric motor and an internal combustion engine but keeping the core concepts of a basic automobile.

Over the course of the last 120 years in the automotive industry, all types of innovation presented have been witnessed. Some innovations exhibit elements of two or more innovation types. However, as the industry has perfected cars over the years, it has been commonplace to witness mostly modular and radical innovations within component subsystems and sub-assemblies. Incremental innovation becomes better suited to generate a better functioning overall system the more complex a system becomes.

Architectural innovation requires changes at a higher level of abstraction affecting the overall vehicle architecture. In doing so, these innovations may challenge not just the structure of the product, but also the systems and organizations that drive the product development and manufacturing of the product. When architectural innovations enter the market, incumbents relying on incremental enhancements are required to judge whether their firm's core competencies must be adjusted to remain competitive.

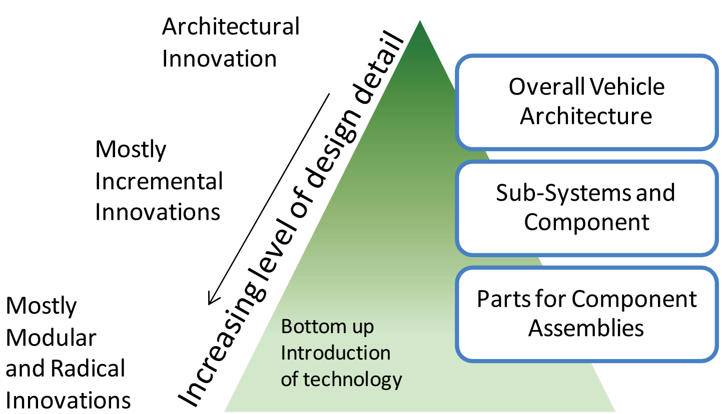

Figure 2-5 Traditional types of Innovations applied to a vehicle architecture's level of detail

Figure 2-5 shows a representative component pyramid depicting a breakdown of the total vehicle architecture into sub-systems and then further into parts for sub-assemblies. The innovation typology presented usually occurs at different levels of abstraction (or detail) within this hierarchy. Architectural innovation will in fact have a profound impact at a high level of abstraction, as it generally occurs at the tip of the pyramid during the initial concept product development stage.

Architectural innovation has both elements that are core competence enhancing and others that may destroy competence. The new architecture design requires re-linking functions, components and their configuration. If the firm cannot build knowledge quickly enough to adapt to architectural change by means of restructuring its organization, it might seek for ways to buy knowledge from suppliers or competitors. When this occurs across several firms in a particular market segment, the market supply chain can experience shifts in terms of supplier power and buyer power. Economic power will go to where "right" core competencies are being generated.

Such realignment of power is evident in the automotive industry as hybrid electric vehicle (HEV) architectures enter the market. HEVs require both knowledge in producing battery electric and internal combustion engine (ICE) powertrains. Most of today's major automotive manufacturers lack the first and hold the latter. Not surprisingly, when Japanese automakers Toyota and Honda entered the hybrid vehicle market in 1999, competing firms looked to create joint ventures with specialty suppliers of hybrid core components. Alternatively, competitors simply bought licenses of the new hybrid technology, as was the case of Ford’s license purchase of Toyota’s hybrid system for the Ford Escape in 2003. Because the heart of the electric power train lies in high voltage battery technology, firms that can supply this core competency require a hefty premium for their products placing pressure on the automaker's profit margin.

2.2 Innovation Lifecycle S-Curve Theory

This section explores the lifecycle behavior of vehicle architectures. The hypothesis in this section is that vehicle architecture lifecycles follow an S-curve like development similar to the established technology innovation theory. As a first step in exploring this hypothesis, technology lifecycle theory is introduced.

Everett M. Rogers was one of the first authors to use the basic form of the S-curve in modelling the lifecycle of innovations [ROGERS 1962, pp. 20-36]. The basic theory holds that the spread of innovation occurs in 3 phases: early adoption, fast adoption and saturation. Later, a fourth phase was added outside of the basic model that describes a decline in adoption. Figure 2-6 shows a qualitative s-curve with the four basic stages.

Critics of the S-Curve argue that the theory serves well as a mental model, but that innovation lifecycles are complex and subject to many exogenous variables not easily depicted. For example, the model fails to take into account that radical or disruptive

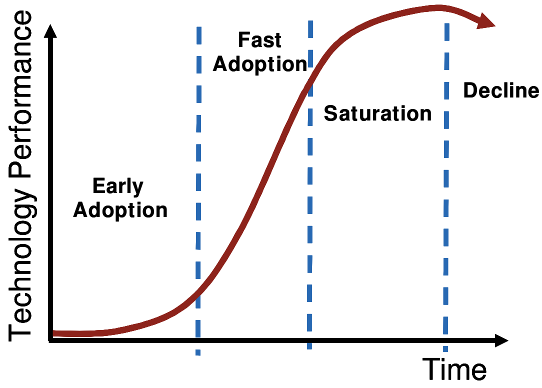

Figure 2-6 Innovation Lifecycle S-Curve

innovations might also strongly alter the shape of the innovation diffusion across a population and might start new s-curves at higher performance levels. Additionally, the model does not account for instances of path dependence that might lock in a certain innovation allowing it to dominate the market, as witnessed by the long dominance of internal combustion engine car. The following analysis will show that the model can be more than a qualitative estimate and that an instance of path dependence will simply lengthen or flatten the S-curve cycle by extending the time scale to the right.

2.2.1 Measuring Performance

A performance measure for vehicle architectures is developed in this section to enable the exploration of vehicle architecture lifecycle behavior according to the innovation lifecycle theory. The equations for a performance measure are briefly presented here, while the results and discussion are the topics for the following sub sections.

A performance index, inspired from vehicle performance measures found in consumer guides, was created to capture vehicle architecture lifecycle trends. In generating the index to rate car performance spanning over a century, the amount of information available becomes a constraint. For example, safety data from standardized crash testing go back only two decades, whereas measures such as weight, fuel consumption, velocity and power offer metrics that span over a century.

The data collected was compiled from basic vehicle specifications put together by museums, history books, and car guides [Conceptcarz 2009]. A database of 93[2] cars was collected on five basic parameters: overall power, curb weight, maximum velocity, fuel consumption in miles per gallon and the manufacturer's suggested retail price. These parameters remain unweighted in our assessment as some parameters have had periods with increased and decreased importance. For example, the overall power was a key parameter in the 1960s, yet today its focus has diminished. The data collected focuses particularly on passenger cars produced in relatively large volumes. The performance index used is described by equation 1.

Power to Weight Ratio

Maximum Velocity

$$\begin{aligned} \textit{Architectural Performance Index} = \sum_i \Bigg[\Bigg(& \left(\frac{\left(P/W\right)_i - \left(P/W\right)_{\min}}{\left(P/W\right)_{\max} - \left(P/W\right)_{\min}} \right) + \left(\frac{V_i - V_{\min}}{V_{\max} - V_{\min}} \right) + \\ & \left(\frac{L/100km_{\max} - L/100km_i}{L/100km_{\max} - L/100km_{\min}} \right) + \left(\frac{MSRP_{\max} - MSRP_i}{MSRP_{\max} - MSRP_{\min}} \right)_{in\,2008US\$} \Bigg) \div 4 \Bigg] \end{aligned} \qquad (1)$$

Fuel Economy

Manufacturer's Suggested Retail Price (in 2008 dollars)

Where P represents maximum power output; W is the vehicle's curb weight; V represents the maximum velocity; fuel economy measured in *liters per 100km*, and *MSRP* is the manufacturer's suggested retail price converted to 2008 dollars. The index is made up of four categories pointed out in equation 1 that result in indexed values from 0 to 1 for each category within parentheses. The nomenclature of max and min refers to the maximum or minimum value for the particular variable within the database in the appendix section 9.1. Each parameter with the subscript i refers to the particular car considered in the database. The sum is then normalized by 4 in order to come up with an overall performance score that also lies between 0 and 1 for each car data point.

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[2] The data set presented in the appendix section 9.1 taken from www.conzeptcars.com was last accessed on 11 December 2008 and represents mostly models that where available in the US and Europe.

Should a specific data point score higher than all other cars in the database in all four categories the performance index calculation results in a value of 1. Likewise an overall score of 0 requires that the car's data is the worst in all four categories.

The first category comprises the overall **power to weight ratio**. The power to weight ratio is proportional to the acceleration the car can achieve as well as its ability for hill climbing. A high power to weight ratio is a measure of good performance and should be maximized when possible.

The second category is **maximum velocity**. This measure is one that helps differentiate early cars from more modern cars in their performance. During the early years, velocity was a key factor that differentiated car architectures. Winning a local race with a certain brand car during the weekend would result in increased sales during the subsequent months. This of course made racing a very attractive sport for major auto manufacturers. From 1885-1905, a top speed of 20mph in a city environment was considered plentiful as long distance driving was not possible due to a lack of a highway infrastructure. In this speed range, architectural competition flourished amongst steam, electric and internal combustion cars. Today most cars can comfortably achieve a 130 km/hr (80 mi/hr) velocity and can reach upwards of 240 km/hr (150 mi/hr) for sports cars.

The third category is the measure of **fuel economy** in liters per 100km, a performance measure where less is better. Fuel consumption was, and still is, a definite measure of car performance. The data on fuel consumption however is somewhat tricky, as laws designating standard driving cycles for measuring fuel consumption did not come about until the 1970s. This means that the data collected prior to 1974 is more an estimate than an agreed value. Furthermore, flexible fuel cars were taken into account by using a liters equivalent per 100km (L*e*/100km) measure. The measure normalizes the energy content of various fuels to that contained in one liter of gasoline. For example, an electric vehicle's Le/100km is a function of the maximum electric range the vehicle can achieve in miles and battery energy capacity with respect to a liter of gasoline as shown in equation 2.

$$L_e/100km_{EV} = \left(\frac{Net\ Battery\ Capacity\ (kWh)}{Electric\ Range\ (km)}\right)\times\left(\frac{1L_{gasoline}}{9.7kWh}\right)\times 100 \qquad (2)$$

Finally, the fourth category used is the **manufacturer's suggested retail price (MSRP)**. Including a measure of retail price in the performance index allows awarding a higher score to those car architectures that provide the most performance per dollar spent. The data on price was adjusted for inflation by converting all values to 2008 dollars using equation 3.

The inflation rate *j* used in the calculation was taken to be 3% as a approximation of US

$$MSRP_{2008i} = MSRP_{year\,i}\times(1+j)^{(2008-year\,i)} \qquad (3)$$

inflation from 1885-2008 based on average values of the consumer price index fluctuations recorded from 1914-Present by the Bureau of Labour Statistics [US DEPARTMENT OF LABOR 2009].

2.2.2 Architectural Innovations in the Automotive Industry (1885-2008)

As a first step in understanding how automakers can best select car architectures in the future, more than a century of automotive history is considered. Figure 2-7[3] shows architecture performance for automobiles between 1885 and 2008 and the cyclical nature of the market. Three basic periods have been identified: initial architectural competition, architectural dominance of the ICE and renewed architectural competition.

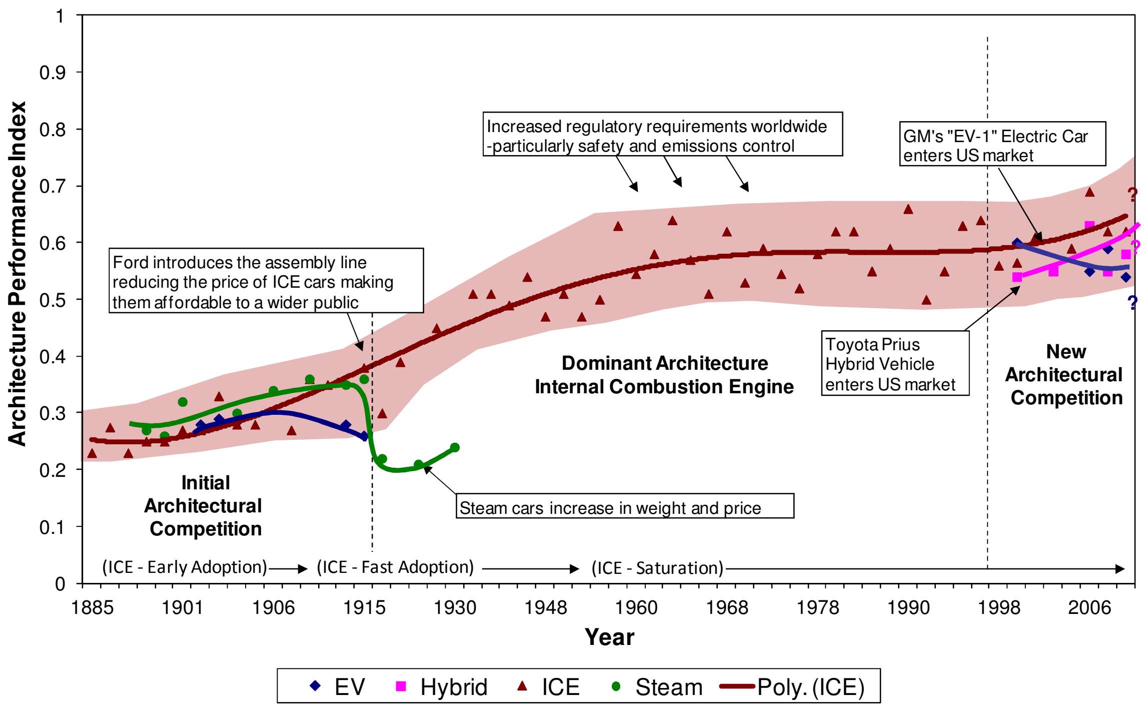

Figure 2-7 Performance of various automotive architectures from 1885-2008 [GORBEA et al. 2008]

The ICE architecture that is shown throughout the entire period follows the innovation S-curve stages presented earlier, however the duration in time for this S-curve to form has lasted over a century. One explanation for this long duration is the fact that complex product architecture is an aggregation of many technological innovations within its subsystem. This idea is further discussed in section 2.2.3.

[3] For each architecture type (ICE, Steam, EV, Hybrid) in Figure 2-7 shows an average value for every year – not all 93 data points are shown

The first time period (1885-1920) shows that three different architectures -electric, steam and internal combustion- where competing to dominate the market. At this early stage, automakers (large and small) innovated around the basic structure of a car but with significantly different concepts. The market exhibited a time of architectural innovation where a variety of power train elements were linked in various ways to enable the function of propelling the car.

The second time period (1920-1998) shows a shakeout in the market that allowed one architecture to dominate all others; the ICE car. Because the entire market adopted this dominant architecture, the basic risk of not knowing which architecture will prevail was completely eliminated. This allowed manufacturers to focus on innovation at the sub-system level as opposed to the overall system architecture level.

Incremental innovation flourished during this time period. Generations of cars exhibit only improvements to major sub-systems while keeping with the same basic architecture concept. During this time of architectural dominance, automakers paid little attention to alternative power-trains and focus primarily in generating core competencies that support the optimization of the dominant architecture.

The current time period (1998-Present) shows a renewed focus on vehicle architecture. The key historical event that marks the beginning of this new age is the re-introduction of electric vehicles in the market and the first mass produced hybrid electric cars. At the moment, some auto manufacturers are trying to shift their focus from incremental innovation to that of architectural innovation. The shift has not come easy as most organizations have been structured around the major subsystems within the automobile. Most auto manufacturers have invested in developing their core competencies in areas specific to the design of internal combustion engine cars. Presently, automakers that compete on architecture are shifting to build competency in other areas pertinent to fuel flexible architectures such as hybrid, fuel cell and electric cars.

The shift towards architectural competition is significant because it can place established firms in jeopardy if they are not able to adapt to the new competitive landscape that is developing [HENDERSON et al. 1990]. This was the case of most steam car manufacturers during the 1920s that failed to adapt to market changes. Firms that develop methodical ways to achieve architectural innovations are considered to be better placed in generating a competitive advantage over firms that stay the course of incremental innovation in the future market for automobiles.

Presently, some leading automotive manufacturers such as BMW have opted to invest early in new electric based vehicle architectures in light of the forthcoming architectural competition. In 2009 BMW unveiled a test fleet of the MINI E electric car as part of its "Project i" initiative to study both customer and technical behaviour of the new technology for follow on electric mobility. Although Norbert Reithofer, BMW's CEO, is proud of the company's Project i and the forthcoming MegaCity EV, he doesn't expect to turn a profit from the first generation of production vehicles or even recoup the cost of the project. "Electric cars will be expensive vehicles in the beginning," Reithofer said during an EV conference in Germany. "It may be that you don't earn any money with such technologies during the first product cycle. Here, conventional drive has to cross-subsidize the new technology." [PETERSON 2010] BMW's creation of a decoupled development stream for electric powertrains and increased investment is uncommon behaviour in the automotive industry, but one that makes sense in addressing architectural competition.

2.2.3 Analysis of Architecture Lifecycles

In complex technological systems, each contributing sub-system or component technology finds itself at a different stage of maturity in their innovation Lifecycle [Schulz et al. 2000]. The net effect a new technology has on the overall system will depend on at which system

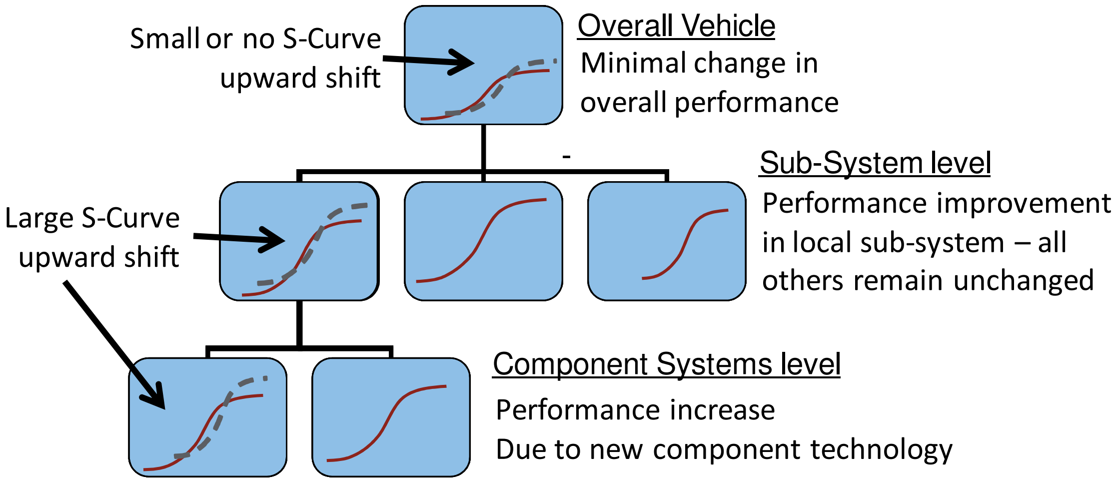

Figure 2-8 Damped bottom -up effect of incremental innovation from component to the overall system

level the technology being implemented is found on. Figure 2-8 shows a qualitative picture of how a shift in a new technology within a car's component has a strong effect within its direct sub-system lifecycle but a lesser effect on the overall system.

Take for example the introduction of a new fuel injection technology that allows for a more complete combustion within the engine's cylinder. This technology will have a great impact on the performance of the engine – its major sub-system - but a more limited impact on the performance of the overall car's architecture.

According to the theory presented, once a dominant architecture exists, incremental innovation methods will focus on integrating new technologies at the component level. This allows firms to build expertise in sub-system integration and optimization. In contrast, when architectural competition takes place, technological innovation occurs both at the component level and sub-system level having a more direct impact on the overall system's performance. Architectural innovation methods are more suited for this type of competition as the firm must manage innovation at all levels of the product's system hierarchy.

2.3 The Road Ahead into Architectural Competition

The historical performance of architectures present the basis for future estimates of how the market might develop. What will happen in the future during this new age of architectural competition? Will the industry move to a new paradigm such as “electric mobility’ or will the internal combustion engine architecture reinvent itself and dominate the market again in the future?

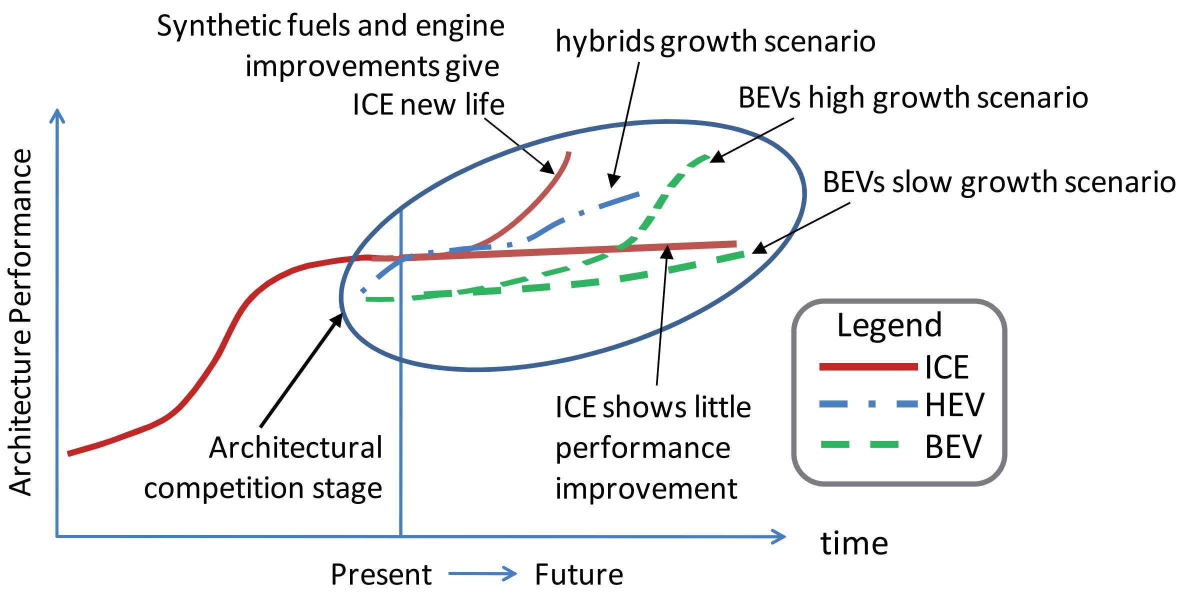

Figure 2-9 Possible scenarios in a new age of Architectural Competition

Projecting the development of vehicle architectures into the future can be accomplished by developing scenarios. The goal of **scenario management** in early product development is to enable present decisions that are robust to future expected situations [GAUSEMEIER, I. J. et al. 1996, p.159]. Figure 2-9 qualitatively shows some possible future architecture outcomes for the purpose of discussion. Each scenario represents the performance growth of the ICE, HEV and BEV architectures.

ICE slow growth scenario – The current ICE has reached a mature age of saturation for which performance increases in sub-systems will not bring about a big overall change for the ICE architecture’s performance. The flat line extending throughout will continue for a long time until other architectures deliver higher performance capability.

ICE fast growth scenario - If synthetic fuels become cost effective, the ICE architecture becomes sustainable (not limited by available oil reserves). Under these conditions and further emission reduction improvements, the ICE architectures could in fact outperform the new entering electric powertrains.

Hybrids growth scenario – Hybrid vehicle growth scenarios could favor a transition to electrical powertrains. These architectures offer increased performance by mixing concepts from the ICE and electrical architectures and should grow along together with the ICE and BEV architectures. If ICE architectures take on a fast growth scenario micro hybrids would be favored, whereas if BEVs are favored then PHEVs will deliver performance improvements.

BEV slow growth scenario - electric cars that underperform ICEs enter the market to offer OEM fleet emission reductions in order to meet regulatory standards. The performance of BEVs improves slowly as gains in battery technology are slow to materialize.

BEV high growth scenario – the BEVs incorporate new battery technologies that allow for orders of magnitude increase in power density. BEVs become comparable in performance to ICEs but offer the benefit of zero tailpipe emissions. Law makers in cities allow for emission free zones near city centers where BEVs are favored effectively increasing the performance values of BEVs.

These qualitative scenarios can be further quantified by use of methodologies such as cluster analysis using consistency matrices as presented by LINDEMANN, UDO 2007, p.87. Such methods require a detailed analysis of boundary conditions affecting the future situations. It is likely that a more detailed analysis results in a co-dominance mixed scenario or that entirely new vehicle architecture such as hydrogen enters the market further along in the future. A more detailed look at factors affecting architectural change is the topic of the next chapter.

Central to this discussion is how exactly "architecture performance" in Figure 2-9 is defined. The definition proposed by equation 1 represents one generalized set of goals based on historical information available. However, as cars become more complex, new goals have come into prominence such as vehicle safety, connectivity, comfort, image and so on, a redefinition of the traditional performance goals of cars can result in a drastic change of how architectures perform in reference with each other.

For example, if a car's range is a prominent performance factor taken into consideration, today's combustion engine cars can travel over a 950km on a tank of petrol, whereas a battery electric vehicle might be limited to only 80km putting it at a drastic disadvantage. However, in a market of city cars, electric cars with 80km range could suffice and not be classified as a performance deficit. At the moment plug-in hybrids tend to offer a happy medium between these two extreme positions and could invariably emerge as a preferred architecture. Accounting for the right performance index measures can vary between customer classes and consumer market segment. As a consequence there may be a larger variety of "winning architectures" in the future, depending on consumer context (e.g. city versus urban, cold weather versus tropics, etc.).

2.3.1 Extending Established Vehicle Architecture Lifecycles

The ICE car is far from becoming extinct. However, architectural competition will force automakers to decide to what extent the ICE architecture lifecycle should be effectively prolonged. Two questions come about from this discussion. Is it possible to extend the lifecycle of an incumbent architecture? If so, how long and through which means is this best accomplished?

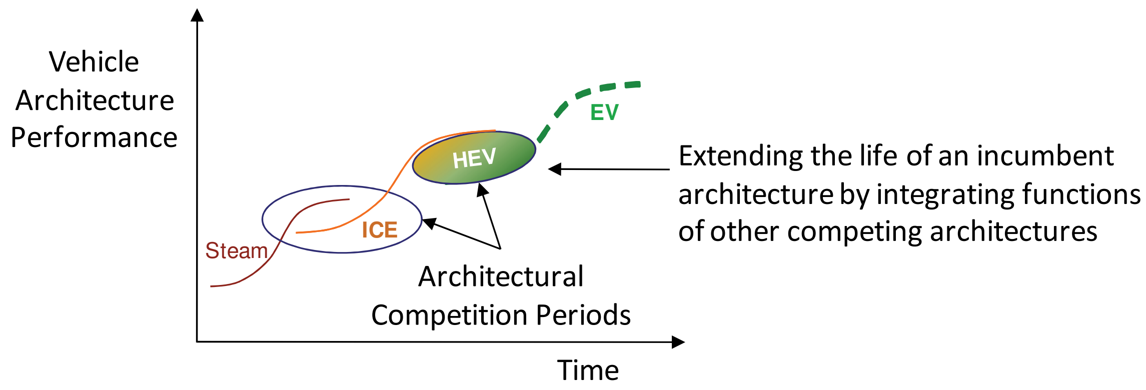

Figure 2-10 Extending an Architecture's life by incorporating functions from competing vehicle architectures during market transitions

The follow on hypothesis to the S-curve theory presented here is that incumbent architectures can be prolonged by incorporating features from other competing product architectures. Conforming to this hypothesis, Figure 2-10 shows the S-curve transitions with periods of architectural competition and presents the HEV merely as a means to extend the ICE's performance until a full transition to electric cars is achieved. The transition to electric cars is achieved only when the electric vehicle architecture performance is higher than that of other vehicle architectures.

The response of some automakers to the introduction of hybrid cars can hint that the "architecture prolongation" hypothesis might hold some truth. The so called "micro-hybrid" car architectures feature only the added functionality of a "start-stop system' and in some cases the ability for light "regenerative braking", without the introduction of a high-voltage electric drivetrain. Micro-hybrids, are referred to as "advanced ICE architectures" because they feature only some, but not all, functions offered by hybrid and electric cars. This allows the car to increase its performance level at minimal cost to the manufacturer and customer resulting in an effective extension of the ICE architecture lifecycle within a new market of hybrid cars.

The early period of architectural competition in the early 1900s also saw some attempts at mixing functionalities of competing architectures. The 1903 Lohner Porsche is known as the first hybrid vehicle developed by a young Dr. Ferdinand Porsche. This invention was motivated by enhancing the racing performance of the early ICE cars by incorporating elements of the battery electric vehicle architectures.

However, no early examples exist of ICE-steam combinations or steam-electric hybrid cars during the initial architectural competition stage. These concepts are now being studied under the field of ICE waste heat recovery [FREYMANN et al. 2008, p.404-413, BUTLER 2008].

Extending a vehicle architecture lifecycle is only justified if performance improvements over competing architectures can be achieved. In the example of micro hybrids, this can be done by incorporating limited functionality of competing architectures.

Entering vehicle architectures to the market can also use a similar approach in acquiring market share. The offering of "mixed" architectures as a transition away from the dominant product architecture is effective in creating small steps in the transition. The establishment of a new dominant architecture will depend on its ability to quickly develop increased performance over all other competitors similar to the ICE car between 1915 and 1930.

2.3.2 Implications of Architectural Competition

As a new age of architectural competition commences, the potential exists that it may extend for a prolonged period of time. The more complex architectures become, the longer transition to new dominance can be expected. As a frame of reference, it took roughly 30 years for the combustion engine architectures to dominate the market between 1885 and 1915, despite the simplicity of early designs. Based on this observation, a new architectural competition period can be estimated to last twice as long and result in multiple dominant architectures for varied segments and use cases.

The variety of offerings during this new age of architectural competition can be extensive. A panel of experts formed by the California Air Resources Board (CARB) expects that by 2050 ten different vehicle types will be mass produced and offered for sale [CARB 2007]. For each type of architecture a variety of sub-categories can be expected. For example, today the ICE car includes gasoline, diesel, CNG, LPG and others. Likewise, hybrid architectures will also bring extensive variety as evidenced by micro, mild, full, and plug-in hybrids with varying functionality, component structures and electric range capabilities.

The value of such expert panels can vary as has been documented by the German Fraunhofer Institute for Systems and Innovations Research using the Delphi methodology since the early 1970s. The methodology is based on statistical analysis of questionnaires filled out by experts from academia and industry worldwide within popular research fields. In the questionnaires, experts express their prognosis in anonymity of when technologies or innovative situations will be realized in the future. Important to working with the **Delphi method** is to allow for the questioned experts to state their level of expertise for each prognosis and allow for multiple rounds of questioning where experts can explain their answers to others to allow for convergence in situations where no clear prognosis can be inferred.

In the Frauenhofer institute's 1998 questioning of experts to the statement "next to conventional ICE powertrain cars, hybrids cars are available in large quantities along with and electric vehicles in lesser quantities" the overwhelming majority of over 110 experts within two rounds of questioning found that this statement would be true between the year 2006 and

2010 or earlier [CUHLS et al. 1998]. In 2009 hybrid vehicles represented less than 10% of new vehicles in Japan, 2.8% of new vehicles sold in the US and less than 1% in Europe [ASSOCIATED PRESS 2010]. Electric vehicles are yet to truly enter the mass market. This example of a missed prognosis shows that the future is difficult to predict despite the experience of experts in a particular field.

With the many vehicle architecture variations it is difficult to determine now which will eventually prevail, or be most popular in the future. What is certain is that a new age of architectural competition brings with it an added dimension of risk to automakers – firms must compete in multiple architecture segments without knowing which will be ultimately more popular or profitable. Mitigating this architectural risk will require firms to create flexibility in their architecture offerings to easily adapt to changes in emerging customer needs.

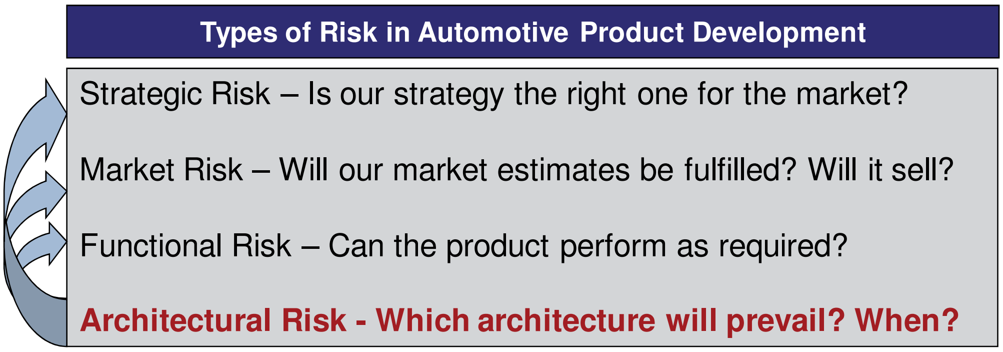

Figure 2-11 Architectural risk is an added risk to auto manufacturing firms that affects all other forms of risk already affecting traditional product development

Figure 2-11 shows how **architectural risk,** referring to uncertainty of a product architecture's success in the market, has coupled effects to other types of risk known within product development process. Other risks include strategic risk that deals with the selection of a market strategy - such as low cost, high volume strategies or high cost, high quality as examples. Market risk entail whether customers will buy the projected production volume and functional risk deals with whether a product can achieve the functionality it is designed to accomplish. In the automotive industry architectural risk has been relatively small over the decades of ICE architectural dominance. The introduction of new architectures, such as the hybrid electric vehicle, brings with it new functional risk in the form of battery performance and lifetime, market risk in terms of achieving demand estimates and strategic risk in competition with other hybrids as well as conventional cars in the market. In short, architectural risk affects all other forms of risks that were previously present in the market.

Government intervention will also play a significant role in influencing architecture decisions. Emissions regulations, fuel economy standards, stimulus incentives and tax schemes can make vehicle architectures more or less attractive for consumers to purchase by offsetting costs of ownership. On the supply side, manufacturers can also be directed by governments to produce specific architectures.

Additional consequences of architectural risk can be extrapolated to future OEM “make or buy” decisions during periods of architectural competition. Established manufacturers that want to bring new architectures to market rapidly might not be able to do so without outsourcing to suppliers. This is in part due to problems of architecture “lock –in” as described by UTTERBACK 1996, p.25. Firms that have grown with the conventional car have fine tuned their core competencies in creating engines and car designs around a particular power train over the last 50 years. Items that fall outside this core competence are usually outsourced.

One example of outsourcing can be seen in the production of tires. Although all cars use tires, no major auto manufacturer produces their own tires. Tires are interchangeable standard parts of a car that provide little differentiation between auto brands. Tires are outside the core competence of most car makers and are best sourced from suppliers. Now, as OEMs shift to new architectures that entail competence in electric drive systems, a choice must be made to either make it part of the manufacturer’s core competence or simply buy products from suppliers.

Deciding to build new competence in electric mobility is a strategic decision architectural competition has brought to the board rooms of major auto OEMs today. Deciding for electric mobility will require capital, skilled labor, and a new organization that will revolutionize the way cars are built and sold.

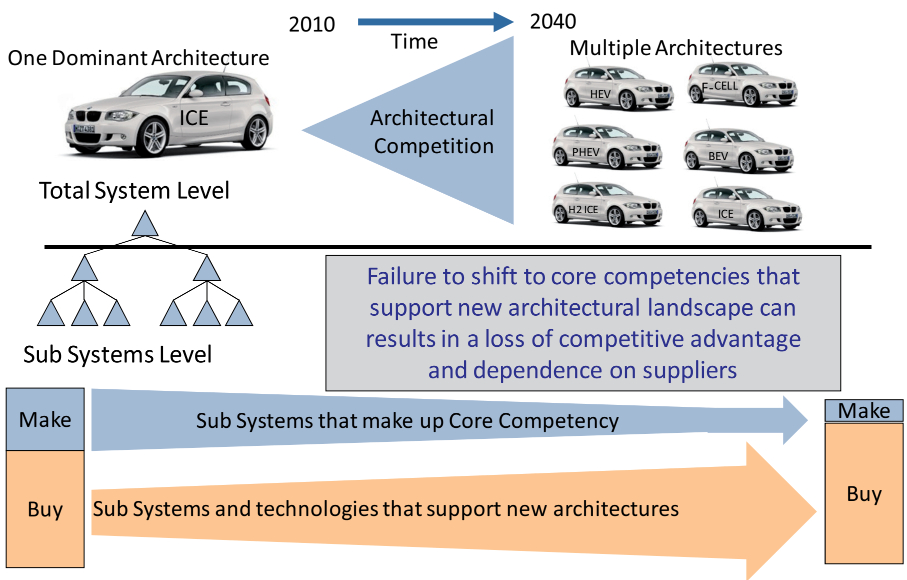

Figure 2-12 Architectural competition will require that major manufacturers reconsider where to build new core competencies and which system components to make or buy from suppliers. The bottom of the figure shows the effect of maintaining core competencies unchanged in a future market where architectural competition requires OEMS to buy expertise outside the firm resulting in a loss of competitive advantage for premium automakers.

Figure 2-12 shows that failure to incorporate core competencies that support new vehicle architecture markets, along with decisions of which system components to make or buy, affects the firms competitive positioning. At the moment, most manufacturers focus their competency in the optimization of the combustion engine. If this expertise goes unchanged, the firm will need to outsource parts that support new powertrain architectures to remain competitive in the new vehicle architecture market segments. The bottom of the figure shows the effect of maintaining core competencies unchanged in a future market where architectural competition requires OEMS to buy expertise outside the firm resulting in a loss of competitive advantage and eventual reduction of profit margins.

Transitional difficulties for major OEMs towards new vehicle architecture offerings will open a window of opportunity for small niche market entrants to fill the gap in the electric mobility segment. These new competitors could enter the market with niche-products that might not seem to compete directly with established manufacturing firms. By entering in new market segments not competed in the market, these new firms can circumvent major barriers to entry the large automotive firms have enjoyed for years. Additionally, government involvement can protect new small firms as they ramp up production by sponsoring new vehicle architecture market segments. More on the current increase in competition for electric mobility is presented in section 3.3.

2.4 Summary on Architecture Lifecycles and Competition

Taking a close look at automotive innovation history can serve useful in learning lessons that apply to the new competitive landscape in the automotive industry. This chapter built on basic concepts from innovation theory to explore the hypothesis that vehicle architectures composed from an aggregate of many technology innovations should also follow an S-curve lifecycle. A historical analysis of vehicle architecture performance indicates that the hypothesis is well founded. However, further analysis of this hypothesis is required given the long time horizon involved for complex product architectures and the variations that can be used in measuring performance.

The literature review in section 2.1 introduced the terms vehicle architecture, architectural competition and the typology of innovations. Vehicle architecture derives from product and system architecture definitions that encompass the link between overall product sub-systems and their functionality based on geometric, energy flow and a number of cross-functional vehicle requirements. Architectural competition refers to the customer’s affinity towards product architecture choices in the market. Finally, an architectural innovation is one of four types of innovation that involves the reconfiguration of known components in a new way to enhances new overall product performance.

The discussion in section 2.2 shows that automotive industry has entered a renewed stage of architectural competition similar to the early 1900s when steam, ICE and BEVs where competing for market dominance. Effective product development strategies differ considerably during times of architectural dominance and competition. During architectural dominance, incremental (or evolutionary) innovation has proven to be a successful development strategy. OEMs focus on core competencies needed to produce the dominant architecture and the continuous development of key component systems. Architectural competition forces OEMs to re-focus on the overall vehicle architecture strategy and the new linkage of sub-systems within the car as experienced by the auto industry during 1895-1915 and from 1998-until present.

Architecture lifecycles encompass many components with different levels of maturity in their lifecycle as seen in section 2.2.3. An improvement at the component level might have a strong effect in improving the performance of a subsystem but have little effect on the overall system. System architecture lifecycles can also be modelled using the S-curve framework used in technology or innovation lifecycle theory. Automakers that focus their product development activities on new or upcoming architectural competition can create competitive advantages over firms that continue on a path solely based on incremental innovation at a likely cost of reduced profits during the transition period as described in section 2.3.2.

The use of performance indexes can serve as a useful tool in showing trends in architecture development. Figure 2-7 shows that today's gasoline hybrid vehicles have not yet surpassed ICE cars in terms of overall performance. However, as battery technology and pricing of hybrid power train components improve hybrids, plug-in hybrids and electric vehicles will become more attractive.

Having entered a new age of architectural competition, it is important to attempt to map scenarios for the way ahead. Central to the discussion is defining the criteria for vehicle performance for future cars. Essentially the architectures that offer increased performance above all others will dominate the market.

In section 2.3.1 a further hypothesis postulates that the life of existing vehicle architectures can be extended by incorporating functions or features of competing architectures. The theory is qualitatively supported by examples from recent and past periods of architectural competition. One such example refers to diesel power trains with limited hybrid functions such as the "motor-start-stop" function that offers customers comparable or superior benefit over gasoline-hybrids. A preliminary assumption is that the life of any product architecture will be able to continue in the market so long as it delivers enhanced performance over other product architectures in fulfilling customer needs.

The current period of architectural competition has the potential to last several decades until dominance or co-dominant architectures are established. This period also brings in a new element of risk – Architectural risk. In section 2.3.2 Architectural risk is defined as the risk that particular product architectures will not prevail in the future market. Architectural risk affects all other forms of risk including strategic, market and functional risk.

Finally, during periods of architectural competition customers will have more choices to make. Not only must they choose car segment, body type, and price category, but also powertrain architecture. OEMs building new core competencies in electric mobility will require capital investments, skilled labor and a re-organization of the development process. A need to re-think the way cars are manufactured, sold and used can result from this change. Increased regulatory activity might favor some vehicle architectures over others, allowing small manufacturers to enter and establish niche markets.

3 Factors Affecting Vehicle Architectural Change

Complexity is the realization that many factors, directly or loosely related, have behavioral effects on the system in consideration. In the automotive industry products continue to increase in complexity despite efforts to avoid, reduce or control complexity in product design. Lindemann and Maurer describe the sources of complexity to arise from the market, product, organization and the processes in developing products [LINDEMANN, U. et al. 2008, p.4].

This chapter focuses on factors that affect vehicle architectural change that add to the complexity of the design situation. These include environmental considerations, government regulations, customer needs, competition in the market and the manufacturing firm's business strategy. The developments in these areas are shaping the market for the introduction of hybrid and electric vehicle architectures.

3.1 Environmental Considerations

The environmental challenges the world is facing on global warming and the scarcity of oil are presented here as factors that influence change in vehicle architecture. These considerations have risen in global importance throughout the last two decades focusing primarily on the reduction of greenhouse gas (GHG) emissions and the search for alternatives to the combustion of fossil fuels.

The signing of the Kyoto Protocol in 1997 marked the first multinational agreement where 37 industrialized countries and the European Union agreed on goals for reducing GHG emissions through local law implementation. The protocol required a 5.2 percent reduction from 2008-2012 of six GHGs in reference to their 1990 levels. The six GHG include: carbon dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), Sulphur hexafluoride (SF_6), hydro fluorocarbons (HFCs) and perflourocarbons (PFCs) [GERL 2002]. Today 182 countries are members of the Kyoto protocol for which the goals of GHG reduction are implemented through local laws.

The Kyoto Protocol is significant for the transportation industry as it represents the first agreement where legally binding actions have been set forth to stabilize the amount of GHG production. This agreement stems from environmental considerations established through scientific research on global warming presented in section 3.1.1. Its potential renewal in 2012 will generate a need for cars that emit less CO_2 emissions and burn less petrol.

In section 3.1.2 the scarcity of petrol fuels is addressed. A self-performed analysis of Peukert's peak oil theory is discussed with emphasis on repercussions on vehicle architectural change. Moving away from petrol fuels has a secondary effect of reducing GHG emissions produced from mobile power plants and will only imply a reduction in GHGs if the emissions from the current energy production mix are reduced by the use of cleaner fuels.

3.1.1 Global Warming and Anthropogenic Greenhouse Gas Emissions

Values determined from ice cores spanning many thousands of years have shown that human activities since the start of the industrial revolution of the 1750s have increased the levels of green house gases in the atmosphere at an alarming rate. Scientists believe that anthropogenic greenhouse gas (GHG) production can be linked to increases in global temperatures of 0.74⁰C ± 0.18⁰C over the past century [Solomon et al. 2007].

The increase in temperature results from the fact that GHGs remain trapped in the atmosphere creating a so called "greenhouse effect." This GHG layer allows solar radiation from space to enter the atmosphere but traps infrared radiation emitted back from the earth. The entrapment of infrared radiation energy results in an average rise in temperature of the earth's surface and lower atmosphere. The effect is not all bad. In absence of the green house effect, the earth's average surface temperature of ca. 14 °C (57 °F) could be as low as −18 °C (−0.4 °F), the black body temperature of the Earth [Kushnir 2000]. However, the warming effect is amplified with the increasing rate of GHGs present in the atmosphere. The effects of rising average temperatures include the melting of the polar ice caps and an increase in sea levels that can adversely affect our eco-system.

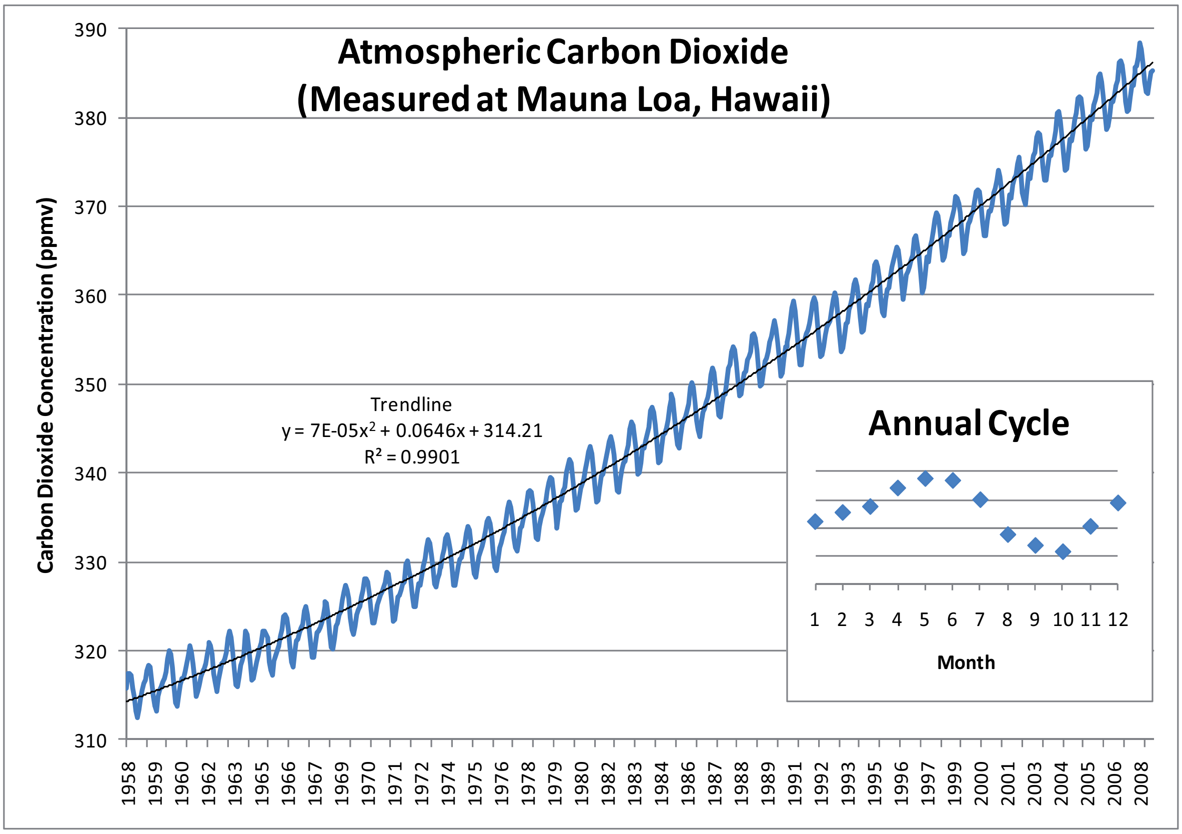

Figure 3-1 Current atmospheric CO_2 measurements (NOAA). Annual cycles reflect seasonal fluctuations due to plants removal of atmospheric CO_2 between late spring and summer months for the Northern Hemisphere[Data taken from KEELING et al. 2009].

Measurements of atmospheric CO_2 concentrations from the National Oceanographic and Atmospheric Administration (NOAA) at the Mauna Loa, Hawaii station presented in Figure 3-1 show an increase of roughly 16.25 parts per million per decade since 1960. As of 2009, the current atmospheric concentration in the Northern hemisphere averages 385ppm. The figure shows that the rise in CO_2 concentration follows a quadratic growth function when taking the average values for each year of measurement. Each year the CO_2 concentration measurements follow a sinusoidal pattern due to more removal of CO_2 during the late spring and summer months as opposed to the fall and winter months where the concentration rises as shown in the annual cycle box in Figure 3-1.

The United Nations Intergovernmental Panel on Climate Change (IPCC) has modeled GHG levels and its effects on global surface warming resulting in six possible scenarios. These scenarios represent possible GHG stabilization values in ppm in which an effective increase in GHG production is mitigated through a change in human behavior.

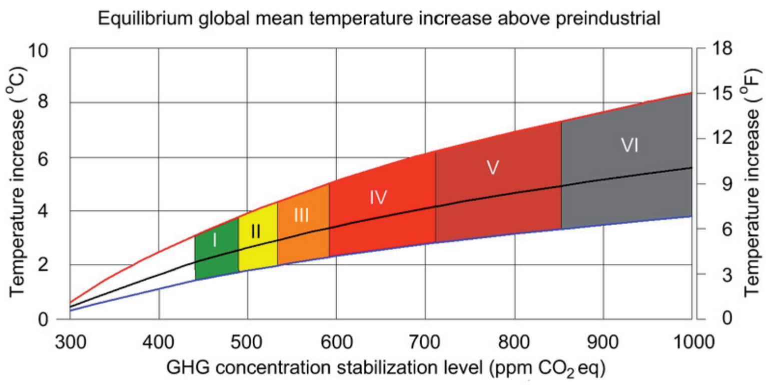

Figure 3-2GHG concentration stabilization levels (according to IPCC)

Figure 3-2 shows the six stabilization range scenarios for GHGs and the effects such increased levels might have on global surface temperature warming and rise in sea levels. The roman numerals in the figure represent each of the six scenarios with the respective temperature and GHG stabilization concentration range. The color scheme represents the risk involved with each stabilization range; green is the least damaging whereas gray is the most damaging.

The first three scenarios are the target scenarios for the IPCC. These scenarios effectively limit the global warming effect to no more than a five degrees Celsius increase via a large number of measures taken by member countries. Should these measures not deliver the desired stabilization effects, scenarios four through six, result in catastrophic consequences with temperature increases over five degrees Celsius.

It is important to note that both past and future anthropogenic carbon dioxide emissions will continue to contribute to warming and sea level rise for more than a millennium, due to the timescales required for removal of this gas from the atmosphere. There is little debate on whether a need exists in slowing the increase of anthropogenic GHGs production, the debate lies on which measures are going to be most effective. For example, a large regulatory focus in the US and Europe has focused on reducing automotive new fleet emissions although Figure 1-3 shows that transportation results in only roughly 16% of CO_2 generation. Ironically, controls for reducing the power generation mix CO_2 responsible for more than 40% are arguably less aggressive.

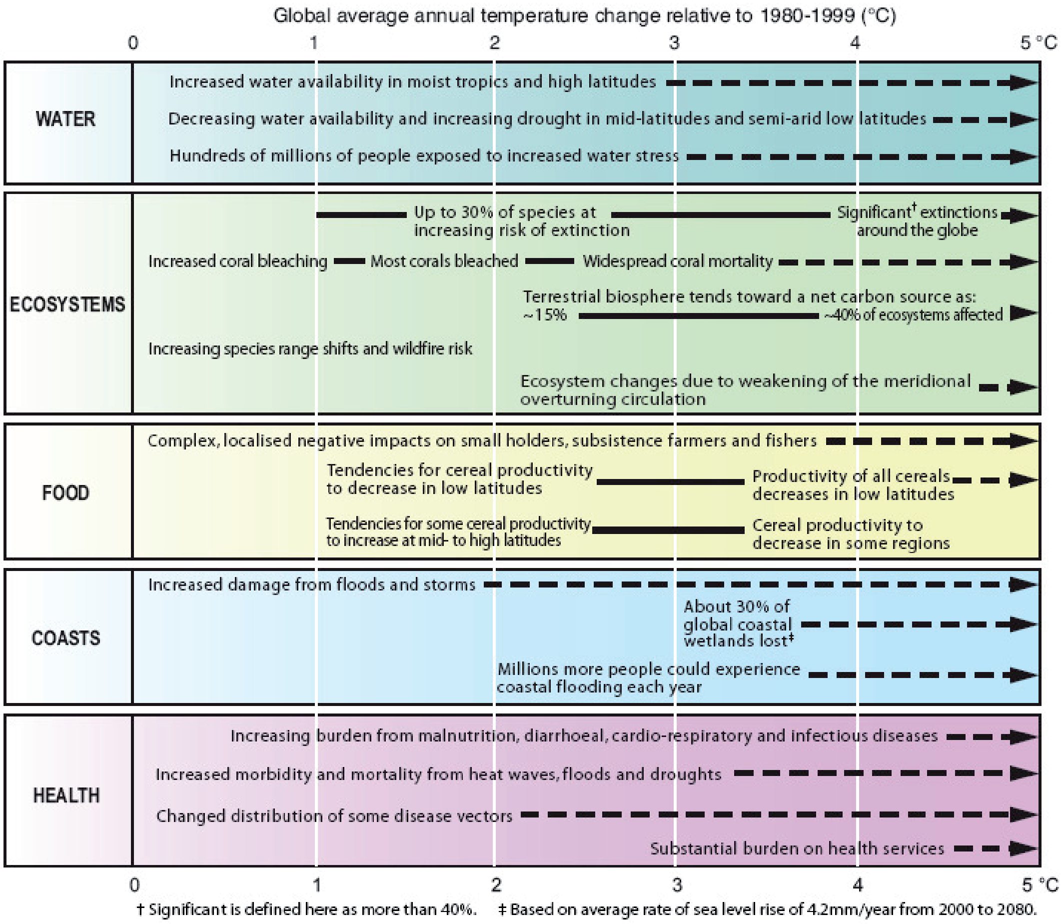

Figure 3-3 Examples of impacts associated with rise in average global temperatures[according to IPCC 2007]

Figure 3-3 provides insight on what adverse affects can be expected on water, ecosystems, food supply, coastal regions and implications on human health [IPCC 2007]. The effects presented are based on panel discussions with experts and in some cases empirical evidence and simulations. The figure shows the impact within the first three target stabilization scenarios presented by the IPCC.

Ecosystems begin to show adverse changes with a 2 degree rise in temperature as the first major area affected. With a 3 degree increase, coastal areas are impacted heavily with flooding and storms and about 30% of the world's wetlands are expected to recede. Human health issues begin to blossom with mortality due to heat waves, and changed distribution of some disease vectors bringing about a substantial burden on health services. The food supply starts showing effects as well with a decrease in cereal productivity at low altitudes. Finally, water becomes a scarcer resource in many parts of the world leading to stress in the fresh water supply.

These scenarios are important to consider and discuss openly as their realization could lead to a chain of catastrophic consequences. The option to wait and see if these hypothesized scenarios are truly realized can lead to an extremely costly future outcome. Transportation emissions, although not the leading source of GHG emissions leading to the global warming problem is perhaps one of the first GHG emission sources that can be curbed to produce less emissions in the future. Law makers, local activists and the market are already making significant advances in pushing car emission levels lower.

3.1.2 The World "Peak Oil" and the End of Cheap Fuel

How long can the world rely on petroleum as the main source of fuel to power automobiles? This sustainability question is best addressed by analyzing current supply and demand for oil worldwide.

Demand Side - Table 3-1 shows projections for the growth of worldwide vehicles in operation, personal transportation activity and transport related fuel use. The figures show an increasing trend for personal mobility in terms of passenger-kilometers travelled per year, with significant contributions from vehicles introduced in developing economies in India, China and Latin America. The projected stock of light duty vehicles worldwide is expected to continue increasing to 2 billion by 2050.

Table 3-1 Sustainability Projections on Personal Mobility [adapted from WBCSD 2004, p.8]

Year	2000	2010	2020	2030	2040	2050	Average Annual Growth Rate 2000-2050
Worldwide Number of Light Duty Vehicles in Operation (billions)	0.6	0.8	1.1	1.3	1.6	2	2.4%
Worldwide Light Duty Vehicle Use (Trillions of Passenger Kilometers/year)	32	36	45	52	60	73	1.70%
World Trans. Related Consumption (Trillions of Liters Gasoline Equivalent)	2.2	2.6	3.2	3.8	4.3	5	1.70%

By 2010 the transport related fuel use including diesel, gasoline, and jet fuel is projected to account for 2.6 trillion liters of gasoline equivalent (which is roughly 68 million barrels per day production)[4]. Given the current 2009 production rate of 85 million barrels per day worldwide according to the US Energy Information Agency (EIA) [EIA 2009a], roughly 80% of production capacity is used in satisfying global transportation needs alone. The projections in Table 3-1 suggest that production will need to continue its increase in order to meet demand at a rate of 1.7% per year.

Supply Side – Figure 3-4 shows world oil production figures according to the International Energy Agency (IEA) statistics and the German Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenshaften und Rohstoffe - BGR). As of 2009, the world supply of oil has generally met demand needs over the past two decades despite the growth in demand from the transportation sector. However, meeting the needs of a 1.7% growth rate per year going forward will be a challenge as most experts expect world oil production to peak sometime within the next 15-30 years, with most models

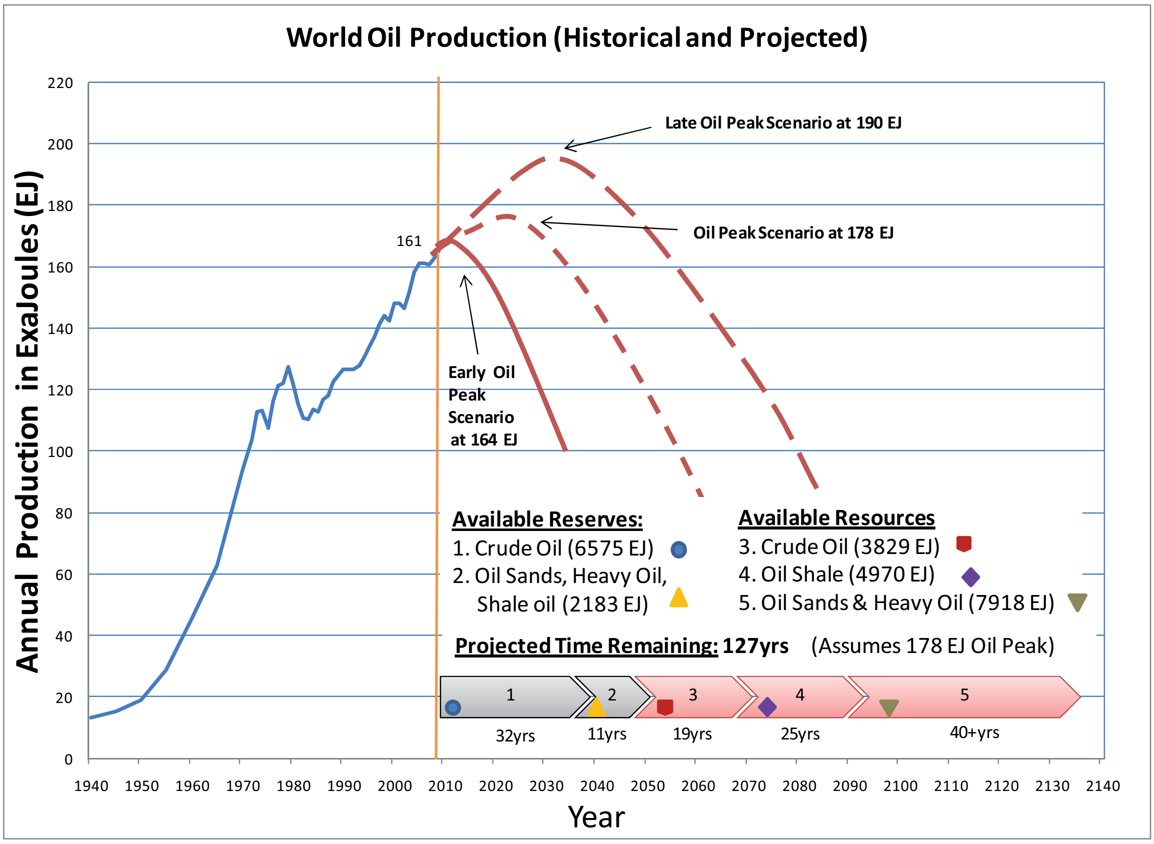

Figure 3-4 Depiction of various "World Oil Peak" scenarios. Historical statistics taken from the US Energy Information Agency [EIA 2009a](left side) and projections calculated based on statistics from the German Bundesanstalt für Geowissenshaften und Rohstoffe [BGR 2009](right side).

[4] 2.6x10[12] liters of gasoline equivalent / (105 liters per barrel of oil x 365 days per year) = 67.8 million barrels per day

suggesting an early peak as early as 2010-2013 [FOUCHER 2009].

Peak oil is the point in time in which oil production increases no longer occur. Unless the demand for oil can peak jointly with market production, demand will outstrip supply after the oil peak, ultimately raising oil prices. The higher the unmet demand is, the greater the increase effect on prices should be. At higher prices, oil companies have larger incentives to engage in more cost-intensive oil extraction techniques in order to satisfy the excess demand.

The left hand side of Figure 3-4 displays the historical world oil production, whereas the right side shows the near and long term projections of oil supply. The unit of measure for oil energy is in Exajoules (1x10^{18} Joules) per year[5]. The available *oil reserves* represent known oil fields that can be extracted with the current technology and cost levels today. In addition, *oil resources* are demonstrated quantities of oil that cannot be recovered at current prices and technology but might be recoverable in the future, as well as quantities that are geologically possible but not demonstrated [BGR 2009].

Given the figures of available oil reserves and resources from the BGR and the current consumption rates from the IEA, a conservative scenario was modelled with an oil peak in 2018 at 230 EJ (middle curve in Figure 3-4) suggesting that world has 43 years of oil reserves remaining and just over 84 years of oil resources available. Not included in these numbers is the increasing role of unconventional liquid fuel resources such as coal-to-liquids, gas-to-liquids and bio fuels.

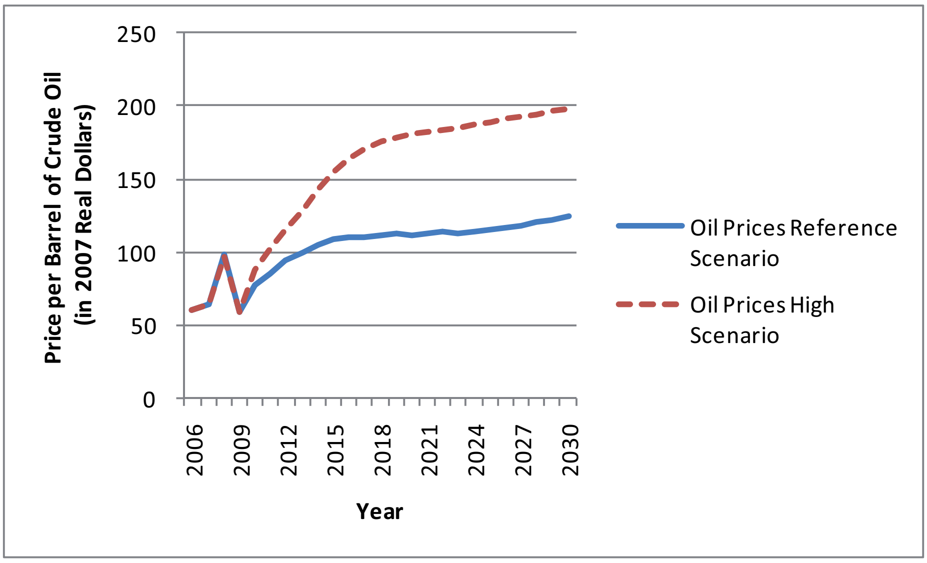

Figure 3-5 Price of Oil projected development 2006-2030 [adapted from DOMAN et al. 2009]

[5] According to the BGR, 1 EJ is roughly equal to 525.07 million barrels of oil per day (for reference 1 million barrels = 158, 987 m^3; so 525.07 mbbl = 83.5 million m^3). However, energy conversions to barrels of oil or tons of coal equivalents vary by quality and energy content of the oil considered. Thus the 2007 production figure shown in Figure 3-4 of 161 EJ represents roughly 84,403 mbbl.

According to the EIA's 2009 International Energy Outlook, the price in 2007 inflation adjusted real dollars of oil is projected to rise from $61 per barrel in 2009[6] to anywhere between $110 and $195 per barrel[7] in 2030 as shown in Figure 3-5[8] [DOMAN et al. 2009].

Given supply and demand analysis presented, significant increases in oil prices from the 2006 levels will most likely take place. However, the price increase at the pump to consumers will ultimately be the significant factor in changing consumer behaviour and making alternative car architectures more attractive.

3.2 Government Regulations

A large factor affecting vehicle architectural change is local government regulations in the leading vehicle markets around the world. Much of the environmental considerations discussed in section 3.1 are reflected in these laws that limit the GHG emissions of new cars together with overall new car fleet fuel consumption.

Figure 3-6 shows the unequivocal downward trend in emissions regulations worldwide with Japan, the European Union (EU) and the US (California) leading in efforts going beyond 2010 [PEW CENTER 2006]. The data presented was translated in some cases from fleet fuel

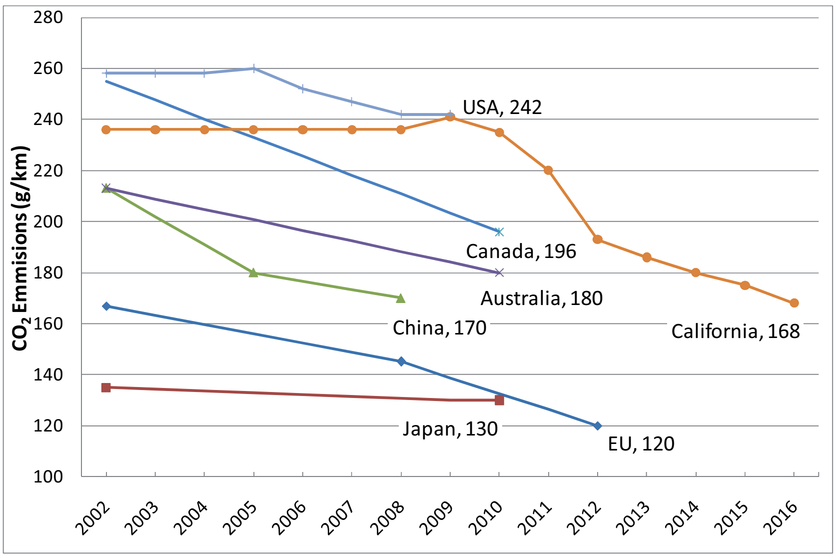

Figure 3-6 CO_2 Emissions Regulations in Various Markets adapted from Pew Center for Climate Change

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[6] Equivalent to $0.38 per liter; 1 barrel of oil is equivalent to 159 liters of oil

[7] $0.69 per liter and $1.22 per liter respectively

[8] As a reference the mid-July 2008 the 2007 real dollar price per barrel was at $100 ($147 in nominal dollars).

consumption requirements to allowable fleet CO_2 emissions. These conversions should be taken with caution as regulatory cycles vary considerably between countries. For example, a 2009 BMW 328i tested with the US test cycles patterns is rated as having CO_2 emissions of 180 g/km, whereas a similar car tested using the less realistic European NEDC cycle results in a value of 160 g/km. The difference is in the test cycle's dissimilar profiles of speed versus time.

For purposes of comparison, CO_2 emission values for ICE cars are directly proportional to fuel consumption values. For gasoline engines 140g/km are equivalent to a fuel consumption of approximately 6 liters per 100km or 39 MPG[9]. For diesel engines the value lies at 5.3 l/100km or 44.3 MPG due to the higher energy content in diesel fuel.

3.2.1 United States CAFE Standards

On April 22, 2008, the U.S. National Highway and Transportation Safety Administration (NHTSA) released final draft regulations outlining new U.S. Corporate Average Fuel Economy (CAFE) standards for 2010 through 2015. The rules are part of the Energy Independence and Security Act of 2007, which requires that U.S. light vehicles will have to achieve a CAFE standard of 35 MPG by 2020, versus 25 MPG in 2010. More than half of this (31.6 MPG) improvement is to be achieved by 2015[10].

The NHTSA estimates the cost of compliance with the 2015 standards at $47 bn. GM estimates that achieving the U.S. CAFE standard of 35 MPG by 2020 will cost the industry $100 billion per year ($5,000 per vehicle). And given the 5-7 year product cycles that prevail in the industry, automakers have begun to consider the technologies that will be required to meet these standards, and those beyond this timeframe. The director of the EPA's Office of Transportation and Air Quality, indicated in an April 2009 speech that passenger cars and light trucks may have to average 75 MPG (3.14 l/100km) by the 2030s in order to achieve a proposed 50-80% cut in greenhouse gas emissions by 2050 using 2000 GHG levels as a reference.

3.2.2 California Zero Emission Vehicle (ZEV) Mandate

The California ZEV law is perhaps the most progressive regulation worldwide in mandating the introduction of new vehicle architectures. This law is responsible for incentivizing significant technological advances in hybrid electric powertrain technologies. The discussion in this section describes the general points of the law to illustrate how government initiatives can mandate a change in vehicle architecture.

The Zero Emission Vehicle (ZEV) regulation was first adopted in 1990 as part of the Low Emission Vehicle Program. Although it has been modified several times over the years, it still remains an important program for California's air quality and has spurred many new

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[9] 1 liter per 100km = 235.21mpg

[10] 25 MPG = 9.4 l/100km, 35 MPG = 6.72l/100km; 31.6 MPG = 7.44 l/100km

technologies that are being driven on California's roads. The California Air Resources Board (CARB), the authority behind the ZEV law has played a leading role in reducing vehicle emissions and improving fuel efficiency. Its efforts have been emulated in several states depicted in figure 3-7 and is expected to trigger similar national federal standards by the US Environmental Protection Agency (EPA).

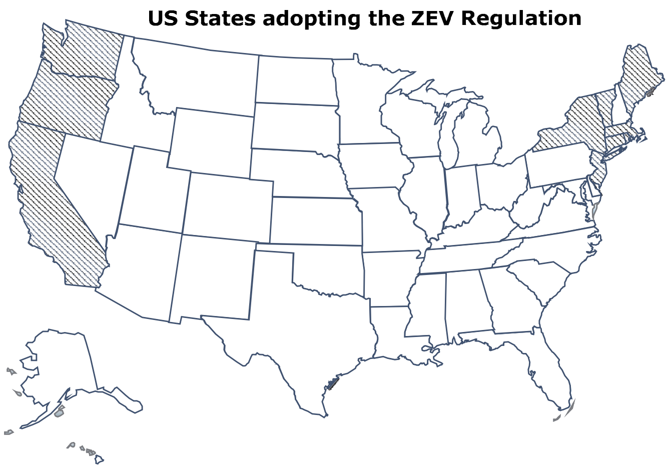

Figure 3-7 The California ZEV Regulation has been adopted so far by 10 US States. These include: California, Oregon, Washington, Maine, Vermont, New York, Massachusetts, Rhode Island, Connecticut and New Jersey

The ZEV law resulted as a direct response to years of smog problems in major urban areas in California, which for many years have exhibited the worst air quality levels in the US. The regulation requires that auto manufacturers incorporate "emissions-free" vehicles in a percentage of their new car fleet for sale, delivery or demonstration.

In the September 2009 revision of the law, this percentage is set to increase in 3 year steps from 11% in 2009 to 16% by 2018. Failure to meet this law would result in a system of fines for manufacturers per vehicle not in compliance and an eventual bar from the sales of cars within the state as the most severe consequence.

The intent of the California law is to establish a market for battery electric vehicles and fuel cell electric vehicles with zero tailpipe emissions and encourage manufacturer's efforts in developing cleaner vehicle technologies. The fulfillment of this ZEV fleet percentage has been a matter of debate since the law's first conception in the 1990s. Auto manufacturers filed and won a federal law suit to stop the ZEV mandate in 2000, claiming that the state could not hold stronger emission standards than the federal law or force the selling of vehicle technologies where no market existed to buy them.

The California regulation was thus amended to allow for phase-in periods where OEMs could develop and introduce new technologies within conventional cars designated as partial zero emission vehicles (PZEV) through a system of credits in lieu of ZEVs vehicles. The law was also scaled back in other areas. For example, auto manufacturers selling less than 4500 vehicles per year were exempt from the law altogether.

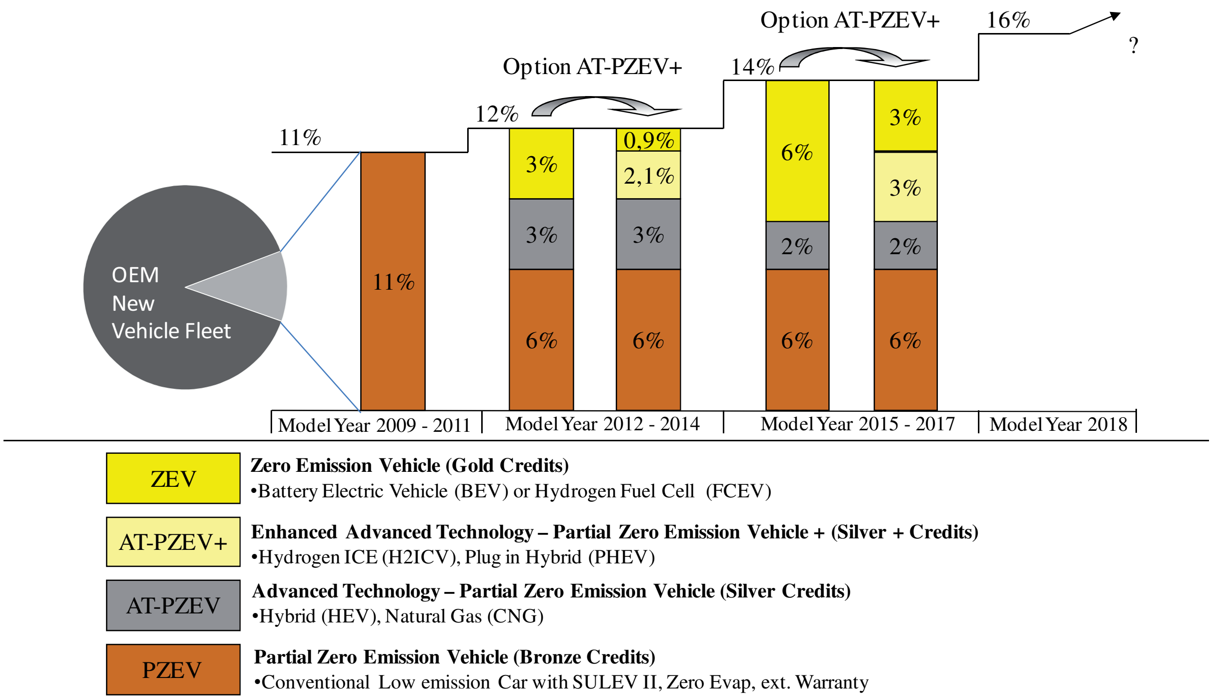

Figure 3-8 California Zero Emission Vehicle law [adapted from CARB 2007]

Figure 3-8 shows the 2009 revision of the CARB mandate showing the various pathways to fulfill the ZEV mandate. First it is important to start with the terminology of the law:

Zero Emission Vehicle (ZEV): Gold Credits – This category includes only BEV or FCEVs. The law designates one “gold credit” for each of these vehicles sold in the market or leased in a test fleet to customers. Each manufacturer that wants to do business within the state must sell a percentage of “gold credit” vehicles within its new vehicle sales fleet. Because the market for ZEVs is currently under development, the law allows for equivalent sales of “silver +,” “silver” and “bronze” credit vehicles during specified 3 year intervals starting in 2009. These equivalent formulas will be phase out by law makers once the ZEV market is established.

Enhanced Advanced Technology – Partial Zero Emission Vehicle + (AT-PZEV+): Silver + Credits – This vehicle category includes hydrogen ICE (H2ICV) and Plug in Hybrid vehicles.

Advanced Technology – Partial Zero Emission Vehicle (AT-PZEV): Silver Credits – This category includes Hybrid and Natural Gas vehicle architectures.

Partial Zero Emission Vehicle (PZEV): Bronze Credits – This category is made up of conventional ICE cars with low emissions. The standard for low emissions is covered by the

California Super Ultra Low Emission Vehicles (SULEV II) standards[11]. In addition, PZEV cars are designed to not generate evaporate emissions from the gas tank, and have a lifetime warranty for all emissions relevant components. According to Figure 3-8, for cars sold from 2009 – 2011, the entire ZEV percentage can be satisfied with PZEV "bronze credits." In following years PZEV cars are limited to 6%, thus forcing manufacturers to introduce a mix of gold, silver + or silver credit earning cars.

Table 3-2 Projected Impact of the CARB ZEV Mandate 2009-2014 [according to CARB 2007, CARB 2009]

	2009-2011	2012-2014
Number of pure electric vehicles (BEV, FCEV)	2,500	7,500-25,000
Number of plug-in hybrid vehicles	0*	0-58,000
Number of conventional hybrid vehicles	> 150,000	~150,000
Number of ultra-clean gasoline vehicles	> 1 million	> 1 million
* The plug-in hybrid category does not go into effect until 2012. Prior to 2012 automakers can still receive credits for producing PHEVs under the conventional hybrid classification		

Table 3-2 shows the estimated impact the ZEV law will have in California. Between 2009 and 2011 the values of this 2007 projection estimate over 150,000 new hybrid vehicles. The law has been delivering more than planned. California was the leading state for hybrid sales with 91,417 in 2007 [HYBRIDCARS 2008], 74,932 in 2008 [HYBRIDCARS 2009], and 55,553 in 2009 [HYBRIDCARS 2010]. From 2012-2014 the law expects similar performance in HEVs along with up to 58,000 PHEVs.

The ZEV law has already obtained worldwide recognition as an example of how regulations can bring about vehicle architectural change. Because the law has been adopted by an additional 10 US states starting in year 2012, more than double the amount of hybrids and electric cars in California will be required, generating a generous market niche. The ZEV regulations will thus place millions of new car architectures on US roads and is a further catalyst for change in every major car market worldwide.

3.2.3 European Regulations

The European regulations take a less prescriptive approach to those in California, providing manufacturers more flexibility on which specific technology should be implemented. At the same time, the EU laws are more stringent in the reduction of new car fleet CO_2 tailpipe emissions (and fuel consumption accordingly) offering a series of incentives or taxes as shown in figure 3-9. Despite the technological flexibility, the European

[11] SULEV II emission standards require less than 0.062 g/km of HC+NOx, 0.006 g/km Particulate Matter, 1.3 g/km Carbon Monoxide (CO)

standard projects for an average of 130 g/km CO_2 for new car fleets from 2012-2015, a measure that can only be achieved through wide introduction of partial or emission free solutions such as those offered by hybrid and electric cars.

The European goal roughly translates to cars with 45 miles per gallon, well above the US average light duty vehicle current average of 20.1 MPG [BANDIVADEKAR 2008 p.16]. The industry estimated cost of compliance with these regulations is estimated in the $23 billion range and is expected to increase as regulators push for reductions in CO_2 emissions beyond the 100g/km mark by 2020 [LACHE et al. 2008 p. 5].

Table 3-3 European Union tailpipe emission standards from 1992-2014

	Euro 1		Euro 2		Euro 3		Euro 4		Euro 5		Euro 6	
Emissions	from 1. Jul. 1992		from 1. Jan. 1996		from 1. Jan. 2000		from 1. Jan. 2005		from 1. Sep. 2009		from 1. Sep. 2014	
CO	3,160	3,160	2,200	1,000	2,300	640	1,000	500	1,000	500	1,000	500
(HC + NOx)	1,130	1,130	500	700 / 900*		560		300		230		170
NOx					150	500	80	250	60	180	60	80
HC					200		100		100		100	
NMHC		180		80 / 100 *		50		25	68	5	68	5
PM									5*		5*	
Tax rate [€] pro 100 cm³	15.13	28.55	7.36	17.25	6.75	15.44	6.75	15.44	**Tax rates not published yet**			

Emissions in **mg/km** | Gasoline | Diesel (shaded) | * Direct fuel injection

HC = Hydro Carbon
HC+NOx = Sum of Hydro Carbons and Nitrogen Oxides
NOx = Nitogen Oxide

CO = Carbon Monoxide
NMHC = Non-Methanous Hydro Carbons
PM = Particulate Matter

Similar to regulations in the US and Japan, the EU tailpipe emission controls requires that new cars undergo a test driving cycle to determine a tax or incentive application as shown in various member states in Figure 3-9. The EU norms have followed a steady reduction of non-CO_2 combustion products based on the scheme presented in Table 3-3. The greater the compliance rates, the lower the amount of taxes charged and vice versa.

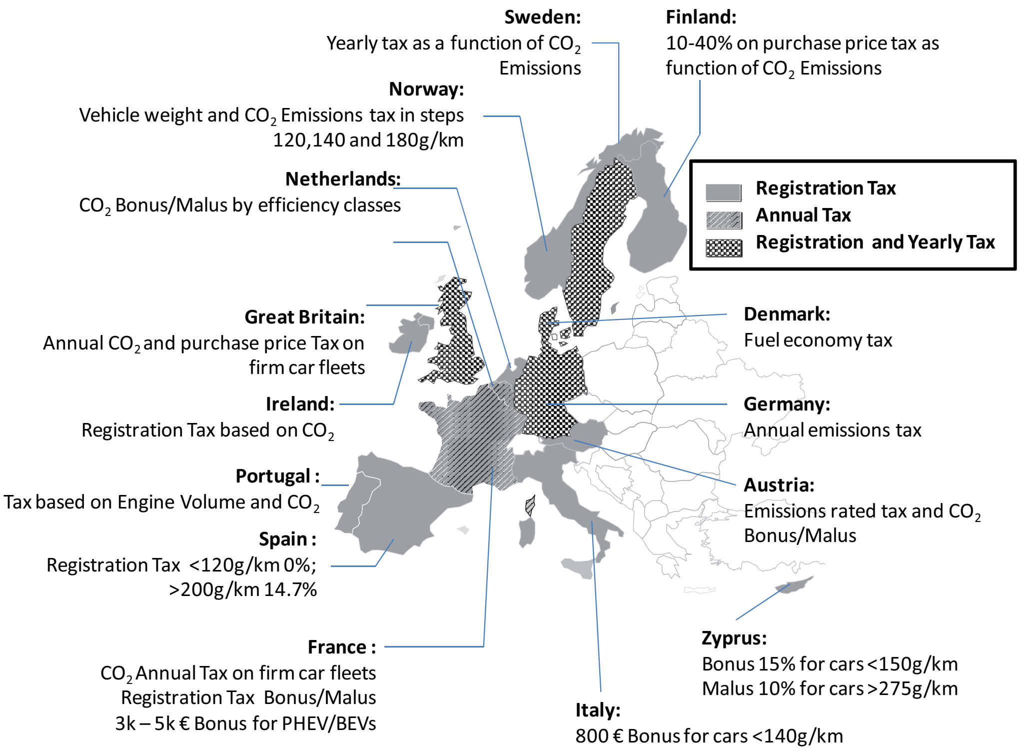

Figure 3-9 Summary of European CO_2 Reduction Regulations

The EU wide CO_2 / fleet fuel consumption regulations in Europe are dependent on vehicle curb weight. The 2009 regulations set the allowable emission levels to a linear relationship between curb weight and CO_2 emissions, such that the average passenger car requires 160 g/km as shown in Figure 3-10.

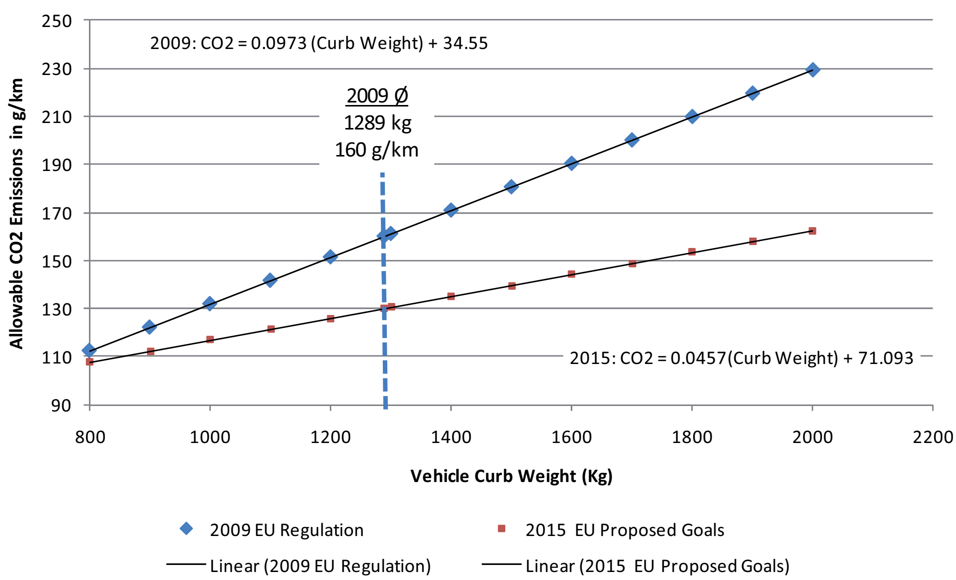

Figure 3-10 Proposal for EU CO_2 Limits for 2012

The slope of the linear relationship determines how strict the standard is for vehicles above and below the average curb weight. Larger luxury limousines that usually exhibit higher fuel consumption are allowed higher than average emissions and smaller cars are held to tougher standards since they possess a weight advantage.

The EU's new goal is to set fleet emission standards to130 CO_2 g/km by 2012 with an additional 10 gram reduction coming from complementary measures including greater use of biofuels. The new linear relationship has a lesser slope (refer to Figure 3-10), meaning large cars will need to make stronger advances in reducing fuel consumption than smaller cars. The new proposal accepted by the European Auto Manufacturers' Association also stipulates the following [ACEA 2009b]:

- 65% of new cars will have to comply with the emission requirements in 2012, 75% in 2013, 80% in 2014 and 100% in 2015
- Eco-innovations will count for up to 7 grams.
- There are special provisions for niche manufacturers.
- A new objective of just 95 grams per kilometer was fixed for 2020. This will be conditional on an impact assessment.
- Penalties will be imposed on a sliding scale. Manufacturers that exceed their target by more than 3 grams will pay 95 euro per excess gram. Lesser transgressions will be charged between 5 and 25 euro. From 2019, penalties will always be 95 euro per gram (subject to review in 2013).
- In 2014, there will be an evaluation of the average mass (weight) development of cars over the previous three years; with a possible adjustment of the CO_2 targets implemented in 2016. There will be a review every three years thereafter.

3.2.4 Summary of Government Policy Options

In addition to the specific laws referred to in the previous sections, there exist a number of other policy measures that are being implemented to reduce fuel consumption and emissions of new vehicles. These measures normally provide an economic incentive, a regulatory requirement, public investment or a combination of these strategies [BANDIVADEKAR 2008, p. 21].

Table 3-4 Government Policy Options to effect change towards new vehicle architectures (E-Economic Incentive; R-Regulatory Requirement; I-Public Investment)-[Adapted from BANDIVADEKAR 2008]

Policy Measures	Type of Policy E	R	I	Anticipated Response/Action	Example
Retiring Old Cars	x	x		Provide incentive to retire old vehicles with higher fuel consumption for new vehicles with lower fuel consumption	USA: "Cash for Klunkers" ; EU: Abwrackprämie
Government R&D Incentive			x	Provide Government funding for the development of new car architectures that are more fuel efficient	USA: "Freedom Car - DOE"
Subsidies/Tax incentives	x		x	Provide incentives to purchase more fuel efficient vehicles	USA: "Hybrid tax exemptions"; France: 5000Euro consumer subsidy for electric cars and PHEVs
Pay-at-the pump Tax	x			Create a large cost of ownership difference between fuel efficient and non-fuel efficient cars; Provide incentives for the use of certain fuels	EU: ca. 40-60% Tax on Fuel; Difference in taxation between Diesel and Gasoline
Emissions Tax	x			Increase the cost of operation and reduce vehicle miles traveled	EU: Auto Registration Tax and Yearly Emissions Tax
Carbon Tax (Economy Wide)	x			Provide incentive to purchase and use more fuel efficient vehicles by incorporating the externality costs to society	USA: Proposed "Cap and Trade" for CO2 emissions, EU: Carbon tax and credits trading system (only energy producers not implemented in auto industry)
Bonus - Malus (Feebates - a system of fees and rebates based on fuel consumption of vehicles)	x	x	x	Reward those that purchase and use more fuel efficient and tax those that continue to drive less fuel efficient cars	China: Fuel Consumption Tax - higher % of retail price tax to OEM based on higher engine displacement volume
Tradable Fuel Consumption Fleet Credits	x	x		Increase flexibility for manufcaturers in achieving fleet emission goals	USA: CAFE tradable fuel consumption Credits
Attribute based Standards		x		Incorporate fuel efficient technologies, reduce average vehicle weight	EU: Weight based CO2 standards
Tailpipe Emissions standards based on driving cycles		x		Develop a basis for comparison amongst fuel efficient technologies for customers,	USA: FTP72 Cycle, EU: NEDC Cycle
Environmental Zones and City Mout	x	x		Create reduced CO2 zones in urban areas by imposing a fee on cars with high emmisions while allowing only fuel efficient or electric cars to drive unrestricted at no cost	GER: Environmental zones in urban areas where only cars are categorized by emissions class can enter the city; UK: London City Mout - tax for non hybrid and electric cars entering the city limits

Table 3-4 provides a summary of government policy options currently being implemented in various countries with the intent of reducing fuel consumption and CO_2 emissions and setting the conditions for the entrance of new vehicle architectures to market.

3.3 Competition in a New Automotive Market

Over the past decade, Globalization has led to the entrance of more automotive suppliers and the steady creation of new vehicle market segments. As segments become saturated with competition, OEMs have less influence in influencing prices. For example, in China through July 2009, sales of vehicles eligible for state support soared 49%, but many of these cars earn manufacturers as little as $100 each, according to research from J.D. Power & Associates. This example is similar to government incentives in the US and Europe for retiring old cars resulting in increasing sales, yet tiny profits. [ROWLEY 2009].

As the lower priced segments become more competitive, OEMs look towards differentiation opportunities in segment creation that can achieve higher pricing and profits.

Table 3-5 Vehicle Segment Classification Sub-Categories

Size Class	Doors	Type	Transmission	Drive	Architecture	Fuel Type
Mini	1-Door	Wagon	Manual	All-wheel	Spark Ignition ICE	Gasoline
Economy	2-Door	Limosine	Automatic	Front Wheel	Compression Ignition ICE	Diesel
Compact	3-Door	Convertible	CVT	Rear Wheel	Micro Hybrid	CNG
Intermidiate	4-Door	Open Air All Terrain	Hybrid	4-Wheel	Full Hybrid	LPG
Standard	5-Door	SUV	Electric	Electric	Plug-in Hybrid	Fuel Mix
Full Size	6-Door	Pick up	...	...	Electric	..
Premium	...	Coupe			Fuel Cell Electric	
Luxury		Passenger Van			...	
Oversize		Roadster				
...		Crossover				
		...				

Table 3-5 shows the multitude of product offering categories that can be combined to create new cross-over product placement segments including new architecture technologies and

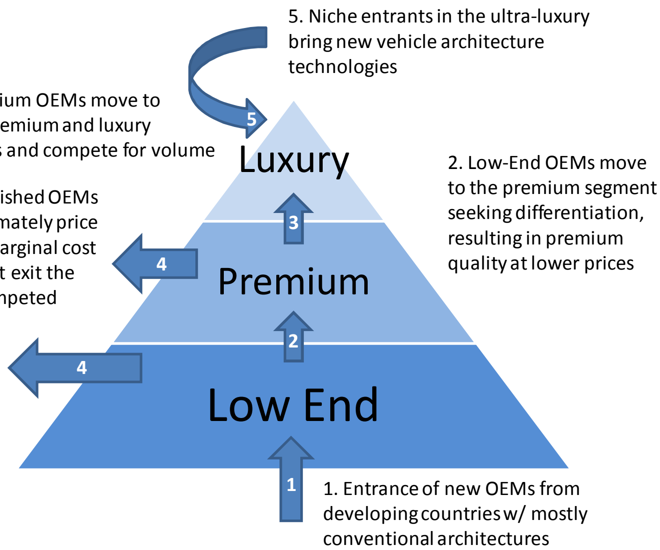

Figure 3-11 Increased Competition resulting in a more dynamic market with entrance and exit of OEMs featuring both conventional and new technologies

alternative fuel offerings.

Figure 3-11 shows that as more mature suppliers move out of the lower end of the market pyramid, the premium or high-end markets become more crowded. This heightened competition is manifested in lower pricing for high quality product features and technologies, along with the exit of established OEMs from the market altogether.

Going forward, differentiation in the premium market will grow in importance as competition grows stronger. Outside of innovative outer designs, premium car makers differentiate themselves primarily by incorporating new features and technologies in their cars or by creating new cross over categories to those listed in Table 3-5. Maintaining a level of differentiation requires continued research and development to improve on existing car offerings.

In recent years, manufacturers looking to establish themselves in new or less crowded market spaces have turned to the electrification of powertrains through private and government investment. In 2009, France alone committed over 1.5 Billion Euros towards bringing 2 million electric and hybrid vehicles to market by 2020, with Renault -Nissan committing an additional 4 billion in research and development [Frost 2009]. The introduction of new vehicle architectures is a costly undertaking. However, the benefit of differentiation has already attracted a new niche market that is projected to capture increasing market share and further open new complementary industries.

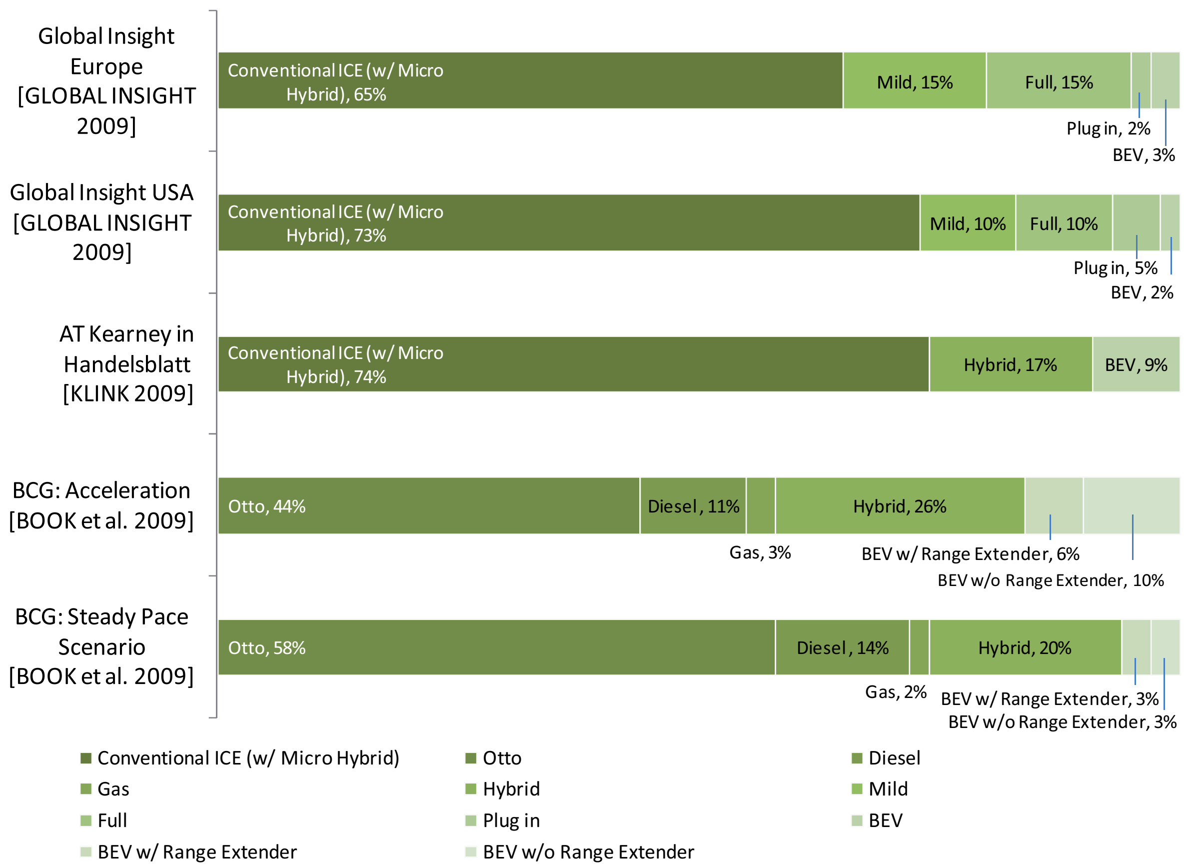

Figure 3-12 Various market share projections of vehicle powertrains by 2020

Figure 3-12 shows the expected market growth of hybrid and electric powertrains estimated from different sources [BOOK, M. et al. 2009, KLINK 2009, WERTEL 2008, GLOBAL INSIGHT 2009]. According to the figure, the electrification of vehicle powertrains will be responsible for roughly 20% of new cars sold worldwide by 2020. In the first three projection studies, micro hybrids are added as a conventional vehicle architecture including both Otto and Diesel engine cars. In the last two BCG studies micro hybrids are included in the hybrid vehicle percentage and the conventional vehicle percentage is detailed to include gasoline cars under the designation Otto and Diesel for compression ignition conventional cars.

In the United States where, gasoline engines dominate the market, mild and full gasoline hybrids are expected to continue to increase in sales and lock in most of the alternative powertrain market. Plug-in hybrids and electric cars that will require external charging are expected to gain up to 6 - 10% of the new US car fleet by 2020.

In Europe, the high penetration rate of diesel vehicles reduces the attractiveness of gasoline-hybrids as both technologies offer comparable fuel consumption. Micro hybrid architectures that are compatible with both gasoline and diesel cars will dominate the European market with an expected penetration rate of 5% already by 2012 due to the stringent emission norms discussed earlier and the voluntary ACEA agreement signed by all European OEMs.

3.4 Car Buyers in a Changing World

Most methods for product development recognize that customer input is essential in developing product requirements. These customer requirements shape the early product concept stages. It is critical for developers to consider what type of customers they will be serving. Is it a customer who lives mostly within a city, or does the person commute longer distances on highways? How much cargo space is needed? Does the customer have the ability to charge an electric car at home or at work? These and many other questions derive a catalog of requirements that help developers create concepts focused toward customer groups.

The problem facing developers is that customer input through traditional market research will rarely dictate a preference for futuristic technologies. Instead, the customer describes improvements from the established product and generates wishes that could lead to a product innovation.

The Quality Function Deployment (QFD) [AKAO 1990] methodology (also referred to as the House of Quality (HoQ) [HAUSER et al. 1988]) is a tool that is utilized to translate customer requirements into technical requirements. In addition, this tool facilitates an assessment between competitors and the firm's own product. The procedural model can be incorporated throughout the development process to maintain the so called "voice of the customer" present in design decisions at each product development stage. The limitation of this methodology is that a too detailed examination rapidly becomes too complex to develop decisions at the aggregate product level [LINDEMANN, UDO 2007].

The "voice of the customer" translated to the "voice of the engineer" using the QFD/HoQ can be very useful in making improvements to generations of product families but can be limited in its scope to seek out new technologies. If you ask average drivers today to offer input for future car products, they will base their suggestions mostly on their current driving experience that is based solely on ICE architecture cars. The customer will seek improvements to the existing architecture which engineers will fail to translate into a "customer need" for new vehicle architectures altogether such as electric cars. The voice of the customer can thus lead to further "lock in" of particular product architecture.

3.4.1 The innovators dilemma

Firms that are leaders in their market and suddenly fail due to the introduction of a radical innovation in the market are said to have been trapped in an innovator's dilemma. Incumbent firms who listened to the "voice of *their* customer" in improving their products usually fail to act in time to counter customer acceptance of new product entrants.

The vehicle architecture competition, already underway, may lead to the failure of established automotive firms that are not flexible in adapting or lack anticipatory behavior. The accumulated institutional knowledge can become a liability when market conditions change. This phenomenon is documented in various case studies where incumbent firms that face an architectural innovation challenge decide to resist change, even after better product architecture solutions clearly emerge [HENDERSON et al. 1990].

Christensen notes "that finding new applications and markets for these new products seem to be a capability that each of these firms exhibited once, upon entry, and then apparently lost. It was as if the leading firms were held captive by their customers, enabling attacking entrant firms to topple the incumbent industry leaders each time a disruptive technology emerged." [CHRISTENSEN 1997, p.23]

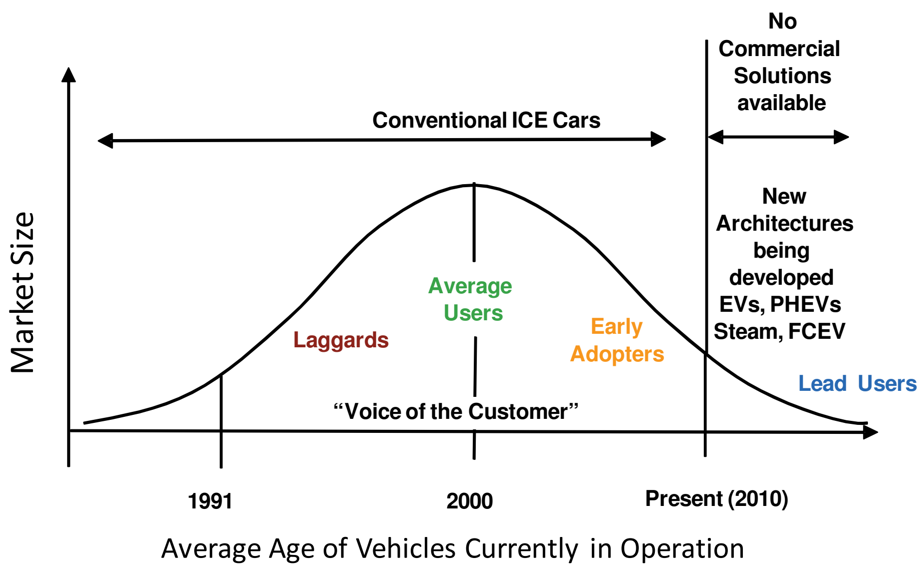

Figure 3-13 Schematic showing the distribution of customer typology (based on registered vehicle data from the US Department of Transportation 2008 report) [adapted from VON HIPPEL 2005]

Figure 3-13 helps explain why the innovator's dilemma occurs. The average driver according to the US Department of Transportation (DOT) in their 2008 annual report is registered to drive a 2000 model car [FHTA 2008]. The average customer is represented in the middle of the distribution, whereas "early adopters" are consumers driving newer than average cars and "laggards" are drive older than average cars.

Only lead users are those customers that have modified existing cars to meet their special needs, and have created their own vehicle architecture [VON HIPPEL 2005, p. 4]. The "voice of the customer" extracted from conventional market studies results from a population that is far away from the newest automotive innovations. Hence, requirements extracted from market studies reinforce the incumbent dominant vehicle architecture and opens opportunities for new entrants to enter the market with a disruptive new vehicle architecture.

Lead users active in the development of plug in hybrids have the ability to create awareness of a new niche-technology. In 2004 Felix Kramer and others founded Cal Cars[12], an organization set up to increase awareness of plug in hybrid technologies. What started as a lead user demonstration conversion of a Toyota Prius into a plug-in hybrid car has now become a successful PHEV conversion niche market provider in California. Lead users with entrepreneurial ambitions can thus create a limited market segment of products without attacking the market segments of incumbent manufacturers directly.

[12] More information under http://www.calcars.com

3.4.2 Identifying Customer Future Needs

The auto industry uses a number of methodologies to extract customer feedback, some of which are shown in Table 3-6. The question arises, can customer needs for new car architectures be identified using these conventional methods?

Table 3-6 Popular methodologies to determine future customer needs in the auto Industry [Expanded from HEISSING 2008]

Methodology	Description
Customer Concept Clinic (Konzept-Klinik)	Selected customers satisfying the profiling requirements are invited to critique models or new car concepts
Auto Show/ Trade Fair Studies	Data is collected from auto show and trade fair visitors contemplating new car concepts or technologies to generate feedback from the market.
Customer Reviews from Market Research Studies / Virtual markets	Market Research agencies compare both subjective and objective product features that lead to purchase preferences. Data collection on particular customer and product groups are frequently collected. Virtual markets represent a new way of collecting consumer information.
Service Center Feedback	Service and Retail shops deliver feedback to developers on technical problems and special customer needs
Opinion leaders	Opinion leaders include technical press, consumer report journals and publications, celebrities and trendsetters
Benchmarking of Concept Cars and Lead User Innovations	The customer is influenced by competitors and niche player offerings in the market for new car architectures

For the most part, the methodologies presented in Table 3-6 are used to complement incremental product development innovations and most methodologies fail to address the initial purchase motivation of future vehicle architectures.

3.4.3 Customer Profiling Methodology – Who is the Customer?

A two-step customer profiling method is presented in this section as one way to learn what customers might look for in a new car architecture offering taking the PHEVs as an example. A group of developers experienced with electric powertrain concepts were given the opportunity to brainstorm solutions to the question: Why should a customer buy a PHEV?

As a first step, a wide spectrum of answers was recorded in cards filled out by participants and then clustered to create customer profiles following general brainstorming techniques. As a second step, the results were then transferred to create a mind map picture of the group's answers [LINDEMANN, UDO 2007; Brainstorming p. 250, Mind Map p.277].

Table 3-7 Who is the PHEV customer? Profile categories from brainstorming amongst experts

		Customer Profiles					
Characteristics		**Resource Conscious**	**Environment Friendly**	**Thrifty**	**Trend-setter**	**Driver (Sporty)**	**Practical Person**
	Consumer Interest	•Energy Security, •Foreign Oil Reduction	•Reduced CO2-Footprint, •Reduced Emissions	•Low Costs	•Image, •Lifestyle, •Technology	•Sport, •Driving Pleasure	•Comfort, •Space, •Security
	Examples	•Economist, •Conservative Motivations	•Environmental Protectionist, •Eco-Conscious	•Commuters, •Car Fleet Mangers, •Long distance Drivers •Train Customers	•Early Adopters, •Technologist, •Progressive Professional	•Sports Driver, •Racer on Fast Lane, •Speed, •Motorcyclist's Fun Car	•Soccer-Mom, •Stationwagon owner, •PickUp-driver, •Expects Functionality
	Expected Driving Behavior	•Patriotic Buyer, •Avg. Driving speeds	•Fuel Efficient driving, •Reduced speed •Carpooler	Fast Driver, Fuel and time efficient driving	•Aggressive Driver, •Car is a status symbol	•Aggressive Driver, •Fast mover	•Tow capability, •Careful Driver, •Avg. Driver
	Important Vehicle Characteristics	•Low Fuel Consumption	•Low Emissions & Fuel Consumption	•Low Fuel Consumption •Price Discounts	•Car Design •Image •User Interface Consoles	• 0-100km/h •0-4s Accel •$Velocity_{MAX}$	•Number of Seats, •Load space Features, •Crash Rating
	Weighting from OEM	2	2	1	3	3	1

Table 3-7 shows six customer profiles subjectively determined at a leading German premium automobile manufacturer. The categories described allow developers to place themselves in the perspective of a potential customer group to extract possible motivations behind purchasing a Plug-in Hybrid car. A brief explanation of each profile scenario is provided below and depicted in the mind map shown in Figure 3-14:

Resource Conscious – The resource conscious customer's purchase decision is motivated by political/moral reasons. This person seeks alternative vehicle architectures to reduce his country's dependence on foreign oil imports. The resource conscious person wants to achieve personal energy independence. Image is an important factor for his decision to buy a PHEV. His driving behavior is no different to that of average ICE users but expects higher fuel efficiency. This customer is ready to pay a premium for the new fuel efficient technology and prefers to buy cars manufactured locally to support his nation's economy.

Environmentally Friendly – Saving the environment from green house gasses is top in this customer's motivation to buy a PHEV. The ability for Zero Emission Driving for most short commutes is a key purchase consideration. This person will rather take longer getting to his or her destination so long fuel is conserved and unnecessary emissions are avoided. This customer will look for access to car pool lanes and display his hybrid car logo proudly as it enhances the environmentally friendly image.

Thrifty – The thrifty customer buys a PHEV because it generates savings in comparison to conventional cars. This customer will closely examine all models in the market and consider Lifecycle costs including: sticker price, rebates, tax breaks, toll reduction incentives, reduced fuel costs and other cost savings in ownership and operation.

Trend-setter - The trend-setters purchase of a PHEV is motivated primarily by image. The trend-setter is a typical early adopter that is fascinated with new technology. He will look for features that allow him the flexibility to choose driving modes and will be boasting all new functionality a PHEV brings that is different from a conventional ICE such as quiet driving, the engine start-stop functionality, rapid charging, and above all electric driving. The trend setter tends to drive aggressively and will be looking to show others the car's technological features.

Driver (Sporty) – The most attractive features of a PHEV for sports drivers lies in its vehicle dynamics. The ability to accelerate faster than most cars in the market is a key purchasing argument. The electric powertrain is preferred for having the capability to provide high torque to the wheels when accelerating from rest and adding additional "boosting" power to the ICE. Fuel efficiency is a plus.

Practical Person – Convenience and Comfort is the key reason this type of customer is inclined in buying a PHEV. This includes less re-fueling stops, access to environmental zones open to only zero emission vehicles, enhanced city parking privileges incentives for PHEVs

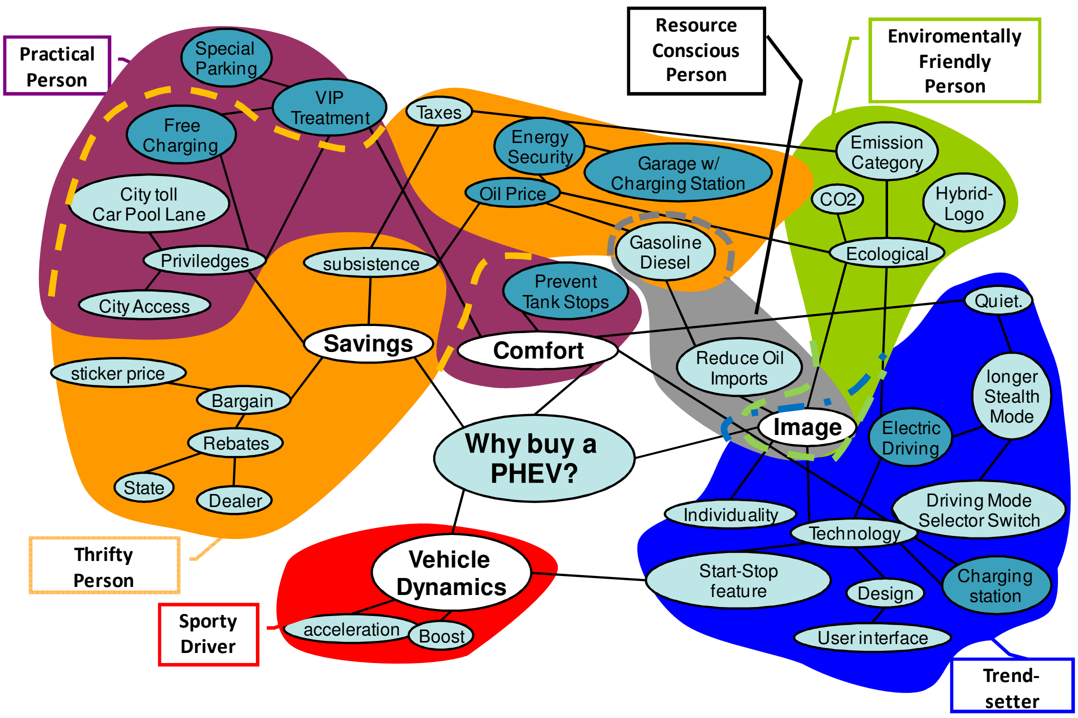

Figure 3-14 Customer Profiles for Plug-In Hybrid Cars (mindmap adapted from Andreas Rucker BMW)

and access to free or subsidized charging stations. The car must also provide a comfortable interior and possibilities to carry passengers or load space.

The profiling Methodology is helpful in identifying who the intended customer could be for a technology that is still in development. Most consumers will identify themselves with one or more customer profiles. A positive conclusion to the work presented is that almost every customer type has multiple reasons as to why purchase a new type of car architecture. The methodology can also demonstrate synergies that may exist between the purchase motivation of future PHEV buyers and the firm's current customer base. Finally, the profiling methodology can go further than what is presented here by determining gender, age, income and cultural preferences in more detail by the use of market research within the categories presented. In contrast, to the "voice of the customer" this profiling method allows for developers to experience a qualitatively devised future customer to extract the market needs that might be forthcoming. Once profiles are formulated, they may be validated by virtual market studies and customer inquiries.

3.4.4 Customer Profiles for Use Case Development

Customer purchase motivations can be further complemented by studying consumer behavior. This section considers three aspects of consumer behavior that are essential in the design of new hybrid and electric vehicle architectures as presented in Table 3-8. These aspects were identified as the most influential factors to designing electric mobility in panel discussions with experts at a leading German automotive manufacturer.

Table 3-8 Important consumer behavior characteristics for electric powertrain design

Consumer Behavior Characteristic	Design Relevance
Average length of trips and daily distance traveled	Vehicle architects of electric powertrains can determine a desired all electric range and judge the monetary fuel savings to the customer versus the added costs of the electric powertrain
Average velocity and acceleration profiles	Helps developers determine electric system power requirements and control strategy of the hybrid system.
Rest time between trips	Allows developers to consider charging time opportunities between trips if an electric charging infrastructure is available

Trips and Daily Distance Traveled - According to the US National Center for Transit Research's 2001 Nationwide Household Transportation Survey (NHTS) the average daily vehicle miles travelled per day averages 32.73 miles (52.67 km) in the United States [HU et al. 2004, p. 26].

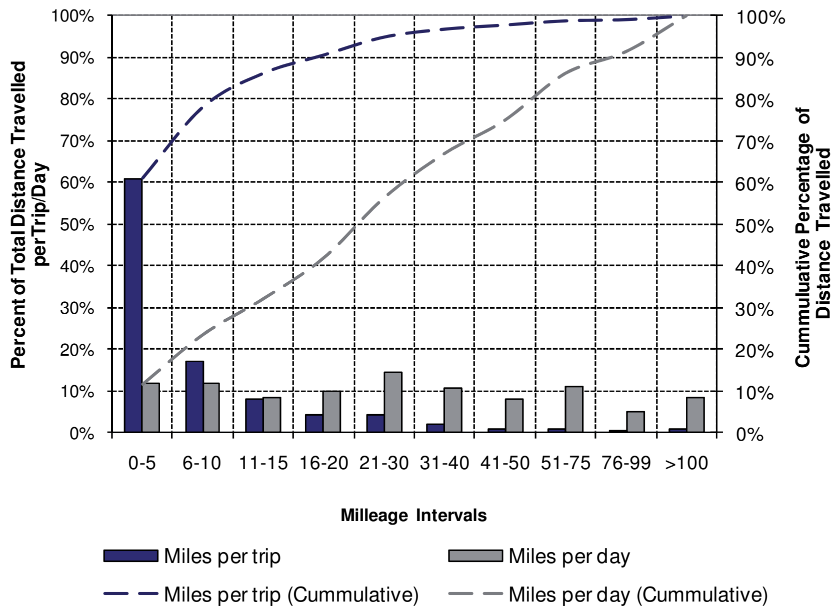

Figure 3-15 Length of trips and daily vehicle miles travelled statistics [data taken from FHTA 2001]

Figure 3-15 provides further details of the NHTS data to show that roughly 60% of all trips taken fall within 0-5 miles (0-8 km) and that 40 miles (64 km) traveled per day covers roughly 65% all cumulative daily travel. Similar findings have been more recently published by MARKEL, TONY 2006, based on 227 vehicle driving profiles from the St. Louis metropolitan area yielded an average daily travel distance of 29 miles (46.4 km). In Europe, studies conducted at BMW show that the profiles are similar to the US, albeit the average distance traveled per day is on average 35km per day.

The driving profiles suggest that cars electric powertrains that can cover as little as 10 or 20 miles (16 or 32 km) in an all electric mode can offer substantial displacement of conventional liquid fuels and in most cases a significant reduction in energy costs[13]. Coupling consumer behavior with profiling can thus help lay the design objectives for the electric systems of HEVs, PHEVs and BEVs.

Average Velocity and acceleration Profiles – Real world acceleration and velocity profiles are quite different from the regulatory test cycles. Test cycles are used in determining catalog values on fuel consumption and emissions, however real data taken from GPS tracking system studies allow designers the opportunity to simulate how a particular electric vehicle concept will perform for the average customer. This assumes that driving behavior of hybrid and electric car owners are similar to today's ICE car driver's behavior.

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[13] A detailed lifecycle cost analysis is found in chapter 6.

GPS driving behavior data on acceleration shows that the variations in acceleration at lower speeds in real world driving exhibit a much larger spread that those displayed in the regulatory test cycles [GONDER J. 2007, p.8]. Cars that are driven regularly with large variations in acceleration and speed, for example in city driving conditions, can benefit from hybridization. HEVs and PHEVs in these conditions tend to perform better than in dynamometer test cycles due to efficiencies during brake energy recuperation and electric boosting when accelerating.

Rest time between trips – For electric and plug-in hybrid electric vehicles the rest time between trips provides an insight on opportunities for recharging. Unlike the short refueling time required by conventional ICE cars, battery charging for cars can take from 4-8 hours depending on the battery charging system and battery capacity.

Most lithium ion battery systems charge in a two stage process; fast charge and trickle charge. The fast charge happens at constant current allowing the battery to reach its maximum cell voltage, whereas the trickle charge maintains the maximum cell voltage constant as the current slowly decreases to its minimum value. This charging procedure allows for 60%-80% of the battery capacity to be recharged in 1/3 of the full charging time and the remaining 40%-20% charge takes roughly 2/3 of the charging time [BUCHMANN 2001, p.68].

Should a charging infrastructure be developed, fast charging times might be enough to provide substantial electric range capability for PHEVs and BEVs. According to the 2001 National Household Transportation Study (NHTS) [FHTA 2001], 50% of all rest periods between trips are longer than 50 minutes - not including overnight rest periods. This provides an opportunity for at least a 1 to 2 hour “fast charge,” provided that the charging infrastructure is available.

3.5 Business Strategy

The manufacturing firm’s business strategy can have a profound effect on the market’s transition to new vehicle architectures. In this market transition period, the auto manufacturer’s business strategy is the only factor it can *internally* control. All previous factors presented including social and environmental considerations, government regulations, competitors and consumer behavior are *external* factors that will shape the firm’s business strategy.

The firm’s business strategy requires managers to answer the question “What actions will most likely achieve the organization’s goals given its internal and external context?” There is no simple prescription for action that will work in most situations because the relationship between action and context is complex [SALONER et al. 2001].

3.5.1 Developing Strategy under Uncertainty – Informational Cascades

When is it the right time to bring about a new vehicle architecture to market? Moving first might earn a firm the reputation of a pioneer, however costs and the high uncertainty that the new product will succeed are large deterrents. Taking on a fast follower strategy might entail buying still unproven technologies at a high premium. Not taking action can lead to the innovator's dilemma presented in section 3.4. The heightened level of uncertainty in the market can lead to irrational decisions similar to what occurs in the creation of fashion fads or technology hypes.

Most competing firms take on development strategies based mostly on the actions others take until they gather enough information to re-evaluate their strategy. The so called "me too" strategy derives from situations where only limited information is found within the firm and all competitors are facing a *real option* of whether or not they should invest in the new architecture now, in order to have the ability to enter the market at a later time. Because information is so scarce early on, if one competitor commits to enter the market with a new vehicle architecture, it is in fact *exercising* its *real option*[14].

The firm that commits to the new architecture releases positive information about the new innovation since options can be assumed to be only exercised if they deliver value. Other competitors facing a similar decision attempt to improve their own information by observing what other in the market do. This can lead to an *informational cascade* where multiple firms commit to the new architecture, attracting others that are watching their actions to do so as well.

HIRSHLEIFER 1995 has studied these informational cascade problems from the customer perspective of buying new products and concludes that informational cascades on average lead to good decisions. However, if the early consumers take on a wrong decision the cascade can lead to irrational behavior and harm successors. Once the consumer can obtain more complete information on the product, fads that seemed to be right can be proven wrong and disappear just as quickly as they appeared.

At the moment most major auto manufacturers have invested in HEV real options. Meaning, they are building knowledge in order to be able to enter the market in the future if need be. However, as several firms have already exercised their options to enter the HEV market, others that have been watching are following with their own HEV models.

[14] "Real options" and "architecture options" are discussed in more detail in section 4.1.4

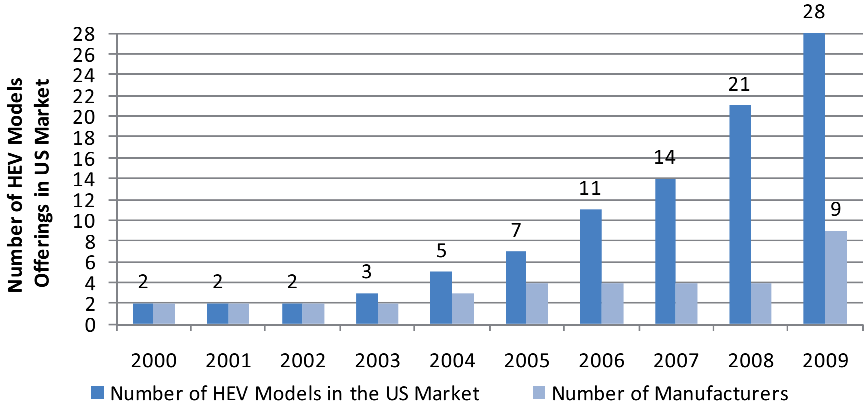


Figure 3-16 Growth of HEV model offerings (Toyota Prius, Honda Insight, Saturn Vue, BMW 7, etc.) and HEV manufacturers in the US Market suggests the pattern of an informational cascade

Figure 3-16 suggests that an informational cascade favoring the introduction of hybrid vehicles is well on its way. The speed of integration of HEVs in the market can be used as a benchmark for the introduction of other architectures such as PHEVs and BEVs.

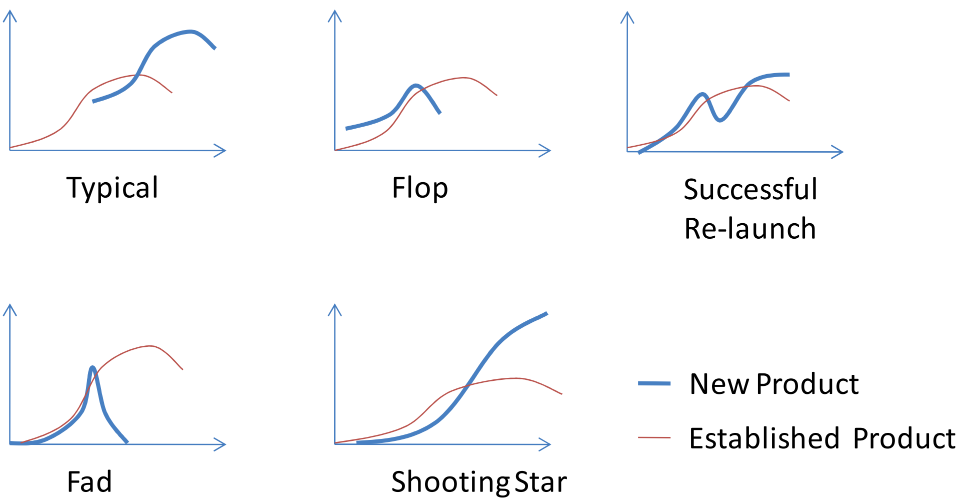


Figure 3-17 Performance vs. time qualitative graphs for Product Lifecycles Transitions

Firms need to continually evaluate and track architecture performance in order to ensure an informational cascade remains correct and that the trend will not disappear. Figure 3-17 shows performance versus time graphs for various types of product lifecycles (adapted from [Matys 2008, p.124]). So long as the performance of new vehicle architectures are below that of the established architecture types, they still have a chance to disappear as is the case of a “flop” or a “fad.” Architectures that exhibit higher overall performance will continue to grow and may remain to dominate or co-dominate the market.

3.5.2 Business Dynamics

The firm’s business strategy must be flexible to changes in the internal and external context it finds itself in and be ready for asset allocation or asset deployment as conditions change with time. The complexity of business actions can be modeled using the system dynamics methodology. This methodology uses a modeling approach to understand complex systems that is based on stocks (state variables that accumulate and can be measured as levels) , flows (rates of change) and feedback loops (circular flows amongst variables) [STERMAN 2000, pp.192-200]. The basic steps of the system dynamics methodology are described below:

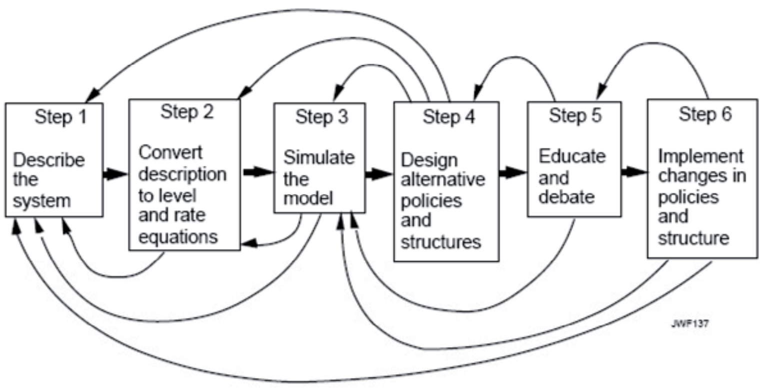


Figure 3-18 System Dynamics methodology steps [according to Forrester 1994]

Figure 3-18 shows the stepwise progression from system description to policy implementation and features a number of necessary iterations [FORRESTER 1994]. The methodology begins with a description of system elements relevant to the problem at hand. The modeling process begins in step 2 by synthesizing the system description into stocks, flows and feedback loops with equations. The simulation in step 3 allows for insight on how the system reacts to input variables over time and allows for further refinement of steps 1 and 2 in an iterative process. The deepened understanding of the system through step 3 leads to policy creation and debate in steps 4 and 5 that can be tested in the simulation model. Finally, a close look at the effects of policy implementation over time can lead to further model adjustments and validation.

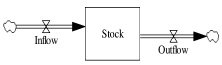
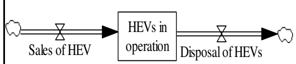
The methodology is an ongoing process that can significantly aid in understanding complex environments and supporting decision making through modeling. As with any modeling technique, the simulation tool is an approximation of the real world and will never account for all the uncertainties and risks inherit in real world situations.

3.5.3 Modeling the Adoption of New Vehicle Architectures

The system dynamics methodology according to FORRESTER 1994 is applied here to the dynamics of new vehicle architecture adoption in the market. The steps of the methodology are developed in a practical example that presents a complex network of business dynamics that can help explain new car architectures adoption scenarios. As the methodology is developed, many of the iterations between steps presented in Figure 3-18 are left out of the discussion. The simulation model is built using STERMAN 2000, pp.392-403 as a reference.

The aim of the model presented in Figure 3-19 is to explain market network effects and other factors that make the adoption of new vehicle architectures more (or less) attractive in the future. Most of the items in the model have already been discussed in this chapter and are revisited here in a simulation model. In order to follow the modeling logic a few basic rules are explained in Table 3-9.

Table 3-9 Logic symbols in system dynamics model [according to STERMAN 2000, p.139, 194]

Symbol	Interpretation	Mathematics	Example
X → (+) Y	All else equal, if X increases (decreases) then Y increases (decreases) above (below) what it would have been.	$\frac{\partial y}{\partial x} > 0$	Product Attractiveness → (+) Product Market Share
X → (-) Y	All else equal, if X increases (decreases) then Y decreases (increases) below (above) what it would have been.	$\frac{\partial y}{\partial x} < 0$	Cost of Operation → (-) Product Attractiveness
 A **Stock** is represented by a rectangle. **Inflows** are represented by a pipe arrow pointing into the stock. **Outflows** are represented by pipe arrows pointing out of the stock. **Valves** control the flows. Clouds represent the sources and sinks for the flows outside the boundary of the model.	A Stock is an element in the model where the state of the system agregates inflows and outflows over time. In the example "HEVs in Operation" is a stock that accumulates (HEVs sold - HEVs disposed). The valve elements control the inflows and outflows of the stock being measured.	$Stock(t) = \int_{t_0}^{t}[Inflow(t) - Outflow(t)]ds + Stock(t_0)$	 $HEV\ in\ Operation(t) = \int_{t_0}^{t}[HEV\ Sales\ (t) - HEV\ Disposal(t)]ds + HEV\ in\ Operation(t_0)$

The elements in a system dynamics model are linked by directional arrows with either positive (+) or negative (-) polarity. A connection between two elements with positive polarity describes a cause and effect type relationship that increases or decreases in the same direction for both elements over time. For example, if we define *product attractiveness* and *product market share* as elements that have a relationship with positive polarity, it simply states that when the product attractiveness increases over time it has an increasing effect on the product market share. Symbolically this is represented by placing the cause element at the arrow base and the effect element at the arrowhead with a “+”sign over it as seen in Table 3-9.

In contrast, a relationship between two elements in a system dynamics model with negative polarity results in opposite effects development over time. For example, a higher *cost of operation* a product exhibits over time has the effect of generally lowering overall *product attractiveness* as less customers will be able to afford the vehicle. Likewise, the depiction of this dependency is provided on Table 3-9, 2nd row.

Stocks and flows are a central concept to system dynamics. Stocks represent a state variable (or level) that is to be measured based on inflows and outflows. Stocks can thus be explained mathematically using integrals that aggregate the flows over time as explained in Table 3-9. Flows on the other hand can be explained as rates or time derivatives.

In the example in row 3, Table 3-9, the *sales of HEVs* serves as a flow valve for the accumulation of the stock *HEVs in operation*. The *disposal of HEVs* serves as an outflow valve to that stock. To find the quantity of HEVs in operation over time we simply need to take the integral of a function that describes *sales of HEVs* minus the *disposal of HEVs* over time.

Step 1 – According to Forrester, the first step in the system dynamics methodology is to describe the system of interest based on the goals of the model. In this case, the model aims at studying new vehicle architecture adoption. The elements relevant to the problem encompass relationships that include: the total demand for all cars in the market; the market share of each vehicle architecture considered; the price of gasoline and electricity; the cost of operating a vehicle; government incentives or taxes; the maturity of the electric powertrain technology; retail price premiums of HEVs and BEVs over that of conventional IC engine cars; and network effects that make a car more desirable to the customer.

The selection of these elements stem from asking basic questions of what items are relevant to the adoption of new vehicle architectures and why they are important. The model boundaries are established and feedback loops are created when a set of elements are linked in a cycle. The model is not meant to be all encompassing, but rather a path depiction of variables that help explain the central problem in a cause and effect reasoning chain. At this point the resulting visualization is called a “casual loop diagram” in system dynamics terminology [STERMAN 2000, p.13, p.102].

Step 2 -The second step in the methodology requires converting the system description into level and rate equations. In this step, all elements that show linkages develop a mathematical explanation. Variables that are explained by others within the model are said to be endogenous or internal, whereas variables that are explained by external information or user value inputs are exogenous to the model. In Figure 3-19, exogenous variables are colored in red for easy identification.

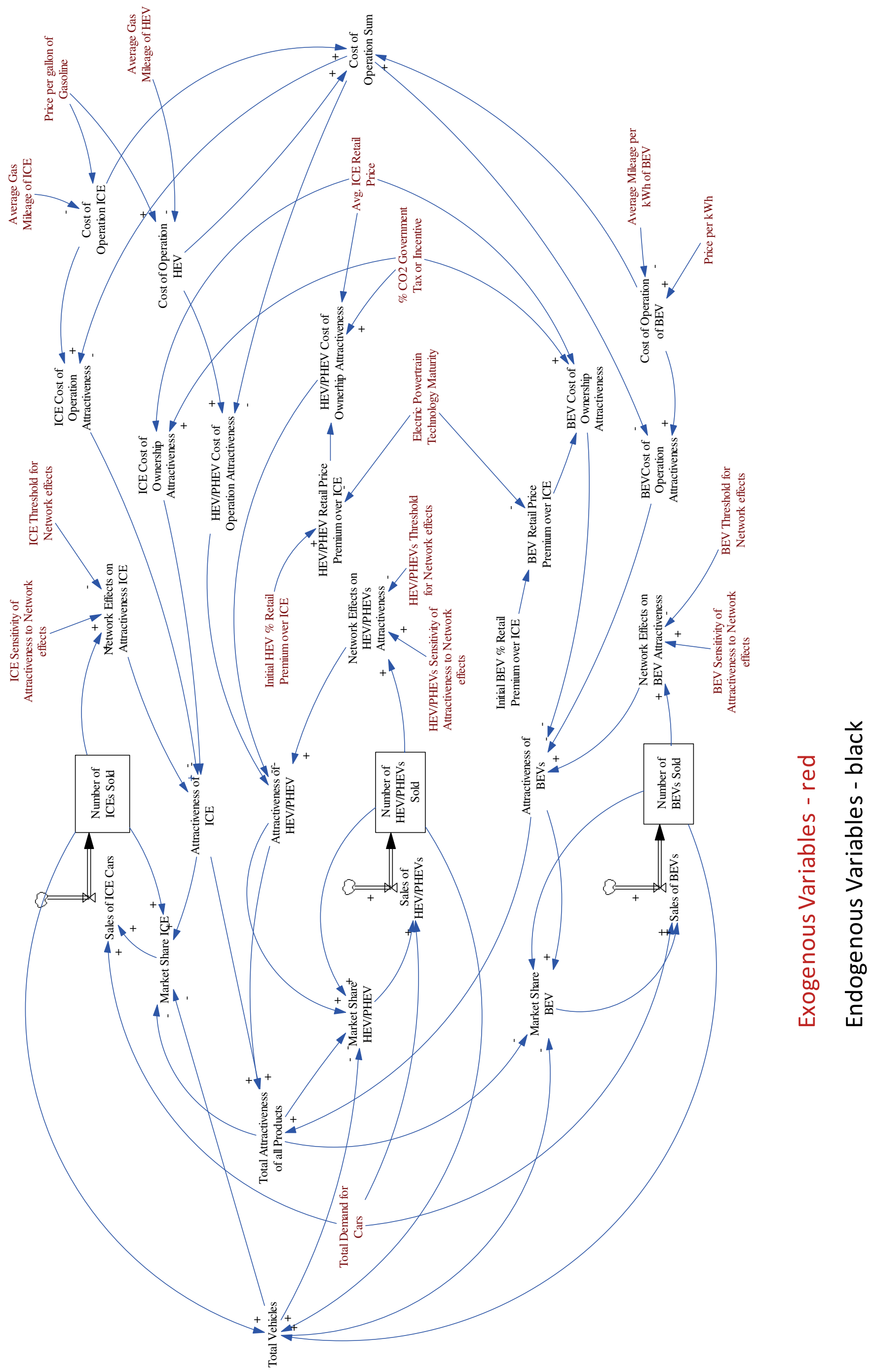


Figure 3-19 Diagram of a System Dynamics model examining future vehicle architecture adoption scenarios

Because the number of vehicles of a particular architecture sold is central to the model, three stocks are designated in Figure 3-19: 1. the *number of ICE cars sold*, 2. the *number of HEV/PHEVs sold*, and 3. the *number of BEVs sold*. A time horizon of 10 years is assumed for which the simulation time step is set to one year each period. The disposal of cars is left outside the boundaries of this model and is not explicitly shown. At each time step, the simulation calculates the chain of effects that propagate throughout the system based on the mathematical definitions resulting in a year to year increase in vehicles sold. If we assume that the starting year is 2010, then by the end state of the model results in a projection for vehicle sales in year 2020.

Step 3 -The simulation step in the systems dynamics methodology is facilitated through mathematical equations for all variables in the model. By looking at the model diagram in Figure 3-19 and comparing with the equations below, it becomes clear that the mathematical equation defining each element is a function of the input relationships to that element. The appendix Table 9-1 presents a listing with all equations and assumptions for all variables in the vehicle architecture adoption model.

This simulation model focuses on the number of vehicle architecture sold each year that add to the installed base of the vehicle architecture type already in operation[15]. The installed base of each vehicle architecture type is defined by the parameter *number sold Architecture i* expressed as a stock by equation 4. Because this parameter represents an accumulating quantity, it can be measured by taking an integral through time. Initial values in the model include ICEs 12 Million, HEV_PHEV 600,000, and BEV 500 – simulating the current new vehicle fleet for sale in the US market in 2010.

$$Number\ Sold\ Architecture\ i = \int_{t=0}^{10} Sales\ of\ Architecture\ i + initial\ installed\ base_{t=0} \quad (4)$$

Of particular interest is the definition of vehicle architecture attractiveness, a dimensionless value used for assigning market shares. The flow into our "stock" described in equation 4 is the sales of vehicle architecture types. The total market demand is set to be a constant number sold per year, in this case study 13 million units per year every year. Equations 5-8 explain the chain of mathematical relationships leading to sales in the model.

$$Sales\ of\ Architecture\ i = Total\ Demand\ for\ Cars * Market\ Share\ of Architecture\ i \quad (5)$$

$$Market\ Share\ of\ Architecure\ i = \frac{\left[\left(\frac{Attractiveness\ of\ Architecture\ i}{Total\ Attractiveness\ of\ all\ Architectures}\right) + 10\left(\frac{Number\ Sold\ Architecture\ i}{Total\ Vehicles}\right)\right]}{11} \quad (6)$$

$$Total\ Attractiveness = \sum_{i=1}^{n} Attractiveness\ of\ Architecture\ i \quad (7)$$

$$Total\ Vehicles = \sum_{j=1}^{n} Number\ Sold\ of\ Architecture\ j \quad (8)$$

[15] The term *i* or *j* in the equations that follow refers to ICE, HEV or PHEV and BEV vehicle architectures.

The market share of an architecture type is a weighted function of the attractiveness ratio and the vehicle sold ratio. The vehicle sold ratio in this case is weighted to be 10 times larger than the attractiveness ratio as seen on equation 6. The weighting reflects the fact that manufacturers will produce more of what sells in the market rather than what early adopters find attractive. The value of 10 should be considered an approximation and could be later refined to become an exogenous variable in future model refinement.

Attractiveness represents the customer's affinity for buying the product. This parameter depends on a wide range of variables that are hard to quantify such as emotional aspects of the design, quality perception, selling price, availability, service, features, and so on. In this simplified model, overall attractiveness is a function of the *costs of ownership*, *cost of operation* and the *network effects on attractiveness* as presented in equation 9.

By studying the equations behind the dependencies in Figure 3-19, attractiveness has a positive dynamic feedback loop from the "network effects" that represent the emotional intangibles of quality, perception and word of mouth reinforcing effects on sales. Attractiveness is balanced by the effects from cost of ownership and operation elements that quantify costs to the customer.

$$Attractiveness\ of\ Architecture\ i = \frac{Network\ effects\ on\ Attractiveness\ for\ Architecture\ i}{(Cost\ of\ Ownership\ Attractiveness\ i + Cost\ of\ Operation\ Attractiveness\ i\ )} \quad (9)$$

The two variables in the denominator contain information on the selling price and the costs to operate the vehicle. The higher the costs a particular architecture exhibits, the less attractive the architecture type will be in the market, and thus be subject to lower sales. In contrast, the stronger *network effects on attractiveness for Architecture i* are, the more attractive it is in the market.

$$ICE\ Cost\ of\ Ownership\ Attractiveness = \frac{((1+\%CO2\ Government\ Tax\ or\ Incentive) \times Avg.ICE\ Retail\ Price)}{Avg.\ ICE\ Retail\ Price} \quad (10)$$

$$HEV\ or\ BEV\ Cost\ of\ Ownership\ Attractiveness =$$

$$\frac{((1+\%CO2\ Government\ Tax\ or\ Incentive) \times Avg.ICE\ Retail\ Price \times Price\ Premium\ over\ ICE)}{Avg.\ ICE\ Retail\ Price} \quad (11)$$

$$Retail\ Price\ Premium\ over\ ICE = (1 + (Initial\ \%\ Retail\ Premium\ over\ ICE - Electric\ Powertrain\ Maturity \times Initial\ \%\ Retail\ Premium\ over\ ICE)) \quad (12)$$

The cost of ownership equations (10-12) explain costs involved in owning and purchasing a vehicle architecture type. The variable *$\%CO_2$ Tax or incentive* can take on a positive (CO_2 Tax) or negative (Government Incentive) value representing here government emissions regulatory activities. A tax makes the cost of ownership higher and the overall attractiveness of the architecture smaller, whereas an incentive has the opposite effect. The model assumes an average selling price of an ICE car at $35,000 representing a traditional mid size passenger sedan. Exogenous inputs such as the *average ICE retail price* can be easily changed to explore other scenarios.

The dimensionless parameter *retail price premium over ICE* represents a means to measure of how much more a PHEV, HEV or BEV retails over a conventional ICE car. This term is a function of the *electric powertrain maturity* to represent the development state of the high voltage battery technology. The estimate of the technological maturity of the battery system is modeled as a constant value between 0 and 1 in equation 12: (A value of 0 = not mature; 1= very mature – meaning an off the shelf component). When the value is zero, the full retail premium value is taken making the cost of ownership larger, whereas a value of one reduces the extra price premium to zero.

The cost of operation equations presented in equations 13 and 14 exhibit a balancing (negative) effect on overall attractiveness of a particular vehicle architecture. Hence, the vehicle architecture that generates the least cost of operation wins out in generating the most attractiveness.

$$Cost\ of\ Operation\ Attractiveness = \frac{Cost\ of\ Operation\ of\ Architecture\ i}{Sum\ of\ Cost\ of\ Operation\ for\ all\ Architectures} \quad (13)$$

$$Cost\ of\ Operation\ of\ Architecture\ i = \frac{Price\ of\ Fuel\ (or\ Electricity)}{Average\ Fuel\ (or\ Electric)\ Consumption\ of\ Architecture\ i} \quad (14)$$

The *cost of operation attractiveness* of a particular architecture is defined as a ratio to all other architectures. This definition allows assigning the highest value towards cost of operation to the architecture that carries the highest operating cost. The actual cost of operation is a function of the price of fuel, or electricity in the case of BEVs, and the energy consumption.

The prices are exogenous variables to the model to allow for the creation of various price scenarios. The price of gasoline is based on the US Energy Information Administration (EIA) projections from 2010 to 2030. The price of electricity in the model is left as constant at $0.11/kWh as the EIA projects little change in its pricing over the next 10 years. Both exogenous variables can be further studied for sensitivity.

The *network effects on attractiveness* in turn is constructed to capture the positive influence a larger installed base of a particular architecture type has on the attractiveness for further sales of that type. This relationship is described by means of an exponential function as seen on equation 15.

$$Network\ Effects\ on\ Attractiveness = e^{\left[(Sensitivity\ to\ network\ effects) * \frac{Number\ Sold\ of\ Architecture\ i}{Threshold\ for\ Network\ Effects}\right]} \quad (15)$$

This exponential function has three terms that control the positive feedback on the sales of more vehicles for a particular architecture type: a sensitivity constant, the number of vehicle sold (our stock) and a threshold constant. The parameter *sensitivity to network effects* controls the strength of the exponential growth effect. The threshold is essentially a scaling factor that represents the size of the installed based above which network effects become important.

The use of an exponential curve to describe network effects is a plausible model. For new technologies entering a market, this is similar to the so called “snowball” dynamic where the sales of a new technology grow exponentially after enough customers have adopted the new market standard. Once the technology dominates to the point all customers have the product, network effects on sales reduce.

As an example, consider the relatively unknown BEV architecture. The sensitivity parameter is set to 4, the threshold to 5 million vehicles and the initial number of vehicles sold initially is assumed to be only 500 cars. Before the number of BEVs sold reaches the 5 million vehicle mark, the network effects are relatively weak displaying almost linear growth (initially set at $e^{4*(500/5000000)}$). Once the number of BEVs sold reach the threshold of 5 million, the exponential function simply becomes e^5. Finally, once the number sold surpasses 5 million units sold, network effects become much stronger as the right side term in the exponential function becomes a multiplier allowing sales to expand at a powerful increasing rate year to year.

Steps 4 and 5 – These steps in the system dynamics methodology require interpretation of the simulation results that lead to a deeper understanding of how variables described in the model represent reality. This understanding must then be communicated to others in order to educate and debate potential policy or strategic actions.

Table 3-10 Vehicle architecture adoption simulation model results based on initial conditions and equations described in appendix section 9.1

Time	Number of ICEs Sold	Number of HEV_PHEVs Sold	Number of BEVs Sold	Total Vehicles	Market Share ICE	Market Share HEV_PHEV	Market Share BEV	Attractiveness of ICE	Attractiveness of BEVs	Attractiveness of HEV_PHEV
(years)	(millions)	(millions)	(millions)	(millions)	%	%	%	(dimensionless)		
0	12.5	0.6	0.0005	13.1	90.27%	7.38%	2.35%	0.8	0.5	0.7
1	24.2	1.6	0.3	26.1	87.90%	8.82%	3.28%	1.0	0.7	1.0
2	35.7	2.7	0.7	39.1	86.16%	9.94%	3.89%	1.4	0.9	1.6
3	46.9	4.0	1.2	52.1	84.65%	10.96%	4.38%	1.8	1.4	2.5
4	57.9	5.4	1.8	65.1	83.25%	11.96%	4.79%	2.4	2.2	4.3
5	68.7	7.0	2.4	78.1	81.92%	12.95%	5.13%	3.1	3.7	7.7
6	79.3	8.7	3.1	91.1	80.67%	13.94%	5.39%	4.1	6.3	14.4
7	89.8	10.5	3.8	104.1	79.52%	14.93%	5.55%	5.3	11.0	28.4
8	100.2	12.4	4.5	117.1	78.49%	15.91%	5.60%	6.8	19.6	58.8
9	110.4	14.5	5.2	130.1	77.59%	16.88%	5.53%	8.8	35.1	127.5
10	120.5	16.7	6.0	143.1	76.81%	17.84%	5.35%	11.3	62.4	290.3

The simulation was run using the Vensim PLE Plus® System Dynamics software using the equations and initial conditions described in the appendix section 9.1. Selected model results are displayed in Table 3-10. Initially, the number of new vehicles sold is set to 13.1 million units set to grow annually at a rate of 13 million new cars – roughly the size of the US light duty vehicle market. The numbers of vehicle sold accumulate throughout the 10 year period to 143 million vehicles.

Initially the ICE architecture has a dominant position in sales and slowly looses market share to the HEVs, PHEVs and BEVs as they become more attractive. The losses in market share are due to the exponential explosion in attractiveness the HEVs and BEVs experience once the threshold for network effects is achieved (8 million for HEVs/PHEVs and 5 million for BEVs). At the end of ten years, the percentages for each architecture type is as follows: 84% ICE cars sold; 12% HEV and PHEV cars sold and 4% BEV cars sold. The final year market shares result in 77% ICE cars, 18% for HEV cars and 5% for BEVs. These results are comparable with industry projections presented in Figure 3-12.

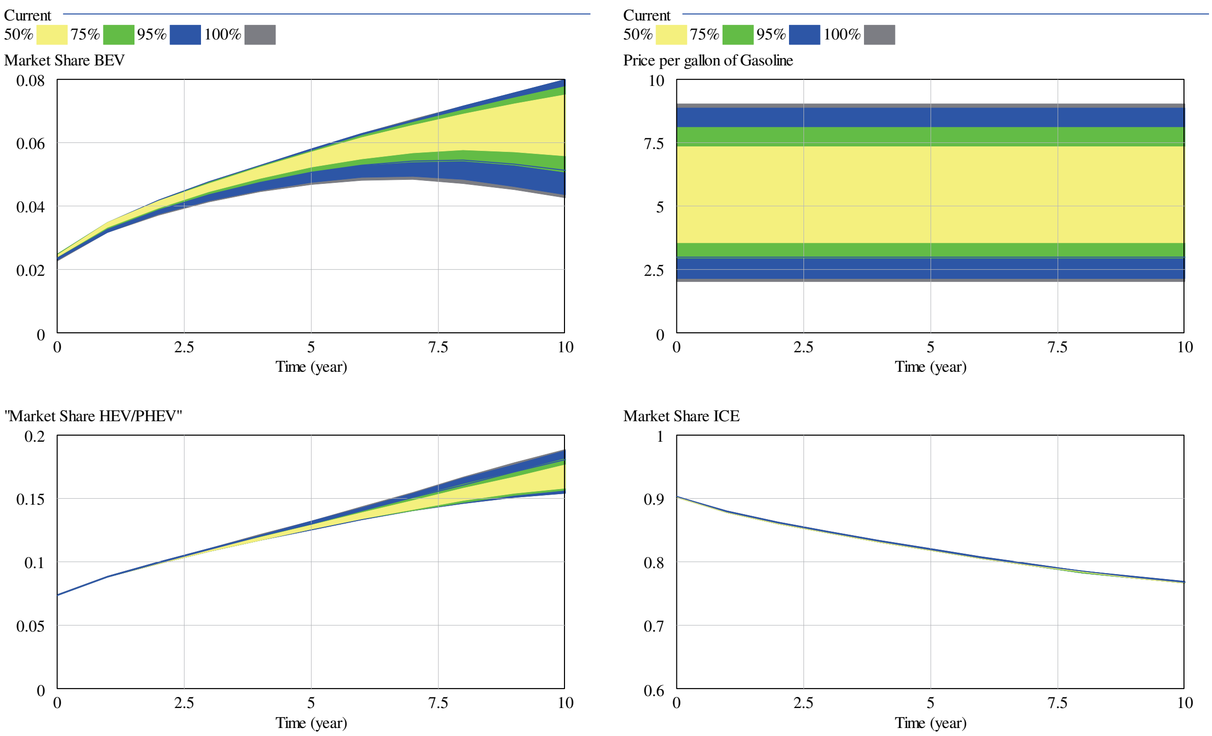


Figure 3-20 Vehicle Architecture adoption model market share confidence intervals resulting from 200 simulations varying price of gasoline as a random variable between $2 and $9 per gallon (roughly 0.42 Euros/liter and 1.87 Euro/liter)

The simulation permits the study of sensitivities between variables to gain insights on how changes propagate in the model. For example, Figure 3-20 displays the results of the simulation run 200 times allowing the price of fuel to randomly vary between $2 per gallon and $9 per gallon (roughly 0.42 Euros/liter and 1.87 Euros/liter respectively) using a standard normal distribution. The results allow for exploration on how sensitive market share values are using the aid of confidence intervals as seen in the graphic above.

From Figure 3-20 it is interesting to note that the market share of ICEs is not sensitive to changes in fuel prices - as might be thought of originally. In contrast, changes in fuel prices propagate much more markedly in the market share for HEVs and BEVs evidenced by a broader distribution.

A closer examination reveals that the variance for the BEV architecture grows larger after the 3rd year - and after the 5th year for the HEVs. The reason for these results is that the price of fuel affects the *cost of operation* metrics, which then in turn have an effect on the attractiveness of the vehicle architecture types. Variations in attractiveness for the two BEV and HEV architectures are more pronounced as the number of vehicle sold reaches the threshold for network effects as seen in table 3-12. The attractiveness metrics of ICEs are less affected because the sensitivity to network effects is set much lower than that of the new vehicle architectures. This assumption in the model relates to the fact that the ICE is dominant and network effects have been satisfied by almost every user already owning an ICE car.

Besides gaining knowledge on how changes in the system propagate, the model has clear policy implications for firms looking to use positive feedbacks to their advantage. The use of network effects to gain market share is one example. During the introduction of new vehicle architectures where no prior standards have been established, network effects will be relatively weak. The market share will be primarily determined by the proven products of the installed base. As a result, the first movers in the new vehicle markets will likely face limited market shares for the high costs of innovation and development. As the new market develops, a small window of time exists for second market movers to offer an improved version of the new vehicle architectures and capture the market share as it becomes available.

The model shows that the time window to be successful as a second mover is limited, as it is powered by exponential growth after a period of seemingly linear growth. The second mover strategy needs an improved product at the right time. In the automotive industry this "right time" must be backwards planned to allow for 3-6 years development time. By the time the new market develops, it is too late to start the innovation and development process for a second mover in the market.

Finally, it is important to note that many factors – not included explicitly in the model - can drastically affect the dynamics of vehicle adoption as described in this chapter. For example, the regulatory banning ICEs in some of the megacities might have a drastic impact to new electric and hybrid vehicle adoption in that local market. Exogenous variables that explore these developments can be added to the model in an exploratory basis.

3.6 Summary of Factors Affecting Architectural Change

A shift towards electrified powertrain architectures is evident in today's automotive industry. New electric and hybrid vehicles concepts have taken the front stage at major automotive trade fairs, where automakers want to ensure not to be left out in a new and potentially lucrative market. The factors that affect this fundamental change in the market include environmental considerations (section 3.1), government regulations (section 3.2), market competition (section 3.3), customer wants or needs (section 3.4) and finally the manufacturing firm's own business strategy (section 3.5). The main topics are briefly summarized below.

Environmental considerations pushing the market towards electrification focus primarily on the reduction of both anthropogenic GHG emissions and oil consumption for transportation use. The effects of the GHG related global warming phenomenon is expected to range from a rise in water levels to basic subsistence shortages. To mitigate these risks, the automotive industry has already been required to take action in reducing the tail pipe emissions of cars. Likewise, oil reserves vital to the transportation industry are rapidly being depleted. A world "oil peak" is projected to take place between 2010 and 2020 resulting in an increase in fuel prices and a consumer shift to new transportation options. Alternatives that offers greater fuel efficiency to the established combustion engine technology are expected to become more attractive.

Government regulations worldwide are requiring an increase in fuel efficiency along with reductions in GHG emissions. The US CAFE, the California ZEV law and the European emission standards presented in this chapter and are examples of leading regulations. These laws require directly or indirectly the development and market release of alternative vehicle architectures.

Increased market competition through globalization has made the conventional automobile a commodity in the low end market segments. A decrease in prices across the industry is evidence of large supply stocks and heightened market competition. As a result, the premium automotive market will continue to be more competed as established firms move up from already crowded low-end product offerings. New vehicle architecture introduction is one means of differentiation that can develop into a competitive advantage. Analysts expect that by 2020 roughly 20% of new car sales will exhibit some form of electric powertrain in the form of hybrid or electric vehicle architectures.

Firms that fail to develop new vehicle architectures might be vulnerable to a disruptive, market changing innovation according to the innovator's dilemma proposition. Studying possible consumer profiles and driving behavior data can assist developers understand upcoming customer needs for new vehicle architectures changes in the market.

The manufacturing firm's business strategy must consider all external factors affecting the market to determine which internal actions it must take to achieve its performance goals under the uncertainty of future developments. Firms that have invested in the development of hybrid cars can be considered to have purchased a real option. The real option allows for the right, but not the obligation, for the firm to enter the HEV market at a future date. The entrance of several firms into the market signals to others holding these real options that there is value in exercising the real option. These signals result in the entrance of more firms to the HEV market forming an informational cascade that holds the risk of being merely a temporal "fad" or "hype."

In the case of HEVs, OEMs have gathered enough information over the last decade to know that HEVs will continue to grow in the future, making this informational cascade a sound decision. The systems dynamics methodology can help develop understanding of the complex factors pressing for change in the automotive industry. A model for new vehicle architecture adoption is examined in section 3.5.3 as an example to the methodology.

Table 3-11 Qualitative comparison between various vehicle architecture concepts taking a parallel full hybrid concept as the reference architecture

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

++ Very Advantageous; + Some Advantages; o Average; - Some Disadvantages; - - Many Disadvantages

Finally, a qualitative comparison of the vehicle architecture types considered in this chapter are summarized in Table 3-11 taking a full hybrid vehicle as a reference. Overall, the benefits of electrification lie in reduced tank to wheel emissions, better fuel consumption, an enhanced ecological image and support from government incentives that make these new electrified powertrain architectures more attractive. The disadvantages of electrified powertrains lie in increased weight; reduced driving range; higher manufacturing costs; and commercial risks related to the replacement or servicing of the high voltage battery. These disadvantages are the technological risks that first movers in the new vehicle market must be ready to improve on to gain and secure an advantage in the market.

4 Hybrid Vehicle Architecture Fundamentals

Vehicle architects rely on system design principles and methodologies to guide them in creating new car concepts. This chapter begins by presenting the basic principles of system architecting as a foundation for the processes used in the development of new vehicle architectures. A follow on discussion of methodologies and frameworks that have evolved over the past three decades within the field of multidisciplinary systems engineering design builds on these principles.

In applying these methodologies, system architecture practitioners have learned that in today's rapid design of complex systems more design flexibility is required throughout all stages of development. The ultimate flexibility comes in systems that are designed to be changeable within their operating lifecycles [FRICKE et al. 2005]. Design for changeability is briefly presented together with the concept of architecture options as a means to determine the value added by incorporating change opportunities within the lifecycle of product architectures [ENGEL et al. 2008].

Included in this chapter is a deeper analysis of the variety of engineering design choices encompassed in hybrid vehicle structural configurations. The design of cars in this new age of architectural competition focuses primarily on innovations that entail a reconfiguration of a known sub-system components. A discussion of alternative designs shows that not all hybrid cars are necessarily useful and that a wide variety of technologies can be incorporated for different vehicle types. Finally, an overview of a vehicle architecture pre-selection road map at the conclusion of this chapter is developed that is used in follow-on chapters culminating in a practical example in chapter 7.

4.1 Systems Architecting

The shaping of structure and behavior of elements within a complex system is known as *system architecting*. Over the years, many authors have contributed basic principles that help in the analysis, creation, management and reconfiguration of systems and their behavior. In this section the methodologies these authors' developed to assist in the design of complex systems are reviewed.

The total *system* refers to the product as a whole. The principles of system architecture apply to all levels of abstraction within the system's boundaries, which in this case are limited to the vehicle product itself. The system architecture plays a central role in the design of elements in both structure and behavior as seen in Figure 4-1, and defines the system's properties, functional behavior, emergent behavior and level of complexity.

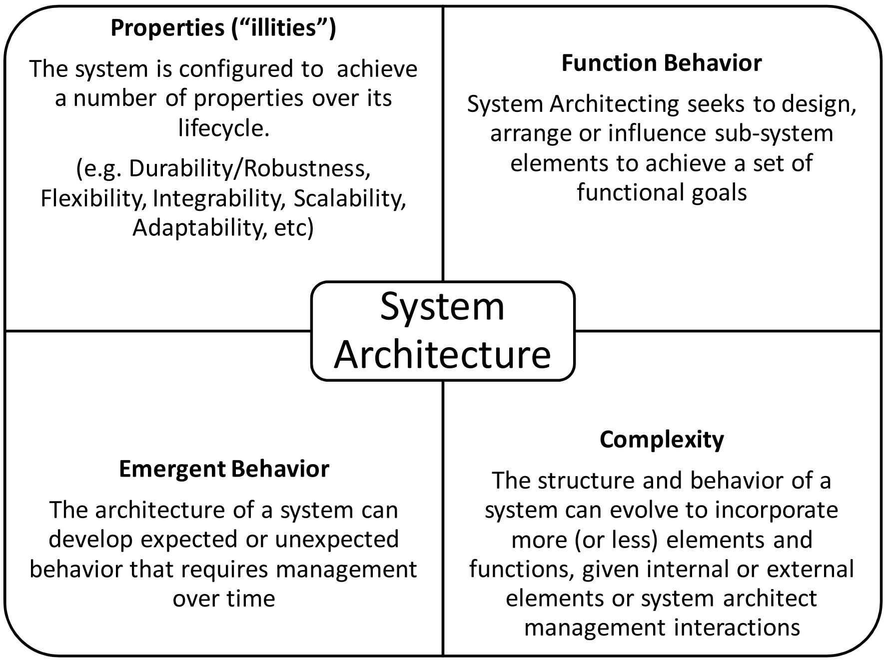


Figure 4-1 Aspects of System Architecture [CRAWLEY et al. 2004]

The **properties of the system** (the "ilities") can usually be recorded over a system's lifecycle. For example, system architects can create a system that shows durability and robustness by incorporating redundant sub-systems or by adding additional safety tolerances to system design requirements. Often, not all system design properties can be achieved. System architects must consider trade-offs of properties in the design of a system. The more complex the system is, the more trade-offs might need to be remedied.

A system's **functional behavior** refers to the desired set of goals developers seek in structuring a system. Once in operation, the system might evolve and create expected or unexpected behavior. For example the functional behavior of a plug-in hybrid car can be to achieve reduced fuel consumption through extended electric driving, and an **emergent behavior** could be that plug-in hybrids become an integrated part of the national electric grid by providing capabilities to store the excess electric energy capacity at night. The second behavior might not have been intended originally.

Systems architecture is intrinsically related with **complexity**. Complex system architectures that combine multiple sub-systems can display aggregate behaviors that no single sub-system has. The evolution of a system can turn to chaotic complexity through unstructured growth, as in the case of the internet system or it can achieve simplicity with time as often witnessed in the construction industry by working towards modular architecture interfaces.

4.1.1 System Architecting Principles

Several key principles and methodologies to system architecture analysis and handling can be extracted from the fields of system engineering and product development. The following is a list taken from various publications applicable to system architecting.

- **Systems Thinking** – [based on ULRICH, W. 1988;HABERFELLNER et al. 2002; EHRLENSPIEL 2003, NEGELE, H. 2006] In developing product architecture, systems thinking allows developers to understand the overall structures, patterns and cycles in systems rather than considering only specific aspects or elements within. Important in systems thinking is developing system boundaries and determining how elements or sub-systems are related. Once system boundaries are defined open or closed system modeling can be applied to more closely understand the behavior of the system. Open systems have interacting inputs and outputs with their environment whereas closed systems are modeled to have only endogenous relationships.

- **Partitioning** – [based on DÖRNER 2000; SAGE 1992] Complex problems are commonly found in the product architecture development processes. The principle of problem partitioning allows us to "divide and conquer" by understanding where sub-problems interfaces are found that can be partitioned into simpler problems. The same principle applies to system partitioning, where complex assemblies, organization and resources are divided to allow for better understanding and management. Partitioning requires the careful analysis of interfaces that allow a sub-system's reintegration to a larger whole. System integration is a challenge for fine partitioned systems. For example, in project management of complex products the product development processes are divided into smaller partitions to allow for easier handling and task accomplishment as part of the work breakdown structure [BROWNING 2001].

- **Abstract to concrete** – [PAHL et al. 2006] As presented earlier in section 2.1.1, the development of product architectures can be oriented based on the level of abstraction or concreteness. Generally, product planning and development occurs in more abstract levels to reduce complexity while focusing on concept development. Once the design concept is developed the product architecture is handled in more concrete terms. Jumping between levels of abstraction can be used as a method to solve design problems [LINDEMANN, UDO 2007].

- **"Form follows Function"** – This principle stems from civil (building) architecture disciplines to clarify that functional intent of a building structure is a primary consideration, whereas the stylistic form is said to follow function. A nice looking building that cannot perform its intent is merely a work of art. In product architecture, the principle of "form follows function" is one that generates much debate, as some consider that the product's outer design generates requirement constraints for the functional construction of the product. According to ULRICH, K. T. 1995 there is no such thing as one optimal product architecture, however the configuration of design elements must accomplish the functional goals required of the product. The form of the product architecture can be more integral or more modular depending on the functional behavior the product is to perform.

- **Focus on the Early Development Phases** – [based on Ishii, K in KUSIAK 1993] Focusing resources in the early development phases allow for thorough product planning and architecture concept development. The front loading of cross functional design efforts that consider the products objectives, constraints, and Lifecycle parameters such as customer requirements, regulatory requirements, market requirements, product esthetics, manufacturability, assembly, serviceability and recyclability, lead to a successful product development process with fewer iterative steps. The field of concurrent engineering is based on this principle and allows for shorter development periods, increased cost savings, reduced risk and greater flexibility in meeting market demands.

- **Top-Down Development, Bottom-Up Integration – [**based on HABERFELLNER et al. 2002] Systems engineering theory is based on breaking the product architecture into component modules for purposes of design and dimensioning to increase resolution (see V-Model in Figure 4-4). Once product modules are tested to achieve the desired behavior at the component level, integration with other component sub assemblies takes place in a bottom-up approach. Here, it is important to consider module interfaces that might have not been considered in component level testing. The bottom up integration process must provide feedback to the top-down development process by means of design iterations until the required product quality is achieved.

- **Consideration of the entire Lifecycle – [**based on SHISHKO 1995] Product architecture requirements must consider the entire Lifecycle of the product including planning, concept definition, development, production, and use all the way through to disposal/recycling. Lifecycle metrics provide a broader picture of product performance. For example, designing for cost reductions might result in production or purchase savings for the manufacturer but a cost increase in use and ownership costs for the customer, making the product less attractive. The developer can keep the customer use and ownership costs in check when lifecycle costs are considered. More on this example can be examined in chapter 6.

- **User and Customer oriented –** Requirements to the development of product architecture must also serve a basic customer or user need. Product architectures that fail to meet consumer requirements lack market potential and are not cost-effective for their lack of utility.

- **Use of System Modeling –** [based on STERMAN 2000] System modeling allows product architects to develop a simplified representation of a complex product or system. The key ingredient to a successful model is a purpose that clearly articulates the model's intent. Modeling is an iterative process between experimental learning in both the modeled representation and real world observations. Modeling helps facilitate informed decisions for choosing a product architecture configuration.

- **Thinking in Alternatives –** [based on HABERFELLNER et al. 2002] It is possible to devise a variety of ways the system goals can be achieved once these are understood. The product architect should avoid jumping to a favored solution without considering whether the product's functional requirements can be met more efficiently using other alternatives. By collecting alternative solutions the chance for a design innovation is increased. Thinking in alternatives is also important in mitigating uncertainty stemming from customer acceptance in the market, actions from competitors, government regulation development and the introduction of competing technologies.

- **Interdisciplinary Cooperation –** [based on EHRLENSPIEL 2003] Product development is most successful when all stakeholders have input to the design process. This includes development engineers, finance, marketing, sales, service, customers and users to name a few. All stakeholders should have an opportunity to provide input to the design process in a systematic way. The early incorporation of stakeholders in the design process is a tenant of integrated product development.

- **Documentation –** A product development process that goes undocumented will be revisited in the future without the benefits of learning. Documentation helps in the optimization of the development process and aids new product development. The result of a well documented project allows system architects to learn from mistakes and save time in future design iterations. Detailed documentation processes are part of good system architecture practice.

4.1.2 Methodologies and Frameworks

System architecture features the use of procedural models to enable system development and management. These frameworks can be categorized into linear models, phased models with iterations and network models.

- *Linear Models* - These models are characterized by a linear series of process steps that require an activity to be accomplished before moving on to the next step. The benefit of linear models comes from the simplicity they provide in sequencing activities and decisions. In linear models, complex system architecture development can be handled in discrete phases that lead to decision points. Each decision point represents the processing of input information and generating output actions. If at a decision point criteria for continuing to the next stage is not met, the process is interrupted or prolonged until the conditions are achieved to move on to the next phase.

Examples of linear models used in product architecting are the integrated product development model according to ANDREASEN et al. 1985, the Stage-Gate Model according to COOPER, R. G. 1990 and the product development process according to ULRICH, K. T. et al. 2004. These models are considered to be meta-models that show the macro-logic of the overall procedure.

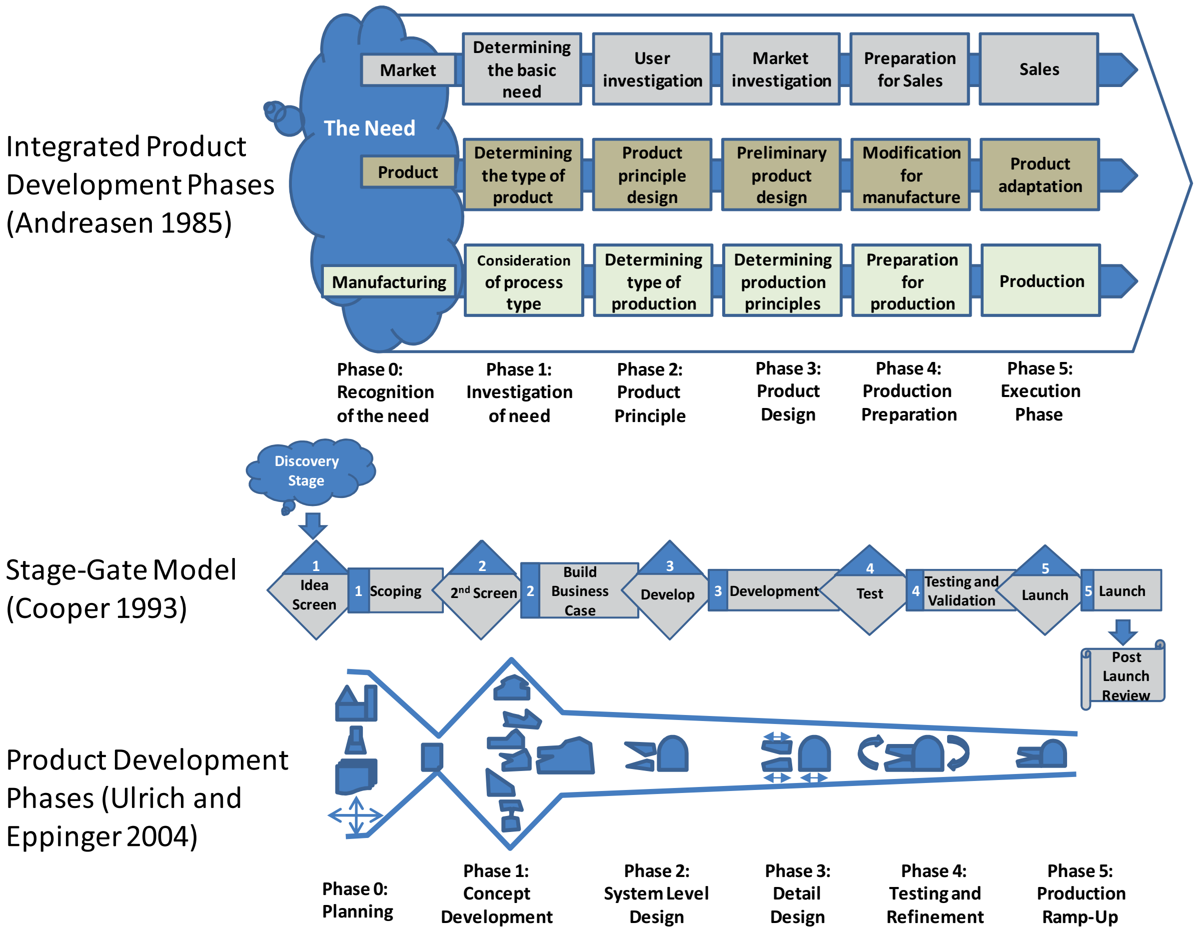


Figure 4-2 Linear models for Product Development in phases

Integrated product development phases - [ANDREASEN et al. 1985] At the top of Figure 4-2 the integrated product development process according to Andreasen is shown. The process is described in a linear model in six phases in parallel stemming from customer needs and integrating market activities (top path), product development activities (middle path) and manufacturing activities (bottom path). Each path has basic "gates" similar to the stage-gate model where interdisciplinary input is required to move on to the next activity phase. Important in this model is that the product architecting requires parallel synchronization of marketing, sales, product development, and manufacturing along with a fundamental presence of the customer's needs.

Stage-Gate Model - [COOPER, R. 2003] The stage-gate model depicted at the middle of Figure 4-2 results from a number of industry research studies from which general guidelines for successful product development processes were observed. In Cooper's model, *gates* are milestones or decision points in which the results of the previous *stage,* or project phase, are analyzed for a decision to: go, kill, hold or recycle. "Go" decisions allow the project to move on to the next stage, "kill" stops the project, "hold" pauses or delays the stage, and "recycle" prolongs the stage until desirable conditions are met for further movement into the next phase.

The stages presented in Cooper's work describe the development of a product from ideation to product launch. The discovery stage represents the first decision to commit resources to the project are based on an immediate idea. The *idea screen gate* ensures that the product idea meets the company's criteria for further development. The *scoping stage* determines the project's technical and market place merits that lead into a secondary screening stage. A "go" at the *secondary screening gate* commences the creation of a business case where detailed information is gathered on competitive analysis, manufacturability, customer attractiveness, and a detailed financial assessment of a new product launch. A "go" from the *develop gate* commences the detailed development work stage which leads to a *testing gate*. A "go" at the *testing gate* then enables a product launch which should be studied and measured to provide feedback to development process for continuous improvement.

Product development process – [ULRICH, K. T. et al. 2004] The bottom of Figure 4-2 depicts the product development model according to Ulrich and Eppinger. Product development occurs in phases which open the field of consideration to widen or limit scope as the design progresses from concept to production. The initial planning requires integration of various disciplines that are funneled into a development plan. The concept phase opens the design solution field and then narrows it as the design becomes more detailed with time. Emphasis is placed on interdisciplinary activities for planning the development process and the need to go from abstract design to detailed design by partitioning. Each component design module partition is then reintegrated to a tested and refined product.

One general limitation of the linear models is that their abstract representation fails to show the iteration necessary in product architecture development that is implicit amongst and within each phase.

- *Phased Models with Iterations* – Most product architecture development frameworks and methodologies plan for an iterative process explicitly. Here, product design is considered to contain discovery processes that are iterative in nature. As product architecture is considered from abstract concepts to detail component designs, requirements are identified that are hard to foresee at the start of the design process. As the design gains resolution in its parts, often it is necessary to take a step back and re-consider previous decisions with the new acquired learning.

Several examples for phased models with iterations include the VDI guideline 2221 [VDI 1993], Integrated product development model [EHRLENSPIEL 2003], and the systems engineering V-model.

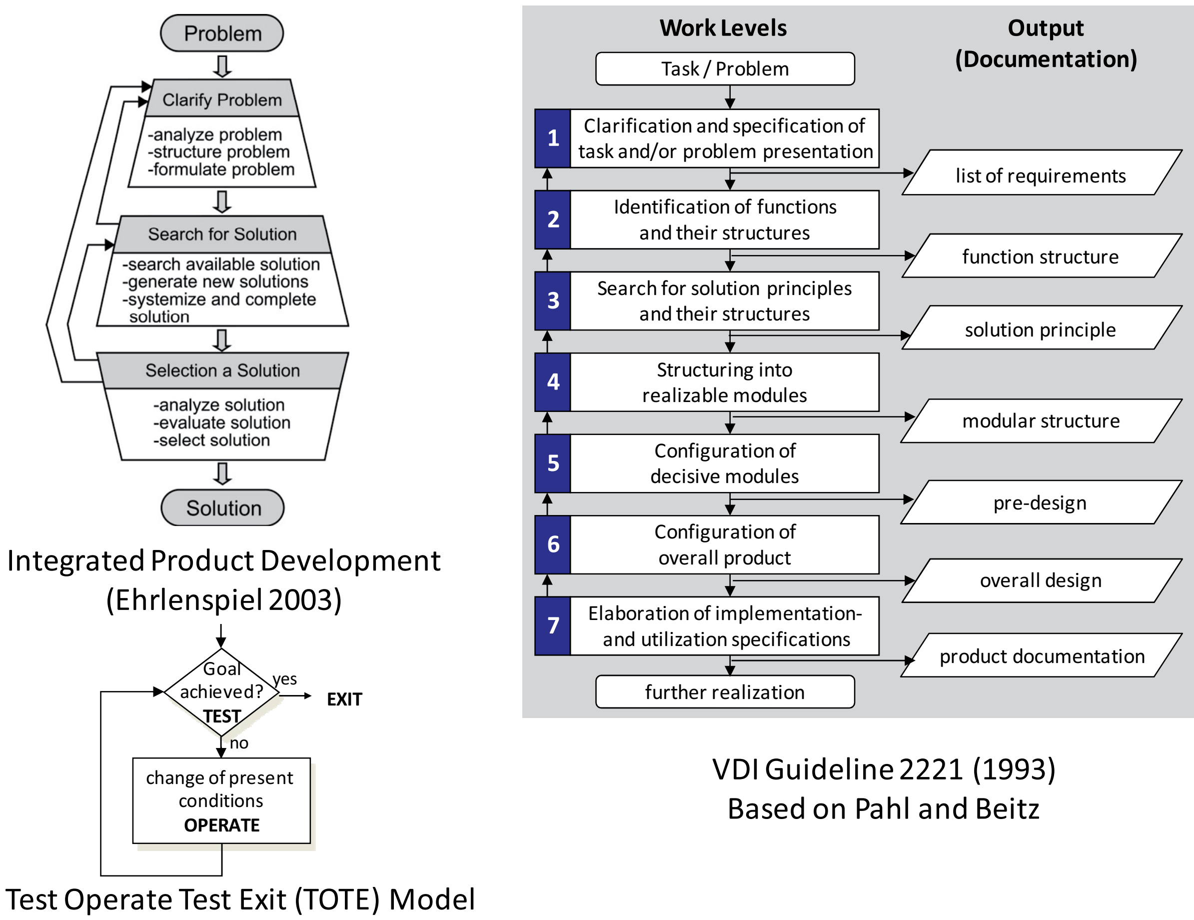


Figure 4-3 Examples of Phased Models with Iterations

Integrated product development - [EHRLENSPIEL 2003, p.77-85] – Ehrlenspiel's integrated product development procedural model follows a linear progression, however it anticipates iterations within each phase of the process explicitly. The iterations follow the "Test –Operate -Test – Exit" scheme in its three main steps as shown in Figure 4-3 bottom left. This scheme explicitly identifies the necessary recursion that occurs in the development of products and their architecture. The key steps in Ehrlenspiel's model include:

1. *Clarifying the Problem* – This step has the highest priority as it entails analyzing, structuring and formulating the problem. At this phase, the goals of the product are defined along with the requirements it must satisfy.
2. *Seeking Solutions* – The solution search starts with considering established solutions that can be improved upon and the search for new solutions. If the solution field is too heavily constrained by the goals and requirements, an iteration of the first step is required.
3. *Selecting Solutions* – The selection of solutions requires methodologies to analyze, evaluate and select solutions from the solution space created in the

previous step. The criteria for solution selection are established by the goals and product requirements in step one. If these requirements are not clearly defined, a return to step one is necessary. If the solutions available are not feasible or distinguishable from each other, revisiting step 2 is required.

4. *Implementing a Solution* - A final step is the implementation of the solution and a follow on to the next problem. Ehrlenspiel describes his approach as a problem solving methodology that can be implemented throughout all product development phases and integrated through all departments relevant to the design of a product including the development, marketing, sales, and manufacturing departments to name just a few.

In a similar fashion to Ulrich and Eppinger, Ehrlenspiel, identifies the varying levels of information in a double cone structure. During the first two steps of the model information is increasing depicted by an increasing cone, whereas in the selection step information decreases as the process must funnel solutions and decide which to implement.

Product Development Procedural Model according to VDI 2221 - [VDI 1993] The Association of German Engineers (Verband Deutscher Ingenieure (VDI) in German), published guideline 2221 as a framework for product development. The methodology follows primarily the work of Pahl and Beitz [PAHL et al. 2006] and follows a linear progression with output documentation products necessary for follow on steps. Iterations throughout the design are embedded in a generic way allowing for development cycles. A close look at the steps and documentation in Figure 4-3, will present similarities to previously discussed models. Important in the VDI 2221 is the focus on the principles of partitioning and documentation.

Systems Engineering V-Model – [FORSBERG et al. 1994] [HASKINS 2003] The V-Model describes a methodology for the interdisciplinary development of complex systems and products. The V shape represents the two fundamental parts of the model. The left-hand side describes system decomposition, whereas the right-hand side describes steps necessary in system integration and verification. The depiction in Figure 4-4 shows an adaptation of the V-Model to the development of automobiles through the entire lifecycle of the product.

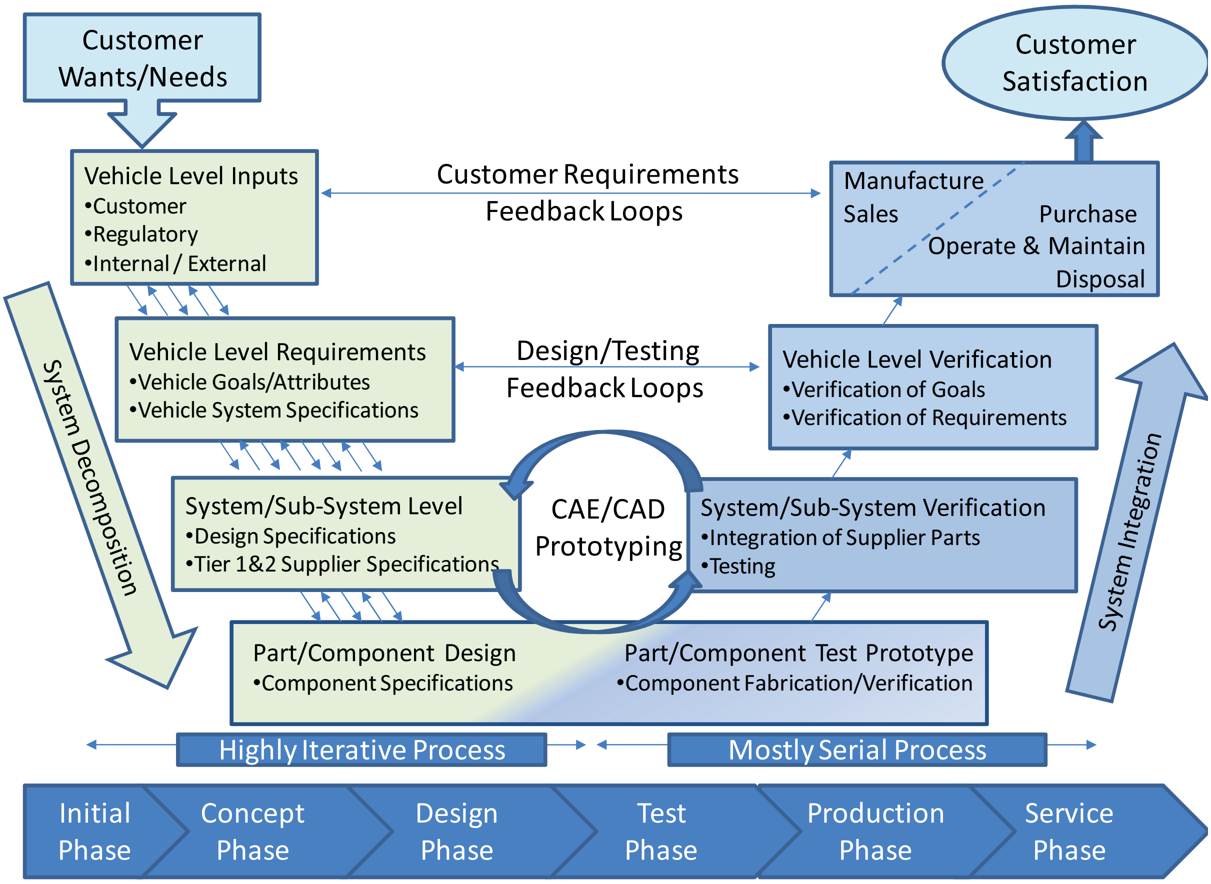


Figure 4-4 Adaptation of the Systems Engineering V-Model to Vehicle Development

The V model starts with the customer needs and ends with customer satisfaction, implying that product/systems are built primarily for customer or user utility. The right hand side is highly iterative as the system is clarified and partitioned. The partitioning starts from gathering the vehicle level inputs from the customer, competitor's products, government regulations and the firm's own requirements. These inputs are formalized in vehicle requirements that are further broken down into vehicle sub-system requirements. Finally, the component solution search, selection and design occur at the bottom of the V-Model with the help of computer aided engineering, design models and prototyping.

Requirements develop in a cascading manner providing increasing resolution at each process step as more detailed requirement information. Likewise feasibility feedback acquired through the design causes iterations in the search for solutions as the project moves from the initial planning phase and on through the concept and design phase.

The right hand side of the V-model shows the integration and testing of the many system parts to make a functional whole. This process is mostly serial, meaning that iterations are greatly reduced. Inputs to the system verification side of the V-model come from the appropriate levels of abstraction on the left hand side. Once the component level design and prototype fabrication is worked out (bottom of the V-Model), the testing phase begins starting at the component level, working its way through assemblies of components, into the sub-system verification level and finally into the total vehicle verification. The production use and disposal of the vehicle ensue at the top of the left hand side. These process steps show that the model extends throughout the lifecycle of the system or product.

Important in this framework of the V-model is that it follows a timeline to the right hand side that can be described in the traditional product development process phases as shown in the figure. This timeline association is found in early literature from United States authors, whereas it is excluded in German literature although the V-Model as such was developed concurrently in both countries as early as 1979. With the mapping to a timeline, the V-Model's decomposition and integration phases show overlapping progression that is part of the fundamental concept of simultaneous or concurrent engineering [SWINK 1998]. By overlapping design decomposition phases, engineers have an opportunity to share information that enables significant reductions in design time, reduction of costs and quality improvements through interdisciplinary collaboration in all design phases. Common to all V-Model representations in systems engineering are the principles of top-down to bottom-up development, starting from an abstract concept and progressing into concrete partial designs that aggregate to a whole working system.

- *Network Models* – Building on the linear and iterative models, network models provide a more flexible approach that allows the user to adapt the procedural steps and design phases to his current situation. The network structure allows for navigating through a number of working methods and loose networks steps offering flexibility in jumping between levels of detail and completion. An example of a network procedural model for product development is the Munich Procedural Model by Lindemann.

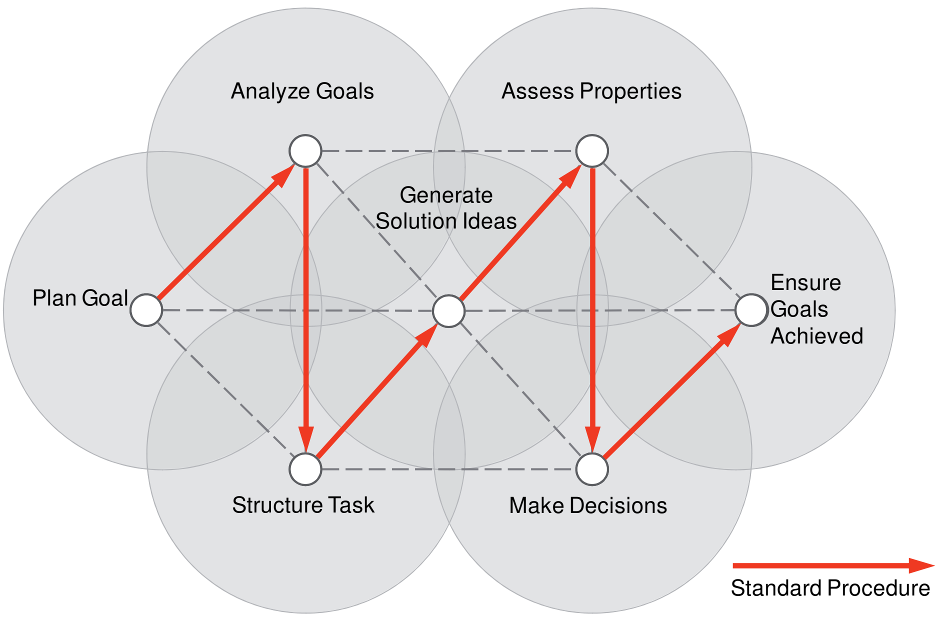


Figure 4-5 The Munich Procedural Model [LINDEMANN, UDO 2007]

The Munich Procedural Model (MPM)– [LINDEMANN, UDO 2007] – Lindemann's MPM is composed of seven equidistant nodes that are connected in a network manner. Around each node is a circle that represents activities and a collection of "working" methodologies that support a particular node's purpose - similar to a Venn diagram. These working methodologies can easily overlap into other nodal areas and provide inputs towards other nodal steps as commonly occurs in a highly interrelated and integrated product development process.

The standard development pathway denoted by the arrows corresponds to steps covered in previously described leading procedural models. However the developer's situation dictates the path the developer should take and allows for iterations between nodal steps. For example, after having gone through the standard procedure the developer might find a subsequent property that needs to be addressed for which a new solution is required. The procedure might then start at the "ensure goals are achieved" node moving to "assess properties", a "re-analysis of goals", "a solution search" , followed by a follow on "decision." Emphasis is placed on flexibility and the developer's situation allowing for various entry and exit points to the model.

Table 4-1 details each node of the MPM explaining key tasks and supporting working methodologies. Lindeman's approach suggests that in complex systems the ability to change and break away from a standard development process might be necessary and even useful. The design process flexibility can be just as valuable as product flexibility itself.

Table 4-1 Summary of Steps and working methods linked to the Munich Procedural Model

MPM Node	Summary [Lorenz 2009 on Lindemann 2007]	Example of Working Methods Available
Plan Goal	1. Analysis of the developer's situation and problem formulation 2. Examination of market, customer, competition and other external influences on the product goals	Market Research, SWOT Analysis, Scenario Building, ABC Analysis, Portfolio Analysis, Consistency Matrix
Analyze Goal	1. Formulation of specific detailed requirements for the new product 2. Analysis of interdependencies between various requirements, including goal conflicts	Requirements List, Reverse Engineering, Mind Mapping, Cause and Effect Analysis, Checklists, Consistency Matrix, Benchmarking, Target Costing
Structure Task	1. Structuring the system, resolving its subsystems and determining core actions 2. Formulating the goal and defining degrees of freedom	Black Box, User Related Functional Modeling, Relation-oriented functional modeling, QFD/House of Quality, DSM, Weighting schemes, Problem Definition
Generate Solution Ideas	1. Search for a solution by applying engineering design methods 2. Aiming at structured and concise representation of alternative solutions	TRIZ, Morphological Matrix, Compatibility Matrix, Research, Method 635, Brainstorming, Synectic, Bionics, Effect analysis, Construction Catalogs
Assess Properties	1. Analysis of available alternatives for their relevant and measurable properties 2. evaluation of single alternatives and combined systems	Similarity Analysis, Properties list, Estimates, Calculation, Numeric Simulation (HiL, FEA)
Make Decisions	1. Interpretation of assesment results 2. Choice of optimal solution	Preselection matrix, Trade Space Analysis, Goal Preference Matrix, Weighted Score, Value Functions, Comparison in pairs, Balaced, Sensitivity Analysis,
Ensure Goals Achieved	1. Reconfirm goals to minimize risk 2. Documentation and if necessary initiation of preventive measures	Risk Analysis, Failure Mode and Effects Analysis (FMEA), Cause and Effect, Story telling, Balanced Score Card, Return on Investment, Checklists, Performance Tracking

4.1.3 Changeable Architectures

Incorporating changeability or flexibility has become an important consideration for vehicle system architecture. Incorporating the ability to change the vehicle architecture at a future time within the product lifecycle can deliver value to both the manufacturer and customer. Changeability could be incorporated to the development of product family variations, or by allowing upgrades to a vehicle during the use phase to adapt to new environments.

The philosophy of incorporating flexibility to vehicle architectures to allow for later changes can be seen as practical alternative to problems encountered by late changes commonly encountered in the development of complex systems [FRICKE et al. 2005, p.343]. The current practice of front-loading the development process to prevent the "**rule of ten**" effect - stating that with each subsequent development phase the introduction of a design change increases tenfold in cost [BOEHM 1981, p.125, EHRLENSPIEL et al. 2007b, p.11] - can be mitigated to some extent by incorporating a philosophy of "architectural flexibility."

The ideas of **changeable architectures** for cars result from three key influencing factors: (1.) technological change towards mechatronic products, (2.) the effects of a dynamic market place and (3.) environmental changes a car must perform in. The principles presented here are based primarily in previous works proposed by [FRICKE et al. 2005, CRAWLEY et al. 2004, HABERFELLNER et al. 2005b, pp. 3-8], [SALEH et al. 2003]. Although the focus of application is to vehicle architectures, the principles of changeability can be applied to product, process and organizational system architectures.

Technological Change to Mechatronic Products - Mechatronic systems are defined as those systems that exhibit a combination of mechanical, software and electronic control systems. Studies have shown that the number of mechatronic technologies incorporated in the overall vehicle product system have exponentially increased since the 1970s [HELLENBRAND et al.]. Most customers get to know these systems as simply optional features to the car including systems such as airbags, anti-lock brake systems (ABS), dynamic stability control (DSC), and the GPS navigation systems to name a few. The development cycles of these technologies are often shorter than the vehicle development cycle and their product lifecycle is commonly significantly shorter than that of the overall vehicle system architecture [FRICKE et al. 2005].

The technological transition to mechatronic systems has worked its way up to more complex sub-systems. Today we can speak of mechatronics at the overall system architecture level with introduction of hybrid and electric vehicles, as described by the pyramid in Figure 2-5 in page 24. This means that a combination of mechanical, electrical and software systems make up the powertrain of the car itself, along with the many other mechatronic features that are included in the product system of systems.

Dynamic Market Place – As discussed in section 3.3 the automotive market place has seen an increase in competition and a quicker cycle time in the delivery of new auto products to market. "Staying ahead of the competition requires high responsiveness in terms of supporting late design decisions. This includes reducing the gap between design freeze and system delivery [FRICKE et al. 2005, p. 343]." In the premium segments, the market for cars requires mass customization, or the developing, producing, marketing and delivering affordable goods with enough variety that nearly everyone finds exactly what they want [PINE et al. 1999, p. 44]. For example, at BMW Group the variety in product features the customer can order makes it statistically unlikely to produce the same car twice for any two distinct customer orders. In fact, a customer is allowed to change major features such as engine type and color of the car up to one week before scheduled production due to the flexible production system and car architecture.

Adaptability to Changing Environments – A third driver for changeability in vehicle architectures comes from the demands changing environments place on modern automotive systems. Adaptability to a changing environment involves adapting to both physical and technological environments outside the system boundaries of the car itself. Examples include the ability to conform to changes in communication, navigation system platforms, or the ability to deliver equitable driving conditions in extreme weather conditions. Another example is the incorporation of external product features such as the connection of an MP3 player. This allows the car to use its internal sound system with the external input of music files available in the car/user environment. Thus the ability to add on components or systems to an established common interface already in place within the car architecture makes adaptation to changes easier throughout the lifecycle of the car.

Applying Aspects and Principles of Changeability to vehicle architectures– FRICKE et al. 2005 describes four basic aspects of changeable systems along with nine principles that enable changes to system architectures as described in Figure 4-6. The four aspects are

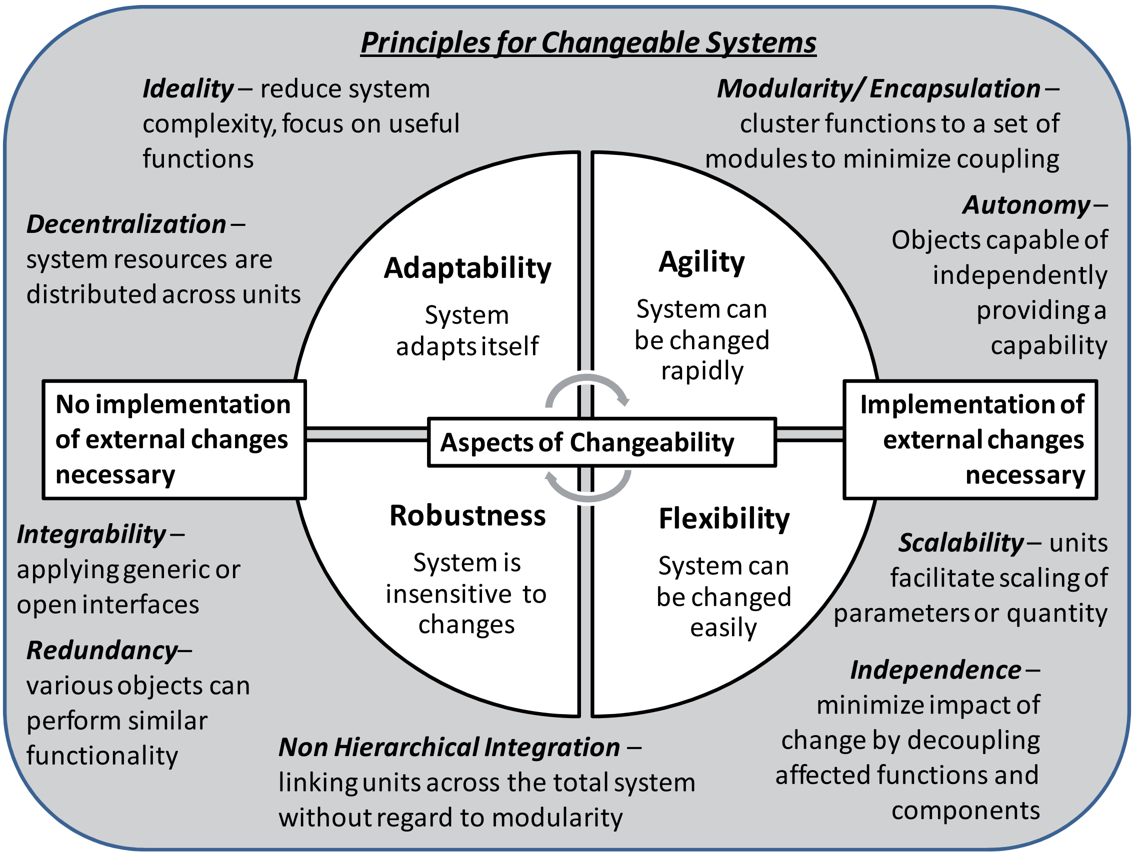


Figure 4-6 Summary of the four basic aspects of changeable systems and principles that enable changes in systems according to FRICKE et al. 2005

described below with current examples in hybrid electric vehicle design:

- **Adaptability** – the ability of a system to adapt itself to environmental changes without external actuation. Adaptability can be achieved through mechanical design using physical laws or material properties as well as with sensing devices.
    - *Example for HEV design* –coupling the powertrain control system of an HEV architecture concept to the navigation system can help determine how to adapt the HEV powertrain control strategy to upcoming terrain or road conditions. This intelligent system may favor the depletion of the high voltage battery during hill climbing knowing that it will have an opportunity to recharge the battery through regenerative braking going downhill. In this example, the principles of integrability, non-hierarchical integration and autonomy work towards system adaptability.
- **Agility –** The ability of a system to rapidly conform to environmental changes. Agility requires the implementation of external changes to the system. The system or product cannot change itself automatically as in adaptability, but has the ability to take on new functionality through common interfaces or integrability. HABERFELLNER et al. 2005a
    - *Example for HEV design* – An agile HEV system design can provide value to the customer by allowing for scaling of the high voltage battery based on the user's selection of a desired all electric range. For customers that primarily use their HEV as a second car for use in a small urban area, an all electric range of 10km might be sufficient to cover the needs of the customer. The high voltage battery installed in the HEV will be smaller than that of a customer with a 20km electric range requirement. An example of an agile system design would allow the introduction of the minimally required battery size through a common battery module interface, but allow for upgrades or downgrades later on in the product lifecycle. In this example, the principle of scalability develops the agile system capability.
- **Robustness –** A robust system is insensitive to external environmental changes that allow it to display changeability in its use. A car that can start in both extreme cold and warm weather consistently over its lifetime is considered to exhibit robustness [SALEH et al. 2003, p.937].
    - *Example for HEV Design* – The high voltage battery of an HEV system will vary in performance throughout its lifetime based on temperature considerations, number of charge and discharge cycles, age of the battery, anode and cathode chemistry and the battery depth of discharge window allowance. Robust design can be implemented by determining how to establish design parameters and experiments to establish quality standards over the lifecycle of the vehicle such that the user can expect an overall system behavior level of quality. The result of a robustness study might result in having a larger number of battery modules to achieve the desired "end of life" battery charge capability or perhaps the elimination of systems powered by the battery system. Taguchi methods have been described for this particular design

problem to evaluate quality and develop a methodology for specifying tolerances [CLAUSING 1994, p.74, TAGUCHI et al. 2000, pp.53-60]. In this example, redundancy, ideality (or simplicity) and modularity/encapsulation are key principles in achieving robustness.

- **Flexibility –** Flexible systems are designed to change easily when environmental conditions dictate. Flexibility is achieved by applying principles depicted in Figure 4-6 that support changes in the system's use or its operating environment.
    - *Example for HEV Design* – An HEV production system is built to be flexible in its manufacturing process by identifying common interfaces for the possible addition of an external battery charger, a larger high voltage battery and an additional electric motor in the non-powered axle. By doing this the HEV platform becomes flexible to multiple variants of HEVs during manufacturing and allows for future electric system upgrades to a Plug-in Hybrid Electric Vehicle (PHEV) at a later time in the product lifecycle as an aftermarket sale. In this example, the principles of integrability, modularity, independence, autonomy and scalability achieve system flexibility.

The discussion in this section established the different aspects of changeability with grounded examples in HEV development. It is important to note that not all aspects of changeability are necessarily useful in a particular design situation, or the use of the principles that enable them.

Conflicts between changeability principles are common in engineering design. For example, how much ideality is needed versus modularity? Likewise, combinations of principles might lead to innovative solutions for concept development. Thus the principles presented allow us to develop ideas that enhance changeability in the system. FRICKE et al. 2005 offer a more detailed description of the principles outlined in Figure 4-6.

4.1.4 Architecture Options

Architecture changeability as described in the previous section can bring benefits to the manufacturer, the customer or both. However, the theory lacks a way to value an investment in changeability. Several authors have turned to the field of financial options to develop a way to value changeability in systems.

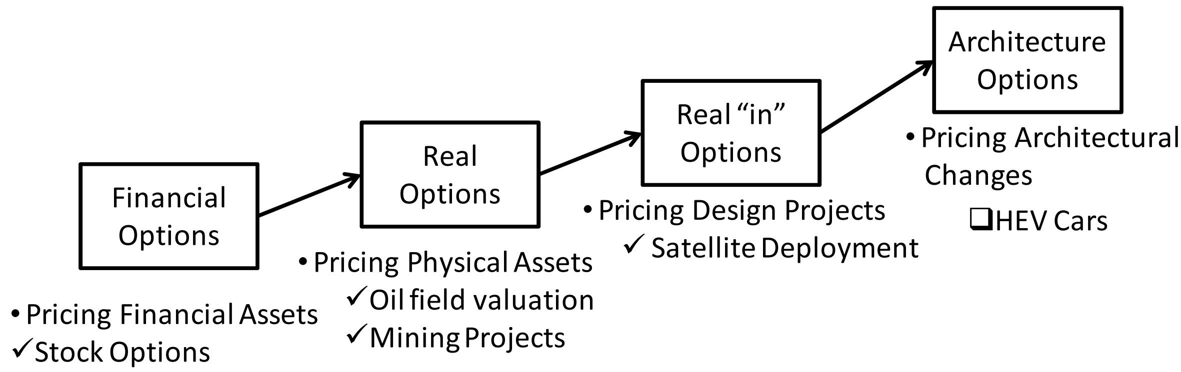


Figure 4-7 The evolution steps from "Financial Options" to "Architecture Options" taken from ENGEL et al. 2008 with additional examples. This works applies aspects of Architecture Options theory to HEV architecture configurations.

Figure 4-7 starts with the Nobel prize winning work from Black and Scholes that described a methodology for the valuation of financial options [BLACK et al. 1973]. This work was further developed by [MYERS 1984, p.127; BALDWIN et al. 2000, pp. 235-239] and others in the context of real options as a way to value physical traded assets or modifications to a design respectively. The application of real options in design projects (also referred to as "real options in projects or simply "real in" options") was further expanded on by [DE NEUFVILLE 2002; DE WECK, O. et al. 2004a, pp.127-134]. De Weck presents a method to value flexibility of deployment options of low-earth-orbit satellite using the binomial method for valuing real options. The research concluded that value of options for staged deployments of Iridium satellites results in 20% savings over the lifecycle of the project, as managers can better make capacity decisions as the market unfolds in the future.

Architecture options [ENGEL et al. 2008] is a term coined by Engel and Browning referring to the valuation of flexible systems building on the previous works mentioned. An *option* in financial terms gives the holder of the option a right to purchase or sell an asset for a specified price, called the *exercise* or *strike price,* on or before an expiration date [BODIE et al. 2006, p. 55]. Following this logic, an **architecture option** involves investing in changeability to have the right, but not the obligation to adapt or upgrade a product system at a later time in its lifecycle. The investment in changeability relates to the four basic aspects described in section 4.1.3 developed by Fricke and Schulz.

Architecture option valuation allows developers to recognize that there is a cost as well as a benefit in investing in a changeable design. The benefit comes in the ability to adapt to an environmental or user change at a later point in time within the product lifecycle at little or no cost. The cost involves designing and building changeability to the product system and the actual costs of implementing change or upgrade at a later point in time (cost of purchasing and exercising the option respectively).

The valuation of changeability can be accomplished at several levels. At the total architecture level, examining the lifecycle costs of possible architecture variations compared to a given "reference architecture" can reveal the costs and benefits at a macro level. This approach was used by de Weck, de Neuville and Chaize. An approach for the evaluation of HEV architectures builds on this work and is described in Figure 4-8.

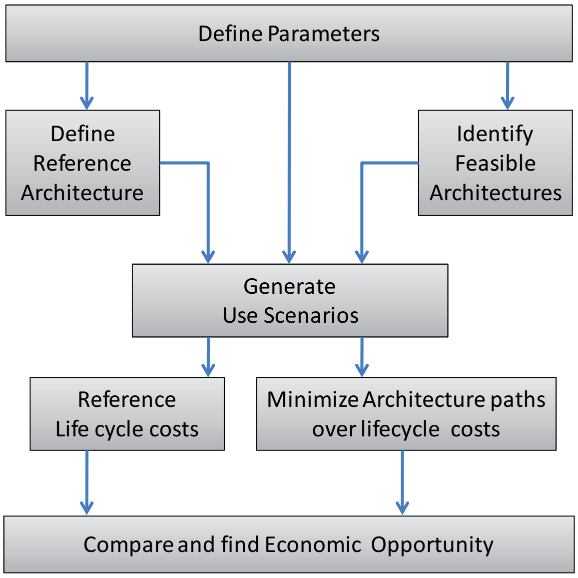


Figure 4-8 Schematic for comparing changeable and reference architectures to determine economic opportunity (adapted from DE WECK, O. et al. 2004a).This method of valuation is demonstrated in chapter 7.

As a first step in Figure 4-8, parameters are defined for the reference architecture, feasible combinations of new architectures and possible use case scenarios. The initial architecture definitions allow for the determination of manufacturing costs, whereas the use case scenarios allow for the calculation of user costs that sum up to a lifecycle cost estimate. The reference architecture yields a specific lifecycle cost that is used as a basis of comparison against other identified architecture configurations. A changeable architecture is worth adopting (or exercising) only if it delivers a greater value at a future date with respect to the reference architecture lifecycle and a specified time horizon. This methodology is developed further in section 4.4, and chapters 5, 6, and 7.

At the component and module level, ENGEL et al. 2008 propose a *component option value* as a way to value the minimal building block in a design. In this form, a *component* is defined as a software or hardware element with specific functionality that interacts with other components and/or the environment. The component option value (COV) is calculated using the Black-Scholes Option Price Model as described in equation 16.

$$COV = SN\left[\frac{ln\left(\frac{S}{X}\right)+T\left(r+\frac{\sigma^2}{2}\right)}{\sigma\sqrt{T}}\right] - Xe^{-rT}N\left[\frac{ln\left(\frac{S}{X}\right)+T\left(r+\frac{\sigma^2}{2}\right)}{\sigma\sqrt{T}} - \sigma\sqrt{T}\right] \quad (16)$$

Where COV is the component option value, S is the component's current value, X is its expected future value, N is the standard normal distribution, σ is the standard deviation of the potential future value, T is the time horizon and r is the risk free interest rate. Table 4-2 offers the analogy for the COV based on the five Black–Scholes formula parameters based on Engel and Browning's publication.

Table 4-2 Black-Scholes Formula and Architecture Options Analogy [ENGEL et al. 2008]

Financial Options (Black-Scholes)	Symbol	Architecture Options Term Name	Architecture Options Analogy	Example Value
Current stock price	S	Component current value	The current value of a given system component	700 €
Stricke price	X	Component future value	The estimated value of the given system component after it is upgraded	1,000 €
Volatility	σ	Standard deviation of distribution of potential future value	The uncertainty in the lifetime-value of the upgraded component within the system as viewed by stakeholders and translated into market-value over the specified period of time	20%
Time to Expiration	T	Upgrade time horizon	The time to start deployment of the upgraded component within a system	3 years
Risk-free rate	r	Risk free inerest rate	Risk free interest rate associated with funding required to upgrade a given system component at a prescribed schedule of project upgrade	4%
Expected Option Value	COV	Component Option Value (COV)	The expected option value of the given system component	39.80 €

The example offered in the right column of Table 4-2 could well refer to the integration of a navigation system component in a car that costs 700€ to integrate in a vehicle. The expected value of the same navigation system with a new software upgrade three years later is 1000€, the volatility is estimated at 20% and the risk free rate is assumed to be 4%. The customer has the option to buy the navigation system for 700€ and no future upgrade or buy an option to upgrade in 3 years at a fixed price of 300€ at the time of upgrade. By purchasing this option valued at 39.80€, the customer has the right but not the obligation to obtain a system upgrade in three years at the fixed price of 300€.

We assume that the original navigation system does not devalue over time horizon (i.e. the upgrade is in form of a software update only). This is similar to a call option in finance. If in three years the value of the upgraded system exceeds the estimated 1000€ the option is "in the money" and the holder of the option profits from the difference in price. Likewise, if in 3 years the upgraded system is less than 1000€ the option is "out of the money" and the option is not worth exercising. Figure 4-9 shows the customer payoff for this example.

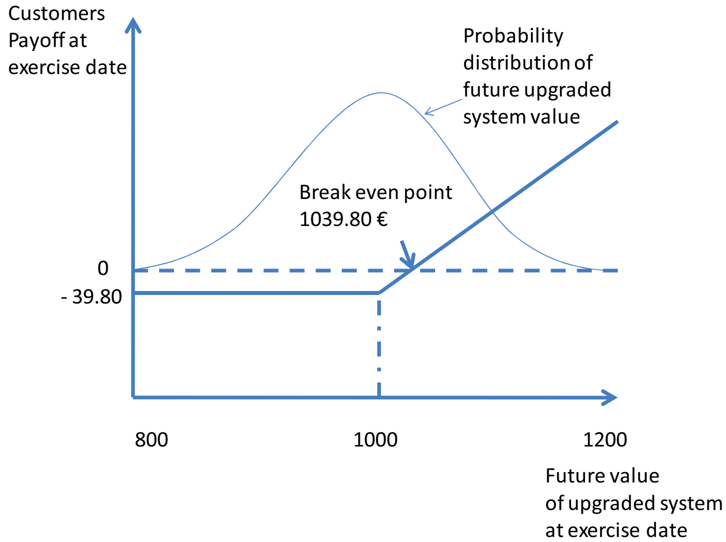


Figure 4-9 Call option payoff for a car navigation system upgrade. The customer purchases a navigation system for 700€ and an option for 39.80€ that allows for a system upgrade 3 years later at fixed price of 300€. The upgraded system value is expected to be valued between 800 and 1200 as depicted in the x-axis. The probability distribution shows that there is uncertainty in what the expected value of the upgraded system will be in the future. The customer exercises the option only if the future system value exceeds the breakeven point.

In this example, it is easy to see that if the assumption of devaluation and upgrading costs are relaxed, the value of the option would be affected. Especially in automotive examples, car components depreciate in value collectively as a function of time of ownership and distance travelled. In this example, the navigation system did not devalue from its original cost between the time of purchase and the three year mark. Additionally, no costs for upgrading the system were taken into account such as time for repairs where the vehicle is inoperable and labor costs.

In order to take into account for the complex set of parameters that represent value loss and upgrade costs, models can be established that allow for these parameters based on use case estimations. In general, the *optimal upgrade strategy* for a product system is one where the sum of value loss and upgrade costs are minimized over the lifecycle of a system as presented in equation 17 taken from Engel and Browning [ENGEL et al. 2008]

$$Min\left(\sum_{i=1,2,...}^{n}[VL_i(t)+UC_i(t)]\right) \qquad (17)$$

Where VL represents value lost to depreciation and maintenance over the product lifecycle time periods. UC is defined as the costs to upgrade a system. The optimal upgrade strategy can be visualized in Figure 4-10. Following the purchase of a product or system, value is lost to depreciation and maintenance related costs depicted by the area below the purchase value line. Likewise, value is also lost as an opportunity cost to the desired value of the stakeholders. A product upgrade can close the "value desired" gap at an upgrade cost. The maximum allowable upgrade cost covers the value gap exactly. The optimal upgrade strategy then focuses on reducing value lost and any costs associated with upgrading the system.

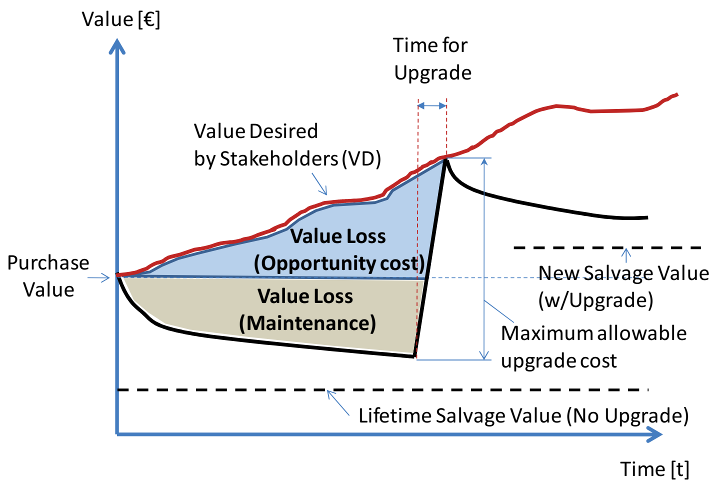


Figure 4-10 Lifecycle value of a system that undergoes an upgrade [based on ENGEL et al. 2008].

Figure 4-10 shows that the maximum allowable upgrade cost cannot exceed the difference between the value desired and the value lost. The optimal upgrade strategy attempts to minimize upgrade costs. This is done by limiting both the value loss of the system due to maintenance and opportunity costs associated with the value desired by stakeholders. The desired value can be estimated with the value of comparable new product technologies or by estimating an alternative future value with an average cost of capital.

4.2 Vehicle Architecture Structures

This section introduces terminology used to describe vehicle architecture structures for the wide spectrum of hybrid and electric vehicle offerings. Following the definition of vehicle architecture presented in section 2.1.1, the classification of vehicle architecture structures is primarily dependent on the functional concept of the system and the general configuration of key component subsystems such as the engine (or fuel converter), transmission, electric motors and energy storage devices described in the following sections. Each configuration differs in the overall vehicle functionality achieved.

Hybrid electric vehicle architectures are composed of two systems, a fuel (1) and an electric (2) power system. Figure 4-11 shows a generic representation of possible hybrid vehicle system configurations.

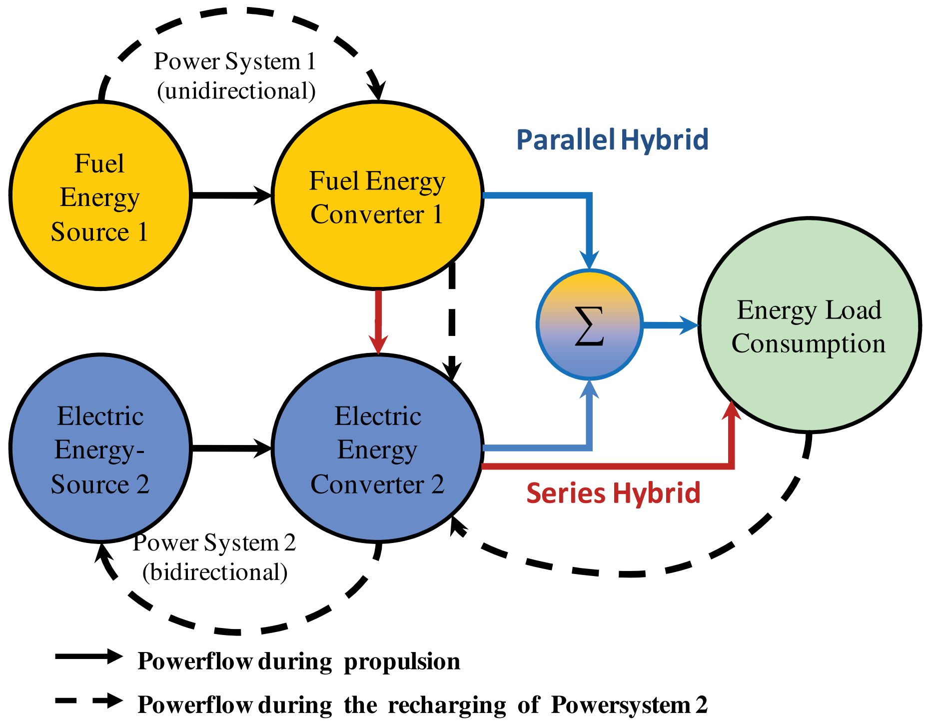


Figure 4-11 Conceptual illustration of a hybrid electric drive adapted from EHSANI *et al. 2009, p.124*

In principle, *parallel hybrid powertrain systems* refer to *additive* systems that combine both drives, whereas the *series hybrid powertrain system* works in a *sequential* manner having the fuel based powertrain provide power to the electric powertrain as seen in Figure 4-11 depicted by the red arrow path. The energy load consumption refers to the energy needed in propelling the vehicle.

The illustration allows for eight different operation energy flows based on the electrical and fuel based power systems. Vehicles that can *mix* features of both parallel and series hybrid operating modes are referred to as *combined hybrid systems*. Combined hybrid vehicles may either split the energy from the fuel converter into the series and parallel hybrid energy paths simultaneously as in the case of power split hybrids. They may also have a distinct switch that allows for only parallel or series drives at once. The operating modes that are possible to meet the load requirements are listed below in Table 4-3 adapted from EHSANI et al. 2009:

Table 4-3 Operating Modes of Hybrid Vehicles based on the figure 4-11

	Operating Modus	Parallel	Series	Comb.
1	Power train 1 alone delivers its power to the load.	x		x
2	Power train 2 alone delivers its power to the load.	x	x	x
3	Both power train 1 and power train 2 deliver their power to the load	x		x
4	Power train 2 obtains power from the load (regenerative braking).	x	x	x
5	Power train 2 obtains power from power train 1.	x	x	x
6	Power train 2 obtains power from power train 1 and the load simultaneously.	x	x	x
7	Power train 1 delivers power to the load and to power train 2 simultaneously.	x	x	x
8	Power train 2 obtains power from power train 1 and delivers to the load and/or is stored by power train 2 simultaneously.		x	x

The operating modes can occur in some cases simultaneously. As shown in Table 4-3, not all hybrid systems provide all operating modes. The classification of hybrid powertrains into additive, sequential and mixed systems is depicted in Figure 4-12. The five key vehicle architecture structures will be the basis of follow-on discussion in the remaining chapters.

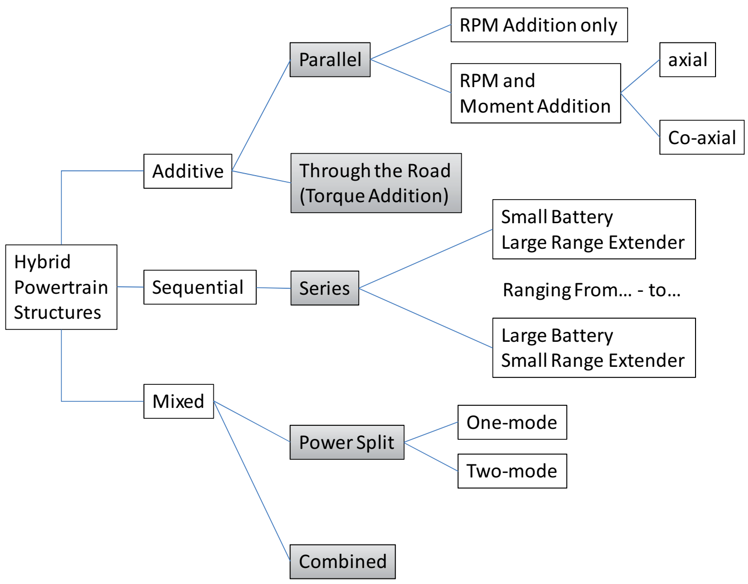


Figure 4-12 Classification tree of possible hybrid powertrain architecture structures

Parallel – These hybrid configurations are additive systems where both the electric and combustion engine power train combine power, torque, moment and rotational speed (measured in revolutions per minute - RPM) to achieve benefits from both systems. Parallel hybrids offer the broadest range of architectural configurations; later in this study over 4000 different configurations of major component systems have been identified to fit the additive powertrain categorization of parallel hybrids. As described in figure 4-12, parallel systems can be further categorized into RPM addition and Moment addition [GÖHRING 1997]. RPM addition systems use planet gears between the combustion engine and electric motor to regulate the RPM of the engine to levels that consume less energy while providing the required power output level. Moment addition systems combine the benefits of both the electric motors and combustion engine's properties. Electric motors exhibit the highest moment starting from rest and at low RPM values, whereas the combustion engine offers high moment offering at high RPM values. Moment addition systems can be configured in an axial or co-axial manner. Axial refers to having both the engine and electric motor components in the same powertrain line, whereas co-axial has the electric motor and engine decoupled into two powertrain lines. The electric motor placement can vary from pre-transmission to post-transmission placement as shown in Figure 4-13.

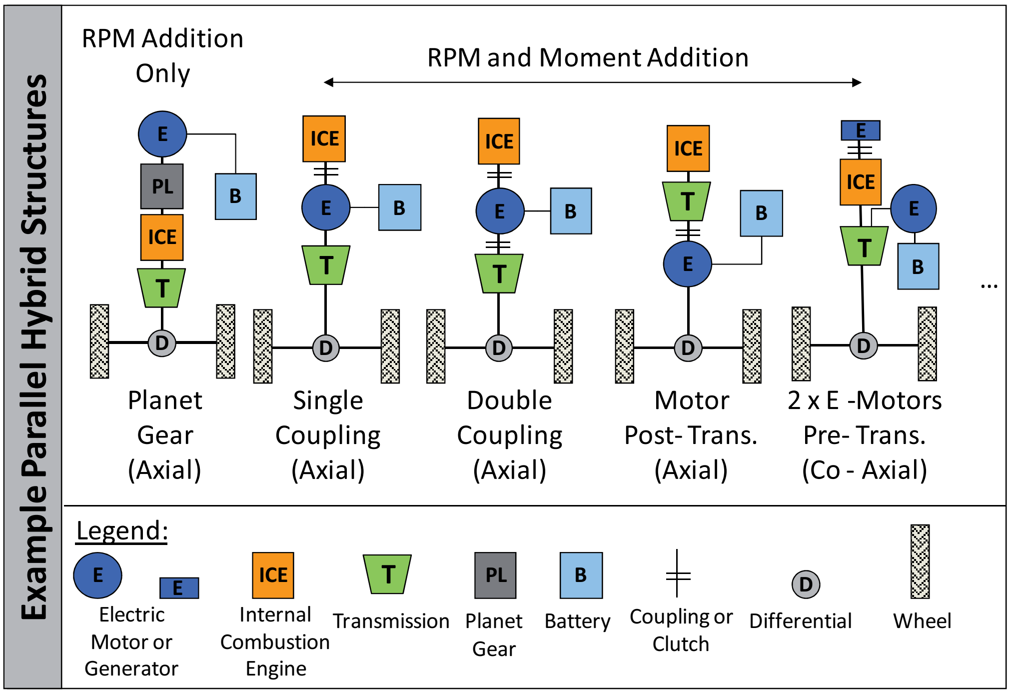


Figure 4-13 Examples of parallel hybrid vehicle architecture structures

A variety of mechanical couplings and placement of the electric motor allow for various forms of parallel hybrids. Taking the double coupling, axial parallel hybrid configuration as an example in Figure 4-13, we see that by opening the coupling between the motor and transmission, the electric motor can serve as a starter generator for the engine. By closing both the ICE-motor and motor-transmission couplings both the electrical and combustion engine system work in a moment additive manner sending an increased power output to the wheels. By opening the ICE – motor coupling but maintain the motor-transmission coupling closed the system performs an all electric drive powered solely by the electric system.

Through the Road – The so called "through the road" hybrid system is a moment additive system that differentiates itself to other parallel systems by the separation the electric and combustion engine in different axels of the vehicle (see Figure 4-14). The only connection between the systems is achieved through the road surface between the front and rear axles of the vehicle. Through the road hybrids perform moment addition (also known as boosting) by both systems providing torque to the wheels simultaneously. In addition the electric motor can be used to generate electricity with any excess power from the combustion engine by setting an additional load from the electric motor – this strategy can be used to vary the engines RPM and moment to an optimal level. By maintaining both systems on separate axels, manufacturers are able to pursue platform strategies that offer conventional cars and electrified powertrains keeping the combustion engine axle unchanged. Other advantages include simplicity in not having to connect and disconnect both powertrain systems mechanically.

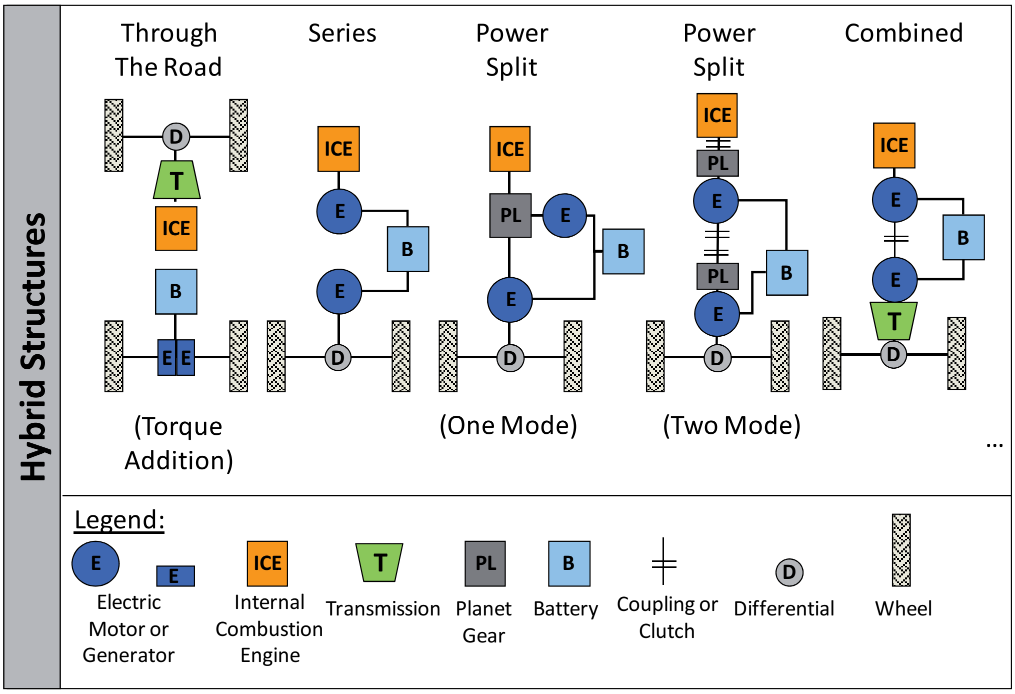


Figure 4-14 Examples of multiple HEV architecture structures

Series – The series hybrid uses both powertrain systems in a sequential manner. The main function of the combustion engine powertrain is to generate electricity that can be either stored in the high voltage battery or delivered directly to the traction power electric motor. The combustion engine has thus no direct link in delivering power to the wheels as with parallel hybrids. Therefore, the electric motor is the only drive system propelling the vehicle. Because series hybrids focus on electric driving, their electrical system's power output is normally dimensioned equal or larger to that of the combustion engine. The first commercial series hybrid vehicles are referred to as **electric range extended vehicles** or EREV. As the name indicates, series hybrids are closer to electric vehicles with a smaller combustion engine providing a range extending capability. Alternatively, the combustion engine and generator set that constitutes the "range extender" can be replaced by other power generating sources such as a gas turbine-generator or fuel cell-generator combination.

Power Split – Power split hybrids feature one mode and two mode systems. The "one mode" system made popular by the Toyota Prius features a planetary gear that couples an electric generator motor, a traction motor and the combustion engine as depicted in Figure 4-14. The power split concept combines features of both the series and parallel concepts. This concept allows for RPM and moment addition as well as use of part of the engine power to charge the battery during vehicle operation. Thus the planet gear system allows for the engine and motor power outputs to be split for both generative and propulsion purposes.

The two mode system integrates a more complex configuration based on three planetary gears and two couplings to split and combine power from the engine and the electric motors as needed for a number of use cases. The two mode system is able to use one to three power sources (consisting of the two electric motors/generators and the combustion engine) to transmit power to the wheels. The BMW X6 Active Hybrid is an example of a two-mode hybrid vehicle architecture.

Combined – The combined hybrid architecture, also referred to as a "series-parallel hybrid" allows for both series and parallel hybrid operation by means of including a coupling between the electric motor and generator as depicted in Figure 4-14. When the coupling is open, the system works exactly like a series hybrid. When the coupling is closed the system operates like a parallel hybrid. Combined hybrids are normally dimensioned to carry large battery systems. These are designed to drive in a series hybrid charge depleting mode (electric only) for city driving, but once the battery is discharged to a limit the vehicle can switch to a parallel hybrid charge sustaining mode, where the combustion engine becomes the primary power generating system. The charge sustaining mode maintains the level of the battery charge constant by using the electric system only to assist the combustion engine. If the vehicle turns to a high power operation use case, such as highway driving, the parallel hybrid operating strategy is adopted allowing the combustion engine to power the wheels directly.

4.2.1 Conceptual Typology of Vehicle Architectures

The conceptual typology of hybrid vehicle architectures can be described in a two dimensional solution space of electrical driving range and degree of electrification as depicted in Figure 4-15. The first dimension entails the electric distance the car can achieve with the electrical propulsion system alone (operation modus 2 in table 4-3), whereas the *degree of electrification* (DOE) is determined by the ratio of the cumulative peak electric motor power to the maximum combined electric and engine power.

$$Degree\ of\ Electrification\ (DOE) = \frac{kW_{peak\ electric}}{kW_{max\_ICE}+kW_{peak\ electric}} \qquad (18)$$

A DOE of zero describes a conventional internal combustion engine car with no electric system, whereas a DOE of one describes a battery electric vehicle with no internal combustion engine installed.

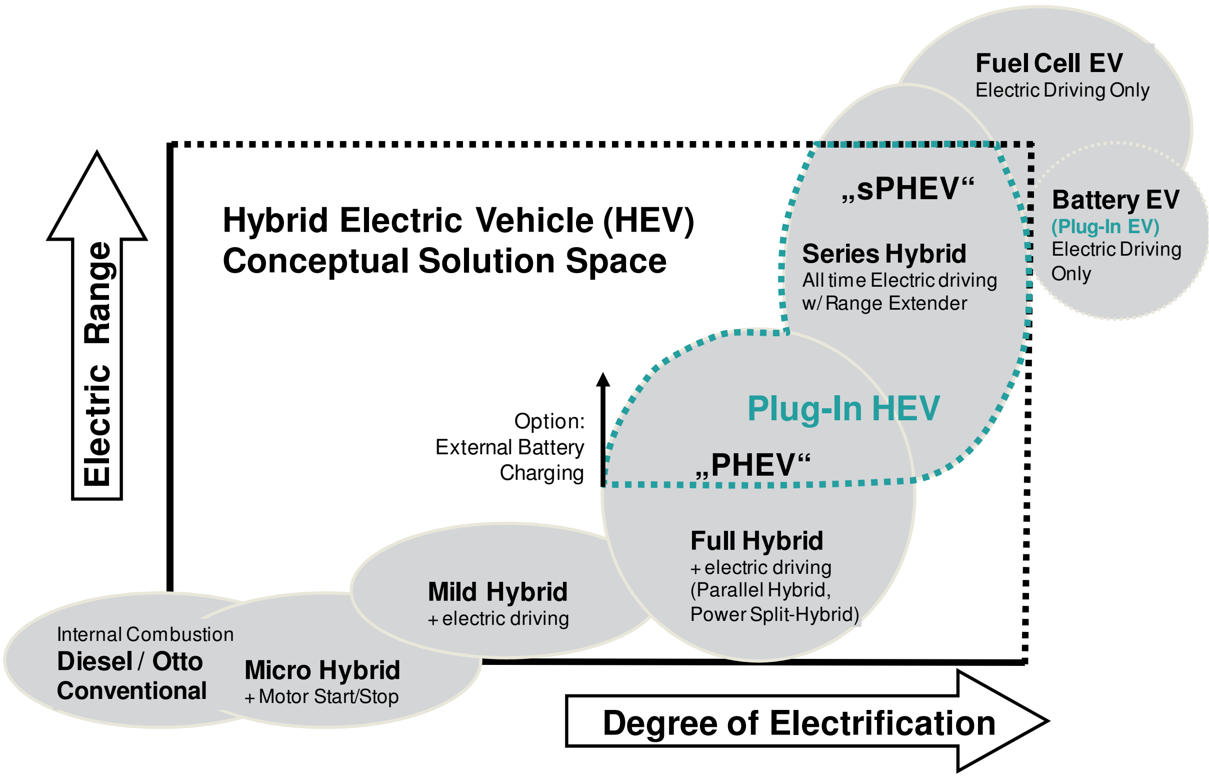


Figure 4-15 The hybrid electric vehicle conceptual solution space showing the general vehicle concept areas based on electric range and degree of electrification (Source: BMW Group –Jürgen Kammerer)

There are seven basic architecture concept types that populate the car architecture solution space: conventional ICE, micro hybrid, mild hybrid, full hybrid, plug in hybrid, the battery electric vehicle and fuel cell electric vehicle.

- *Conventional internal combustion engine*: The conventional ICE car concept is the current dominant architecture. The most popular conventional cars feature a diesel or Otto cycle engine and are defined by a DOE and electric driving range of zero, meaning no electrical propulsion system is installed.

- *Micro Hybrid Electric Vehicle*: Micro hybrids achieve propulsion exclusively by an ICE but offer some functionality of hybrid vehicles, most importantly the motor start-stop function. The start-stop function of a micro hybrid can be achieved by a 12-16V electric battery system and requires a more robust starter generator system. Some micro hybrids also exhibit limited regenerative braking. Micro HEVs are sometimes referred to as advanced ICE cars due to the fact that they are essentially conventional cars with no electric driving capability and minimal electrification.

- Mild *Hybrid Electric Vehicle*: Mild hybrids differentiate themselves from micro hybrids in that they offer limited functionality in electric driving (some mild hybrids do not offer electric-only driving). Mild hybrids thus include the three key components of the electric drive system including a high voltage battery, electric starter-motor for propulsion and a control system that determines when the electric and the combustion engine systems work together. Mild hybrids are solely parallel systems as described in Table 4-3 and offer additional functionality of motor assist and expanded regenerative braking.

- *Full Hybrid Electric Vehicle*: Full hybrids display larger degree of electrification (10%-30%) than mild hybrids and are characterized by short electric driving distances (for example from 500 m to 3 km). The primary propulsion system still remains with the internal combustion engine but the electric system can assist in providing power to the wheels. Most full hybrids exhibit parallel or combined configurations. Full hybrids exhibit all functions of mild hybrid and have a larger capacity for regenerative braking.

- *Plug In Hybrid Electric Vehicle*: Plug-in HEVs are differentiated from other HEV types by the ability to charge the high voltage battery externally through a battery charger and plug to an external energy source. PHEVs come in a wide range of architectures including parallel, series and combined configurations and offer extended electric driving ranges (from 5km to ~160km). PHEVs offer a degree of electrification typically above 35%. The range extender (ICE plus generator) of series plug in hybrids (sPHEV) can vary from large ICE power systems to small "limp home" emergency system IC engine.

- *Battery Electric Vehicle*: The battery electric vehicle falls outside of the HEV solution space with a DOE equal to one. BEVs have no internal combustion engine installed and are plug-in vehicles by definition - electricity is the only energy source. The electric range of BEVs is dependent on the level of electrification installed.

- *Fuel Cell Electric Vehicle*: Fuel cell cars exhibit an electrochemical cell that converts a source of fuel into an electrical current. FCEVs are primarily configured in a series architecture where the fuel cell power system provides energy to the electrical power system for propulsion. Fuel cell cars are outside the scope of this work.

Overview of architectures and concepts – The discussion of architecture structures and concepts so far has focused primarily on structural configuration and basic functionality. Now we summarize the relationship between architecture concepts and structural configuration by alluding to key component sizing. Figure 4-16 depicts a qualitative proportional sizing relationship in terms of power and energy storage for the leading three components of hybrid systems: the energy storage system, fuel converter and electric motor [WALLENTOWITZ et al. 1999]. The graphic shows how component sizes can be varied while maintaining a constant overall system power output and performance level. On the left side of Figure 4-12, the conventional ICE system (DOE=0) is augmented with an electric powertrain moving towards the right, as in the case of additive and mixed hybrid systems. As the proportional size of the electric motor/s and electric storage device (or high voltage battery) increase from left to right, the combustion engine is allowed to reduce in size until completely replaced by the electric power system as in the case of a BEV shown at the center of the diagram. This potential to reduce the internal combustion engine power output as the electric system is scaled up is referred to as *engine downsizing*.

Taking the BEV center line as a point of departure towards the right, sequential systems such as plug in series hybrid vehicles add a small range extender using a combustion engine or fuel cell system to drive an electric generator. The range extender can vary in size based on the functional goals prescribed by requirements. As the range extender increases in energy production capability, the energy storage system can also be downsized allowing power generated to flow directly for vehicle propulsion. The far right extreme is suitable for fuel cell based hybrid vehicle systems.

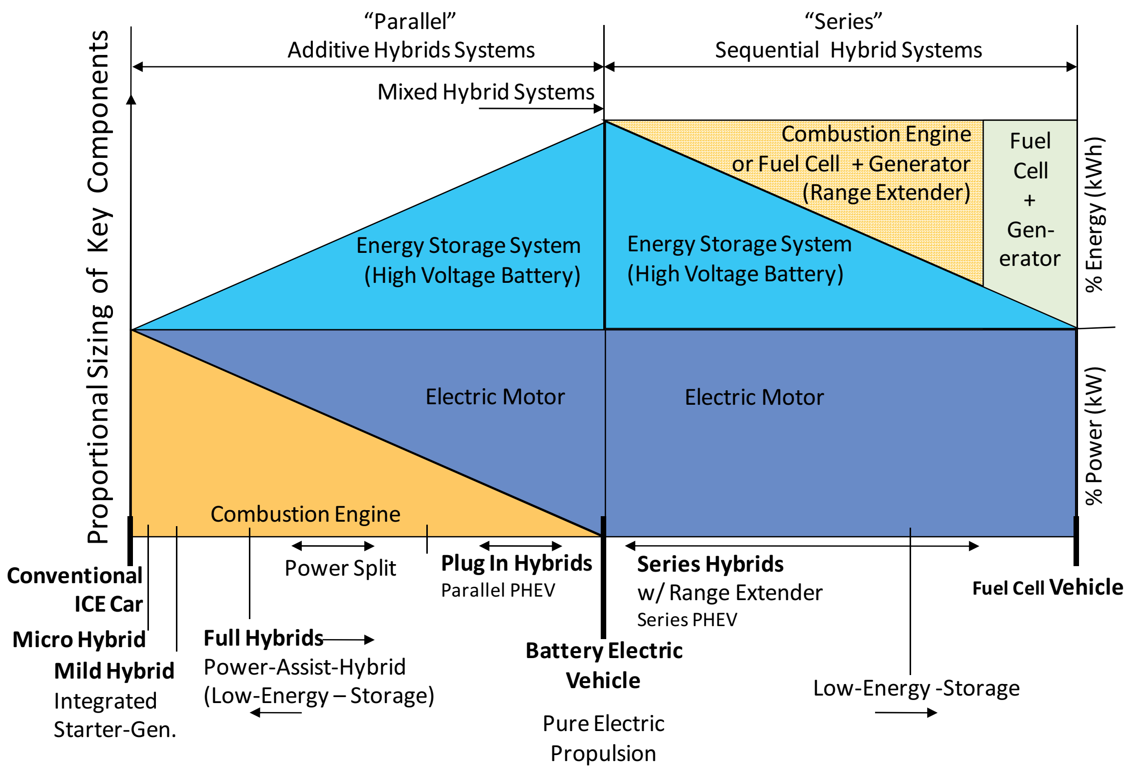


Figure 4-16 Qualitative dimensioning of key components for various car concepts and architecture structures adapted from WALLENTOWITZ et al. 1999

4.2.2 Hybrid Electric Vehicle Functions

Seven basic hybrid vehicle functions encompass the value added of hybrid systems for the customer. These functions pertain directly to the various operating modes discussed in Table 4-3 and are explained briefly in this section. The seven hybrid functions include: motor start-stop, regenerative braking, power boost, electric driving, load level increase (battery charging), external battery charging and gliding. These functions are briefly discussed below.

Motor Start Stop – The motor 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 and be prevented from idling. The engine is restarted by means of an electrical motor or starter-generator as soon as there is a power requirement that merits it to start again. In micro hybrid systems that do not offer electric driving, the automatic start stop feature is able to start the engine and have it available for acceleration in less than a second. The driver's signal to start the engine is normally depressing the clutch for manual transmission cars or releasing the brake for automatic transmission cars.

For architectures that have electric driving capability, the transition from rest to starting the engine can be delayed by using the electric driving mode as a first means of propulsion before starting the engine for additional power.

Figure 4-17 taken from NAUNIN 1989 shows a 5-7% saving in fuel consumption from a reference conventional car facilitated by the elimination of idling through the motor start-stop function during city driving conditions. Under optimal control strategy the author estimates further 5-9% savings by combining the functions of power of load level increase, boosting, electric driving and gliding. The values are accurate for full hybrid powertrains with limited electric driving and are not representative of plug in hybrid systems that can essentially replace fuel consumption in greater proportions.

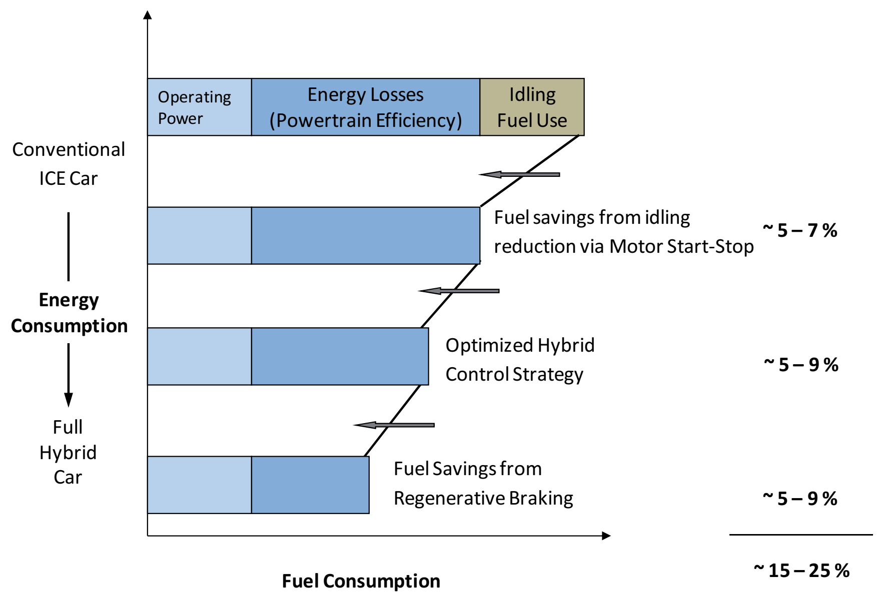


Figure 4-17 Fuel consumption saving potential for full hybrid systems [NAUNIN 1989]

Regenerative Braking – The term regenerative braking refers to the capturing of braking energy that would normally be lost to friction and heat in conventional car systems. Brake energy recuperation is achieved by setting the electric traction motor in a generative mode that serves as a counter force to the vehicle's direction of movement. The energy obtained through regenerative braking can be directly stored in the high voltage battery and later used for boosting, or powering the electrical system components.

The use of electric motors as brakes could be sufficient for most braking situations. However, redundant friction braking systems are still required for safety purposes. Hybrids with high voltage battery systems (> 42V) display a regenerative braking capability that can prolong the life of traditional friction brakes as an added benefit to the customer. Regenerative braking is limited by the battery system's ability to allow for impulse power storage in short time scales. Super capacitors have been proven to be well suited for regenerative braking in the case of micro and mild hybrid systems, where 2-3 seconds of high power inputs and outputs are used in charging and discharging from the capacitor device. Sustained electric driving is not possible with super capacitors.

Power Boost – When the driver's situation requires excess acceleration power beyond what the combustion engine can deliver the electric motors 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.

Boosting is particularly effective in improving a car's 0-100km (0-60mph) acceleration specifications. Figure 4-18 shows that the electric motor delivers the highest moment starting from rest and low RPM values (0-900 RPMs), whereas the typical otto-cycle combustion engine achieves maximum power at higher RPM values (2000-2500 RPMs). In a typical hybrid car the resulting system performance is enhanced when accelerating from rest by initially using the moment the electric motor supplies to the drive train.

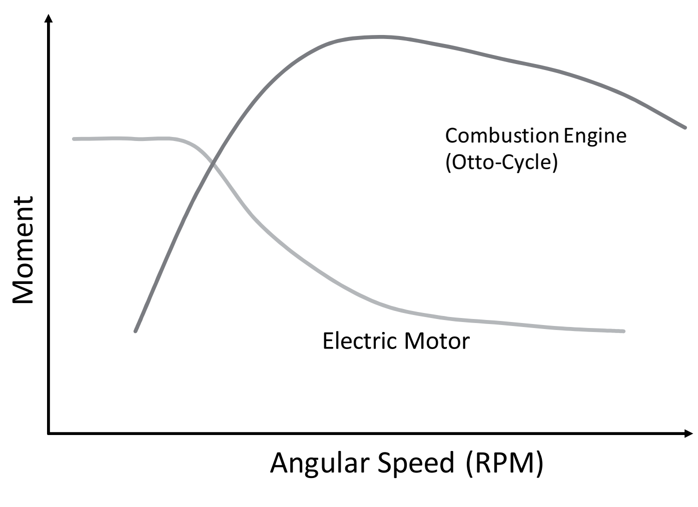


Figure 4-18 Exemplary Moment versus Speed in RPM for an electric motor and combustion engine. Boosting in hybrid systems allows for additional torque for acceleration especially when starting from rest.

Load level Increase – The load level increase or generative mode allows the engine to deliver some of its excess power to generate electricity together with an electric motor in generative mode. The extra load level can be used to increase the engine moment and RPM to a more efficient operating point when excess power is available. The generated electricity can be used to charge the battery or power other electrical system loads.

Electric Driving – Electric driving is achieved by using electric energy stored in the high voltage battery to power the traction motor to power the wheels. During the electric driving mode, the combustion engine is decoupled from the powertrain. It is either shut-off or used to generate electric power. Electric driving is limited by the energy availability of the electrical storage system.

External Battery Charging – External battery charging differentiates plug-in hybrid concepts from all other hybrid vehicle concepts. In addition to the typical hybrid components, a battery charging unit can be added to the car with the possibility to plug into an external electrical grid. Otherwise, an electrical charging station is required. Both charging strategies pose a limitation to the PHEV market, as customers are forced to have access to plug in their cars at home or a charging station.

The possibilities of connecting hybrid and electric cars to the electrical grid opens up possibilities for night time charging when electricity is cheapest and the electric load capacity of local power stations are at their lowest level. Vehicle to grid studies within electric mobility research are complementary areas of study that have garnered recent attention [SANDALOW 2009, p.69].

Gliding – The last hybrid function of "gliding" is somewhat trivial but never the less useful in optimizing a hybrid control strategy. Gliding refers to the decoupling of both the engine and the electric system from the wheels and using the force of gravity to propel the vehicle without friction losses of powertrain loads. Conventional vehicles can glide when placed in neutral during downhill operation. Hybrids however, must have the ability to rapidly connect the appropriate powertrain that best suits the driving situation moving in and out of a gliding operating environment.

Table 4-4 provides a functional summary for the various hybrid and electric concepts discussed in this section.

Table 4-4 Functional definitions of hybrid vehicle concepts with architectural configurations (Adapted from BMW Group – Andreas Rucker)

	ICE +	Hybrid (HEV)						Plug-In Hybrid (PHEV)						Battery Electric Vehicle (BEV)
	Micro ICE With Added MSA	Mild	Full					Mild	Full					
			parallel	Through the Road	Power Split	Combined	Series		parallel	Through the Road	Power Split	Combined	Series	
Functions:														
Motor Start- Stop	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO
Energy Recuperation	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Boost, Load level Increase	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES	YES	YES	YES	YES
Electric Driving	NO	NO	YES	YES	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES
External Battery Charging	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES	YES	YES	YES	YES
Configuration:														
ICE on board	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO
Combustion Engine powers the wheels mechanically	YES	YES	YES	YES	YES	YES	NO	YES	YES	YES	YES	YES	NO	NO
Pre-Transmission Electric Motor integrated with ICE	NO	YES	YES	NO	NO	NO	NO	YES	YES	NO	NO	NO	NO	NO
Electric powered axle as propulsion source	NO	NO	NO	YES	NO	NO	YES	NO	NO	YES	NO	NO	YES	YES
Mech. Power Split as transmission device	NO	NO	NO	NO	YES	NO	NO	NO	NO	NO	YES	NO	NO	NO
Series and Parallel transmission modes available upon selection.	NO	NO	NO	NO	NO	YES	NO	NO	NO	NO	NO	YES	NO	NO

Fuel Cell Vehicles can also be classified using this scheme (Energy Conversion done with Fuel Cell instead of Combustion Engine)

4.2.3 Hybrid Electric Powertrain Components

Now, the more important component systems are addressed that will be relevant in the architecture selection and costing of HEVs and BEVs. Four broad component categories are described in this section: energy converters, energy storage devices, transmission and other additional powertrain components. The purpose of this section is to provide a brief assessment of advantages and disadvantages with respect to the various hybrid concepts.

4.2.3.1 Energy Converters

Internal Combustion Engines – Most ICEs have already been researched in combination with hybrid systems. Important to this brief discussion is what advantages and disadvantages do the various types of ICEs offer the hybrid powertrain.

Otto-Cycle, Diesel-Cycle and Atkinson- Cycle engines are the most prevalent ICEs that have been produced commercially in hybrid electric car models. In addition, the Wankel Cycle rotary engines, 2 stroke engines and small gas turbines, offer advantages in volume and weight reduction. These engine types have been experimented as possible range extenders for a series hybrid drive that focuses on a very specific power load operating window.

Table 4-5 presents a qualitative summary of these combustion engines applied to the various hybrid concepts. It is important to note that micro hybrids are not considered in Table 4-5, as the start-stop system has been successfully incorporated into both gasoline and diesel cars successfully. All engine types benefit from the prevention of idling losses in a micro hybrid concept. However, the diesel- micro hybrid has proven particularly useful as it can achieve equal emission and fuel consumption savings to a gasoline full hybrid, without the added costs of high voltage electrification components. This presents a great value proposition for customers in Europe where diesel cars represent over 40% of the market.

Table 4-5 Comparison of Internal Combustion Engine for Hybrid Vehicle Concepts

Hybrid Concepts	Criteria	4 Stroke				2 stroke		Gas Turbine
		Otto	Diesel	Atkinson	Wankel	Otto	Diesel	
Mild Full Parallel PHEV	Emissions	+	o	+	-			
	Fuel Consumption	o	++	+	-			
	Power/Weight	+	o	+	++			
	Noise and Vibration	+	o	+	++			
	Cost	++	o	++	+			
	Technology Risk	++	++	+	o			
Series PHEV (Range Extender)	Emissions	+	o	+	-	- -	- -	++
	Fuel Consumption	o	++	+	-	- -	- -	- -
	Power/Weight	+	o	o	++	++	++	++
	Noise/Vibration	+	o	+	++	- -	- -	- -
	Cost	++	o	o	++	++	++	++
	Technology Risk	++	++	+	o	o	o	- -
	Downsizing Potential	+	+	o	++	++	++	o

++ Very Advantageous; + Some Advantages; o Average; - Some Disadvantages; - - Many Disadvantages

- **Otto-Cycle**

Advantages: The spark ignition (SI) gasoline engine is the most popular ICE for automotive use worldwide and offers the most flexibility for hybrid vehicle applications. The technology is well known and has been improved over the years posing little technology risk. It is widely available at low costs due to large scale economies for parts. The spark ignition Otto engine allows for good combustion characteristics at lower pressure values than Diesel engines allowing for good noise and vibration in well balanced multi-cylinder engines with controlled firing. Otto engines offer advantages over diesel engines in power to weight ratio for equal power output, as diesel engines normally require heavier engine blocks to mitigate the higher combustion stresses of compression ignition. Modern Otto cycle engine efficiencies for passenger cars lie between 28-32%. The efficiency zones of Otto Engines exhibit broader RPM versus Torque operating windows than in Diesel engines. Electrification of SI gasoline engines allow for good use of electric motors for torque addition over the lower RPM range keeping engine operation within its best efficiency window. Otto cycle motors are commercially available in 1, 2, 3, 4 and 6 cylinder configurations, can be readily downsized in a parallel hybrid electric configurations and serve well in range extender applications for series hybrids.

Disadvantages: Gasoline fuel contains less energy density (9.135 kWh/kg – Super Plus) than that of Diesel fuel (9.987 KWh/kg). This fact along with the lower efficiencies of Otto-Cycle versus Diesel in practice result in a shorter overall range for cars with gasoline engines (given the same tank size). To compensate, gasoline cars are sized with a larger tank volume. This creates packaging challenges when including the electrical system components of the hybrid system such as the high voltage battery, electric control unit, electric motors etc. Another disadvantage for Otto cycle lies in the limitations posed by the 3-way catalytic converter that require Otto engines to maintain a fuel-air mixture near stochiometric conditions, instead of running the engine at fuel lean air to fuel ration (excess air). This constraint reduces the efficiency (roughly 3-5%) that could otherwise be achieved by running the engine 15% lean [HEYWOOD 1988, p.832, p.655].

- **Diesel- Cycle**

Advantages: Modern Diesel engines offer the best specific fuel consumption of ICEs. Diesel engines are widely available offering little technology risk. Today's Diesel engine technologies such as turbo charging, particle filters, inter-cooling, common-rail fuel distribution and direct injection have made diesel engines improve fuel efficiency and past emission, noise and vibration limitations. Combining diesel engine technology with the parallel hybrid powertrain allows for further fuel efficiency and boosting capability. Diesel engines are also good candidates for downsizing. Three cylinder Diesel engine models with equivalent power of larger engines are well suited for basic downsizing and range extender alternatives for series hybrids. Because series hybrid engines are used solely for electric energy generation the engine can be operated within its most efficient rpm versus torque window.

Disadvantages - Presently the power to weight gap between Gasoline and Diesel engines has been reduced by the implementation of lightweight metals such as magnesium alloys, however they remain heavier and the cost of Diesel engines is on average 10-30% higher than equivalent powered Otto engines. Integrating a hybrid powertrain with a Diesel engine makes the car even more expensive for initial sale; however, the user savings can accumulate more rapidly with vehicle distance travelled. Diesel engines have a more complex emission after treatment to mitigate particulate emission using filters and a two stage process to reduce CO, HC and NO_x emissions respectively. The more complex emission treatment system increases weight and takes away volume space for electrification components [HEYWOOD 1988, pp.657-660].

- **Atkinson- Cycle**

Advantages: The Atkinson cycle features an over-expanded exhaust stroke that can be applied to traditional 4-stroke SI engines by suitable choice of exhaust valve opening and intake valve closing positions relative to the piston's bottom dead center. This feature allows for a reduction of pumping losses and an increase in engine fuel efficiency by expanding the work output per cycle [HEYWOOD 1988, p.183-186]. Atkinson SI engines offer most of the same advantages as the Otto-engine as far as emissions, noise, vibration and cost. Atkinson cycle engines have made a comeback to the market with new hybrid vehicle offerings, as they offer better fuel efficiency than Otto SI engines. The loss in power of the Atkinson cycle is compensated by the introduction of the electrical motors within the hybrid system.

Disadvantages: Atkinson cycle engines have one major disadvantage in that the indicated mean-effective-pressure and power density is decreased significantly. This disadvantage has kept Atkinson engines from seeing much commercial production in a market place where power rating is of outmost importance. For this reason a lower technology risk value in comparison to the Otto engine is recorded in Table 4-5. The Atkinson cycle can be applied to smaller SI engines; however the power losses make it impractical for further downsizing. The strategy of engine downsizing requires that engines provide better power to weight to compensate for the reduction in volume.

- **Wankel Engine**

Advantages: The Wankel rotary engine's biggest advantage is in power to weight, power to volume, inherent balance and smoothness during operation. Wankel engines have less moving parts and feature reduction of pumping losses due to the engine's rotor and housing configuration. The Wankel engine attains 3 power strokes per revolution allowing small Wankel engines to attain higher power outputs than conventional SI engines of the same power category. Cost is also reduced by the reduction in volume and by the wide use of aluminum for most engine parts. Wankel engines offer only average technology risk as their commercial use is limited in the automotive industry. The Wankel engine offers an extraordinary advantage in downsizing potential, especially for use in series hybrid configurations as a range extender where operation at an optimal torque versus RPM window mitigates disadvantages in emission and fuel consumption.

Disadvantages: Parallel hybrid applications with Wankel engines have not been commercially pursued due to the general fuel consumption and emission weaknesses, despite many technical improvements by means of port injection for better fuel mixing and double spark ignition for better flame propagation (used by Mazda). These improvements have achieved comparable fuel consumption values to that of Otto engines and emission levels that can achieve the stricter California SULEV emissions standards. The Wankel technology might achieve a re-introduction in the PHEV market, however the largest mechanical disadvantage in Wankel engines are leakage problems between the side housing and the rotor that account for power losses over time.

- **2 Stroke Otto and Diesel Engines**

Advantages: Two-stroke cycle spark ignition engines bring the advantage of low cost and higher power per unit displaced volume with twice the number of power strokes per crank revolution. Two stroke engines might have a place in the hybrid landscape as range extenders for so called “limp home” systems that require sporadic starts over long periods of time of non use.

Disadvantages: Two stroke engines show disadvantages in high fuel and oil consumption. They exhibit high emissions and generally exhibit higher noise and vibration problems than four stroke engines. During scavenging (when both the intake and exhaust port are open) some fresh mixture can flow through the engine. Oil is normally added to the fuel to lubricate the piston rings and surfaces resulting in increased emissions - although newer technology eliminates this problem. Technology risk is also a disadvantage of two stroke engines as they are most commonly used for marine outboard engines and have little application in the automotive market.

- **Gas Turbine (Rankine Cycle)**

Advantages: Gas turbines are only considered in combination with a series hybrid configuration as part of the range extender module. In this configuration, the turbine is allowed to operate at full load and optimal efficiency conditions. By design turbines burn fuel continuously at high air to fuel ratios that ensure complete combustion with low emissions and require little or no cooling system. Turbines offer great power to weight ratios at the aircraft scale, however when downsizing to vehicle applications this advantage lessens, as the thermal efficiency does not scale well downwards because it is a function of the compressor pressure ratio [MORAN et al. 2003, p. 393]. For small turbines, reformers are used to increase efficiency by recirculation of hot exhaust gasses to increase intake air temperatures and compression. The use of these heat exchangers result in more volume and weight than typical Otto-cycle ICEs. Small gas turbines exhibit very good balancing and avoid vibrations challenges inherent of most conventional SI and CI combustion engines. Finally, turbines can achieve fuel efficiency values between 40-60% at their best operating conditions.

Disadvantages: Turbines are not practical for operating at partial loads or under start-stop conditions. Fuel consumption under continuous combustion is a disadvantage for light load automotive applications as well as noise generation during operation. Finally, costs of turbine engines for automotive applications remain high, along with high technological risk making them commercially unattractive.

Electric Motors - Electric motors are energy converters that take in electrical energy as input and convert it to a mechanical power output. Electric motors have the benefit of being reversible when functioning as generators, hence mechanical power can be transformed to

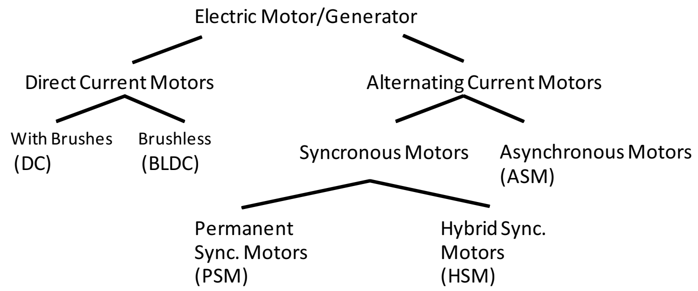


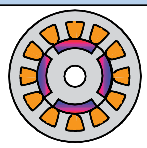
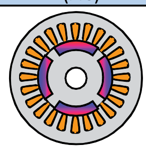
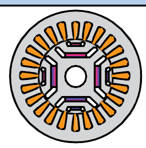
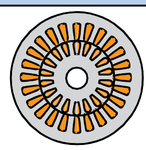
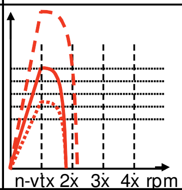
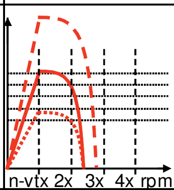
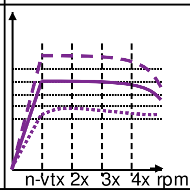
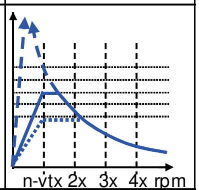
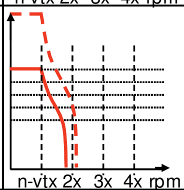
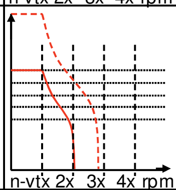
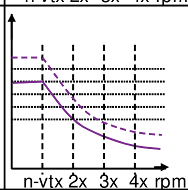
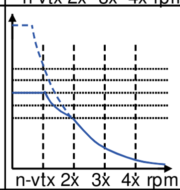
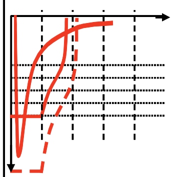
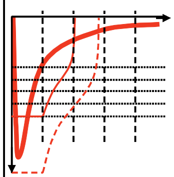
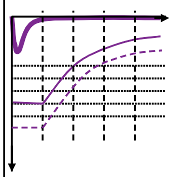
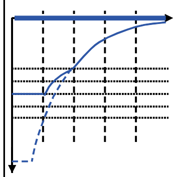
Figure 4-19 Classification of motor types

electrical power and stored in a battery. The best efficiency operating points of electric motor/generators lie much better than ICEs ranging from 75-95% depending on motor construction. Figure 4-19 depicts a general classification of various electric motor types.

During the early 1900s the first electric cars featured direct current (DC) brush motors due to the ease of transferring electricity from and to the DC batteries to power the wheels without great transformation efforts. Today most powertrain DC motors are brushless DC motors (BLDC), which reduce friction losses, improve efficiency and are used in many automotive applications already, for example as servo motors. DC Motors are best suited for high moment at low shaft speeds and are limited by efficiency losses at high RPM values. Motors with permanent magnet rotors exhibit high cost for the magnet materials.

AC motors offer greater variety for hybrid and electric vehicle powertrains as they contain various configuration strategies that reduce the need for costly magnet materials while

Table 4-6 Qualitative Assessment of Electrical Traction Motors for Hybrid drive systems (adapted from STEINHAUER *2009)*

	BLDC Brushless DC Motor	**PSM** Permanent Synchronous Motor (AC)	**HSM** Hybrid Synchronous Motor (AC)	**ASM** Asynchronous Motor (AC)
Exemplary Sketch of Motor (cylindrical cut showing inner rotor and outer stator configuration. Magnet material red-blue, copper windings orange)				
Power (kW) vs. Speed (RPM) (Motor Mode Depicted) 30 -Seconds: continous Line 2-Seconds Moment: dashed line Continuous Power: Pointed line				
Moment (N-m) vs. Speed (RPM) (Motor Mode Depicted) 30 -Seconds: continous Line 2-Seconds Moment: dashed line				
Braking Moment (N-m) vs. Speed (RPM) (Generator Mode Depicted) Braking Moment: Bold Line 30 -Seconds: continuous Line 2-Seconds Moment: dashed line				
Power to Volume	++	++	+	o
Efficiency at 10% Load	++	++	+	o
Efficiency at Peak Vertex	++	++	+	o
Motor Costs	-	--	+	++
Inverter/Electronics Cost	++	+	o	--
Maximum Speed	--	o	+	++
Braking Moment Losses	++	++	o	--
Noise - Stability	o	o	+	+

++ Many Advantages, + Some advantages, o Average, - Some disadvantages, -- Many Disadvantages

controlling moment, speed and power characteristics. In short, motors with greater proportion of rotor permanent magnet material (BLDC and PSM) offer greater peak power potential, whereas AC motors offer better constant power ratings at higher RPM along with savings in magnet material.

Table 4-6 shows a qualitative description of DC and AC motors. The exemplary sketch depicts a cylindrical cut of the motor's rotor (center rotating shaft) and the Stator (fixed outer windings). The table offers a simplification of basic motor properties and the reader should note that a large number of variations and motor types exist for both AC and DC motors. The basic structure of the BLDC and PSM rotor depicted is comprised of permanent magnet material, where as the HSM and ASM motors feature inductive copper windings that increase in number and complexity as magnet material is replaced. The structure of the windings and poles in the stator create variations in the inducted magnetic field to create the driving moment in the rotor.

In Table 4-6, the difference in mechanical power (*P*), moment (*M)* and rotational speed (ϖ) in revolutions per minute (RPM) are shown in qualitative diagrams. The magnet rich BLDC and PSM motors display higher torque and power at lower speeds, whereas the HSM and ASM motors have the ability to offer sustained power at higher speeds. A property of all electric motors is that they produce the highest torque during the first two seconds of operation and can sustain a relative high level of power for the first 30-seconds. After the vertex point the power and torque properties taper off with motor speed as losses are encountered during continuous operation.

A negative moment is induced during braking. This moment is subject to losses when changing electric polarity of the stator. Losses are more pronounced in motors with high permanent magnet content such as the BLDC and PSM. The HSM and ASM configurations thus have a marked advantage in switching from positive to negative torque and are better suited for continuous electrical driving. The efficiency of a motor is the relationship between input and output power. Equations 19 thru 21 show the relationships between electrical and mechanical efficiencies.

$$P_m = M \times \omega \quad (19)$$

$$P_e = V \times I \quad (20)$$

$$\eta_{motor} = \frac{P_m}{P_e} \qquad \eta_{Generator} = \frac{P_e}{P_m} \quad (21)$$

For power hybrid systems dimensioned to assist the internal combustion engine, PSM and BLDC motors offer the best capability in terms of efficiency and low rotor losses at lower speeds. For hybrids that feature sustained electric driving hybrid synchronous motors (HSM) offer better performance characteristics in terms of power to weight and efficiency combining the benefits of PSM and ASM configurations. As a rule of thumb, when magnet material is replaced with windings – moving from left to right on Table 4-6 – the more complex and costly the electric control system and AC/DC inverter becomes. Asynchronous AC motors (ASM) offer ferromagnetic material savings and good efficiency for very high speed and power applications at the expense of a larger volume, more complex electronics and efficiency reduction for high moment loads.

4.2.3.2Energy Storage Devices

Energy storage devices used in hybrid cars include the fuel tank for the internal combustion engine and the high voltage batteries or super capacitors for the electrical system. The focus in this section lies on the electrical system storage devices for which Nickel-Metal Hydrate, Lithium Ion and super capacitors will be discussed as the leading storage devices being developed for use in hybrid cars.

Perhaps the biggest hurdle for electric mobility is the fact that battery systems today offer so little volumetric energy density and specific energy density. Table 4-7 shows how transportation liquid fuels are more than an order of magnitude higher in energy density over leading battery systems. For example, the energy content of a 38 liter NiMH battery that would weigh 106 Kg is equivalent to just 1.18 kg contained in a liter of diesel fuel!

Table 4-7 Energy Content for various fuels by mass and volume [HEYWOOD 1988, p.180], [EHSANI et al. 2009, p.290]

Energy Source	Energy by Volume		Energy by Weight	
Diesel Fuel	10,700	Wh/l	12,700	Wh/kg
Heating Oil	10,400	Wh/l	12,800	Wh/kg
Gasoline	9,700	Wh/l	12,200	Wh/kg
Butane	7,800	Wh/l	13,600	Wh/kg
LNG (-160°C)	7,216	Wh/l	12,100	Wh/kg
Propane	6,600	Wh/l	13,900	Wh/kg
Ethanol	6,100	Wh/l	7,850	Wh/kg
Methanol	4,600	Wh/l	6,400	Wh/kg
250 Bar Natural Gas	3,100	Wh/l	12,100	Wh/kg
Liquid Hydrogen	2,600	Wh/l	39,000	Wh/kg
150 Bar Natural Gas	405	Wh/l	39000	Wh/kg
NiMH Battery	280	Wh/l	100	Wh/kg
Li-Ion Battery	200	Wh/l	150	Wh/kg
Lead-Acid Battery	40	Wh/l	25	Wh/kg
STP Propane	26	Wh/l	13900	Wh/kg
STP Natural Gas	11	Wh/l	12100	Wh/kg
STP Hydrogen	3	Wh/l	39000	Wh/kg

High Voltage Batteries – The high voltage battery transforms electrical energy into chemical energy functioning as an energy storage device during load level increase and regenerative braking. For plug in hybrids. the high voltage battery serves as an energy reservoir for electric energy supplied from an electric power source outside the vehicle. Energy stored in the high voltage battery can be readily used for powering the electrical on-board networks and to fulfill electric only driving or boosting by means of the electric motor converting electrical energy into mechanical energy. The battery itself is composed of battery modules of battery cells. The various battery types differentiate themselves by battery chemistry of the anode and cathode, battery shape (cylindrical, prismatic, pouch or button), quantity of modules and number of cells.

Batteries are normally compared by specific power (W/kg) and specific energy content (Wh/kg). Figure 4-20 shows the tradeoff between specific power versus energy in a ragone plot] that displays the areas of operation of commercially available battery types according to

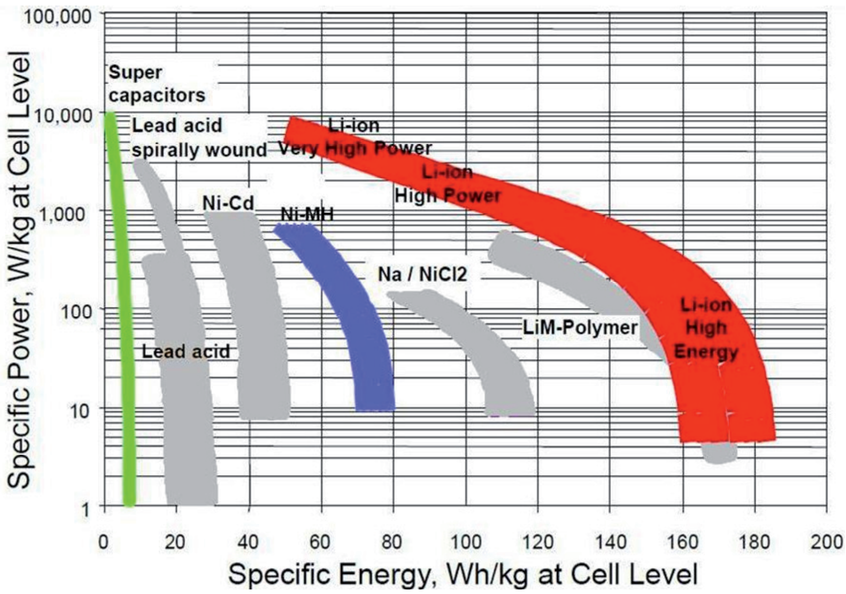


Figure 4-20 Specific Power vs. Specific Energy for various cell types from KALHAMMER *et al. 2007, p.25*

[KALHAMMER et al. 2007, p.25. Power density (W/kg) is plotted in the vertical axis on a logarithmic scale. Energy density (Wh/kg) is represented on the x-axis for a specified discharge rate say C/1 (full discharge in one hour). The light gray bands represent the power and energy capabilities of lead-acid, nickel-cadmium, ZEBRA (Na/NiCL2) and lithium – polymer chemistries. Highlighted in green is the super capacitor band, in blue the nickel-metal hydrate band and in red the variety of lithium ion chemistries.

The appropriate cell chemistry for a particular hybrid car is dependent on the power and energy requirements of the electric system. Super capacitors offer high power discharge but very limited specific energy, whereas Lithium ion batteries offer the broadest range of specific energy and power packaging. At the moment, nickel-metal-hydrate batteries represent the most widely used battery type for commercial applications of hybrid vehicles for their proven performance and safety considerations. However, lithium ion batteries are expected to come to prominence within the next 10 years in automotive market applications.

Nickel-Metal-Hydrate – Nickel metal hydrate batteries offer the best longevity in calendar and cycle life (more detail in Figure 4-23, p. 128), as well as a large temperature operating window (from -40°C to 50°C) [STAN 2005, p.229]. The energy density is more than double that of Lead acid and 40% higher than that of NiCads as seen on Figure 4-20. NiMH Batteries are considered safe for automotive use as they show robustness in taking overcharge and over-discharge conditions. The primary drawbacks in relation to the lithium ion technology are the limitations in specific power to energy ratio, the high self discharge rates and low prospects for future cost reductions as the technology is its reaching maturity. In a production of 100,000 units per year, NiMH prices may fall as low as 530 \$/kWh for a PHEV with 10 miles electric range [AXSEN et al. 2008, p.14].

In the nickel metal hydride (NiMH) cell chemistry, the positive electrode is made from nickel hydroxide which has the ability to absorb large quantities of hydrogen under reaction [Woodbank 2005]. Such metallic alloys, termed hydrides, can provide a storage sink of hydrogen that can reversibly react within the cell. Nickel metal or nickel alloys are used for the negative electrodes. The electrolyte, which is also a hydrogen absorbent aqueous solution such as potassium hydroxide, takes no part in the reaction but serves to transport hydrogen between the electrodes. The reaction follows Table 4-8. Based on its chemistry, the NiMH cell operates at a voltage of 1.2 Volts which is small in comparison with other cell types.

Table 4-8 Chemical Reaction for NiMH Cells

	Charging	↔	*Discharging*
Positive Electrode	$2\ NiOOH + 2\ e^- + 2\ H^+$	↔	$2\ Ni(OH)_2$
Negative Electrode	H_2	↔	$2\ H^+ + 2\ e^-$
Cell reaction	$2\ NiOOH + H_2$	↔	$2\ Ni(OH)_2$

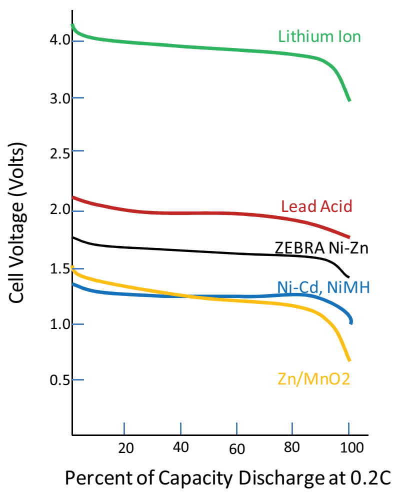


Figure 4-21 Discharge curves for various cell types at C/5 according to WOODBANK 2005

Figure 4-21 shows the typical discharge curves for a range of cell chemistries when discharged at 0.2C rate. Each cell chemistry has its own characteristic nominal voltage and discharge curve. Some chemistries, such as those found in Lithium-Ion batteries, have a fairly flat discharge curve between a discharge window of 20 to 80 percent discharge with large changes at the end of charge or discharge. Others such as Lead acid have a pronounced slope but less deviation at the extremes. The power delivered by cells with a sloping discharge curve decreases progressively throughout the discharge cycle. This could give rise to problems for high power applications towards the end of the cycle. Developers limit problems of overcharge and discharge by limiting the window of charging and discharging also known as the depth of discharge (DOD) window.

Lithium Ion – Lithium ion technologies display the greatest flexibility in selecting the optimal power to energy placement for the wide spectrum of hybrid vehicle applications from micro hybrids to plug-in hybrids and electric vehicles. Lithium is the lightest of metals and has the greatest electrochemical potential which makes it one of the most reactive of metals. It is for this reason that the typical cathode material does not use free lithium but rather a

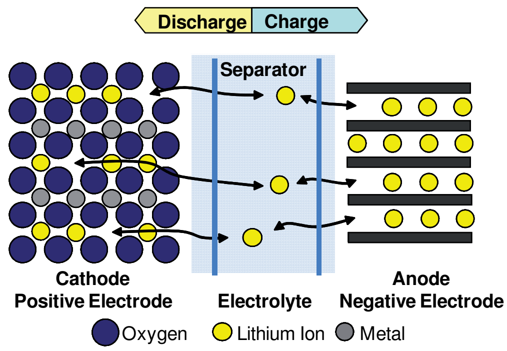
Table 4-9 Chemical Reaction for a Lithium Cobalt Oxide Battery (for 0<x<1)

	Charge	↔	*Discharge*
Positive Electrode	$Li_{(1-x)}CoO_2 + x\,Li^+ + x\,e^-$	↔	Li_xCoO_2
Negative Electrode	Li_xC_6	↔	$C_6 + x\,Li^+ + x\,e^-$
Cell Reaction	$Li_{(1-x)}CoO_2 + Li_xC_6$	↔	$Li_xCoO_2 + C_6$

lithium compound. The anode material is typically made from graphite or silicon/carbon composites. Finally, the electrolyte is usually based on a Lithium salt in an organic solvent or a gel polymer with a porous separator. Table 4-9 applies for a Lithium Cobalt oxide battery commonly used for laptop battery applications and consumer electronic products. Lithium ion batteries containing cobalt are expensive for the high material cost of this metal.

The selection of cathode and anode material chemistries results in a tradeoff between voltage potential (V) and specific cell capacity (Ah/kg) as shown in Figure 4-22. Power cells use carbon or graphite based anodes along with high voltage cathodes, whereas energy cell configurations tend to use silicon-carbon composites. The voltage potential for lithium-ion battery cells lies between 1,25V - 4.2V.

Cathodes	Potential
Li / $LiMnNiO_2$	4.3V
Li / $LiCoO_2$	4.1V
Li / $LiMn_2O_4$	4.2V
Li / $LiMn_{1/3}Co_{1/3}Ni_{1/3}O_2$	4.0V
Li / $LiFePO_4$	3.3V
Li / $LiM_xFe_{1-x}PO_4$	3.2V
Anodes	
Li / Li+	0V
Li / LiC_6	0.1V
Li / $Li_4Ti_5O_{12}$	1.5V



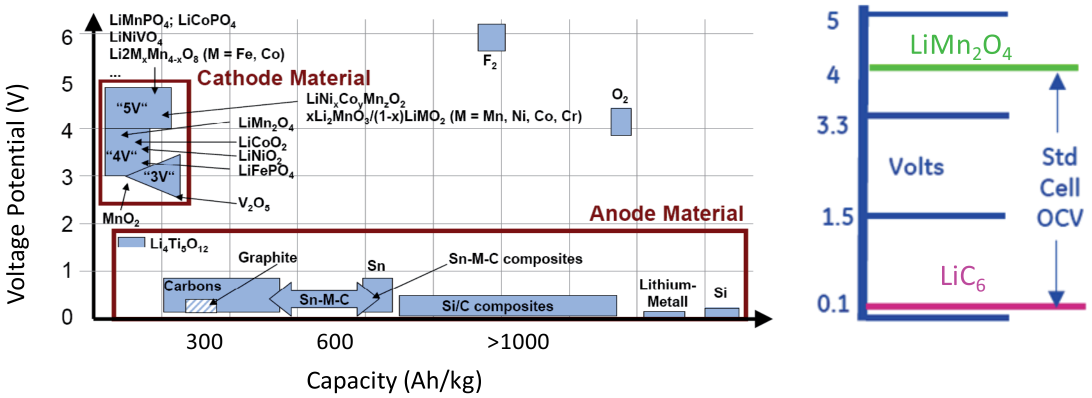


Figure 4-22 Common chemistries of Lithium Ion Battery electrodes and their open circuit voltage(top left); bottom tradeoff between voltage potential and capacity (bottom left); schematic of Lithium Ion battery structure (top right); example of standard cell open current voltage (OCV) potential (bottom right) [Adapted from SAVAGIAN 2008]

For use in automotive applications Lithium manganese oxide ($LiMn_2O_4$) and Lithium iron phosphate ($LiFePO_4$) are particularly interesting for their lower cost potential due to the use of less expensive metals. The latter is particularly favorable for its light weight, low cost and ability to eliminate explosive reactions during crash testing [CHU 2009]. Safety is perhaps the most important consideration for automotive considerations as lithium ion cells can experience uncontrolled reactions during overcharging that can lead to cell damage and short circuit battery discharge burn out.

Super Capacitors and dual storage systems – Double layer capacitors, super capacitors or ultra capacitors have been long considered as an ideal storage medium for micro and mild hybrid systems that only use energy for acceleration boosting, regenerative braking and the engine start-stop function. These storage systems offer high specific power for short periods of time (i.e. 3-10 seconds). Capacitors have the benefit of better temperature operating ranges over batteries, and lower costs to manufacture [EHSANI et al. 2009, p.293]. The cell voltage of a capacitor is determined by the circuit application, and is not limited by the cell chemistry as with batteries. Very high cell voltages are possible; however, there is a trade-off with capacity.

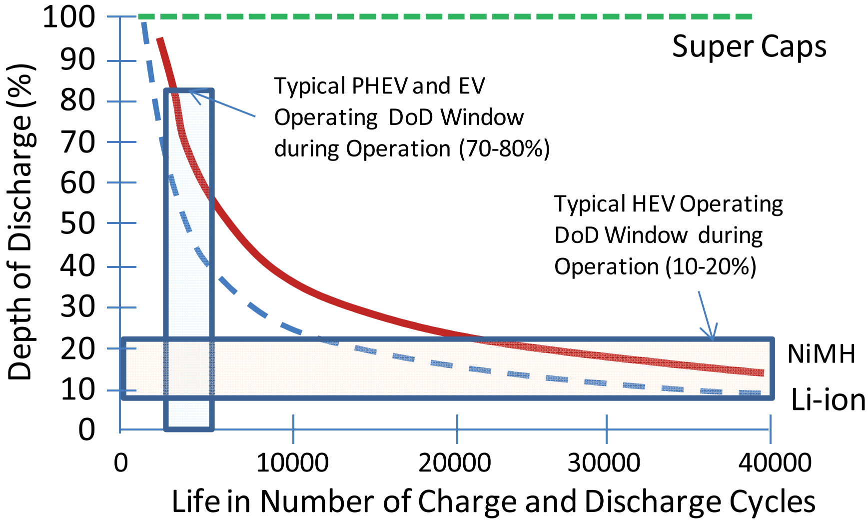


Figure 4-23 Battery Cycle Life Comparison [adapted from MARKEL, TONY 2006]

In comparing battery lifecycle between the three electric energy storage concepts, the advantages of the super capacitors stand out. Figure 4-23 displays the tradeoff between battery depth of discharge allowed by the control system and battery life measured in number of cycles.[16] In order to increase the life of NiMH and Li-ion batteries, auto manufacturers limit the allowable depth of discharge window. For high power applications such as in HEVs the typical discharge window is limited to 20% allowing for a considerable life extension of the high voltage battery. In contrast in high energy applications such as with PHEVs and EVs, the depth of discharge window is set at 70-80% to fulfill the all electric range of the vehicle at the expense of battery life.

Super capacitors can be combined with a primary battery system to provide an effective short duration peak power boost allowing the prime battery to be downsized. However, since the capacitor is normally connected in parallel with the battery in these applications, it can only be charged up to the battery upper voltage level and it can only be discharged down to the battery lower discharge level, leaving considerable unusable charge in the capacitor, thus limiting its effective or useful energy storage capacity and adding weight and bulk of the system.

Disadvantages of super capacitors lie in the low energy density and rapid self discharge. During discharge capacitors tend to have a linear voltage drop that can pose a challenge in using all available energy. These shortcomings render super capacitors unsuitable as primary power source for EV and HEV applications. [WOODBANK 2005].

[16] A similar depiction following a logarithmic scale can be seen in Figure 6-6

Table 4-10 Summary of HEV Battery and Super Capacitor Energy Storage Devices

	NiMH Battery	Li-Ion Battery	Super Capacitor	Lead Acid
Specific Power (W/kg)	o	++	+	-
Specific Energy (Wh/kg)	o	++	--	-
Applicability for deep discharge	o	+	++	-
Cycle Lifetime	+	o	++	+
Shelf Life	+	o	++	+
Ability to Maintain Charge	o	+	--	+
Ability for High Power Short Time Charging	-	+	++	-
Temperature Operating Window	-	-	++	++
Safety	+	-...+	++	++
Battery Efficiency	o	++	-	o
Cost ($/kW)	o	o	+	++
Cost ($/kWh)	o	++	--	o
Cost Reduction Potential	-	++	o	-
Simplicity of Charging Electronics	o	-	++	++
Applicability for Micro Hybrid Primary Storage Device	-	-	+	++
Applicability for Mild Hybrid Primary Storage Device	o	+	+	-
Applicability for Full Hybrid Primary Storage Device	o	+	--	--
Applicability for Plug-In Hybrid Primary Storage Device	o	+	--	--

++ Very Advantageous; + Some Advantages; o Average; - Some Disadvantages; - - Many Disadvantages

* Li-ion battery safety varies widely based on chemistry. LiFePO4 Batteries offer comparable safety to NiMH

Table 4-10 provides an overview of the energy storage discussion provided and includes information on lead acid batteries as they are commonly used in low voltage micro hybrid systems and as secondary low voltage batteries to power the interior vehicle electronics in most hybrid cars. Although the super capacitors offer many good qualities, their marked disadvantages make them better suited as a secondary energy storage system. NiMH batteries dominate the power hybrid market at the moment; however, Lithium ion batteries provide the most promising set of characteristics for future expansion into longer electric range hybrid vehicles.

4.2.3.3Transmissions

The transmission is a component system that provides translation of torque and speed from an energy converter, such as an engine or electric motor, to the drive train. The drive train then powers the wheels of the vehicle to achieve propulsion. A well controlled electric motor in a PHEV or EV would not need a multigear transmission. However, an IC engine has to use a multigear transmission to multiply its torque at low speeds. For automotive HEV applications there are five basic transmissions: automatic, manual, continuously variable, planetary gear and direct (simple) transmissions.

Automatic Transmission – In an automatic transmission an electronic control unit directs the transition between gear ratios based on the drivers pedal signaling for power. The transmission reduces the higher engine speed to the slower wheel speed, increasing torque in the process. The gear switching strategy is programmed to use the optimal motor torque and speed in delivering power to the wheels while reducing friction losses and fuel consumption. Automatic transmissions are most popular in parallel hybrid applications.

Manual Transmission – In a manual and semi automatic transmissions the driver has the ability to determine the gear ratio during driving. Manual transmissions became an easy fit for implementing a micro-hybrid motor start-stop strategy, as the driver must depress the clutch before placing the car on gear when starting from rest. This action is used to signal the control unit to start the vehicle using the starter generator. The basic functional principles of a manual transmission are similar to that of automatic transmission.

Continuously Variable Transmission – CVTs have a gear ratio that can be varied continuously within a certain range. CVTs provide an infinite number of gears ratios that can be used to match the optimal torque and speed requirement, resulting in optimal fuel consumption. The most common CVTs use an inverted double cone pulley and belt assembly. One pulley is connected to the engine shaft, while the other is connected to the output shaft. The metallic belt links the two pulleys for which the distance between the two half pulleys can be varied. The transmission ratio is a function of the two effective pulley diameters. In hybrid vehicles, the electric motor placement is between the CVT and the IC engine separated by a clutch. A control unit varies the pulley distance according to the optimal operating condition.

Electric Continuously Variable Transmission (Planet Gears) – The eCVT transmission achieves the CVT functionality and additionally can combine or separate (or split) power inputs to produce one output or no output at all. This transmission is the only transmission used by power split hybrids described in section 4.2. The planetary gear unit in a one mode power split hybrid has a motor generator used as a starter motor and generator (M/G1) connected to the sun gear. A traction motor used primarily for propulsion and regenerative braking (M/G2) is connected to the ring gear and the IC engine output crankshaft runs the planetary carrier. The basic configuration is shown in Figure 4-24.

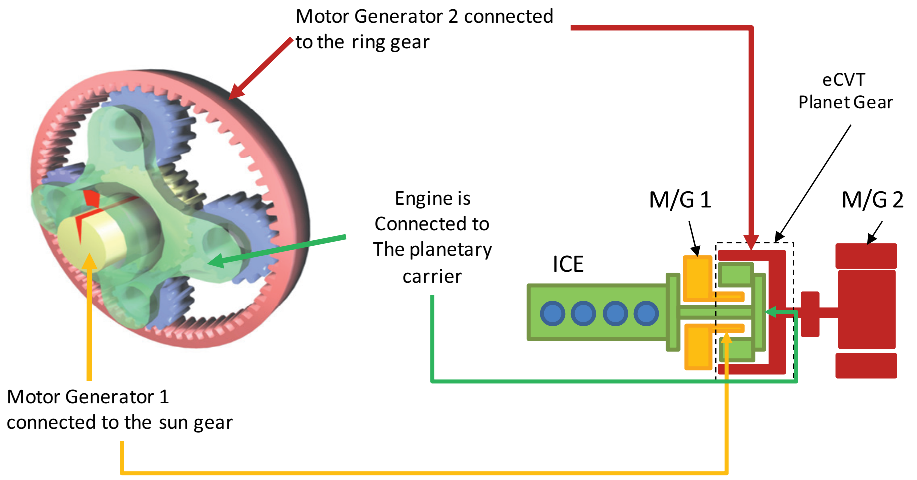


Figure 4-24 Diagram of an eCVT Planetary Gear Transmission in a One-Mode Power Split Hybrid

4.2.3.4 Additional electrical powertrain components

Inverter – The inverter is a device that coverts the high voltage DC electrical power from the high voltage battery into AC power used to power the electric motor/generators. This functionality can be reversed during regenerative braking as the inverter rectifies the input current from the generator to charge the DC battery.

Hybrid Control Unit - The hybrid control unit computer is programmed to follow a certain operating strategy depending on the hybrid concept capabilities and the driver's actions. An example of a qualitative parallel hybrid operating strategy is depicted in a simplified form in Figure 4-25.

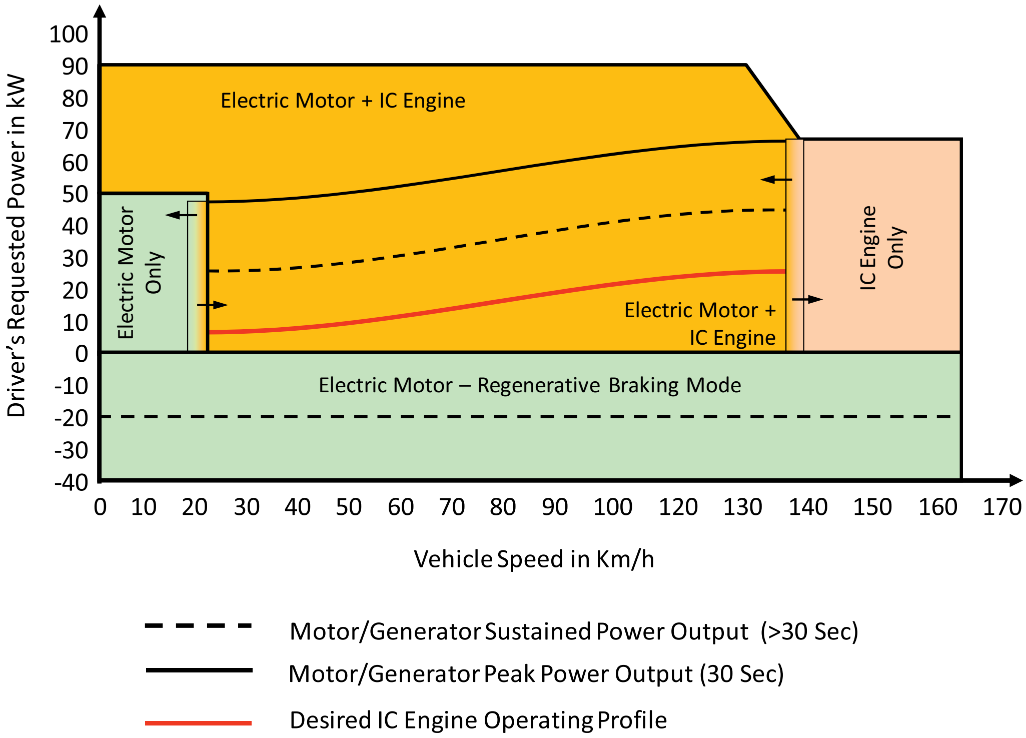


Figure 4-25 Example of a Parallel Hybrid Control Strategy [according to WALLENTOWITZ et al. 1999, p.66]

When the driver requests low power within the limits of the electric motor's capability, the control unit allows for all electric driving up to a speed of 20 km/h. Should the driver's power demands be above what the electric motor can provide (>50 kW in the case depicted) the control unit resorts to the IC engine. For speeds between 20 km/h and 135 km/h both the IC engine and the electric motor work in parallel to power the vehicle. The control unit attempts to maintain the IC engine as close to the best specific fuel consumption line using the electric motor's sustained output power. Should the power required fall below the desired IC engine operating profile, excess power is used to power the electric motor in as a generator to charge the batteries (load level increase). Any braking opportunity also results in energy recuperation through regenerative braking depending on the state of charge of the battery system. Finally, the hybrid control unit allows the IC engine to operate alone at speeds above 135km/h.

The hybrid control unit is networked with electronic control units (ECUs) at the battery to monitor the state of charge, the braking system ECU which controls the use of friction brakes and the electric motor in generative mode and the inverter ECU which controls the electric motor.

For a series hybrid the control strategy revolves around the state of charge of the battery system. Because the function of the IC engine in a series hybrid is to extend the operating range of the vehicle (the term *range extender* refers to the IC engine and generator combination), the hybrid control unit essentially operates in two distinct modes of charge depleting and charge sustaining.

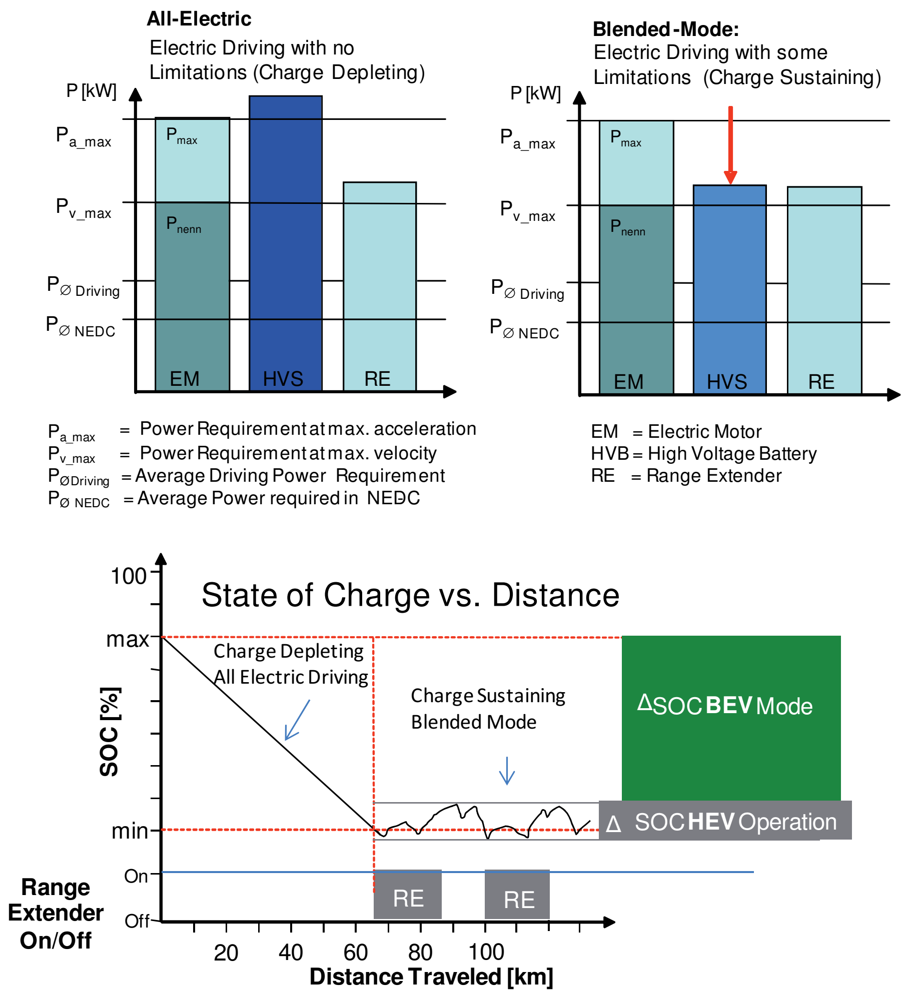


Figure 4-26 Example control strategy description for a series hybrid (graphic contributed by STEINHAUER 2009)

The charge depleting mode uses the energy stored in the battery to propel the vehicle in an all electric mode. Figure 4-26 at the top left shows that the battery can deliver more power than what the electric motors can use, thus posing no limitations to electric driving performance. The bottom graphic displays that the depletion of battery charge with electric distance travelled follows a linear path up until a pre-determined state of charge (SOC) limit.

The SOC depletion limit is placed to the so called deep battery cycling level that allows for enough charge to enable a re-charge. Depleting the battery cell beyond the deep battery cycling limit reduces the charging capability of the cell and the lifetime use.

Once the limit state of charge is reached, the battery power available is below the total power the electric motors can deliver, as seen at the top right of Figure 4-26. The IC engine range extender engine module is turned on to transfer energy to the electric motors while also charging the battery with any excess power. This mode of operation is referred to as the charge sustaining mode. In this mode, the battery SOC remains within a 10-20% window until the next plug-in re-charge opportunity. This blended mode relies on the IC engine similar to a parallel hybrid operating strategy.

The biggest advantage of the series hybrid control strategy is the opportunity to drive emission free during charge depleting operation. The dimensioning of the system components can allow for a large range extender and a downsized battery to save on battery manufacturing costs, or a large battery with a small range extender to maximize all electric operation as described earlier in section 4.2. This provides an opportunity to tailor vehicles to individual user range requirements.**Electric Peripherals** – Because hybrid cars operate with engine off conditions, all peripheral systems that conventionally obtained power from the IC engine through belt assisted pulleys need to be decoupled from the engine. The following is a list of components that must be run in electric mode to achieve this uncoupling. Most of these components are either powered by the 14 V conventional lead acid battery or a DC/DC converter is used to step down current from the high voltage battery.

Electric power steering - The EPS system provides power steering assist even when the engine is off. In this case, the power steering's hydraulic system is replaced by an electric servo motor and its control unit. Hybrid power steering systems also exist that allow for hydraulic operation during engine on operation and an electric motor runs the hydraulic pump during engine off operation. These systems are referred to as electro-hydraulic power steering (EHPS) systems.

Electric Pumps **–** The cooling system must run continuously to keep the high voltage battery and inverter at an adequate operating temperature during engine off operation. If these components are water or coolant cooled, the water pump that is normally coupled to the engine in conventional cars must be run by an electrical motor. Oil pumps that keep oil pressure in the engine lubrication system and brake fluid lines may also need to be run electrically.

Regenerative Braking ECUs – The regenerative braking electric control unit provides an interface between the mechanical friction braking system and the electric motor regenerative braking system. The braking system ECU is coupled with the Hybrid system computer. Even though electric motor braking can be used in most driving situations, the friction brakes are necessary for emergency braking.

4.3 Is there an Ideal Hybrid Car?

A hybrid drive is much more than an additional feature offered to consumers. The hybrid vehicle functional spectrum, the many structural configurations and the variety of component choices described in the previous section shows the complexity of design choices. The question commonly posed is which hybrid configuration is best suited for the future market? Although there are many viewpoints favoring particular hybrid concepts, the ideal hybrid car is one that matches the customer's needs the best (refer to the discussion in section 3.4.2). In this section, the suitability for conversion of conventional cars to hybrids vehicles and the lifecycle efficiency across the HEV spectrum is presented.

Electrification of Cars - The hybridization or electrification of cars refers to the conversion of a conventional IC engine vehicle platform to a hybrid electric system. Electrification is best suited for conventional car platforms that have high fuel consumption and performance values as shown in Figure 4-27. Sport utility vehicles and large cars are good examples of cars that are well suited for hybridization as they stand to gain the most from the additional hybrid components. At best, small cars can improve fuel consumption by incorporating a micro-hybrid concept to reduce idling with relatively little weight gain. Small cars that incorporate a high voltage HEV system can improve acceleration performance through the additional boosting capability offered, but can lose out in fuel consumption due to the additional weight of HEV components.

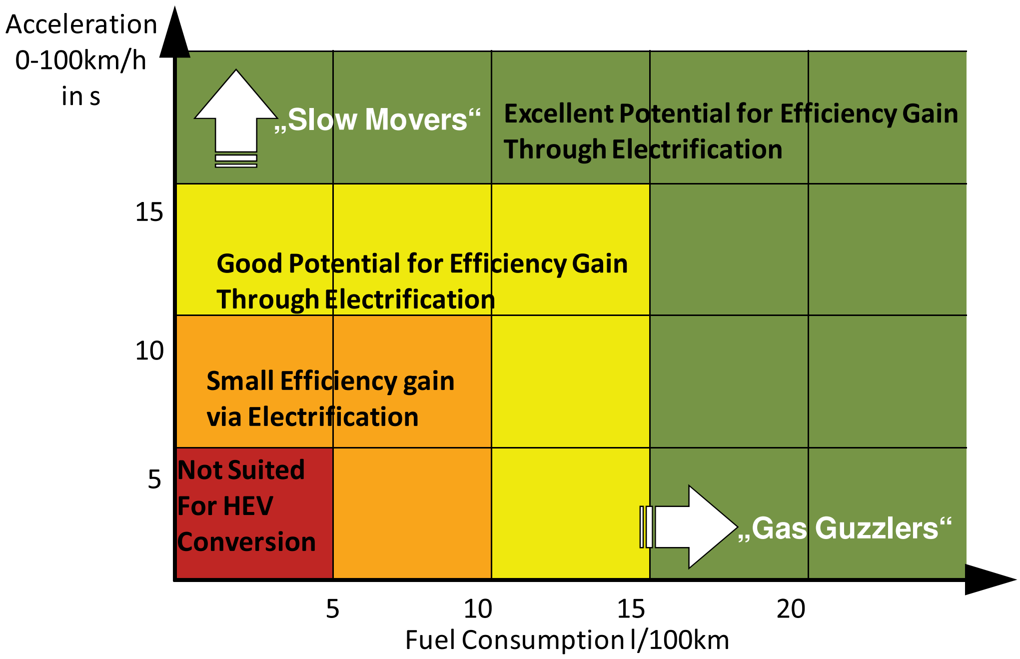


Figure 4-27 Conversion from a conventional vehicle platform to a high voltage HEV concept is best suited for vehicles displaying high fuel consumption values and low performance capability (contributed by Dr. Andreas Penka – BMW Group)

Mass Customization - The farther hybrid concepts move towards electric driving within the spectrum of hybrid concepts, the harder it becomes to offer a “one-size fits all” solution for the mass market. For this reason manufacturers have to develop ways to keep niche markets from becoming too expensive to own, while being able to market the strengths of the hybrid and electric powertrain systems.

PHEV hybrid concepts offer the opportunity for mass customization as a means to increase consumer use savings per kilometer at the expense of higher initial purchase prices. The development of an expandable modular high voltage battery for plug in hybrid vehicles can allow for a custom made electric range. Theoretically, customers could select the size of the battery based on the desired electric range that can cover most of their driving in an all electric mode without building expensive excess battery storage that might go unused. Furthermore, the exchangeability of batteries has already lead to new business models that separate the purchase of the car and the battery. Chapter six explores the costs to manufacture and cost of use for various hybrid concepts.

Plant to Wheels Efficiency Comparison – Lifecycle comparisons are useful when considering energy efficiency defined as energy output available for propulsion to total energy expenditure. Figure 4-28 depicts several common metrics to describe energy lifecycle balance. The most encompassing metric is the so called “well to wheel” analysis that is useful in comparing the many fuel pathways from extraction, to storage, processing, distribution and end use for transportation. Likewise, “well to tank” and “well to plant” refer to the supply chain energy expenditures up to placing fuel in a car’s tank and bringing primary energy sources to the refining or electric power plant respectively.

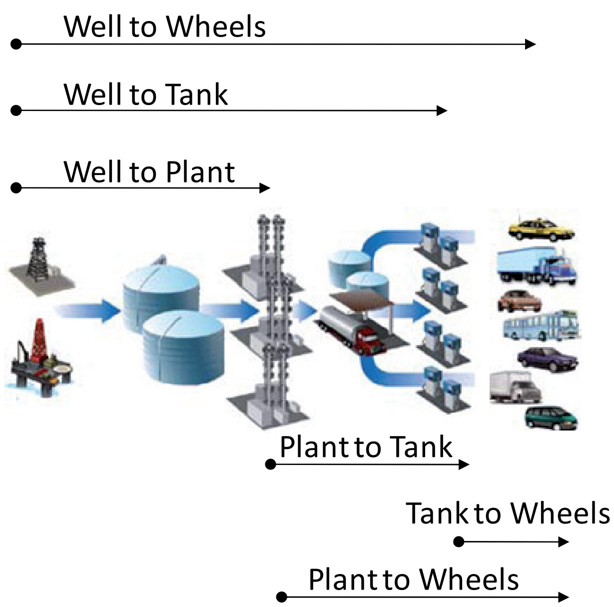


Figure 4-28 Explanation of popular lifecycle terms found in literature to compare various fuel pathways and vehicle powertrain architecture efficiency [KENDALL 2008, pp79-86]. Because the “well to plant” path is similar for most fuels, we focus on “plant to wheels” in this discussion.

When considering only the conventional liquid fuel and electric pathways for diesel, gasoline and electricity the “well to plant” losses are comparable, however there is considerable differences in the plant to wheels comparison. According to KENDALL 2008, p. 85, the US department of energy reports that the liquid pathway has only 17 % losses from the crude oil refining process to the distribution to the fuel pumps, in other words “plant to tank.” The rest of the losses happen within the vehicle as the chemical energy of the fuel stored is burnt in the IC engine. Gasoline cars are assumed to be able to use only 18% of the energy in the tank for propulsion, whereas diesel cars achieve slightly higher values at 23% when all losses are considered (powertrain losses, aerodynamic, rolling resistance, etc).

The electrical pathway is not as efficient as the refining process as fuel must be burnt to create electricity. Plant efficiencies vary from 35% for coal to 42% for natural gas. Transmission and distribution losses amount to 8% [ELGOWAINY et al. 2009, p.31]. Finally, the electric powertrain is conservatively assumed to result in 65% efficiency based on including all vehicle losses.

Using this information, Table 4-11shows that the lifecycle energy efficiency from plant to wheels is slightly improved as car architectures move towards the all electric pathway. The percentages of electric and liquid pathways for the various types of PHEVs are based on comparing conventional car uses with the electrical range capability of the PHEV architecture (see figure 6-6).

Table 4-11 Plant to Wheel Efficiency Estimates for Various Architectures based on KENDALL 2008, p.86

Primary Energy Efficiency		ICE	HEV	PHEV (10 km)		PHEV (20 km)		PHEV (30 km)		PHEV (40 km)		BEV
Plant to Tank	Plant efficiency	83%	83%	83%	35-42%	83%	35-42%	83%	35-42%	83%	35-42%	35-42%
	Transmission & Distribution				92%		92%		92%		92%	92%
Tank to Wheels		18-23%	23-27%	25%	65%	25%	65%	25%	65%	25%	65%	65%
	% Liquid Pathway/ % Electric Pathway	100% / 0%	100% / 0%	82%	18%	69%	31%	58%	42%	50%	50%	0% / 100%
Plant to Wheels (lifecycle)		15-19%	19-22%	21-22%		21-23%		22-23%		22-24%		21-25%

Energy lifecycle efficiency is only one part of story. The “plant to wheels” lifecycle GHG emissions calculation is somewhat of a trickier comparison, as the electric pathway has large variations of emissions based on the production source mix of the electric grid. Looking at Table 4-12, we can see that both in the US and EU there are large variations in GHG emissions production measured in gCO_2/kWh.

Table 4-12 Estimates of GHG emissions for ICE and BEVs according to KENDALL 2008, p.88

		CO2 intensity of energy supply (gCO2/kWh)	(Refining &) T&D efficiency	Vehicle energy efficiency	CO2 intensity of motive energy (lower=better) (gCO2/kWh)
ICE	Gasoline	242	83%	18%	1620
	Diesel	248	83%	23%	1299
US BEV	California	273	92%	65%	457
	Indiana	937	92%	65%	1567
	US Average	620	92%	65%	1037
EU BEV	Austria	221	92%	65%	370
	Greece	781	92%	65%	1306
	EU Average	370	92%	65%	619

Austria in the EU which has 59% of its electric production based on renewable source and California in the US with 89% electricity production from Natural Gas make these areas well suited for the electric powertrains. In contrast Indiana and Greece produce almost solely from coal fired plants exhibiting 937g and 781g CO_2/kWh respectively. A battery electric vehicle in Greece could in fact produce more GHG emissions than a conventional diesel car!

In short, the electrification of cars offers significant GHG emission reductions and lower petrol fuel consumption potential. Critics of PHEV and BEV implementation often state that electric driving is not "emission free," but rather a pass on of emissions elsewhere. This is true, except that the argument neglects that plant emissions are far easier to control and clean than hundreds of thousands of mobile IC engines in cars.

4.4 Methodology for Pre-selection of Vehicle Architectures

As new vehicle architectures take prominence in the market, it is important to develop methodologies for the pre-selection of HEV architectures. A four step process that utilizes matrix based methods and a lifecycle cost assessment is presented in the following chapters. In this section we present an overview of the process:

1. Develop a goal oriented design statement.
2. Develop an architecture solution space with the aid of matrices (Chapter 5).
3. Determine lifecycle cost projections to filter out dominated solutions (Chapter 6).
4. Select architectures for further detailed study that best meets goals. (Chapter 7)

The aim of these 4 steps is to reduce the varied field of architectures to only goal relevant solutions. The process is not intended to describe a method in finding one optimal solution.

Step1: Develop a goal Oriented Design Statement -HEV goals are derived from a myriad of customer requirements, government regulations, influences from competitor's products, and the firm's own market strategy. At this step it is important to structure the design problem into a design statement that exhibits the following four key items:

Objectives – Items designers would like to maximize or minimize as overall goals

Design Variables – Items which developers can change while designing the product

Parameters – Items that can be considered fixed during first assessments

Constraints – Items that limit the design and can be expressed as equalities or inequalities.

By identifying these four items [DE WECK, OLIVIER et al. 2004b], developers can generate a good idea of the degrees of freedom available in the new design.

Step 2: Develop a vehicle architecture solution space with the aid of matrix methods - The focus in this step is to generate a solution space of possible HEV architectures. The Design Structure Matrix (DSM), Domain Mapping Matrices (DMM) and Multiple Domain Matrices (MDM) are used as tools in developing an understanding of how functional elements within an architecture map to their physical components. Chapter 5 offers a step by step explanation of how these matrices are built for known HEV and BEV architectures. The information gained on how component modules relate to functional modules is then used to develop a generic HEV solution space.

Step 3: Determine lifecycle costs to filter out dominated solutions - One of the most effective benchmarks to limit the solution space is the use of lifecycle cost estimation to perform trade studies. Inputs to a lifecycle cost model come from the solution space delineated in step 2 along with the determined design goals from step 1. The lifecycle costing model uses simulation support in testing the functional behavior of our selected models after step 2. The aim of the simulation is to generate a mapping of HEV architectures that achieve overall vehicle goals such that Pareto optimal solutions can be identified [SMALING et al. 2007], along with their lifecycle cost performance for further comparison.

The simulation tool can be understood as a black box that take vehicle architectures with a variety of component sizes as an input and provides overall vehicle values such as fuel consumption, emissions, weight, driving performance and cost as an output for each architecture variation. Pareto dominant architectures can vary based on assumptions made within the simulation process.

It is important to conduct a thorough sensitivity analysis to determine what risk potentials exist. For example, if one of the overall goals is to minimize cost, some vehicle components still under development such as the HEV battery system might have been estimated poorly in the model. A sensitivity analysis can show how small changes in the HEV battery cost can affect the overall vehicle cost.

Step4: Select architectures for further refinement and development - Based on the knowledge acquired within steps 1-3, a decision must be made in selecting a particular HEV architecture for further development. This entails weighing the risks and opportunities defined in step 4 for each architecture option and determining if the original goals can be achieved - the decision criteria in this case are directly taken from the goals and constraints sets in step 1.

The decision made must be properly documented to allow transparency in the selection process. The 4 steps outlined will naturally exhibit iteration as more knowledge is generated during the design. The pre-selection of HEV architectures occurs during the initial steps of product development as discussed in section 4.1.2.

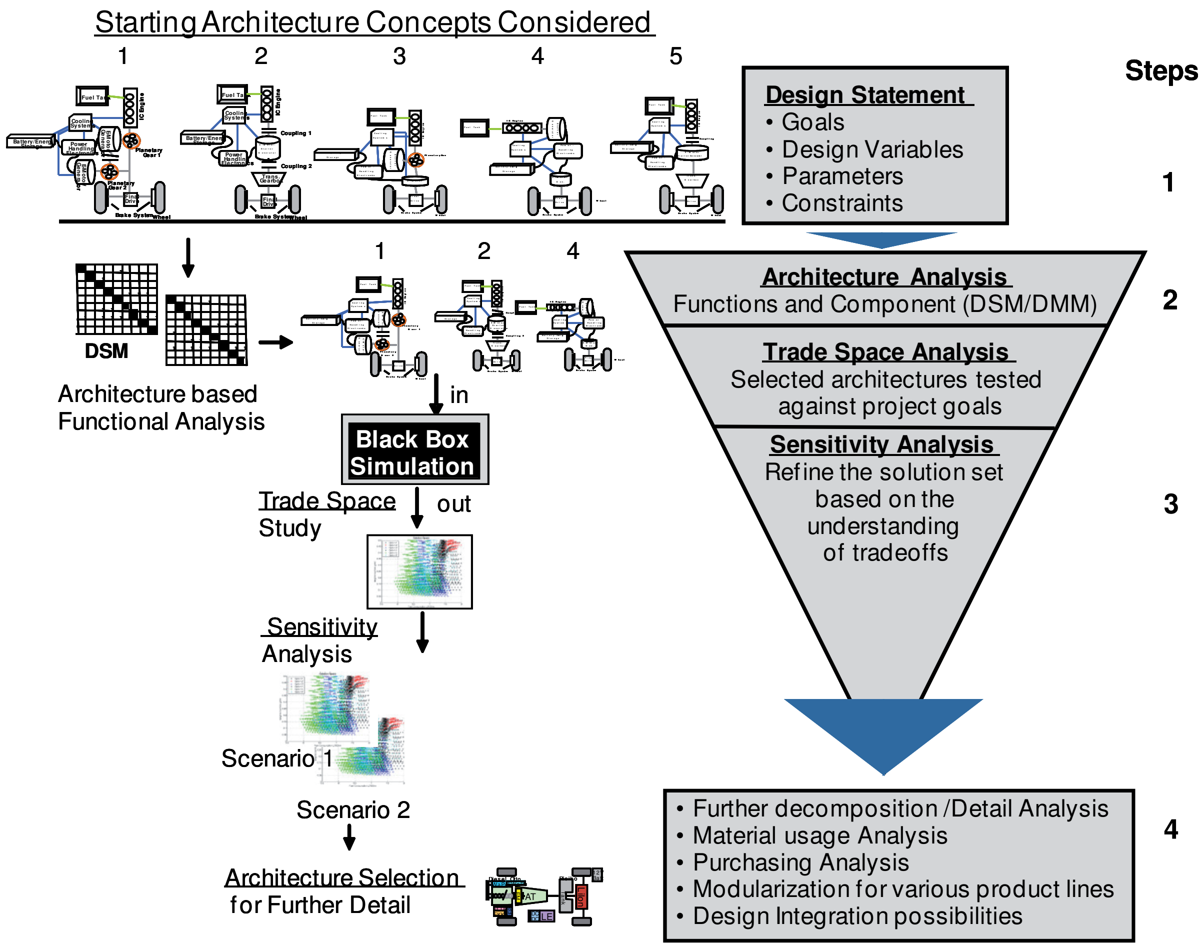


Figure 4-29 Overview of Methodology for pre-selection of HEV Architectures

Figure 4-29 provides a graphical overview of the four step process. In step one the design statement is drafted and the starting architecture concepts are considered. The second step depicts the matrix analysis, for which the concept selection field is reduced or filtered. In the third step a trade space analysis and sensitivity analysis provides information on which architecture concepts dominate the solution space. Finally on step four, vehicle architecture concepts are selected for further detail and study.

4.5 Summary of Hybrid Vehicle Architecture Fundamentals

System architecture plays a central role in the design of system elements. The architecture influences the system properties, functional behavior, emergent behavior and level of complexity. Understanding the overall system structure is the first step in managing the development of new car concepts. The architecture definition of system modules and their interfaces drives the development process.

The twelve system architecting principles discussed in section 4.1.1 make up the foundation of the systems engineering process and the many working methodologies that have developed since the 1970s. The first methodologies that described a product development process featured linear models. The conceptual ideas of these early linear models have changed very little, however phased models with iterations capture in more detail the work flow required in the development of new products. Finally, network models, such as Lindeman's MPM, present product development in the advent of networks, where developers have the flexibility to iterate between the phases of product development nodes.

The need for flexibility in the product development process as described by Lindeman, also translates to the present need for flexibility in the product offering itself. Design for changeability as described by Fricke and others, suggests that a product designed to change within its own lifecycle can create and deliver value. In the context of vehicle architecture, cars can be designed as changeable systems that can (1.) adapt to unforeseen situations, (2.) are agile in changing to perform in a given situation, (3.) are robust to changes in the environment and (4.) be flexible to be easily changed with little or no effort from the user. In this new age of architectural competition, changeable architectures might be the next logical step in delivering more capability to the user.

A method of evaluating the value created by changeability of a product is presented in section 4.1.4 based on Engel and Browning's work on architecture options theory. Economic opportunities for changeable systems can be compared by using the Black Scholes formula used in financial and real options. Another possibility is to generate use case scenarios and compare a changed architecture to reference architecture following De Weck's work. The latter method is further pursued and utilized in the vehicle architecture valuation example presented in chapter 7.

The structural configuration of hybrid vehicles allow for many possible operating modes. Parallel, Through the Road, Series, Power Split and Combined architectures are discussed in detail. Structural arrangement of key component subsystems must be further combined with the functional requirements that drive the sizing of each element. Once vehicle architecture is configured and sized, the functional capabilities can be studied and refined based on a variety of control strategies for which engines, motor/generators, and energy storage device types can be selected.

The discussion in section 4.3 concludes that hybrid cars vary dramatically in functionality and that it is difficult to find a single vehicle architecture that is deemed better than others. Although lifecycle efficiency can be used as one method of comparison, the ultimate decision lies with the customer. The ideal architecture is the one that suits the individual needs of the customer better than all others. As a summary, Table 4-13 provides a qualitative comparison of vehicle architectures taking the HEV as the reference architecture.

Table 4-13 Qualitative comparison of vehicle architecture concepts

Criteria	ICE	HEV (Reference)	PHEV	BEV
Electric Driving Range	NA	O	+	++
Total Range	+	O	O	--
Operating costs	-	O	+	++
Tank to Wheel Emissions	-	O	+	++
Tank to Wheel Efficiency	-	O	eDriving: ++ Total : +	++
Refueling Duration: Electric	NA	NA	-	--
Gasoline/Diesel	O	O	O	NA
Vehicle Weight	+	O	-	-
Manufacturing Costs	++	O	-	--
Commercial Risk (Battery-Tech. Maturity, Service Costs)	++	O	--	--
Ecological Image/ Posible Perks	- -	O	+	++
Political Support	-	O	+	++

++ Very Advantageous; + Some Advantages; o Average; - Some Disadvantages; - - Many Disadvantages

Within the set of criteria presented in Table 4-13, PHEVs offer generally better results in all areas over the HEVs including much better all electric range, operating costs, lower emissions and efficiency. Interestingly, PHEVs also address many disadvantages that make BEVs a niche application such as total vehicle range, refueling duration and weight. Finally, the conventional ICE still excels in offering the lowest manufacturing costs and commercial risk.

Finally, a methodology for the pre-selection of vehicle architectures from the perspective of the developer is presented in section 4.4 as an introduction to follow on chapters 5-7. The methodology begins by the formulation of a goal oriented design statement that explicitly includes: (1.) objectives, (2.) design variables, (3.) Parameters and (4.) Constraints. Once provided, the second step generates a solution space with the aid of matrix. The third step evaluates lifecycle costs to filter out dominated solutions and finally the fourth step selects architectures for follow on analysis. This pre-selection methodology for vehicle architectures is presented in detail in the follow chapters.

5 Matrix Based Vehicle Architecture Analysis

This chapter introduces a vehicle architecture solution space that is generated using matrix based tools. First, a basic introduction to the methodology and tools are presented using applied examples of hybrid vehicle architectures. The study of structural links between components and functions within the architectures modeled allow for the derivation of a generic approach. Second, a system analysis of the most prominent HEV architecture concepts presently known today is discussed.

The presentation of ***ΔMDMs*** *"Delta Multiple Domain Matrices" (section 5.3) and* ***∑MDMs*** *"Sigma Multiple Domain Matrices" (section 5.4) are novel research contributions in this chapter. The idea of a "compatibility matrix" is further developed from previous work to aid in the construction of the vehicle architecture solution space presented in section 5.6. The analysis of dependencies between and amongst the functional and component domains of eight vehicle architectures in this chapter develop a basis of knowledge that concludes with the definition of more than 5,450 HEV, PHEV and BEV structural conceptual configurations from a combinatorial field of more than 290,000 choices.*

5.1 Matrix Theory Review

Matrix-based tools are widely used in systems modeling and analysis. The focus of this chapter lies on methodologies developed by STEWARD 1962 in the early 1960s and formalized over the following decades by various authors [EPPINGER 1991, BROWNING 2001, MAURER 2007, LINDEMANN, U. et al. 2008 to name a few]. Three types of matrices that represent links between a system of elements are presented in the following sections; namely the *intra domain matrix*, the *inter domain matrix* and the *multiple domain matrix*.

A **domain** in the discussion that follows relates to a collection of system elements that can be classified under a common type. In the realm of vehicle architecture, the functional domain collects elements that describe functions of system components. Likewise, the components domain collects physical parts or physical system modules that contain an assembly of parts that in aggregate make up the overall system or vehicle.

The matrix based dependency representations that follow can be depicted in graphic representations taken from algorithmic graph theory [MAURER 2007, p. 47, 52]. The graphic representations are composed of characteristic nodes and edges. A *node* is equivalent to a system element, where as *edges* represent the connections or interfaces between system elements. The edge connections can represent a variety of interfaces including physical or spatial connections, electrical signals, informational transfer or material flow transfer to mention some examples. Graphical representations can be useful in visualizing the overall effects of the structure at hand, but can rapidly become hard to follow. Edges are differentiated by whether they are unidirectional or bidirectional in form. Coloring systems of nodes and edges can help determine which elements are classified to a particular domain. In this chapter the SysViz tool developed at the Institute for Product Development of the Technische Universität München (TUM) is used for all graphical representations and the Loomeo Software from Teseon is used for the matrix based representations.

5.1.1 Intra-Domain-Matrix

The Intra-domain matrix refers to a dependency matrix that links elements within one particular domain. A common example of an intra-domain matrix is the *design structure matrix* or *dependency structure matrix* (DSM) as defined by STEWARD 1981.

Characteristic of a DSM is an equal number of rows and columns. The fields within the matrix represent a systematic mapping of relationship or interfaces between the row and column system elements which all belong to the same classification domain. The binomial links within the matrix fields are similar to edges in graph theory as they show the connection between two elements. The diagonal in a DSM is equivalent to nodes in graph theory as each row and column in the diagonal represents the same element.

Figure 5-1 shows an extract of a binomial DSM of a hybrid vehicle component domain. The component element nodes that form at the diagonal fields are listed in the rows and columns. The edges of this "components" DSM shows physical connections between HEV component systems. For example, the fuel tank is directly connected to the IC engine and vice versa, designated by the numeral "1" in the matrix fields where these two component elements rows and columns intersect. Fields that are left blank or designated by a "0" have no direct connection between row and column elements.

The component DSM results in a symmetric matrix. For such matrices, only filling the cells above or below the matrix diagonal is necessary. The remaining upper or lower half is simply a transposition across the diagonal.

Components - DSM	Fuel Tank	Battery	IC Engine	E-Motor/Generator 1	E-Motor/Generator 2	...
Fuel Tank			1			
Battery				1	1	
IC Engine	1			1	1	
E-Motor/Generator 1		1	1			
E-Motor/Generator 2		1	1			
⋮						

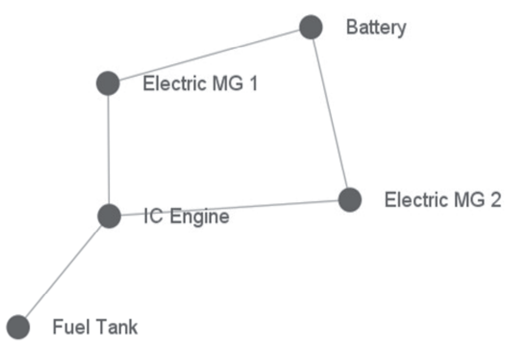


Figure 5-1 Excerpt of a DSM for the components domain. The matrix and analog graphical representation shows physical connections between elements.

In Figure 5-2, an excerpt of a “functions” DSM model of a hybrid vehicle system is shown. In contrast to the components domain DSM, the functional domain is not symmetric. In this case, links between elements (or edges) represent energy flows that can be directional or bi-directional. A function is depicted at the left in a black box representation with a number of given inputs that go into performing a function resulting in outputs to other functions. Functions are described in simplest terms by a verb-noun or verb-clause construction, such as “store-fuel” as the main function description of a fuel tank - this syntax is similar to that of relation oriented functions modeling methods [LINDEMANN, UDO 2007, p.119]. Each function must provide at least one output in order to provide utility in the system and flows can be unidirectional or bidirectional.

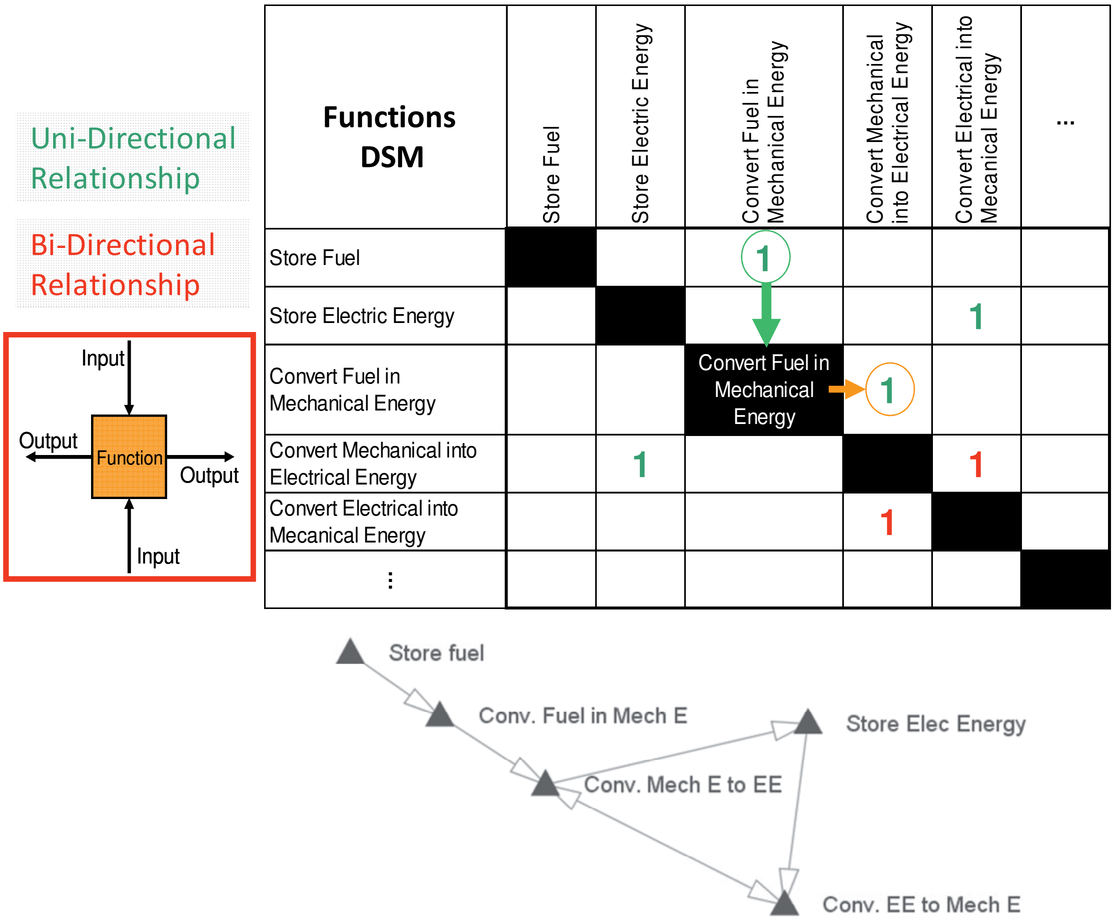


Figure 5-2 Excerpt of a functions DSM with graphical representation

Relation links within columns that can be followed vertically to a black node in the matrix diagonal represent energy flows that are inputs to the function. In contrast, row dependencies represent outputs from the diagonal node function. For example, the function “convert fuel in mechanical energy” (performed by the IC engine) 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 IC engine 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.

According to BROWNING 2001, there are two categories of DSMs: time based DSMs and Static DSMs. In time based DSMs the dependencies are commonly used in solving activity scheduling problems equivalent to PERT/CPM activity network algorithms [BROWNING 1998, p.44]. The elements within the matrix represent activity nodes that are defined by time to completion and the dependencies are the relationship edges that designate which activities are inputs or outputs to other activities. By means of reordering of a DSM’s rows and columns using a sequencing algorithm, a time based DSM can be found that shortens the overall project time of completion by reducing the number of iterations.

In a static DSM, such as in figures 5-1 and 5-2, no time based relationships define the elements of the matrix. In this work, only static DSMs are used in analyzing vehicle architecture structural relationships. Clustering algorithms are used to find modules of DSM elements that could be sensibly bundled together. The DSMs have seen many useful implementations described in academic literature; Table 5-1 shows a brief summary.

Table 5-1 Example of other implementation areas of DSMs [MAURER 2007, p.56] These and many other contributions can be found in www.DSMweb.org

Capturing knowledge	WHITNEY et al. 1999
Process oriented problems and dependencies in information flow	EPPINGER et al. 1994
Transfer of documents and information	YASSINE, A. 2004
Product development processes and reduction of development time	YASSINE, A. et al. 2006
Schedules and cost distribution for the execution of planned tasks	BROWNING 1998
Analysis of systems and product architectures	BROWNING 2001
A method for change prediction and tracking the impact of propagation chains of changes to the product structure	CLARKSON et al. 2004
Increasing the possibilities of product customization	LINDEMANN, U. et al. 2005
In supporting “Design for Changeability”	DE WECK, O. L. 2007

5.1.2 Inter-Domain-Matrix

In contrast to the DSMs presented in section 5.1.1, an inter-domain matrix links elements of two different domains [LINDEMANN, U. et al. 2008, p.54]. Inter-domain matrices are not required to be square matrices and usually adopt an nxm structure. These matrices are widely used in many applications; the center matrix mapping technical requirements to functional requirements in a "house of quality" matrix is one of many examples. DANILOVIC et al. 2001 coined the term *design mapping matrix* or *dependency mapping matrix* (DMM) in applications specific to domain based thinking and the using of clustering algorithms to order DMMs [MAURER 2007, p.58].

Figure 5-3 (left) shows an example of a simple DMM mapping functions to components. In this simple case, each function matches to one component in a 1 to 1 mapping, known as perfectly uncoupled *modular* architecture mapping [ULRICH, K. T. 1995, p.421]. In most cases a more to one mapping of functions and components are exhibited in more *integral* architectures displaying a high level of coupling – figure 5-3 center. Finally in figure 5-3 (right), architecture *independence* is achieved when functions and components are decoupled showing no feedback coupling between functions and components [FRICKE et al. 2005,p.350 quoting SUH 1990]. Independent designs allow for modularity where there is more to one mapping, however, changing one module has minimal change propagation effects.

Uncoupled Design DMM	Function 1	Function 2	Function 3	Function 4	Function 5	…
Component A	1					
Component B		1				
Component C			1			
Component D				1		
Component E					1	
⋮						

Coupled Design DMM	Function 1	Function 2	Function 3	Function 4	Function 5	…
Component A	1		1		1	
Component B		1		1	1	
Component C	1		1	1	1	
Component D	1	1	1			
Component E		1	1	1	1	
⋮						

Decoupled Design DMM	Function 1	Function 2	Function 3	Function 4	Function 5	…
Component A	1		1			
Component B		1		1	1	
Component C			1	1	1	
Component D				1		
Component E					1	
⋮						

Figure 5-3 Several types of Domain Mapping Matrices depicting the relation between the functional and component domains. On the left an example of a perfectly modular uncoupled design; at center an integral design showing a high level of coupling; at right a decoupled design showing architecture independence [FRICKE et al. 2005,p.350].

5.1.3 Multiple-Domain-Matrix

A multiple domain matrix (MDM) is a matrix comprised of DSMs and DMM combinations [LINDEMANN, U. et al. 2008, p. 69]. The simplest MDM consists of two DSMs on the diagonal and one DMM connecting the two domain mapping matrices. The MDM thus contains information of dependencies between elements within a domain, as well as inter-domain relationships captured in the DMM portion as seen at the bottom of Figure 5-4.

The MDM representation of dependencies between components and their basic functions is used as a tool to analyze these complex architecture structures in an organized manner. Clustering of DSMs is best performed before integration of the matrices in an MDM format. Once all elements of an MDM are combined the matrix becomes a square matrix. In the particular case of vehicle architecture representations the off diagonal DMMs are simply a mirror transposition across the diagonal DSMs.

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. In his work, MAURER 2007 formalized the basic definitions and analysis tools available for MDMs.

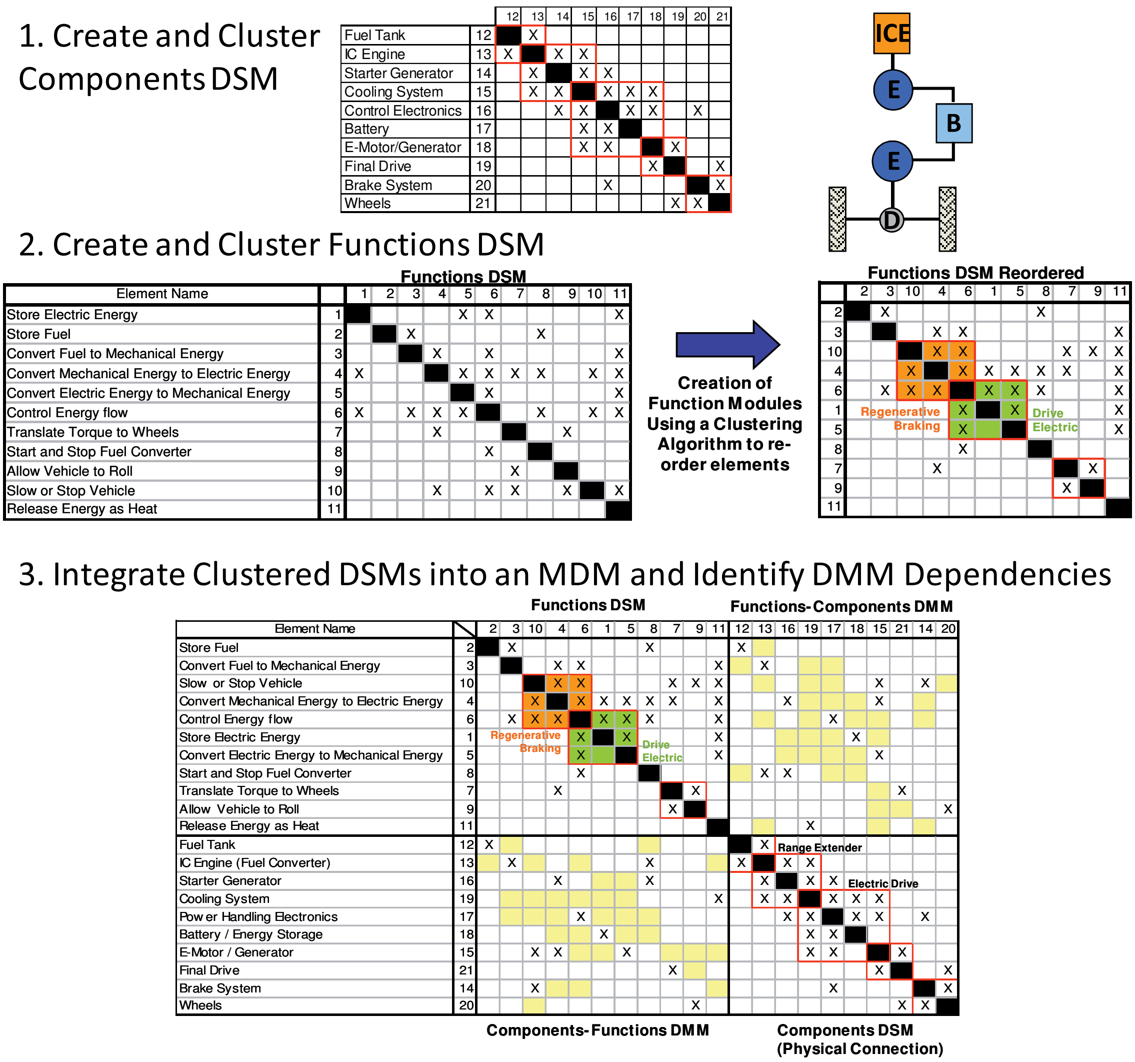


Figure 5-4 Three steps for building an MDM for a series hybrid architecture. The DMM in step three shows both direct (marked by X) and indirect (marked by yellow square) dependencies.

Figure 5-4 provides a simplified example of the step by step construction and analysis of an MDM for a series hybrid architecture. In the first step, the components and structure DSMs are constructed manually based on fundamental concept sketches (such as in Figure 4-13) and expert knowledge of how a series hybrid is configured. To create the components DSM, the key components are listed as elements within the matrix and the information is filled for only the upper or lower diagonal of the DSM due to its symmetry.

The model’s level of abstraction and system boundaries are determined at this point. In this example and those that follow, a high level of abstraction is maintained by keeping the number of component systems to a small set described in section 5.2.1. For example, the component system “ICE” is one element that can be further broken down into the next level of sub-components including the pistons, the engine blocks, crank shaft, rings, and others down to the bare nuts and bolts. The clustering of the components DSM portion can indicate where sensible modules can be formed or partitioned.

For each component identified, the main function or functions of that component is formulated using a verb-clause phrase. A functions DSM is filled in using expert knowledge on the functional mechanical, electrical, chemical and thermal energy flows.

The benefit of the functions DSM lies in the identification of sub-functions related to particular components that can be grouped into more generalized functions, thus providing a formal way to construct and analyze functional hierarchies. In the example in figure 5-4, the clustering of functions “convert energy flow,” “store electric energy” and “convert electric energy to mechanical energy” result in the higher order function cluster “drive electric.”

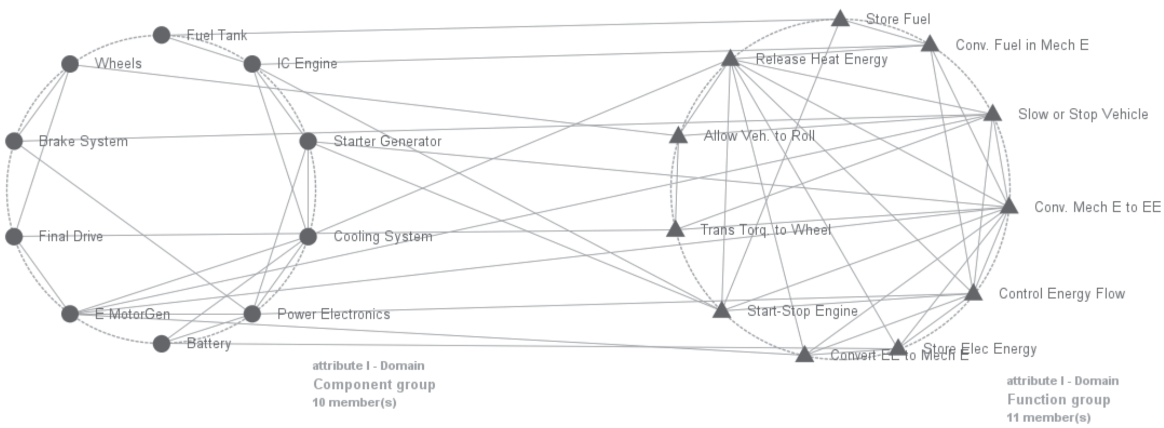


Figure 5-5Graphical Representation of the MDM in figure 5-4 using sysviz software (www.sysviz.org)

5.1.4 Computing Inter-Domain Relationships

MDMs do not have to be always constructed manually. Linear algebra can help in the creation of one matrix given that two other matrices are available. Figure 5-6 shows two examples and formulas. The left side depicts how the functions DSM (Matrix A) can be calculated from filling out the components DSM (Matrix C) and the functions-components DMM (Matrix B). Likewise the components DSM can be computed in a similar manner by knowing the relationship on the right side of Figure 5-6.

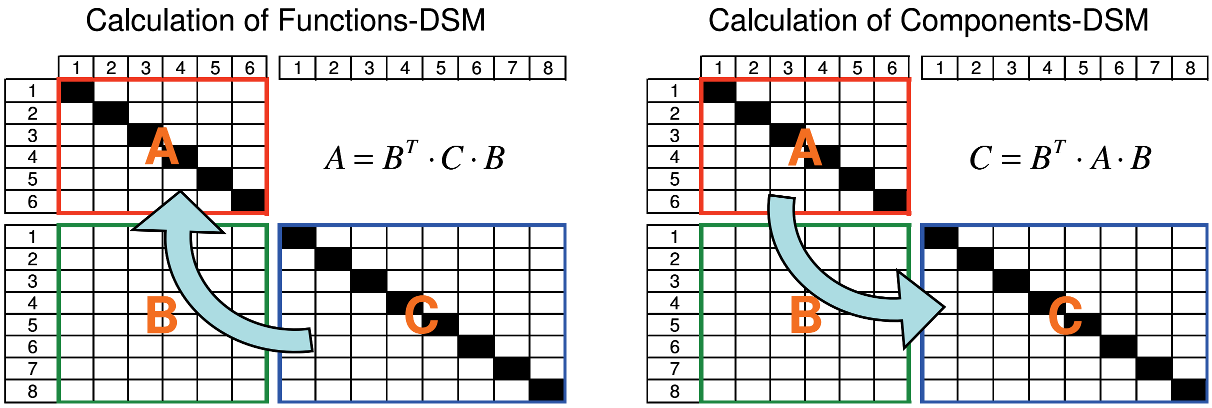


Figure 5-6 Two MDM Matrix calculation possibilities. These and other matrix manipulations for MDMs can be found in M*AURER 2007, p.113-118.*

The key to the calculation of either DSM is the DMM relationship. If a generic DMM could be found for all components and functions relevant to all vehicle architectures, then a selection of components describing a hybrid vehicle can be used to build the entire MDM for a particular vehicle architecture. This idea is demonstrated in sections 5.2 thru 5.5.

5.2 Vehicle Architecture Systems

A fundamental part of system modeling lies in the definition of system boundaries. Most product development methodologies presented in 4.1.2 use the basic principle of partitioning a design problem into more manageable sub-segments. These partitions allow for more detailed modeling within a segment of the overall system to generate a better understanding of the sub-system.

DSM modeling techniques offer a structured methodology in partitioning systems by the creation of clusters. These clusters can be used to move from detailed representations to more abstract renderings of a system. A good rule of thumb is to keep system elements to no more than 10-15 elements, as anything above this number of system element representations are difficult to follow. More research is needed to find matrix sizes compatible human bandwith; however, most DSM tools available today can handle matrices in the order of several thousand elements.

For our analysis, the vehicle as a unit, determines the system boundaries with its environment. The elements of the vehicle that are considered are kept at a high level of abstraction that matches the pre-development stages of vehicle architecture concepts. The architecture descriptions that follow are thus limited to a set of components and their main functionality.

The goal of the work that follows is to generate a solution space of vehicle structures by first analyzing a subset of know vehicle architectures. The differences and similarities amongst these architectures develop a general architecture understanding of how functions and components link to and amongst each other. In a second step, this initial data is used to create a broader solution space of vehicle architectures.

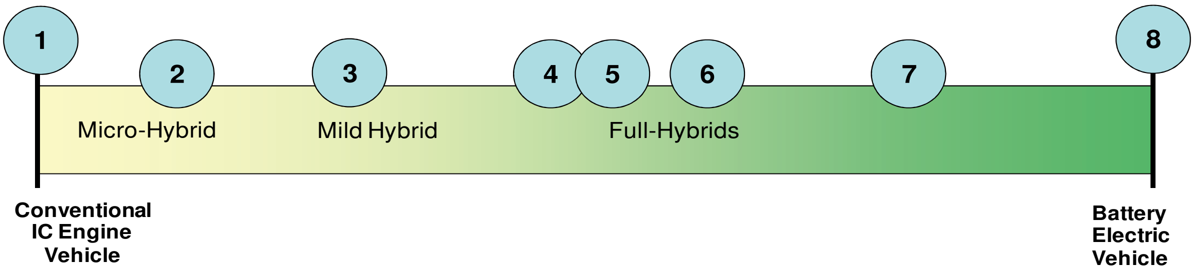


Figure 5-7 Eight vehicle architectures were analyzed across the vehicle electrification spectrum by means of function and component MDMs. 1. Conventional ICE vehicle, 2. Parallel Micro-Hybrid (Belt Alternator Starter), 3. Parallel Mild Hybrid (Integrated Starter Generator), 4. Parallel Hybrid (Double Coupling), 5. Power-Split hybrid (One Mode), 6. Power-Split Hybrid (Two-Mode), 7. Series Hybrid (w/Range Extender), 8. Battery Electric Vehicle

Eight vehicle architecture structures were analyzed as depicted in Figure 5-7. These include one conventional ICE vehicle, one BEV and six hybrid vehicles including: one micro-hybrid, one mild-hybrid with integrated motor assist, a one mode power split full hybrid, a two-mode power split full hybrid and a double coupling parallel hybrid. The results of this analysis can be found in the appendix section 9.2.

5.2.1 Components and Functions

The eight architecture MDMs were built according to Figure 5-4 in a workshop environment along automotive industry experts over two months time. The initial information collected in the matrices went through several iterations of identifying functions and components within the eight systems. A generic construct of the MDMs using an agreed set of component systems proved to be an effective way to develop a deeper understanding of the relationships between components and functions.

Components - The number of components (or component systems) for the ICE, HEV and BEV architectures chosen include a set of 23 components (table 5-2). The level of abstraction desired is meant to include only major subsystems relevant to the conceptual understanding of the particular vehicle powertrains. It is important to note that not all eight vehicle architectures selected for study include all 23 component systems.

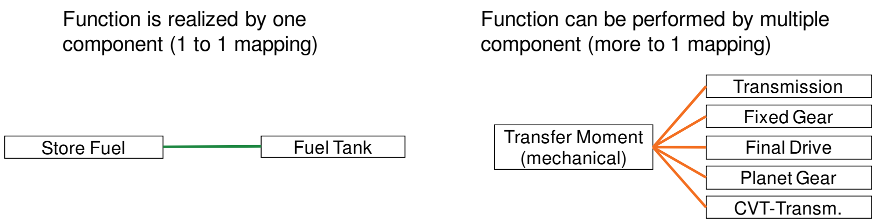


Figure 5-8 Example of Function to Component Mappings

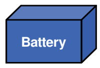
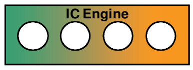
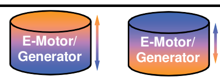
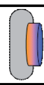
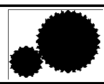
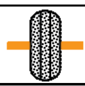
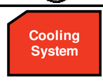
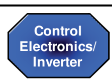
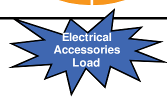
Functions - Each of the 23 components fulfill a specific function or functions that facilitate the overall vehicle system's functional operation. Each component within the design has at a minimum one function, however more to one mapping of functions and components often occur as presented in Figure 5-8.

When one to one mapping occurs, developers have a choice of reducing the number of components by integrating the function elsewhere or dropping the function altogether. Furthermore, the component can be dimensionally downsized or upgraded to achieve functional goals. An example can be the downsizing of a range extender for a series hybrid to reduce cost and weight.

More to one mapping of functions to components is also a possibility as in the case of more integral designs. The number of components is reduced by assigning more functions to one component. The integral design strategy may reduce the number of parts and in some cases cost at the expense of less flexibility achieved by modular designs.

A detailed description of the elements and functions within the 23 major component subsystem remains outside the scope of this work, but can be further developed using a similar methodology to the one presented here. The component systems selected, along with their primary function and diagram depiction is presented in Table 5-2.

Table 5-2 List of Components and Functional Description

Components	**Characteristics/Function**	**Symbolic Depiction**
Fuel Tank	Stores liquid fuel that contains chemical energy (includes fuel pump and transport system)	
Battery	Stores and delivers electric power and energy	
Super Capacitor	Stores and delivers electric power for short duration	
IC Engine	Converts chemical energy stored in fuel to mechanical energy (Fuel Converter)	
Electric Motor/Generator	Coverts mechanical energy into electrical energy and viceversa	
Wheel Motor/Generator	Coverts mechanical energy into electrical energy and viceversa - directly connected to the wheels	
Generator	Converts mechanical energy to electrical energy	
Starter	Used to start the IC Engine - converts electrical energy into mechanical energy	
Transmission	Converts and regulates torque and rotational speed	
Fixed Gear	Transfers moment and rotational speed	
Final Drive	Transfers torque to the wheel axle	
Transfercase Gear Box	Used in an all wheel drive vehicle to transfer torque to the axles	
Planet Gear	Transfers moment and rotational speed	
CVT-Continuosly Variable Transmission	Transfers moment and rotational speed	
Clutch or Direct Coupling	Couples or decouples torque and rotational energy transfer between two elements in automatic or manual transmissions	
Automatic Torque Converter	Allows for coupling and decoupling of moments in an automatic transmission	
Cooling System	Used to transfer heat away from a system component to the environment	
Wheels	Allows a rolling connection between the vehicle and the road that allows for frictional torque transfer to propel the vehicle	
Brakes/Braking System	Stops or slows the vehicle using friction and the release of energy as noise and heat	
Power Handling Electronic Control System and Inverter	In this simplified comoponent system all power handling electronic devices used for the control startegy of the hybrid system and the operation of the electric motors are included	
Plug	In plug in hybrids, this component allows the battery to charge from an external electric energy source	
Additional Mechanical Load Accessories	This simplified component system represent all fans, pumps, pulleys and other mechanical transfer systems not explicitly included that are a mechanical load to the system	
Mechanical Load Accessories	This simplified component system represents electrical load accessories for the vehicle electrical accessories in the 14V or higher networks (lights, radio, power windows, GPS, etc.)	

5.3 Δ Design Structure Matrix Analysis

The comparison of two MDMs can be achieved by means of matrix subtraction, given that both MDM are of the same dimensional structure. The resulting MDM is labeled a "delta MDM" as presented in Figure 5-9. The procedure is analogous to ΔDSM analysis presented by authors such as DE WECK, O. L. 2007, SMALING 2005 in analyzing changes in physical, energy flow, mass flow, information flow, addition and elimination of components of various engine architectures with different fuel reformer configurations.

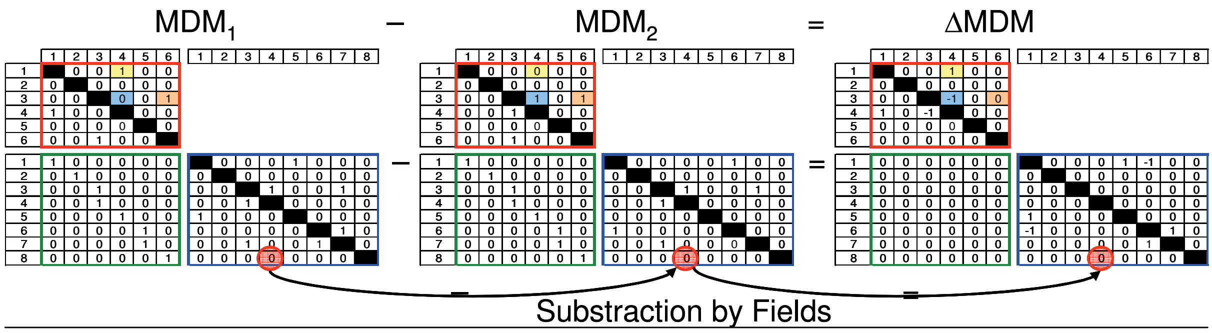


Figure 5-9 Exemplary depiction of a ΔMDM resulting from subtraction by fields of two MDMs

The MDM subtraction by fields is useful only when the component and functional indexes of compared sets match each other. The delta MDM method can be used in comparing two distinct architectures, or one product architecture that has been updated through the development process by tracking its element index changes through time. Index changes indicate that a component or function has been added or dropped.

In Figure 5-9, the ΔMDM method is used to compare two vehicle architectures. Each of the eight MDMs in the analysis set (found in the appendix section 9.3) was built in a workshop environment ensuring that each component and function element included in the analysis was given a distinct element name and index number to facilitate the ΔMDM comparison. In any of the eight MDMs considered, components or functions listed showing no connections are simply not present in that particular vehicle architecture.

The ΔMDM results in matrix fields with values of {-1, 0, 1} given the binary nature of the MDMs considered. A resulting ΔMDM matrix field value of {-1} shows a component or functional element present in architecture MDM_2 that is not contained in architecture MDM_1. ΔMDM matrix field values of {0} denote no change, whereas a value of {1} denotes an element present in architecture MDM_1 not contained in architecture MDM_2.

Two benefits of the ΔMDM method were recognized in practice. First, the changes in components used and functionality provided were easy to detect. Secondly, the method was very useful in catching logical errors in matrices filled by hand within a workshop environment.

5.4 ∑ Multiple Domain Matrix Analysis

∑MDMs provide another useful analysis tool. The ∑MDM, referred to as a “sum” or “sigma” MDM is built by the addition of two or more MDMs as shown in Figure 5-10. The principle of ∑MDMs is based on work with DSM matrix addition contributed by previous authors [BRAUN et al. 2007, GAUSEMEIER, J. 2007].

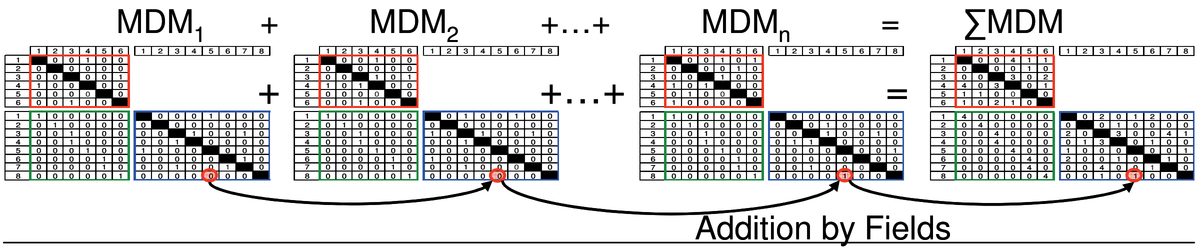


Figure 5-10 Creation of a ∑MDM

Similar to the ΔMDM, the matrices being added must match in terms of the function and component elements within the matrix position indexes. The eight vehicle architecture MDMs manually generated in the data collection workshops were added to create a ∑MDM.

The addition of these MDMs enabled the determination of information that could lead to the formulation of design rules or requirements. For example, components that were found to apply to all architectures are easily identified in the ∑MDM by cells showing a sum value equal to the number of total number MDMs in the sum. Likewise, function or components showing fields with a result of 1 show that the function or component is unique to only one particular architecture from the original set. This information can be helpful to make more targeted technology investments. Further analysis is accomplished by the identification of components are always present together and components that cannot be found together in particular vehicle architectures. The architecture information contained in the MDMs led to a number of design synthesis “if – then” statements, used in developing a configuration synthesis methodology presented in follow on section 5.6.

The fields within the DMM portion of the resulting ∑MDM aggregate matrix are of particular importance to this discussion. This matrix corresponds to the lower left corner of the right most MDM in Figure 5-10. The information contained in this ∑DMM includes all connections between the component and functions domains for the set of architectures considered. Turning the ∑DMM portion of the ∑MDM to a binary matrix creates a generic DMM that applies for the entire set of eight architectures, and any further architecture - limited to the set of functions and components considered. This result is shown in detail in Figure 5-11. In order to build this ∑DMM each component and function considered must be provided a distinct index field consistent amongst all MDMs.

The generic DMM is useful in visualizing architecture information. For example, reading the DMM in Figure 5-11 along a column shows the different components that map to the fulfillment of one function as discussed in section 5.2.1. Reading the DMM across rows that have multiple entries displays the multiple functions a component can perform or is partly involved in performing.

	Generic Components - Functions DMM	1 Store Fuel	2 Store Electric Energy	3 Convert Fuel into Mechanical Energy	4 Convert Mechanical into Electrical Energy	5 Convert Electrical into Mechanical Energy	6 Deliver (Recover) torque to (from) wheels	7 Convert Moment tranfered (mechanical)	8 Equate Rotational Speed	9 Divide Moment between Wheel Connections	10 Couple/Uncouple Moment	11 Release Heat to the Environment	12 Transfer Heat (to Cooling system)	13 Transfer Moment to (from) the road	14 Slow or Stop Vehicle (recovering energy)	15 Slow or Stop Vehicle (releasing Energy - by Friction)	16 Control Energy Flow	17 Connect/Transfer External Electric Energy Source	18 Consume Electric Energy for Auto Accesory OPS	19 Consume Mechanical Energy for Engine Accesory
1	Fuel Tank	1																		
2	High Voltage Battery		1										1							
3	Super Capacitor		1										1							
4	Internal Combustion Engine			1									1							
5	E-Motor/Generator1				1	1							1		1					
6	E-Motor/Generator2				1	1							1		1					
7	E-Motor/Generator3				1	1							1		1					
8	Wheel E-Motor				1	1	1								1					
9	Generator				1								1							
10	Starter					1														
11	Transmission							1												
12	Fixed Gear							1												
13	Final Drive						1	1	1											
14	Transfer Case Gear Box									1										
15	Planet Gear1							1			1									
16	Planet Gear2/3							1			1									
17	CVT							1												
18	Clutch Direct Coupling1										1									
19	Clutch Direct Coupling2										1									
20	Automatic Torque Converter										1									
21	Cooling System											1								
22	Wheels													1	1	1				
23	Braking-system											1				1				
24	Power Control Electronics/Inverter												1				1			
25	Plug w/ Charging device																	1		
26	Additional Electric Accessories Load																		1	
27	Mechanical Accessories Load																			1

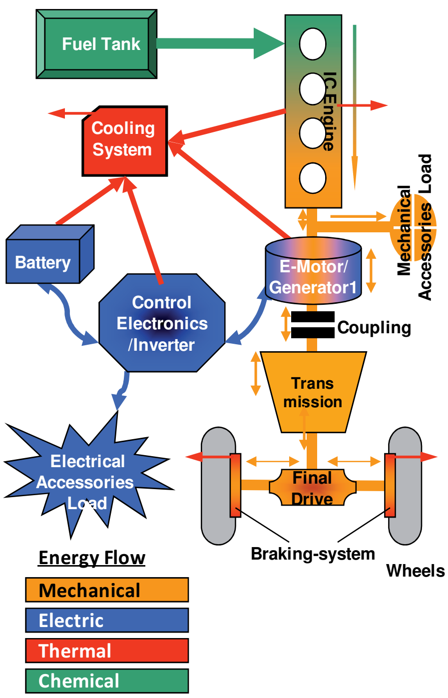
Figure 5-11 Generic DMM resulting from turning the DMM portion of a ∑MDM built from the eight basic vehicle architectures analyzed to a binary matrix.

5.5 Calculating the Functions-Design Structure Matrix

The generic DMM created from the ∑MDM analysis facilitates the calculation of the functions-DSM for any vehicle architecture. The requirement for this calculation is having a particular vehicle architecture's components-DSM structure available according to the relationship presented in section 5.1.4 and equation 22 below (F-C refers to Functions to Components DMM).

$$Functions\ DSM = (F\text{-}C\ DMM)^T \times (Components\ DSM) \times (F\text{-}C\ DMM) \qquad (22)$$

Using equation 22, all eight MDMs were constructed a second time by computation. The advantage of computing the functions-DSM is that it follows mathematical logic with no room for manual input errors. As an example, we take a simplified representation of a mild hybrid (Integrated Starter Generator) architecture for which an MDM analysis is to be computed. The schematic conceptual sketch along with the respective components DSM showing basic component physical connections is shown in Figure 5-12.



Components DSM

		1	2	4	5	11	13	18	21	22	23	24	26	27
		Fuel Tank	High Voltage Battery	Internal Combustion Engine	E-Motor/Generator1	Transmission	Final Drive	Clutch Direct Coupling1	Cooling System	Wheels	Braking-system	Power Control Electronics/Inverter	Additional Electric Accessories Load	Mechanical Accessories Load
1	Fuel Tank			1										
2	High Voltage Battery								1			1		
4	Internal Combustion Engine	1			1				1					1
5	E-Motor/Generator1			1				1	1			1		
11	Transmission						1	1						
13	Final Drive					1				1				
18	Clutch Direct Coupling1				1	1								
21	Cooling System		1	1	1							1		
22	Wheels						1				1			
23	Braking-system									1				
24	Power Control Electronics/Inverter		1		1				1				1	
26	Additional Electric Accessories Load											1		
27	Mechanical Accessories Load			1										

Figure 5-12 Components DSM and schematic representation of a mild hybrid – integrated starter generator (ISG) architecture. The components-DSM shown is reduced to show only the components fields used. A 27 x 27 components-DSM is used to match the generic DMM with zero values for components systems not used according to figure 5-11for purposes of calculation. The schematic representation on the left shows physical connection of components and color coded energy flows with directional and bi-directional functional dependencies referenced later when building the functions DSM.

The components-DSM is simple to build in a workshop environment by basing connections consistent with the schematic representation. The component indexed fields match the DMM in Figure 5-11, even though not all components are necessarily used in this architecture. The schematic depiction of the architecture shows both component physical connection and energy flows. The directional energy flows were useful in determining directionality and bi-directionality of component functions in the functions-DSM during the collaboration workshop.

Using equation 22, the resulting functions-DSM can be calculated resulting in Figure 5-13. A cursory look will suffice in identifying that the calculated functions DSM is symmetric and lacks the "input and output logic" discussed earlier in section 5.1.1, Figure 5-2.

	Calculated Functions-DSM	1 Store Fuel	2 Store Electric Energy	3 Convert Fuel into Mechanical Energy	4 Convert Mechanical into Electrical Energy	5 Convert Electrical into Mechanical Energy	6 Deliver (Recover) torque to (from) wheels	7 Convert Moment tranfered (mechanical)	8 Equate Rotational Speed	10 Couple/Uncouple Moment	11 Release Heat to the Environment	12 Transfer Heat (to Cooling system)	13 Transfer Moment to (from) the road	14 Slow or Stop Vehicle (recovering energy)	15 Slow or Stop Vehicle (releasing Energy - by Friction)	16 Control Energy Flow	18 Consume Electric Energy for Auto Accesory OPS	19 Consume Mechanical Energy for Engine Accesory
1	Store Fuel		0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
2	Store Electric Energy	0		0	0	0	0	0	0	0	1	1	0	0	0	1	0	0
3	Convert Fuel into Mechanical Energy	1	0		1	1	0	0	0	0	1	1	0	1	0	0	0	1
4	Convert Mechanical into Electrical Energy	0	0	1		0	0	0	0	1	1	1	0	0	0	1	0	0
5	Convert Electrical into Mechanical Energy	0	0	1	0		0	0	0	1	1	1	0	0	0	1	0	0
6	Deliver (Recover) torque to (from) wheels	0	0	0	0	0		1	0	0	0	0	1	1	1	0	0	0
7	Convert Moment tranfered (mechanical)	0	0	0	0	0	1		1	1	0	0	1	1	1	0	0	0
8	Equate Rotational Speed	0	0	0	0	0	0	1		0	0	0	1	1	1	0	0	0
10	Couple/Uncouple Moment	0	0	0	1	1	0	1	0		0	1	0	1	0	0	0	0
11	Release Heat to the Environment	0	1	1	1	1	0	0	0	0		1	1	1	1	1	0	0
12	Transfer Heat (to Cooling system)	1	1	1	1	1	0	0	0	1	1		0	1	0	1	1	1
13	Transfer Moment to (from) the road	0	0	0	0	0	1	1	1	0	1	0		0	1	0	0	0
14	Slow or Stop Vehicle (recovering energy)	0	0	1	0	0	1	1	1	1	1	1	0		1	1	0	0
15	Slow or Stop Vehicle (releasing Energy - by Friction)	0	0	0	0	0	1	1	1	0	1	0	1	1		0	0	0
16	Control Energy Flow	0	1	0	1	1	0	0	0	0	1	1	0	1	0		1	0
18	Consume Electric Energy for Auto Accesory OPS	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1		0
19	Consume Mechanical Energy for Engine Accesory	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	

Figure 5-13 Calculated Functions-DSM using equation 22. The calculated matrix is symmetric given that the components-DSM used to calculate it is also symmetric.

Image multiplication templating - To incorporate "the input and output logic" to the calculated Functions-DSM, a generic logic template for the functions-DSM was built showing directionality rules for functional relationships. This template presented in Figure 5-14 is constructed from the ∑functions-DSM portion of the resulting ∑MDM matrix.

Functions across all eight architectures were considered for their directional and bi-directional behavior in each of the manually built MDMs. The functions portion of the ∑MDM helped determine where functions with directional behavior were found. With this information the construction of a generic template within the workshop was straight forward and passed an afternoon session revision with eight subject matter experts.

Figure 5-14 shows the generic template applied to the symmetric calculated functions-DSM of a mild hybrid ISG. The green fields of the matrix are fields where edges are allowed, whereas the gray fields do not allow edges to be considered thus eliminating inconsistent bi-directionality and indirect relationships.

Calculated Functions-DSM	1 Store Fuel	2 Store Electric Energy	3 Convert Fuel into Mechanical Energy	4 Convert Mechanical into Electrical Energy	5 Convert Electrical into Mechanical Energy	6 Deliver (Recover) torque to (from) wheels	7 Convert Moment tranfered (mechanical)	8 Equate Rotational Speed	10 Couple/Uncouple Moment	11 Release Heat to the Environment	12 Transfer Heat (to Cooling system)	13 Transfer Moment to (from) the road	14 Slow or Stop Vehicle (recovering energy)	15 Slow or Stop Vehicle (releasing Energy - by Friction)	16 Control Energy Flow	18 Consume Electric Energy for Auto Accesory OPS	19 Consume Mechanical Energy for Engine Accesory
1 Store Fuel		0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
2 Store Electric Energy	0		0	0	0	0	0	0	0	1	1	0	0	0	1	0	0
3 Convert Fuel into Mechanical Energy	1	0		1	1	0	0	0	0	1	1	0	1	0	0	0	1
4 Convert Mechanical into Electrical Energy	0	0	1		0	0	0	0	1	1	1	0	0	0	1	0	0
5 Convert Electrical into Mechanical Energy	0	0	1	0		0	0	0	1	1	1	0	0	0	1	0	0
6 Deliver (Recover) torque to (from) wheels	0	0	0	0	0		1	0	0	0	0	1	1	1	0	0	0
7 Convert Moment tranfered (mechanical)	0	0	0	0	0	1		1	1	0	0	1	1	1	0	0	0
8 Equate Rotational Speed	0	0	0	0	0	0	1		0	0	0	1	1	1	0	0	0
10 Couple/Uncouple Moment	0	0	0	1	1	0	1	0		0	1	0	1	0	0	0	0
11 Release Heat to the Environment	0	1	1	1	1	0	0	0	0		1	1	1	1	1	0	0
12 Transfer Heat (to Cooling system)	1	1	1	1	1	0	0	0	1	1		0	1	0	1	1	1
13 Transfer Moment to (from) the road	0	0	0	0	0	1	1	1	0	1	0		0	1	0	0	0
14 Slow or Stop Vehicle (recovering energy)	0	0	1	0	0	1	1	1	1	1	1	0		1	1	0	0
15 Slow or Stop Vehicle (releasing Energy - by Friction)	0	0	0	0	0	1	1	1	0	1	0	1	1		0	0	0
16 Control Energy Flow	0	1	0	1	1	0	0	0	0	1	1	0	1	0		1	0
18 Consume Electric Energy for Auto Accesory OPS	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1		0
19 Consume Mechanical Energy for Engine Accesory	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	

Figure 5-14 A generic template to distinguish directional and bi-directional dependencies is applied to the calculated functions DSM for the mild hybrid ISG architecture. The values allowed are seen on the green fields. The resulting matrix is equivalent to image multiplication of matrix elements.

The use of the template requires image multiplication. If we let the green fields of the template take on values of one, and zero in the grayed-out fields in an nxn matrix called A and let our calculated functions-DSM be matrix B; then the resulting elements of matrix C using image multiplication can be described as:

$$C_{ij} = A_{ij} \; x \; B_{ij} \qquad (23)$$

In MATLAB, the function *immultiply (A,B)* follows the multiplication of matrix elements by fields as in equation 23 [LEONARD et al. 1995, p.19]. The complete collection of the MDMs calculated for the eight representative vehicle architectures in this chapter are presented in section 9.3 of the appendix.

Cluster Analysis of the Functions-DSM - Once the functions-DSM is calculated and image multiplied with the generic functional template, the resulting non-symmetric functions-DSM can be clustered to explore higher order vehicle functions. Clustering consists of reorganizing the DSM's rows and columns with the objective of detecting matrix modules that posses many internal dependencies between nodes and as few dependencies as possible from external nodes outside the module structure [MAURER 2007, p.227, EPPINGER et al. 1994, BROWNING 2001, KUSIAK 2000, p.294].

Clustering Analysis of Calculated Functions-DSM

		4 Convert Mechanical into Electrical Energy	14 Slow or Stop Vehicle (recovering energy)	16 Control Energy Flow	2 Store Electric Energy	5 Convert Electrical into Mechanical Energy	10 Couple/Uncouple Moment	8 Equate Rotational Speed	13 Transfer Moment to (from) the road	6 Deliver (Recover) torque to (from) wheels	7 Convert Moment tranfered (mechanical)	15 Slow or Stop Vehicle (releasing Energy - by Friction)	1 Store Fuel	3 Convert Fuel into Mechanical Energy	12 Transfer Heat (to Cooling system)	18 Consume Electric Energy for Auto Accesory OPS	19 Consume Mechanical Energy for Engine Accesory	11 Release Heat to the Environment
4	Convert Mechanical into Electrical Energy	■		1											1			
14	Slow or Stop Vehicle (recovering energy)		■	1														
16	Control Energy Flow	1	1	■	1	1									1	1		
2	Store Electric Energy			1	■										1			
5	Convert Electrical into Mechanical Energy			1		■	1							1	1			
10	Couple/Uncouple Moment	1	1				■				1							
8	Equate Rotational Speed		1					■	1		1							
13	Transfer Moment to (from) the road							1	■	1	1	1						
6	Deliver (Recover) torque to (from) wheels		1						1	■	1	1						
7	Convert Moment tranfered (mechanical)		1				1	1	1	1	■							
15	Slow or Stop Vehicle (releasing Energy - by Friction)								1	1		■						1
1	Store Fuel												■	1	1			
3	Convert Fuel into Mechanical Energy	1												■	1		1	
12	Transfer Heat (to Cooling system)														■			1
18	Consume Electric Energy for Auto Accesory OPS															■		
19	Consume Mechanical Energy for Engine Accesory																■	
11	Release Heat to the Environment																	■

Regenerative Braking

Electric Propultion and Boost

Powertrain Operating Functions

Combustion Energy Creation

Figure 5-15 Cluster analysis of calculated Functions-DSM for a mild hybrid –ISG architecture showing higher order vehicle functions made from sub-component functional modules. In this figure green fields show bi-directional relationships, whereas blue fields are directional relationships.

The clustering of the calculated functions-DSM for the mild hybrid - ISG architecture is shown in Figure 5-15 identifying four modules of functions: regenerative braking, electric propulsion/boosting, powertrain operation and combustion propulsion energy creation. The clustered modules allow for a higher order visualization of modules co-existing inside the vehicle architecture.

5.6 Compatibility Matrix Methodology for Vehicle Architecture Synthesis

In this section, a methodology is presented for the selection of vehicle architecture configurations and dimensioning requirements that builds upon the knowledge gained from the previous MDM analysis. The ideas stem from DSM research work for early architecture concept selection presented by Deubzer et al. 2008 and further refined by Hellenbrand et al. 2008 at the TUM Institute for Product Development. Hellenbrand demonstrates the original idea of the compatibility-DSM used to identify partial design solutions that is used to identify a set of “valid” overall concept combinations of partial solutions.

The compatibility DSM is referred to here as a *compatibility matrix*. This matrix is the inverse of a “consistency matrix” as presented by Pahl and Beitz [PAHL et al. 2006]. The two differ in that the consistency matrix shows which partial solutions of a morphological solution tree are not consistent, whereas the compatibility matrix displays which partial solutions are compatible.

At the conclusion of this section, a solution space of HEV and battery electric vehicle architecture structures is presented. The generated solution space allows system architects to consider many architectural innovations and their impact to the requirements. Single vehicle architectures within this space can be further examined using architecture MDMs as shown in sections 5.3 and 5.4.

It is important to note that the compatibility matrix methodology applies to any choice selection set to include multiple design areas. For the purposes of this study the architecture structure domain and the system requirements domain are the only domains used as examples for demonstrating the compatibility matrix methodology. Other domains can me further linked using a similar procedure to the one presented in the following sections.

5.6.1 Morphological Concept Selection of Consistent Structures

Zwicky demonstrated that a morphological matrix can be used to identify solution concepts available from partial functions in a design [ZWICKY 1966]. The compatibility of the many partial solutions identified in a morphological matrix can be further analyzed using tree structures or a consistency matrix [LINDEMANN, UDO 2007, p.79]. In considering consistent configurations of HEV component subsystems, the latter has proven to be a more useful tool as the number of partial solutions is large and handled easier in a matrix. A four step process for the selection of consistent architectures is presented below.

Step 1: Determine selection choices and possible partial solutions choices

Step 2: Determine which partial solutions are compatible using a compatibility matrix

Step 3: Identify consistent partial solution sets

Step 4: Select consistent partial solutions sets for further analysis

Figure 5-16 shows the four step model in a conceptual description. In step one, four design selection choices are presented (A thru D) as column headers with the possible partial solution choices listed for each selection similar to a morphological matrix. Because not all combinations of partial solutions are consistent, a compatibility matrix (or consistency matrix) shows which combinations of solutions are compatible by filling in the matrix elements with numbers from 0-1, as shown in step 2.

A value of "1" is awarded to partial solutions that are completely compatible whereas a "0" or blank entry shows that the two partial solutions are incompatible. Values that are closer to "1" denote higher compatibility based on the judgment of the design team. In filling out the compatibility matrix, developers only fill the upper triangular half, as it is sufficient to examine all combination pairs of partial solutions.

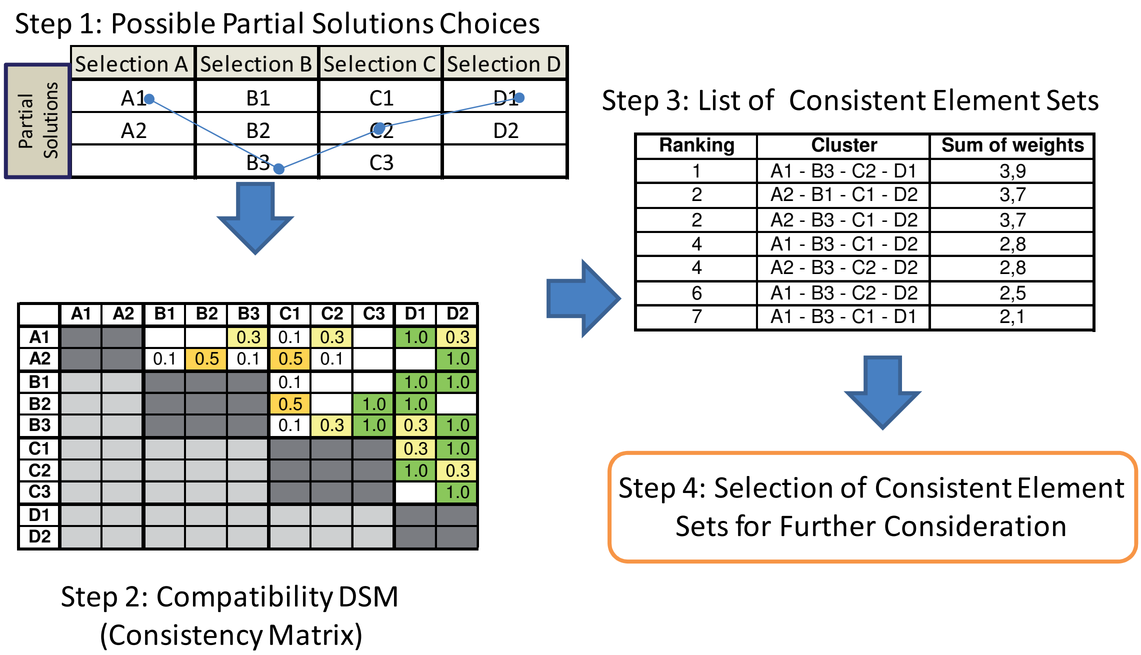


Figure 5-16 The procedure presented above can help map a consistent design space by revealing which choices within the possible selection elements can be combined. The procedure can be used in linking physical components as well a choice set of design requirement parameters. [Hellenbrand et al. 2008]

In step 3, algorithms created to find DSM completely interlinked clusters are used to list all consistent selections, given that at least one partial solution item must be selected from each selection field [LINDEMANN, U. et al. 2008, p.90]. The resulting list includes only valid element clusters that can be successfully combined. HELLENBRAND et al. 2008 shows that the selection process in step 4 can be aided by summing the compatibility values assigned for consistent partial solution sets (or completely interlinked clusters). Those sets with a higher sum are presumably more compatible and can be ranked at the top of the list for consideration. However, when many compatible sets are available with similar compatibility scores, other decision criteria and decision methodologies must be considered.

5.6.2 Methodology Applied to Hybrid Vehicle Architecture Structures

The compatibility matrix methodology is applied to HEV architectures with the goal of exploring possible HEV configurations. The configuration tool allows developers to explore many possible combinations of car concepts[17]. The methodology is detailed below based on the steps outlined in the previous section.

Step 1: Determine concept selection choices and possible partial solutions – Following a week long workshop with industry experts, nine concept selection choices were identified as necessary to generate a generic HEV architecture concept depiction. These selection choices follow a logical order starting at an abstract choice level, working down to specific architecture selections on key component configurations for the engine, electric motors and the high voltage battery.

Table 5-3 "Abstract to specific" architecture selection criteria for electric powertrain vehicles

1. Concept	2. Architecture	3. Engine Placement	4. Engine Orientation	5. Engine Transmission	6. Engine E-Motor	7. Engine Axle
Micro Hybrid	Through-the-Road	Front, 4WD	Parallel to axle	Manual	Pre-Transmission	Axle E-Motor
Mild Hybrid	Parallel	Front, RWD	Perpendicular to axle	Automatic	Starter-Generator	2 Wheel E-Motors
Full Hybrid	P-Split	Front, FWD	No Engine	CVT/ECVT	No Engine	No E-Motors
PHEV	Combined	Rear, 4WD		No Transmission		
BEV	Series	Rear, RWD				
	BEV	No Engine				

8. Other Axle	9. HV Battery Placement
Axle E-Motor	Sandwich
2 Wheel E-Motors	Drive Axle
No E-Motors	Other Axle
	Tunnel
	No HV Battery

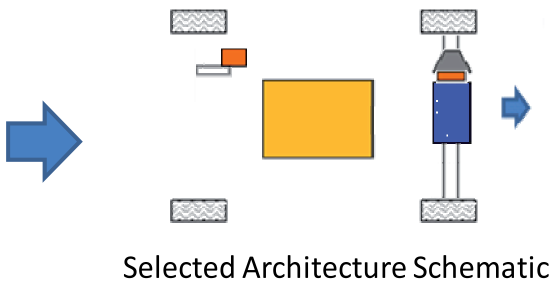


Table 5-3 shows the nine architecture selection choices and the selection order. Developers select one partial solution in each column category to lock-in an HEV/BEV architecture structure in drop down menu manner. Based on the selection choices a schematic

[17] In this study, all electric powertrain architectures spanning from micro hybrids on through battery electric vehicles are included.

depiction of the architecture structure is generated automatically with assistance of a computer program.

It was particularly important to have the team define how detailed the necessary concepts needed to be. In this case, developers were in the early design stages and wanted to open an architecture solution space that did not specify more than the placement of the key component subsystems. This facilitated the reduction of the number of selections to a manageable set of 9 selections and a total of 38 possible choice elements. The names of the selection choices were assigned particular meaning after productive discussion sessions by the team of developers. For example, clear definitions were assigned to what makes a "micro hybrid" different from a "mild" or "full" hybrid. These definitions were tied to system functional requirements.

Step 2: Determine which partial solutions are compatible using a compatibility matrix – Figure 5-17 shows the team workshop results of a symmetric compatibility matrix resulting from the architecture selection criteria. Only the upper triangular of the matrix must be filled out, as links below the diagonal mirror the information on the upper diagonal. A weighting scheme was utilized to determine the degree of compatibility between choice pairs (1 = compatible, 0.5 = compatible but less practical, 0.1 = compatible but impractical, 0 = incompatible). The compatibility of selection pairs was done merely considering structural aspects of the design with no regards to dimensioning of components.

	Concept					Architecture						Engine Placement						Engine Orientatio			Engine Transmission				Engine E-Motor			Engine Axle			Other Axle			HV Battery Placement				
	Micro Hybrid	Mild Hybrid	Full Hybrid	PHEV	BEV	Through-the-Road	Parallel	P-Split	Combined	Series	BEV	Front, 4WD	Front, RWD	Front, FWD	Rear, 4WD	Rear, RWD	No Engine	Parallel to axle	Perpendicular to axle	No Engine	Manual	Automatic	CVT/ECVT	No Transmission	Pre-Transmission	Starter-Generator	No Engine	Axle E-Motor	2 Wheel E-Motors	No E-Motors	Axle E-Motor	2 Wheel E-Motors	No E-Motors	Sandwich	Drive Axle	Other Axle	Tunnel	No HV Battery
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
1	1	0	0	0	0	0	1	0	0	0	0	1	1	1	1	1	0	1	1	0	1	1	1	1	0	1	0	0	0	1	0	0	1	0	0	0	0	1
2	0	1	0	0	0	0	1	0	0	0	0	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	0	0	0	1	0	0	1	1	1	1	1	0
3	0	0	1	0	0	1	1	1	0.5	0.5	0	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0
4	0	0	0	1	0	0.1	0.1	0.1	1	1	0	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0
5	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	1	1	1	0	1	1	1	1	1	1	1	0
6	0	0	1	0.1	0	1	0	0	0	0	0	0	0	1	0	1	0	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	0	1	1	1	1	1
7	1	1	1	0.1	0	0	1	0	0	0	0	1	1	1	1	1	0	1	1	0	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1
8	0	0	1	0.1	0	0	0	1	0	0	0	1	1	1	1	1	0	1	1	0	0	0	1	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1
9	0	0	0.5	1	0	0	0	0	1	0	0	0.1	0.1	1	0.1	1	0	1	1	0	0	0.1	0.1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
10	0	0	0.5	1	0	0	0	0	0	1	0	1	1	1	1	1	0	1	1	0	0	0.1	0.1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
11	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0.1	0.1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	0	0	1	1	0.1	1	0	1	0	0	0	0	0	1	1	0	1	1	1	0	1	1	0	1	1	1	1	1	1	0.5	0	1	0	1
13	1	1	1	1	0	0	1	1	0.1	1	0	0	1	0	0	0	0	0	1	0	1	1	1	0	1	1	0	1	1	1	1	1	1	0.5	0	1	0	1
14	1	1	1	1	0	1	1	1	1	1	0	0	0	1	0	0	0	1	1	0	1	1	1	0	1	1	0	1	1	1	1	1	1	1	0	1	1	1
15	1	1	1	1	0	0	1	1	0.1	1	0	0	0	0	1	0	0	1	1	0	1	1	1	0	1	1	0	1	1	1	1	1	1	0.5	0	1	1	1
16	1	1	1	1	0	1	1	1	1	1	0	0	0	0	0	1	0	1	1	0	1	1	1	0	1	1	0	1	1	1	1	1	1	1	0	1	0	1
17	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0
18	1	1	1	1	0	1	1	1	1	1	0	1	0	1	1	1	0	1	0	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
19	1	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	0	0	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0.5	1
20	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0
21	1	1	1	1	0	1	1	0	0	0	0	1	1	1	1	1	0	1	1	0	1	0	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1
22	1	1	1	1	0	1	1	0	0.1	0.1	0.1	1	1	1	1	1	0	1	1	0	0	1	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1
23	1	1	1	1	0	1	1	1	0.1	0.1	0.1	1	1	1	1	1	0	1	1	0	0	0	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1
24	1	1	1	1	1	0	0	0	1	1	1	0	0	0	0	0	1	1	1	1	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1
25	0	1	1	1	0	0	1	1	1	0	0	1	1	1	1	1	0	1	1	0	1	1	1	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1
26	1	1	1	1	0	1	1	0	1	1	0	1	1	1	1	1	0	1	1	0	1	1	1	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1
27	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0
28	0	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1
29	0	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1
30	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1
31	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1
32	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1
33	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1
34	0	1	1	1	1	1	1	1	1	1	1	0.5	0.5	1	0.5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
35	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0
36	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	0
37	0	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	1	1	0.5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	0
38	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	0	0	1

Figure 5-17 Compatibility matrix for HEV/BEV architecture structures

The compatibility matrix in Figure 5-17 works similar to a decision tree. Once an item is picked in the first selection category "concept," it has a direct influence on which picks are available for the second selection category "architecture" and so on until the last selection category. Consistent solutions are those that allow for one selection for each category. Thus a total of 9 selections are necessary for a consistent architecture as depicted in Figure 5-17 showing the selection flow from the example in Table 5-3. The selection order is not important so long 9 valid selections are made.

In order to check for consistency in the selection computer tool, the compatibility matrix was utilized to power dynamic drop down menus as a tool for checking sets of choices. The dynamic drop down menus clearly shows what tree branches are available based on the previous branch's selection. The meanings of the structural selection fields are briefly discussed below.

- **Concept** – This selection refers to classification for HEVs that are assigned based on functionality of the electric powertrains as defined by the team of experts in the workshop.
- **Architecture** – This selection categorizes a basic fundamental powertrain structure according to specific definitions relevant to the field of HEV/BEV architecting.
- **Engine Placement** – This selection specifies the general engine placement in the front or rear of the vehicle (only 2 axles and four wheels are assumed) and the drive type (Rear Wheel Drive, Front Wheel Drive or Four Wheel Drive).
- **Engine Orientation** – This selection specifies whether the engine is placed parallel or perpendicular to the axle it rests on.
- **Engine Transmission** – Basic selection of transmission type: manual, automatic, or current variable transmission/electric current variable transmission (CVT/ECVT)
- **Engine E-Motor** – This selection field specifies whether there is an electric motor integrated placement within the engine module, between the engine and transmission or as a starter generator module.
- **Engine Axle** – This selection field specifies the placement of an electric motor within the axle where the engine is located.
- **Other Axle** – This field specifies the placement of an electric motor within the axle opposite from where the internal combustion engine is placed.
- **High Voltage (HV) Battery Placement** – This field specifies the placement location of a high voltage battery (only one HV battery system is assumed).

Step 3: Analyze consistent partial solutions – Computer program tools such as Loomeo® and Microsoft Excel® were used to analyze and list the set of consistent partial solutions. Out of 291,600 (5x6x6x3x4x3x3x3x5) possible solution choice sets only 5,451 solutions exhibit compatible architecture concepts. This finding shows that less than 2% of all possible combinations generate a valid HEV architecture structural concept. There are literally thousands of ways to build a hybrid/electric car!

Step 4: Select consistent partial solutions for further analysis – With such a large number of possible hybrid architectures it is clear that the HEV market today still has a number of architectural innovations waiting to come to market. The best architectures are the ones that meet the design requirements brought by the customer, legal requirements, safety, costs and many other considerations. Linking the right product architecture to the requirement set requires decision making methodologies. Examples include trade space analysis or decision matrices.

5.6.3 Compatibility Matrix Applied to Dimensioning Requirements

As stated previously, the compatibility matrix methodology can be applied to any choice selection set. In this section, the methodology is applied to dimensioning requirements relevant to HEV design.

Figure 5-18 shows the resulting compatibility matrix for requirements generated in step 2 of the methodology. The presence of many zero cells, show that the requirement dimensioning choices are more restrictive than the previous structural considerations.

In the example, requirements were selected that could help designers size the electric powertrain system components. These dimensioning requirement parameters include:

- **Electrification index** – A measure of the size of the electric propulsion system. The index is defined as the ratio of peak electric power available to the total power (P_{el}/P_{total}) and is equivalent to the "degree of electrification" metric presented in equation 18 in p.108. A low electrification index number represents car architectures with small electric motors that are used with large internal combustion engine systems, whereas an electrification index value of "1" represents a pure battery electric vehicle with no internal combustion engine.
- **All Electric Range** – This is a dimensioning requirement that defines the all electric range of the car (in miles) without use of an ICE.
- **Power to Energy ratio (kW/kWh)** – The power to energy ratio helps determine the battery chemistry and structure required for the design of the HEV or BEV. Low P/E ratios of 1-5 are characteristic of plug-in HEVs and BEVs whereas high P/E ratios of 20+ are common in hybrids with small electric systems.
- **% Battery Depth of Discharge (% DOD)** – This parameter is important for HEV architecture concept work with battery control strategies. Batteries with small %DOD are found in smaller electric systems and result in longer battery life. Large %DOD is characteristic of electric powertrains designed for large all electric range such as plug in HEVs and BEVs.

			Electrification Index Range (P el / P tot)					All Electric Range (AER) in miles								Power/Energy Ratio (kW/kWh)					% DOD				
			0 - 0.05	0.05 - 0.15	0.2 - 0.3	0.3 - 0.8	0.8-1	0 - 0.5	0.5 - 2	2 - 10	10 - 20	20 - 30	30 - 40	40 - 50	> 50	1 - 5	5 - 10	10 - 20	20 - 30	> 30	10 - 15%	15 - 30%	30 - 50%	50 - 70%	> 70%
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Electrification Index Range (P el / P tot)	0 - 0.05	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0
	0.05 - 0.15	2	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	0	1	1	1	0	0
	0.2 - 0.3	3	0	0	1	0	0	0	1	1	0	0	0	0	0	0	1	1	1	0	1	1	1	0	0
	0.3 - 0.8	4	0	0	0	1	0	0	0	1	1	1	1	0	0	1	1	1	0	0	0	0	1	1	1
	0.8-1	5	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	1	1
All Electric Range (AER) in miles	0 - 0.5	6	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0
	0.5 - 2	7	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	1	1	1	0	0
	2 - 10	8	0	0	1	1	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1
	10 - 20	9	0	0	0	1	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	1	1	1
	20 - 30	10	0	0	0	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	1	1
	30 - 40	11	0	0	0	1	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	1	1
	40 - 50	12	0	0	0	0	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	1
	> 50	13	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	1
Power/Energy Ratio (kW/kWh)	1 - 5	14	0	0	0	1	1	0	0	0	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1
	5 - 10	15	0	0	1	1	1	0	0	1	1	1	1	0	0	0	1	0	0	0	1	1	1	1	1
	10 - 20	16	0	1	1	1	0	0	1	1	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1
	20 - 30	17	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1
	> 30	18	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
% DOD	10 - 15%	19	1	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0
	15 - 30%	20	1	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	0	1	0	0	0
	30 - 50%	21	1	1	1	1	0	1	1	1	1	0	0	0	0	1	1	1	1	1	0	0	1	0	0
	50 - 70%	22	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	0
	> 70%	23	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1

Figure 5-18 Compatibility matrix of electrification system requirement parameters

The compatibility matrix analysis (step 3) of the dimensioning requirements yields 41 compatible combinations out of a possible 1000 (5x8x5x5) selection choice sets. This represents only 4.1% consistency. Having examined structural solutions in section 3.2 and now dimensioning requirements in section 3.3, it is of little value to maintain the information analyzed in separate domains. The question arises, how can various choice element selection sets be combined or linked to complement each other?

5.6.4 Linking Vehicle Architecture Structures with Requirements

In order to link two or more choice sets, a combination matrix with both selection elements can be created by incorporating sub selection elements in the consistency matrix as shown in Figure 5-19. A so called “branch and cut” algorithm [BIEDERMANN et al. 2008] can further be used to determine consistency amongst both elements and sub elements of the matrix. However, the increased number of fields and computations make this approach impractical.

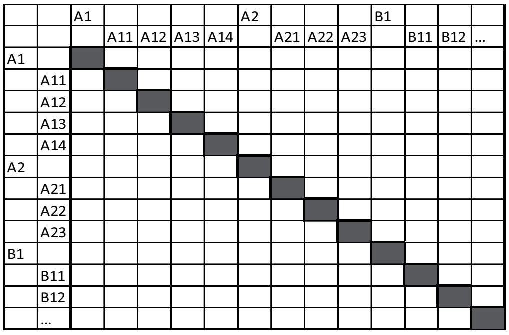


Figure 5-19 An impractical alternative to linking two sets of selection criteria In a consistency DSM by creating sub-selection elements fields

A more practical solution is to create a shared selection field amongst both choice sets as depicted in Figure 5-20. Building on the previous HEV/BEV architecture example, the structural selection choices and the system requirements selection fields are joined through a linking choice set.

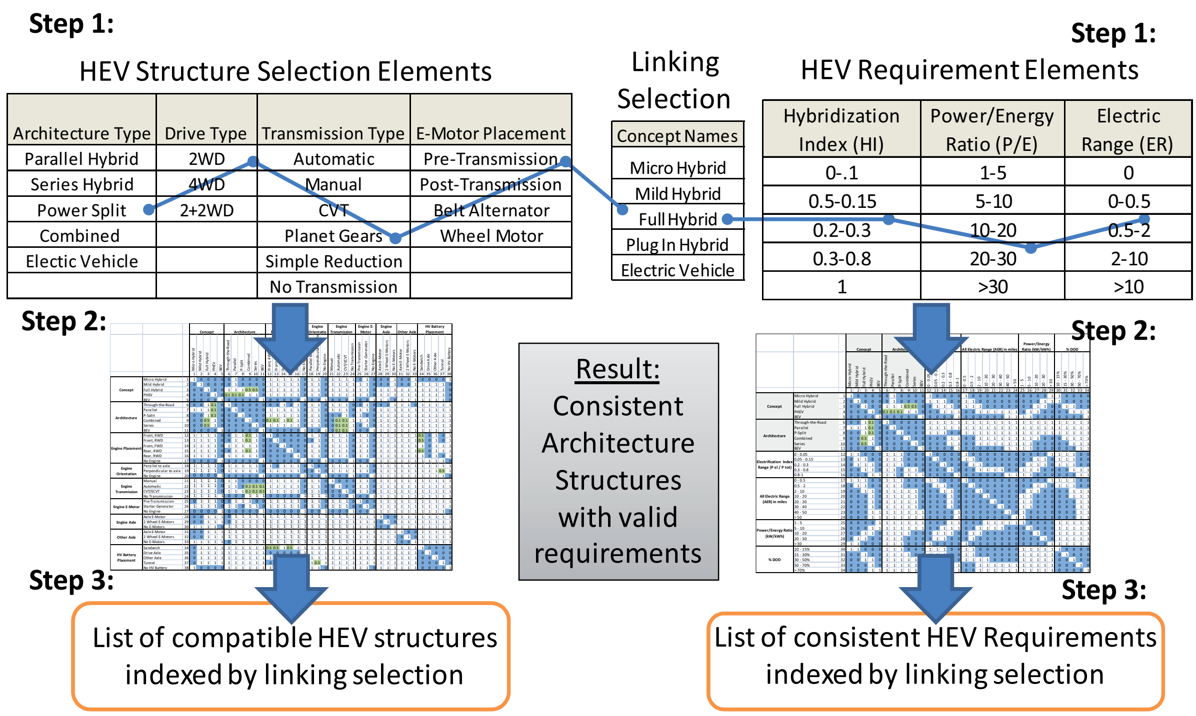


Figure 5-20 By creating one or more linking selections used in both the "HEV requirements" and "structure" selection elements, the system architect can generate a solution space of valid architectures compatible in both domains.

Figure 5-20 designates the selection field "*concept names*" as the selection element that can be found in both the "*requirements*" and "*structural*" selection sets. By selecting one field in each category of the "HEV structure selection elements" (Figure 5-20, top left), there is enough information to generate a detailed architecture component structure. Similarly, a simplified set of "HEV requirement elements" that affect HEV designs are analyzed for consistency (Figure 5-20, top right).

5.6.5 Introduction of a Linking Selection

The first three steps of the compatibility matrix methodology where applied to both the "structural" and "requirements" data sets again using two "linking selections," namely the selection fields "concept" and "architecture" were added to the "requirements" data. Figure 5-21 shows the new compatibility matrix used for the requirements data set incorporating the new linking selection fields. The incorporation of the linking fields allows developers to consider what functional requirement meanings should be linked to the various concept and architecture categories.

			Concept					Architecture						Electrification Index Range (P el / P tot)					All Electric Range (AER) in miles								Power/Energy Ratio (kW/kWh)					% DOD				
			Micro Hybrid	Mild Hybrid	Full Hybrid	PHEV	BEV	Through-the-Road	Parallel	P-Split	Combined	Series	BEV	0 - 0.05	0.05 - 0.15	0.2 - 0.3	0.3 - 0.8	0.8-1	0 - 0.5	0.5 - 2	2 - 10	10 - 20	20 - 30	30 - 40	40 - 50	> 50	1 - 5	5 - 10	10 - 20	20 - 30	> 30	10 - 15%	15 - 30%	30 - 50%	50 - 70%	> 70%
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
Concept	Micro Hybrid	1	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
	Mild Hybrid	2	0	1	0	0	0	0	1	0	0	0	0	1	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
	Full Hybrid	3	0	0	1	0	0	1	1	1	0.5	0.5	0	0	1	1	1	0	1	1	1	0	0	0	0	0	0	0	1	1	0	0	1	1	0	0
	PHEV	4	0	0	0	1	0	0.1	0.1	0.1	1	1	0	0	0	1	1	1	0	0	1	1	1	1	1	1	0	1	1	0	0	0	0	1	1	1
	BEV	5	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	1
Architecture	Through-the-Road	6	0	0	1	0.1	0	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Parallel	7	1	1	1	0.1	0	0	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	P-Split	8	0	0	1	0.1	0	0	0	1	0	0	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Combined	9	0	0	0.5	1	0	0	0	0	1	0	0	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1
	Series	10	0	0	0.5	1	0	0	0	0	0	1	0	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1
	BEV	11	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	1	1
Electrification Index Range (P el / P tot)	0 - 0.05	12	1	1	0	0	0	1	1	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0
	0.05 - 0.15	13	0	1	1	0	0	1	1	1	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	0	1	1	1	0	0
	0.2 - 0.3	14	0	1	1	1	0	1	1	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	1	1	1	0	1	1	1	0	0
	0.3 - 0.8	15	0	0	1	1	0	1	1	0	1	1	0	0	0	0	1	0	0	0	1	1	1	1	0	0	1	1	1	0	0	0	0	1	1	1
	0.8-1	16	0	0	0	1	1	1	1	0	1	1	1	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	1	1
All Electric Range (AER) in miles	0 - 0.5	17	1	1	1	0	0	1	1	1	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0
	0.5 - 2	18	0	1	1	0	0	1	1	1	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	1	1	1	0	0
	2 - 10	19	0	0	1	1	0	1	1	1	1	1	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1
	10 - 20	20	0	0	0	1	0	1	1	1	1	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	1	1	1
	20 - 30	21	0	0	0	1	0	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	1	1
	30 - 40	22	0	0	0	1	0	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	1	1
	40 - 50	23	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	1
	> 50	24	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	1
Power/Energy Ratio (kW/kWh)	1 - 5	25	0	0	0	0	1	1	1	1	1	1	1	0	0	0	1	1	0	0	0	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1
	5 - 10	26	0	0	0	1	1	1	1	1	1	1	1	0	0	1	1	1	0	0	1	1	1	1	0	0	0	1	0	0	0	1	1	1	1	1
	10 - 20	27	0	0	1	1	0	1	1	1	1	0	0	0	1	1	1	0	0	1	1	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1
	20 - 30	28	0	1	1	0	0	1	1	1	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1
	> 30	29	1	1	0	0	0	1	1	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
% DOD	10 - 15%	30	1	1	0	0	0	1	1	1	0	0	0	1	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0
	15 - 30%	31	0	0	1	0	0	1	1	1	1	0	0	1	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	0	1	0	0	0
	30 - 50%	32	0	0	1	1	0	1	1	1	1	1	0	1	1	1	1	0	1	1	1	1	0	0	0	0	1	1	1	1	1	0	0	1	0	0
	50 - 70%	33	0	0	0	1	0	1	1	1	1	1	1	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	0
	> 70%	34	0	0	0	1	1	1	1	1	1	1	1	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1

Figure 5-21 Linking selections are added to the dimensioning requirements data to allow indexing with the structural architecture database.

For example a "micro hybrid" concept can only occur in a "parallel" HEV configuration with a hybridization index (P_{el}/P_{total}) of 0-.05, a minimal electric range of 0-.5 miles, a power to energy ratio above 30 and a %DOD of 10-15%. Given this information valid architecture dimensioning requirements can now be linked to the valid structural configurations for a micro hybrid.

With computational help, step 3 of the methodology provides a listing of compatible structures as well as a listing of compatible requirements. The data generated is presented in a manner that can be further sorted in a database. FFigure 5-22 shows an excerpt of all completely interlinked clusters that are valid in both data sets.

The combination of the two data sets allows developers find architectural innovations from the structural combinational set to which the set of electrification requirements apply. The requirement set is necessary in the dimensioning of key components for an electric powertrain.

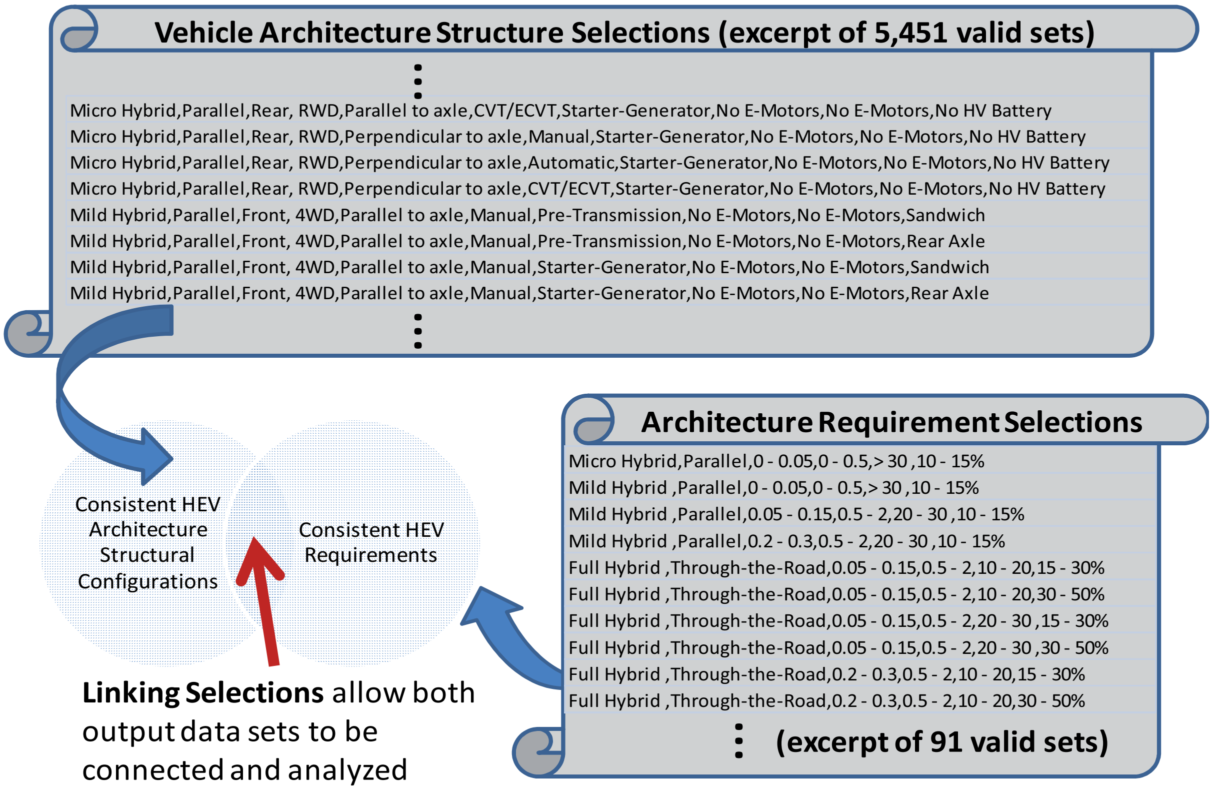


Figure 5-22 Excerpt of results for both valid architecture structure and dimensioning requirement selection choices.

Summary - The compatibility matrix methodology enables a systematic approach that can be applied in the search for consistent design choices throughout the development of a system. The four step working methodology presented in section 5.6 builds on previous published work on concept selection during the early product development stages. This includes the novel addition of a “linking selection” in order to bridge two choice domains. In the example presented, the linking selections allow system architects to explore new structural configurations of HEVs alongside important system requirement parameters.

Some limitations to this methodology lie in the linear linking of choice sets. Consistency depends on the linking of each element with its immediate left and right selections - similar to a decision tree. Linking elements in a linear manner can preclude the identification of cross links that influence the overall design outside the pair wise comparison of two elements. The “linking selections” for new domains must occur at a high level of abstraction to allow for more flexibility – for example the “concept” and “architecture” fields are abstract enough to allow themselves to be linking fields for both the architecture structures and requirements.

5.7 MDM Representation of a New Vehicle Architecture Selection

A product MDM can be constructed for each configuration selected using the compatibility matrix methodology. In this section, an MDM is built as a follow on step to the selection of a novel configuration out of the compatibility matrix.

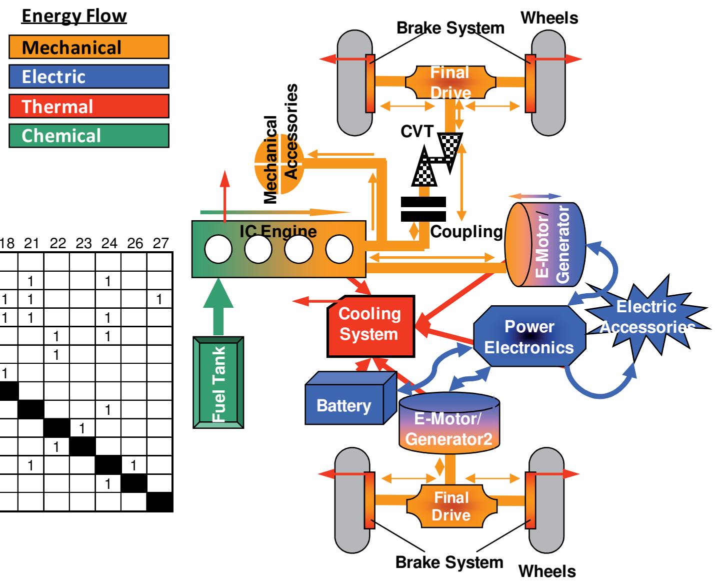
The nine choice sets of the structural compatibility matrix selection path for a "full hybrid through the road vehicle architecture with two wheel motors" is depicted in Figure 5-23 along with a detailed conceptual sketch. The selection choices were checked for validity in the compatibility matrix and a structural depiction was constructed following the selection logic.

For this particular parallel hybrid, the front axle is powered by the combustion engine, while the rear wheels are powered by wheel motors. The hybrid functions of boosting described in section 4.2.2 is facilitated through the road connection between the front and the rear wheels.

A symmetric components-DSM showing physical component dependencies is constructed based on the depicted elements of the conceptual diagram. Once the components-DSM is available, an architecture-MDM can be calculated using equation 22 in section 5.5. Image multiplication templating is then applied to facilitate the conversion of the symmetric calculated functions-DSM into a DSM showing input and output directionality of functions based on energy flows shown in the schematic.

1. Concept	2. Architecture	3. Engine Placement	4. Engine Orientation	5. Engine Transmission	6. Engine E-Motor	7. Engine Axle
Micro Hybrid	Through-the-Road	Front, 4WD	Parallel to axle	Manual	Pre-Transmission	Axle E-Motor
Mild Hybrid	Parallel	Front, RWD	Perpendicular to axle	Automatic	Starter-Generator	2 Wheel E-Motors
Full Hybrid	P-Split	Front, FWD	No Engine	CVT/ECVT	No Engine	No E-Motors
PHEV	Combined	Rear, 4WD		No Transmission		
BEV	Series	Rear, RWD				
	BEV	No Engine				

8. Other Axle	9. HV Battery Placement
Axle E-Motor	Sandwich
2 Wheel E-Motors	Drive Axle
No E-Motors	Other Axle
	Tunnel
	No HV Battery



	Components-DSM	1	2	4	5	8	13	17	18	21	22	23	24	26	27
1	Fuel Tank			1											
2	High Voltage Battery									1			1		
4	Internal Combustion Engine	1			1				1	1					1
5	E-Motor/Generator1			1					1	1			1		
8	Wheel E-Motor										1		1		
13	Final Drive							1			1				
17	CVT						1		1						
18	Clutch Direct Coupling1			1				1							
21	Cooling System		1	1	1								1		
22	Wheels					1	1					1			
23	Braking-system										1				
24	Power Control Electronics/Inverter		1		1	1				1				1	
26	Additional Electric Accessories Load												1		
27	Mechanical Accessories Load			1											

Figure 5-23 Choice selection path for a "full hybrid through the road" architecture along with schematic showing energy flows and a components-DSM depicting physical connections dependencies

The resulting architecture-MDM is depicted in Figure 5-24, including the components-DSM (center right), the Functions-Components-DMM (center left) and the functions-DSM (top right). The functions-DSM is further clustered as shown in the bottom of the figure.

The clustering in the functions-DSM shows the important role the contact between the wheels and the road have in this architecture. The overall vehicle functions of *electric driving*, *boosting* and *regenerative braking* modules are connected to the *IC engine driving* module by the sub-function number 13 "*transfer moment to and from the road*." This dependency is not seen directly in the schematic depiction in Figure 5-23 since the boundaries for the graphic do not include the road surface. However, the function "*transfer moment to and from the road*" is an important transitional node essential to this architecture.

This short example combines the MDM structural matrix analysis and the compatibility matrix configuration methodology. The same steps can be performed for any vehicle architecture structure within the compatibility matrix space.

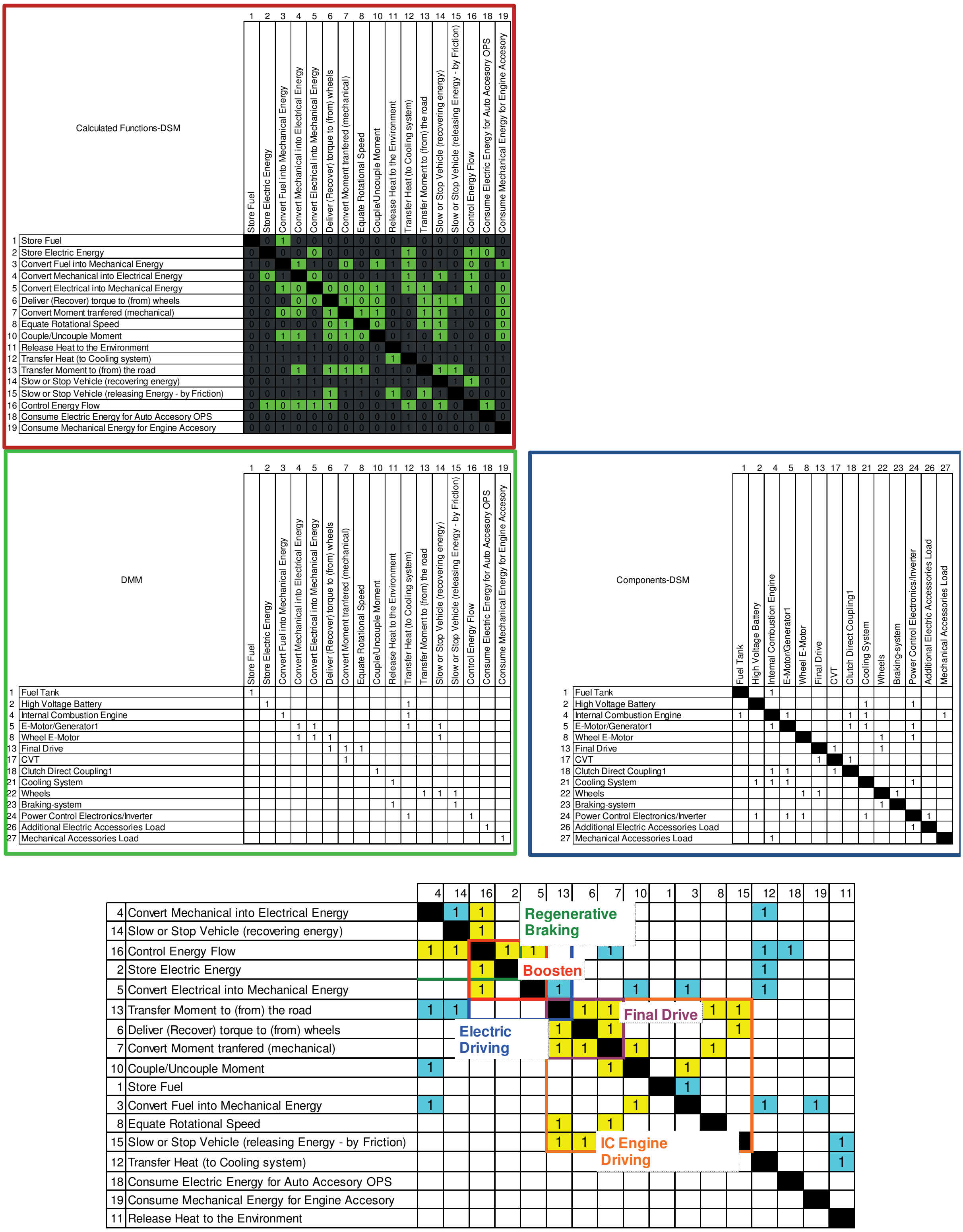


Figure 5-24 Architecture-MDM analysis of a parallel hybrid "through the road" architecture with further clustering of the functions-DSM shown at the bottom.

5.8 Summary of Matrix Based Vehicle Architecture Analysis

This chapter presented examples demonstrating how matrix based working methods are useful in the synthesis and analysis of product architecture concepts. Multiple domain matrices were shown to facilitate link analysis between the functional and component domains. The MDMs shown in this chapter were assembled from components and functions DSMs of selected HEV architectures along with a domain mapping matrix that shows inter domain relationships. Each domain specific DSMs can be clustered to analyze modules within them.

A ΔMDM between two architectures allows for a direct comparison between two product MDMs. The result of a ΔMDM is used to show point differences between architectures in terms of components and functional links.

The ∑MDM is another matrix manipulation used in this application to determine frequency of links between functions and components amongst the considered set. In section 5.5, this information facilitates generating design synthesis rules captured in a generic DMM mapping of components to functions. This generic DMM allows for the calculation of a functions DSMs from a particular components DSM based on equation 22 (page 150). The benefit of the rule set created assisted in finding over 5450 compatible vehicle architecture configurations.

In section 5.6, the compatibility matrix methodology was introduced building on previous work from Deubzer and Hellenbrand. The matrix, much like the consistency matrix enables a pairwise comparison of choice elements. The methodology focused on the three key system design elements of a hybrid vehicle architecture including the internal combustion engine, the electric motors and the high voltage battery. The structural configurations explored were further enhanced by specifying system requirements that can help dimension the three key components in an HEV structure by means of so called “linking selections” as described in section 5.6.4. Combining architectural structure and system dimensioning requirements provides the ability to specify architecture concept parameters important in determining design feasibility.

Matrix tools were shown here to greatly assist in the concept development of new vehicle architectures. The ideas presented are revisited in chapter 7 where an applied example is provided. Once a vehicle architecture is configured and sized, a cost estimate of manufacturing costs and operation costs can be estimated as will be explored in the next chapter. Combined information on product architecture and Lifecycle costs aids developers in making informed decisions during the early development stages.

6 Lifecycle Cost Theory and Modeling

Understanding the factors that affect costs during the earliest stages of product development provides valuable insights for vehicle architecture decision making. This chapter presents a lifecycle costing model used to compare hybrid electric vehicle architectures with varying levels of electrification to a reference conventional internal combustion engine car. Considering total costs of ownership and operation (COO) along with manufacturing costs is critical in formulating strategic business models tailored to delivering value at the point of sale and/or during the use of the product.

The results of various lifecycle cost model scenarios shown in this chapter suggest that HEV architectures with increased electric range capability allow for significant customer fuel cost savings. These savings can be so large as to offset the increased manufacturing cost premium of hybrid vehicle architectures within the first three years of ownership. This is based on projected increases in future fuel prices (refer to section 3.1.2). However, if fuel prices or annual vehicle use remain low, electrification becomes less attractive as payback periods for the new vehicle architecture investment is extended beyond 10 years of ownership.

Customers will be willing to pay a premium for new vehicle architectures offerings if the consumer use benefit can offset the premium over a short time. In contrast, if the additional costs lack enough benefits to the customer, the design or business model must be altered to make the new product more attractive to consumers in some other way. Otherwise, the utility of ownership will not justify the initial purchase investment. Finally, it is important to consider that the consumer benefit includes both emotional and monetary values.

6.1 Vehicle Lifecycle Cost Theory

Product lifecycle costs (LCC) analysis includes both costs to the manufacturer and costs to the consumer. The manufacturer's cost encompasses the cost of all activities in the product development process, from planning to production, as shown on the left in Figure 6-1.

During the initial planning phases, the ability to influence costs is high, given that the product concept is still being defined. In contrast, once the design goes beyond the development phase, changes to the product architecture become extremely costly. This phenomenon is referred to by Ehrlenspiel as the "dilemma in product development" [EHRLENSPIEL et al. 2007b, p.11]. Therefore, it benefits the manufacturer to carry out a continuous cost analysis as early as possible in the planning phases and continually project costs of changes ahead of decision milestones throughout the development process.

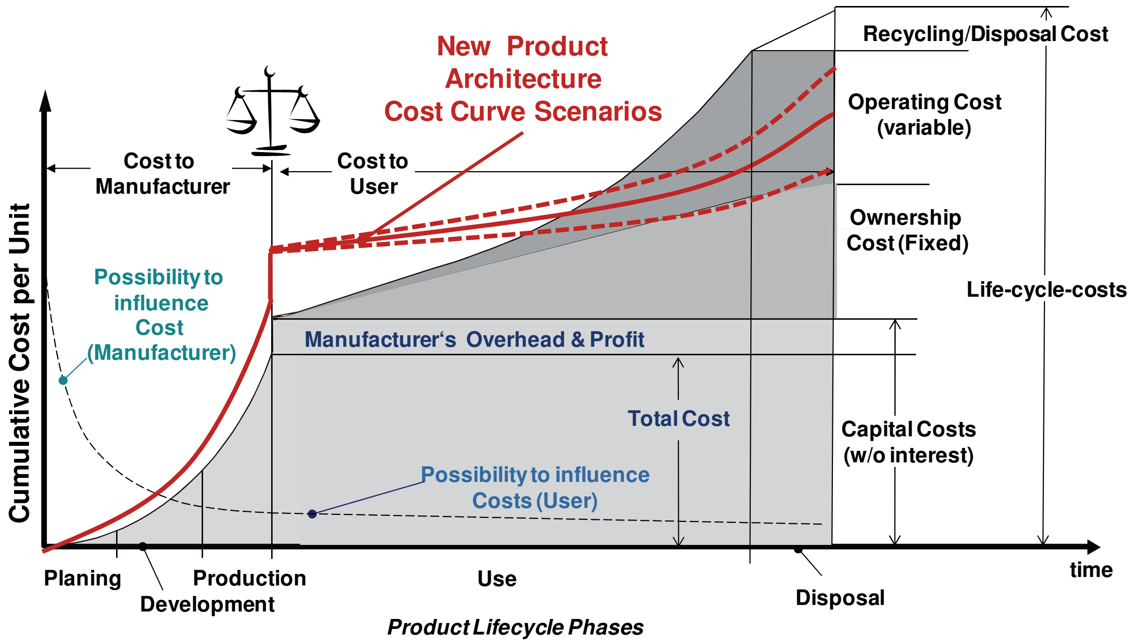


Figure 6-1 Qualitative depiction of lifecycle costs (LCC) for a conventional car (shaded area) and a new product architecture (thick red line). The payback point is where the new vehicle architecture cost curve intersects with the conventional reference architecture – Adapted from EHRLENSPIEL *et al. 2007a*

A discontinuity in the cost function following the accumulated manufacturing costs can be seen in Figure 6-1. This jump in costs represents the manufacturer's overhead and profit mark-ups that are transferred to the customer in the retail price.

User costs begin at the point of purchase. These include both fixed costs, also called ownership costs, as well as variable costs, known as operating costs. Most users are well aware of operating costs such as fuel consumption, car maintenance, and repairs. In contrast, ownership costs, including depreciation; insurance; state fees and taxes, are less obvious to the typical driver as they occur only once a year or are fully realized at the point of re-sale.

Table 6-1, taken from the US Department of Energy - Transportation Energy Data Book (table 10.12) [US DEPARTMENT OF ENERGY 2007], shows that in the United States the variable costs of owning a car is roughly 25% of the total cost of ownership, whereas fixed costs make up 75%. These values have remained relatively unchanged from 1985-2007. The fuel use portion made up merely 14.3% of the total costs of ownership and operation in 2007, primarily varying with the cost of fuel at the pump. Curiously enough, car makers put most of their technical design emphasis and research dollars toward reducing fuel consumption, which roughly makes up only 15% of the car operating costs. Regardless of future energy pricing scenarios, fixed costs of vehicle ownership remain the largest costs to the end user.

Table 6-1 Vehicle Cost of Ownership and Operation according to the US DEPARTMENT OF ENERGY 2007

Car Operating Cost per Mile, 1985–2010

	Constant 2010 dollars per 10,000 miles[a]			Total cost per mile[b] (constant 2010 cents[a])	Percentage gas and oil of total cost
Model year	Variable cost	Fixed cost	Total cost		
1985	1,504	4,177	5,680	56.8	19.9%
1986	1,297	4,590	5,887	58.87	15.1%
1987	1,286	4,469	5,755	57.55	14.7%
1988	1,456	5,585	7,041	70.41	13.6%
1989	1,407	5,135	6,542	65.42	14.2%
1990	1,401	5,432	6,834	68.34	13.2%
1991	1,553	5,709	7,262	72.62	14.6%
1992	1,399	5,881	7,280	72.8	12.6%
1993	1,388	5,617	7,005	70.05	12.7%
1994	1,339	5,644	6,983	69.83	11.8%
1995	1,374	5,730	7,104	71.04	11.7%
1996	1,334	5,827	7,162	71.62	10.9%
1997	1,467	5,907	7,375	73.75	12.2%
1998	1,431	6,057	7,489	74.89	11.1%
1999	1,387	6,099	7,487	74.87	9.8%
2000	1,545	5,982	7,527	75.27	11.6%
2001	1,675	5,690	7,364	73.64	13.2%
2002	1,430	5,908	7,338	73.38	9.7%
2003	1,552	5,788	7,340	73.4	11.6%
2004	1,454	6,502	7,957	79.57	9.4%
2005	1,574	6,043	7,617	76.17	12.0%
2006	1,633	5,069	6,702	67.02	15.3%
2007	1,525	5,011	6,536	65.36	14.3%
2008	1,718	5,468	7,186	71.86	16.4%
2009	1,567	5,617	7,184	71.84	14.3%
2010	1,673	5,719	7,392	73.92	15.4%
	Average annual percentage change				
1985–2010	0.4%	1.3%	1.1%	1.1%	

Source:
Ward's Communications, *Motor Vehicle Facts and Figures 2010*, Southfield, Michigan, 2010, p. 68, and annual. Original data from AAA "Your Driving Costs."

6.1.1 Importance of Lifecycle Costs to the Manufacturer

Why should manufacturers be concerned with user costs in the early stages of product development?

The answer to this question becomes apparent when considering the manufacturer's plan to introduce new vehicle architecture to the market. For example, take into account the manufacturing costs during product planning for a PHEV. It is very likely that cost projections of such a car will be unattractively high compared to conventional car models. This increased manufacturing cost essentially builds a barrier that tends to influence automakers to not pursue a new concept until the leading cost items become less expensive.

However, when the entire lifecycle is considered, users realize that the new vehicle architecture can provide substantial benefits through savings in ownership and operation costs. If this is the case, a payback period for the new architecture can be calculated in terms of years of ownership with respect to a reference vehicle architecture, which in this study is a conventional ICE car.

The "new product architecture cost curve scenarios" red line in Figure 6-1 describes the introduction of new car architecture. Here, the increases in manufacturing costs go well beyond the "overhead and profit" buffer zone of a conventional car. However, the owner cost benefit makes the car attractive to users that plan to own and operate the car beyond the payback period. The payback period is depicted in Figure 6-1 as the intersection of the new vehicle architecture cost curve and the reference architecture curve. At this point both architecture types are equivalent in cumulative costs, followed by a period of savings to the new vehicle architecture owner. Customers that intend to own and operate the vehicle beyond this period should be willing to pay the increased initial purchase price.

Traditionally, cars have a lifespan of 15-20 years [US DEPARTMENT OF ENERGY 2001]. As a rule of thumb, most conventional cars accumulate costs equivalent to the manufacturers' suggested retail price (MSRP) by the fifth year of ownership. It is also at this time that most users finish paying off a traditional 60-month financed car loan. If a new architecture is able to amortize the additional purchase price in the first three to five years, it is usually an attractive offer for car buyers. If these benefits to consumers are accurately communicated, customers could be willing to pay an additional premium for the new product architecture based on anticipated future savings.

Manufacturers should always consider lifecycle costs when making strategic decisions about bringing new vehicle architectures to market. The traditional mindset of focusing solely on manufacturing costs can easily result in continually reinforcing conventional car architectures and missing lucrative opportunities for architectural innovation.

6.1.2 Challenges and Opportunities in Lifecycle Cost Analysis

Perhaps the greatest challenge in conducting a LCC analysis during the pre-development stage is the uncertainty involved in predicting future costs. The most common methodologies for modelling future unknowns are making educated assumptions, analyzing scenarios, and using historic trend data to model future events. Error estimations must be considered when using these methods and, when unavailable, at a minimum, an upper and lower bound estimation should be assumed.

Another major challenge is determining model boundaries. An overly detailed model can result in unproductive effort applied to insurmountable uncertainty. In contrast, a cost model that is too general might provide little help for the assessment of new product architecture concepts.

The main opportunity of a LCC analysis is gaining knowledge of cost influencing factors before early design decisions are made. When this early cost knowledge is available to developers, it should be continually updated throughout the product development stages allowing for the realization of cost reduction opportunities [EHRLENSPIEL et al. 2007b, p.87].

The LCC analysis not only shows the level of costs involved, but also an itemized cost breakdown. This information can foster early involvement of other financial stakeholders such as manufacturing, marketing and strategic planners. Finally, building a diverse team of professionals to conduct the LCC analysis can uncover new business models that may be enablers for future market implementation strategies.

6.1.3 Handling Uncertainty during the Early Development Stages

Uncertainty is inevitable in the LCC estimation process in the context of model-based predictions. The source of these uncertainties can be distinguished between the epistemic and aleatory nature of the uncertainty [DE WECK, O. et al. 2007, ZIO et al. 1996, p. 225; GOH et al. 2008]. These two types of uncertainties result from the lack or abundance of information, conflicting evidence, measurement uncertainty, subjectiveness, and the ambiguity or lack of system maturity. Table 6-2 offers the classification, source and type of uncertainty in data inputs to the LCC model with examples.

Table 6-2 Classification of uncertainties in cost data and models - Classification fields according to GOH et al. 2008, p.8

	Classification	**Source**	**Type**	**Example in Vehicle Architecture Cost Modeling**
Data Uncertainty	Variability	Inherent ramdomness	Aleatory	Number of charge and discharge cycles to HEV battery replacement
	Statistical Error	Lack of data	Epistemic and aleatory	Markup and Overhead costs of Manufacturers
	Vagueness	Linguistic uncertainty	Epistemic and aleatory	The user travels on average 15-40 km per day
	Ambiguity	Multiple sources of data	Epistemic	Expert 1 and Expert 2 see different the cost of a Electric Pump at a volume of 50,000 vehicles per year
	Subjective Judgement	Optimism bias	Epistemic	Over confidence in volume of HEVs entering the market
	Imprecision	Future decision of choice	Epistemic	OEMs will prefer Lithium Iron Phosphate Batteries over
Model Uncertainty	Parametric	Cost drivers/parameters Cost Est. Relationship choice Regression fit Historical data uncertainty Extrapolation	Epistemic and aleatory	Multivariable Linear Regression of HV Battery costs
	Analytical	Scope Level of details Available data	Epistemic and aleatory	Number of components in cost estimation used to estimate the costs of electrification

Epistemic or reducible uncertainty is encompassed in the assessor's lack of knowledge about the parameters that characterize the physical system being modeled. This type of uncertainty is reducible through further study of the system model, consulting experts and refining estimations. This type of uncertainty can be endogenous (internal) or exogenous (external) to the system and its boundaries being modeled [DE WECK, O. et al. 2007]. An example of external epistemic uncertainties can be estimations of market size, whereas internal epistemic uncertainties can relate to the choice of hybrid control strategy for a particular hybrid vehicle architecture.

Aleatory or irreducible uncertainty, also known as inherent variability or noise, is the result of chance and is not reducible through better measurement or study of the system being modeled; but may be reduced by changing the physical system (i.e. the system itself) [GOH et al. 2008]. Examples of aleatory uncertainties are represented from inherent randomness in mean time between failures. Another example pertaining to the HEV high-voltage battery is the aleatory uncertainty in the estimation of number of charge and discharge cycles over the lifetime of the battery or the price development of fuel prices in the market.

For cost models early in the pre-development stages, the cost estimation process breaks down the vehicle costs into component costs. The model that follows is a Δ cost model that adjusts costs based on adding or reducing component costs against a reference baseline vehicle cost. The uncertainty in these types of cost models arise from various sources [GOH et al. 2008, p.4]:

- Lack of definition of the component system or subsystem at the estimation stage
- Level of abstraction and boundaries set for the model
- Different methods for estimating costs used for different component systems
- Complexity and correlation between cost elements [BOOK, S. A. 1999, p.24]

The uncertainty in cost estimating in the early stages can be handled by using a number of techniques. Intuitive and analogical approaches are examples of useful qualitative methods based on analyst's evaluation of similarities of the future system to an existing one. Parametric and analytical approaches consider parameters of the actual system and its sub-components to arrive at an estimate of total cost using cost estimating relationships.

In the following LCC model both simple parametric and qualitative methods are used in the early stages due to a general lack of detailed information. The cost estimation focuses on use cases or scenarios that can be tested by the user for sensitivity and cost variability. In addition, where costs are subjectively estimated, a three-point triangular distribution is used requiring most likely, optimistic and pessimistic scenarios as seen in figure 6-2.

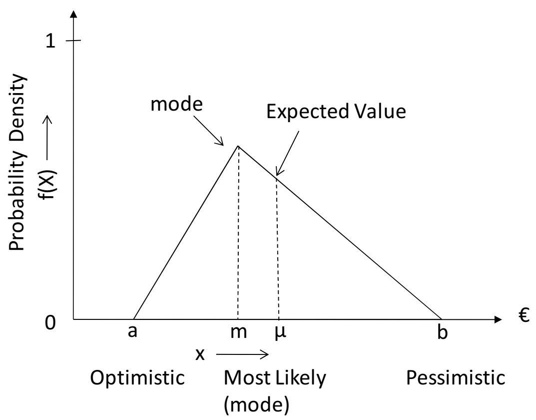


Figure 6-2 Three point estimate triangular distribution with optimistic, pessimistic and most likely according to GAHR 2006, p.99 and HARTUNG et al. 1999,p.196

Where the probability density function and expected value and variance of the distribution according to GAHR 2006, HARTUNG et al. 1999, p.196 are expressed as:

$$f(x) = \begin{cases} \frac{2}{b-a} \cdot \frac{x-a}{m-a};\ if\ a \leq x \leq m \\ \frac{2}{b-a} \cdot \frac{b-x}{b-m};\ if\ m \leq x \leq b \\ 0;\qquad else \end{cases} \qquad (24)$$

$$\mu = E(X) = \frac{a+b+m}{3} \qquad (25)$$

$$\sigma^2 = V(X) = \frac{a^2+b^2+m^2-a\cdot b-a\cdot m-b\cdot m}{18} \qquad (26)$$

The parametric methods used in the LCC model use cost estimation relationships (CER) based on regression analysis. The cost data for these models are taken from BMW internal and external historical cost data found in automotive literature. The main indicator of uncertainty in these models is based on the square of the correlation coefficient, r^2, which denotes the "goodness of fit" or strength of correlation. The r value ranges between 0-1, 1 indicating perfect correlation and 0 indicating no correlation. For example, the scarce data for new technologies, such as the high-voltage battery, made it difficult to achieve high multiple r^2 values ($r^2 = .78$). For many new technologies, the epistemic uncertainty will dominate. However, as more knowledge on market pricing becomes available the uncertainty in the estimation will become more aleatory in nature.

6.2 A Lifecycle Cost Model for Hybrid Vehicle Architectures

How can we model the cost of cars that do not exist? This section provides a practical example of a LCC spreadsheet model built for cars with varying degrees of electrification in comparison to a reference conventional car. In this study the reference set of vehicles across vehicle segments are taken to be 2009 US model BMW and MINI cars.

The model aims at calculating both costs to the manufacturer and costs to the consumer. But, it is not designed to consider either recycling or costs to society resulting from environmental externalities – one such model is presented by CARDULLO 1993.

Figure 6-3 describes the three steps leading to the LCC estimate: a manufacturing costs model, a capital cost calculation, and a lifecycle costs model integrating the previous two.

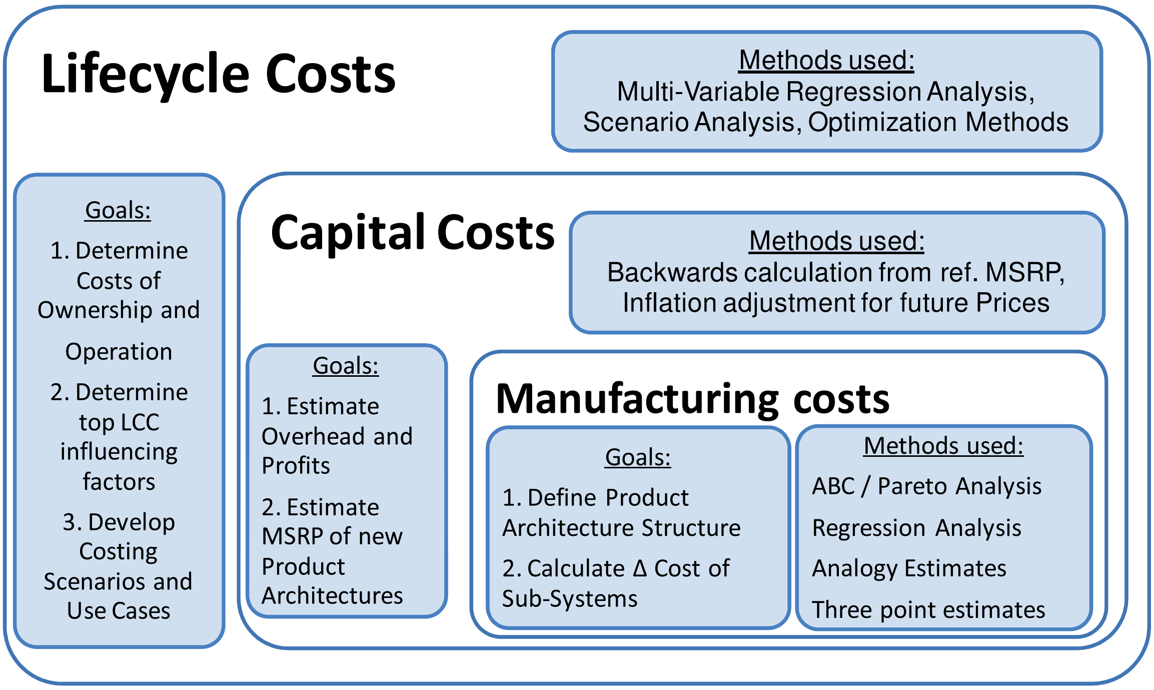


Figure 6-3 Goals and Methodology used in creating a LCC model for future vehicle architectures

6.2.1 Manufacturing Cost Model

Manufacturing costs include all material and labor costs that go into car production. Modelling what future cars will cost with reference to a particular model today, requires calculating which items change from the reference vehicle.

The goal is to first determine which product architectures are being considered and which powertrain components must go into a Δ cost calculation. In the spreadsheet, the user enters vehicle architecture selection for comparison by specifying categories in a series of drop-down menus presented in section 5.6.2 table 5-3.

This input information is enough to determine rules that establish which cost items from Table 6-3 can be included, by means of logic arguments derived from the MDM analysis presented in chapter 5. ΔMDMs as discussed in section 5.3 help determine what component cost items need to be adjusted in the Δ cost calculation. For example, if the user selects a BEV with rear-wheel drive; no engine; a simple reduction transmission; one-axle motor and a battery placed in the front axle, then all electrification components will be included from Table 6-3 with the exception of a pressurized tank, motor start-stop and hybrid transmission in addition to cost savings in all categories pertaining to the reference conventional car. Only cost items that need to be added, omitted or modified from the reference architecture need to be accounted for in the model.

Once vehicle architecture structures are defined, components are to be scaled based on a series of requirements the car must fulfil. Requirements include items such as the electric-only (charge-depleting) range to be achieved, the maximum velocity in electric mode, acceleration requirements from 0-100 km/h, and battery depth of discharge, to name some of the more important requirements. Component sizing allows for the creation of costs and weight estimates. The methodology presented in section 5.6.4 is used in facilitating selection of design requirements.

Table 6-3: Items considered in the Manufacturing Cost Model

Additional costs from electrification components included in the Δ cost calculation	
HV Battery	Δ Cabling/Cooling
E-Motor	Δ El. Clim. Comp.
Power Electronics	Δ El. Water Pump
Hybrid Transmission	Δ El. Low Pressure Pump
Motor Start/Stop Sys.	Δ El. Power Steering
Regen. Braking Sys.	Δ Pressurized Tank
Charger	Δ Chasis Adaptations (Glider Cost)

Cost Savings from reference architecture included in the Δ cost calculation
Internal Combustion Engine
Transmission
Fuel Tank

A Pareto (or ABC) analysis of the items in Table 6-3 reveal that the high-voltage battery, internal combustion engine, electric motors and the power electronics (includes inverter and control unit) comprise the highest-cost components. These high-value items where modelled using regression analysis for various production volumes (low=2,000/yr, medium 20,000/yr. and high 200,000/yr.) referenced from several published sources (DELUCCHI et al. 2000, LIPMAN et al. 2003, pp. 39-43, and MARKEL, T. et al. 2006).

For all other items, three-point estimates including: low cost, average cost, and high cost estimates where left open for user input. A triangular distribution analysis was used in modelling costs for these items as explained in the previous section [GAHR 2006, p.99]. Table 6-4 shows a summary of the manufacturing costs used.

Table 6-4 Manufacturing cost estimates used in LCC model

Component Sub System	Estimation Method	Equation or Estimated Values			Reference / Description
ICE	Linear Regression	IC Engine Cost ($) = 14.5 x kW + 425			kW is the engine peak power rating [Markel et al 2006]
Glider Cost	Backwards Calculation	Glider Cost = (Reference Selling Price) - (ICE Cost) x (1- Manufacturing Overhead)			The Glider cost is defined as the cost of the reference vehicle minus teh IC Engine. The reference selling price is the base price of the reference architecture and the manufcaturers overhead. In the example provided: Base Price is $32,180 (BMW 318i), ICE Cost $2,996, Overhead is assumed to be 55%
Li Ion HV Battery (a)	Linear Regression	HVB Low Production Volume ($) = (0.0613 x P/E Ratio +0.4416) x kWh x 1000 HVB Mid Production Volume ($) = (0.0459 x P/E Ratio +0.2141) x kWh x 1000 HVB High Production Volume ($) = (0.0376 x P/E Ratio +0.0914) x kWh x 1000			P/E Ratio is the Battery Power to Energy Ration (kW/kWh) ; Net kWh is the net battery usable energy content. Production Volume is defined as Low = >10,000 units per year, Mid = 10,000-100,000 units per year, and high = >100,000 units per year. High production volume used on following example. Based on [Delucchi 2000 and Graham 2001]
Li Ion HV Battery (b)	Multi-variable regression	HV Battery Cost (€) = 383.11-15.82 x (Future Year-2009)+5.43 x (P/E Ratio) -1.27 x (Production Volume)+0.0021 x (Production Volume)^2) x (Installed Battery Energy)			This multivariable regression is a refined model based on industry pricing data and Li-ion Battery parameters that explain price such as future start of production year, P/E Ratio of battery in (kW/kWh), installed battery energy (kWh) and production volume of battery systems (ie. equal yearly production of cars)
Electric Motor (a)	Linear Regression	E-Motor Cost Low Production Volume ($) = 778.8+26.69 x kW E-Motor Cost Mid Production Volume ($) = 88.5+14.11 x kW E-Motor Cost High Production Volume ($) = 12.51 x kW			kW is the motor peak power. brushless permanent magnet (BPM) electric motors based on neodymium-iron-boron magnet materials. Production Volume is defined as low = 2,000/year, mid = 20,000/year, high 200,000/year. Based on Delucchi 2000, p. 38 using Lipmann's Data
Electric Motor (b)	Active Volume Estimate	E Motor Cost (€) = 23.13 x Active Volume + 259			Active volume is measured in liters and refers to the volume of electromagnetic material without inclusion of the volume of winding endings and housing ends. The regression is based on european industry cost data. Estimate applies for all types of motors including AC and DC.
Power Electronics	Linear Regression	Power Electronics Low Production Volume ($) = 3000 + 6.1 x kW Power Electronics Mid Production Volume ($) = 800+4.8 x kW Power Electronics High Production Volume ($) = 262+6.9 x kW			The power electronics module includes the inverter (AC/DC), controller (Hybrid ECU, and converter (DC/DC). The production volumes are defined as low = 2,000/year, mid = 20,000/year, high 200,000/year according to Delucchi 2000, p. 39
Δ Electric Climate Compressor	Linear Regression	ECC Most likely($) = 828.41-82.26 x ln (Production Volume);			Regression based on industry data.
		Optimistic	Most Likely	Pessimistic	Three point estimates
Δ Hybrid Transmission	3-Point Estimate	$720 (554€)	$800 (615€)	$960 (738€)	The model allows for user inputs for three point estimates of components with smaller percentage cost (B & C - components in ABC or pareto Analysis). Delta (Δ) values refer to the difference in cost between the reference vehicle and the vehicle architecture analyzed. The estimated values were selected based on discussions with industry experts. Dollar to Euro Conversion rate is assumed as 1.3 Dollars = 1 Euro
Engine Start Stop System	3-Point Estimate	$290 (223€)	$580 (446€)	$1160 (892€)	
Regenerative Braking System	3-Point Estimate	$120 (92€)	$150 (115€)	$180 (138€)	
Battery Charger	3-Point Estimate	$480 (369€)	$600 (462€)	$720 (554€)	
Δ Cabling and Cooling	3-Point Estimate	$45 (35€)	$90 (69€)	$180 (138€)	
Δ Electric Water Pump	3-Point Estimate	$99 (76€)	$124 (95€)	$149 (114€)	
Δ Electric Low Pressure Pump	3-Point Estimate	$40 (31€)	$60 (554€)	$60 (46 €)	
Fuel Tank	3-Point Estimate	$172 (132€)	$ 215 (165€)	$258 (198€)	

6.2.2 Calculating Capital Costs

The capital cost includes all per unit costs from the manufacturer considered in section 6.2.1 plus overhead to cover the development, planning, administration, sales, cost of capital and profit per unit produced. In our model, all these items are combined to one cost item simply label as "overhead."

Typical manufacturer's mark-up figures for conventional cars can range from 145% to 200% of the manufacturing costs depending on the car class and market segment. As a reference, GRAHAM 2001, p. 2-10, estimates the manufacturer's mark up for a midsized sedan to be approximately 1.5 times the component costs with an additional dealers mark up of 16.3%.

Overhead costs figures for future car architectures are estimated to equal that of the reference car (adjusting prices for inflation) with an additional percentage of mark up. The amount of the mark up is estimated as 1% per $1000 of delta manufacturing costs for new architectures. However, the percent overhead and the additional percentage mark up for electrification are left as a user input variable to test scenarios and the sensitivity of this parameter.

For example, a mild hybrid architecture adding $4000 more in manufacturing costs over the reference car would result in a 4% overhead increase over the base car's overhead. If the original estimated overhead was 167% for the conventional car, then the mild hybrid architecture will have a total mark up from the manufacturing costs of 171% (note in equation 27 this is expressed as (1+(67%+4%)), a manufacturers mark up of 100% on component costs is already included in the equation).

The estimated future architecture MSRP is calculated as follows:

$$Pnew = ((MfC_{Base} + MfC_{Delta}) \cdot \left(1 + (1 + (OC_{Fixed}\% + OC_{Delta}\%)))) \cdot (1 + i\%)^{Y}\right) \qquad (27)$$

Where: P_{new} = MSRP of future car architecture

MfC_{Base} = Manufacturing base cost of reference model ($)

MfC_{Delta}= Delta manufacturing costs ($)

$OC_{fixed}\%$ = Percentage overhead for fixed costs - including admin, sales, R&D, and profit margin

$OC_{Delta}\%$ = Percentage overhead costs mark up for electrification - estimated as:

$OC_{Delta}\% \approx MfC_{Delta} /1000$

$i\%$ = Inflation rate - assumed to be 3%

Y = (Year of new architecture purchase) – (Reference car year of production)

The manufacturing costs MfC_{base} and MfC_{delta} result from the manufacturing cost model. The fixed overhead ($OC_{fixed}\%$) can be calculated backwards from the known base vehicle MSRP ($MSRP_{base} - MfC_{base} = OC_{fixed}$ such that $OC_{fixed}\% = OC_{fixed}/MSRP_{base}$).

6.2.3 Introduction to User Costs

Once the MSRP of a new architecture is estimated using equation 27, the lifecycle costs are completed by means of adding the total costs of ownership and operation of the future vehicle. As mentioned in section 6.1, user costs accumulate throughout the use life of the vehicle and consist of both fixed and variable costs. Estimating these costs depend on a number of external variables presented in Table 6-4.

Given the number of input factors, user costs can vary widely between individuals. Scenario building of use cases is useful when comparing car architectures given changing future developments such as energy costs, battery life, government incentives and depreciation.

The uncertainties in estimating user costs are high. Unlike the manufacturing cost model where each item is modelled with a range of error, the user costs assumptions are left open for modelling. However, the reader must also note that user costs in the aggregate tend to remain relatively constant as shown earlier in Table 6-1, p.179.

Table 6-5 User cost model input factors

Influencing Factors for User Cost Calculation (User Inputs to LCC Model)	
General Parameters	*Financing*
Vehicle Class	Percent Down Payment
Year of Purchase	Financing Rate
Yearly Vehicle Distance Traveled	Number of Years
Average Miles per Daily Drive	Number of payments per year
Percent City vs. Highway Distance Traveled	Optional Extra Payment
Energy Costs (yearly over lifetime)	*State and Government Fees/Incentives*
Electricity Costs	Value Added Tax (VAT) - Sales Tax
Fuel Costs	Yearly Fees (Inspection, License Plate)
	Purchase Incentives (one time)
	Yearly Incentives
Battery Lifetime	*Depreciation Model*
Number of charge and discharge cycles	% yearly Depreciation (Regression)

Given the input information from Table 6-5, the user cost model calculates fixed costs of ownership (depreciation, financing, insurance, state fees) and the variable costs of operation (fuel consumption, electricity consumption, maintenance, high-voltage battery replacement and repairs). The methodology for estimating these items is discussed below.

Depreciation - This model was created using data gathered from AUTOTRADER 2009 by means of a multi-variable regression. The depreciation function results in a second-order function using two input variables (mileage and vehicle age) to explain one output variable (price). The vehicles selected for the regression analysis where BMW and MINI model cars with the lowest motorization (engine power) offered. The data collection was conducted in 2009 and the age and mileage of the vehicles were determined by current used vehicle offers for a particular car model. The data was not adjusted to account for years when the manufacturer made significant changes to the outer body design. To validate this model, our results were compared to KELLY BLUE BOOK 2009, EDMUNDS.COM 2009, and INTELLICHOICE 2009 data and found results consistent to within ±5% of the averages from all three models.

Percent yearly depreciation curves for each of the reference models were generated and presented in the figure below. The percentage depreciation loss for an ICE car was assumed to be a worst-case scenario for a hybrid or EV depreciation. All new vehicle architectures were modelled to have equal depreciation curves as that of ICE cars as a conservative estimate. In reality, each vehicle manufactured has its own depreciation curve. Determining what depreciation metrics can affect PHEVs and BEVs is a topic for further analysis.

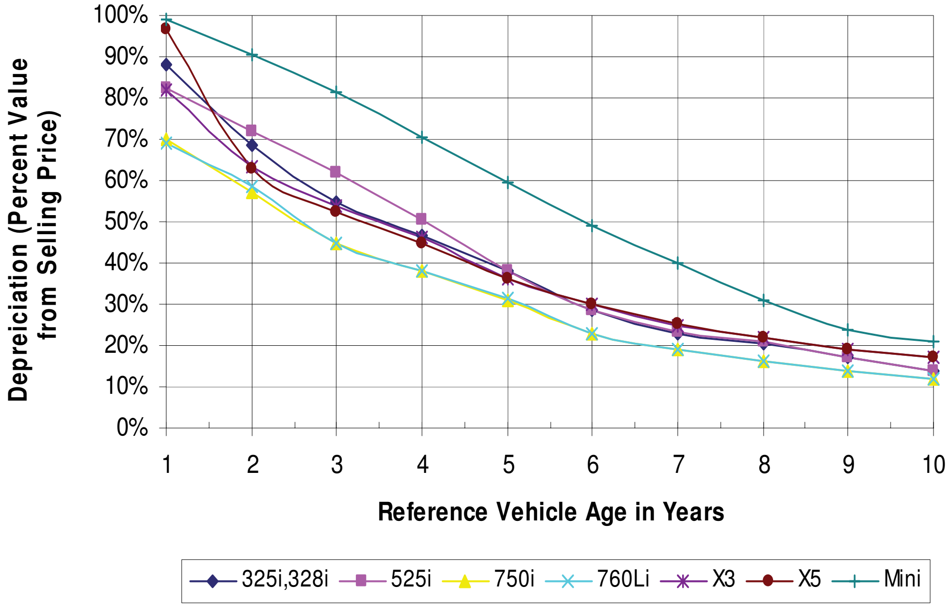


Figure 6-4 Depreciation model results for reference vehicles based on 15,000 miles (24,140 km) annually

Financing – The financing model is determined from a typical loan amortization schedule. Given the financing inputs in Table 6-5 the periodic payment is calculated using equation 28 below:

$$A = \frac{i \times P \times (1+i)^n}{(1+i)^n - 1} \qquad (28)$$

Where A is the periodic payment, *P* is the principal, *i* is the periodic interest rate, and *n* is the number of payments per year [BREALEY et al. 2003, p. 40]. Once the payment amount is known, it is broken down into interest paid and principal paid by subtracting the interest due from the first periodic payment period. The outstanding balance for the second period is then the starting balance minus the principal paid in the first period. This process is continued for each period until the loan amortizes. Ultimately, the customer's cost of financing equates the interest portion of the financed loan.

Insurance – This model was created using data taken from EDMUNDS.COM 2009. It provides projected insurance costs over a five-year period of ownership for each respective reference vehicle class. Due to the fact that insurance costs vary greatly depending on the home state of the driver, values were recorded for the state of Georgia, which maintains the US national average for US auto insurance premiums. A linear regression was then fit to the data using one input variable (time in years) and one output variable (insurance cost). The regression was then used to provide projected insurance for an additional five years beyond the five years estimated by Edmunds, resulting in our desired 10 year insurance cost profile. A model for European insurances was not considered.

Government and State Fees – This item reflects the costs and incentives offered by the government. There are two types of cost items in this model, one-time and yearly fees or incentives. One-time items include sales tax at the point of purchase and government purchase incentives. Yearly fees and incentives include cost for license plates, periodic inspections, yearly vehicle tax or tax breaks depending on the car architecture selected.

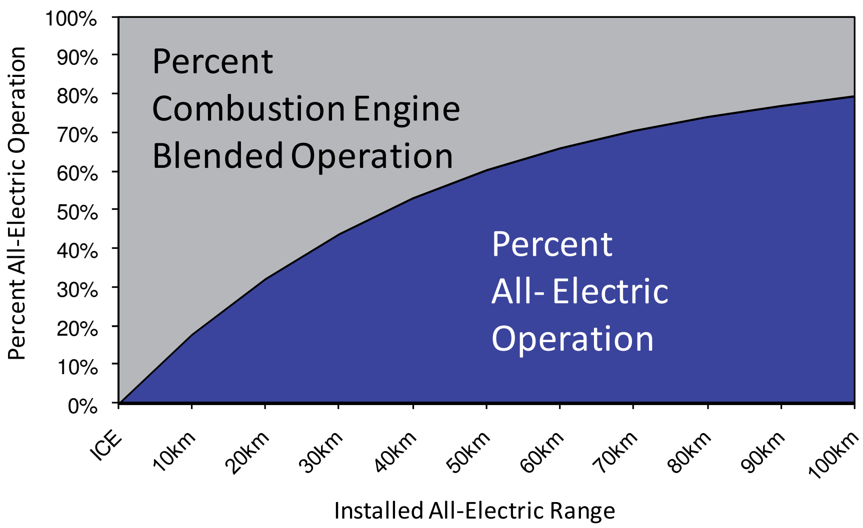


Figure 6-5 Estimate of yearly distances travelled in electric mode for increasing degree of powertrain electrification for hybrid architectures with varying electric range based on a BMW 325i sedan study [GORBEA et al. 2009, p.8] .

Fuel Consumption – City and highway values for the reference cars in each vehicle class were taken from US DEPARTMENT OF ENERGY 2009. These values were applied only to the reference ICE architectures. The city and highway fuel consumption values for modelled architectures are obtained from simulation tools using the FTP72 driving cycle for city values and HWFET driving cycle for highway values.

To determine electric driving values, Figure 6-5 was used to identify what percentage of yearly miles travelled would be driven in a charge-depleting (or electric driving) mode, and what percentage would be travelled using a charge-sustaining (or HEV) mode. Values are based on a customer study of US BMW 335i vehicle use.

The yearly fuel costs are calculated using equation 29.

$$Annual\_Fuel\_Cost = (VDT \cdot (1 - a\%)) \cdot \left(b\% \cdot \left(\frac{P_{fuel}}{FC_{city}} \right) + (1-b)\% \cdot \left(\frac{P_{fuel}}{FC_{highway}} \right) \right) \qquad (29)$$

Where:

VDT = yearly distance travelled (miles or km)
a% = percent of VMT driven electric (from figure 6)
b% = percent city driving
Pfuel= Fuel cost in ($/gal or €/km)
FCcity= Fuel consumption city (MPG or l/100km) for HEV
FChighway= Fuel consumption highway (MPG or l/100km) for HEV

The yearly fuel cost ($/gal or €/km) estimates are user inputs for a 10-year period from the year of sale.

Electric Consumption – This calculation is similar to the fuel consumption as given in equation 30.

$$AnnualElectricityCost = (VDT \cdot a\%) \cdot \left(b\% \cdot \left(\frac{P_{elec}}{EC_{city}} \right) + (1-b)\% \cdot \left(\frac{P_{elec}}{EC_{highway}} \right) \right) \qquad (30)$$

Where: *VDT = yearly vehicle distance travelled (miles or km)*
a% = percent of VDT driven electric (from figure 6)
b% = percent city driving (from figure 6)
Pelec= average price of electricity in ($/kWh or €/kWh)
ECcity= Electric consumption city (miles/kWh or km/kWh)
EChighway= Electric consumption highway (miles/kWh or km/kWh)

The city and highway electric consumption values are user inputs obtained from simulation tools using the FTP72 driving cycle for city values and HWFET driving cycle for highway values.

Extra Battery – This item estimates the cost of replacing a battery for an electric powertrain. For a given battery technology, the user enters the number of lifetime battery charging cycles based on information from battery manufacturers or academic literature. For example, Figure 6-6 shows average battery life in estimated number of cycles for various battery cell chemistries [MARKEL, T. et al. 2006]. One cycle relates to one discharge and charge cycle. It is assumed that every day the vehicle is in operation at least one cycle is consumed as a conservative estimate for PHEVs and BEVs. The extra battery cost is assumed to equal the manufacturing costs of the battery (from section 6.2.1), adjusted for inflation at the point of replacement.

Repairs and Maintenance – These costs were estimated using data taken from EDMUNDS.COM 2009 where projected repair costs are estimated for a five-year period of ownership. A regression was then fit to the data using one input variable (distance travelled in km) and one output variable (repair cost). A similar regression was built to estimate maintenance costs. A vehicle warranty was considered to cover all repair costs fewer than four years/80,000 km (whichever occurs first). These values for maintenance and repairs were assumed to be constant throughout all architectures that contain an internal combustion engine. Future work includes determining differences in maintenance and repair costs for PHEV and BEV architectures.

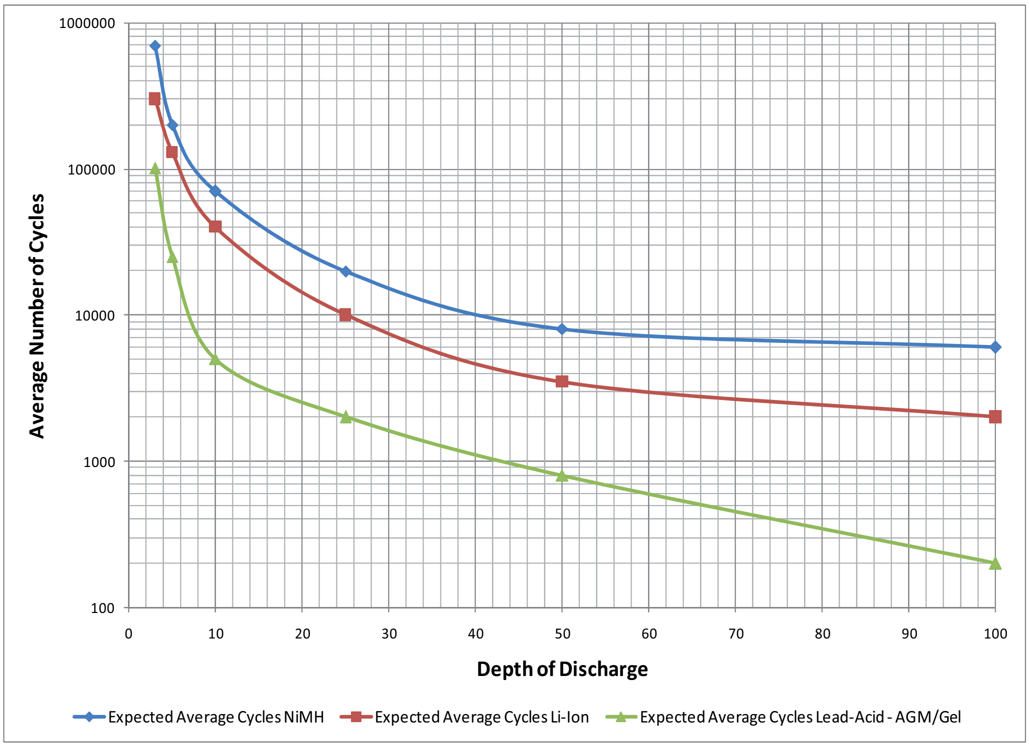


Figure 6-6 Average life of various battery technologies – Adapted from Rosenkranz in MARKEL, T. et al. 2006

6.3 Lifecycle Costing Example of Vehicle Architectures

This section displays the LCC model results for architectures with varying electric powertrains ranging from mild hybrid to a BEV. A 2009 US 328i BMW model is taken as the reference conventional architecture. An initial assumption made was that a 2015 conventional car offering will only differ from the 2009 model in its price adjusted for inflation, but no improvements in fuel efficiency are allowed, as it is necessary to take on a realistic reference value to start the cost estimate. It is important to emphasize again that all values presented here are estimates of hypothetical future cars entering the market in 2015. Cost trends and influencing parameters trends are more important than the actual values presented for purposes of making informed decisions early in the product development cycle.

Table 6-6 LCC Model inputs assumptions for various architectures in the compact sedan segment

Vehicle Architecture Specific Assumptions

	ICE	*Mild*	*Full*	*PHEV10*	*PHEV20*	*PHEV30*	*PHEV40*	*sPHEV50*	*BEV100*
E-Motor Peak Power (kW)	0	15	30	40	50	75	90	110	120
Engine Peak Power (kW)	170	150	145	120	110	100	80	70	0
% Depth of Discharge (DOD)		15%	20%	50%	70%	70%	80%	80%	80%
El.-Range (miles)		0.05	0.75	10	20	30	40	50	100
Battery Power/Energy Ratio		168	30	6	6	6	5	7	4
Fuel Cons. City (MPG)	18	22	23	25	26	27	29	30	
Fuel Cons. Hwy (MPG)	28	31	32	36	38	39	41	41	
Elec. Cons City (Mi/kWh)				3.62	3.53	3.39	3.28	3.17	4.10
Elec. Cons Hwy (Mi/kWh)				2.37	2.31	2.22	2.15	2.08	2.68
Battery Use Life (Cycles)		200000	20000	3500	2750	2750	2200	2200	2200

General Assumptions for all Architectures

Percent City Miles Traveled	60%	Sales Tax	6%
Percent Highway Miles	40%	Percent Down Payment	10%
Yearly Vehicle Miles Traveled	12000	Financing Rate	2%
Number of Days Driven per Yr.	286	Number of Years	5
Average Miles per Daily Drive	42	Num. of payments per yr	12
Inflation Rate	3%	Optional Extra Payment	0

Year	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Cost of Electricity ($/kWh)	$ 0.42	$0.11	$0.11	$ 0.11	$ 0.11	$ 0.11	$ 0.11	$ 0.11	$ 0.11	$ 0.11
Cost of Fuel ($/gal)	$ 2.86	$4.14	$4.24	$ 4.39	$ 4.52	$ 4.61	$ 4.72	$ 4.87	$ 4.99	$ 5.07

The assumptions listed in Table 6-6 represent user inputs to the LCC model for various levels of electrification for a compact sedan in the United States. The cost of electricity and fuel was taken from 2009 forecasts from the Energy Information Agency [EIA 2009b]. Values for fuel and electric consumption were estimated using PSAT [FREYERMUTH et al. 2009], a powertrain simulation tool. Table 6-7 summarizes the LCC model output results.

Table 6-7 LCC Model Results

Δ Production Costs and Δ Use and Ownership Costs over ICE

	ICE	Mild Hybrid	Full Hybrid	PHEV 10	PHEV 20	PHEV 30	PHEV 40	sPHEV50	BEV 100
Δ Production Costs over ICE ($)	0	2696	4649	5674	6545	8763	9816	10810	11864

	Year of Ownership	ICE	Mild Hybrid	Full Hybrid	PHEV 10	PHEV 20	PHEV 30	PHEV 40	sPHEV50	BEV 100
Δ Use and Ownership Costs (Savings) over ICE ($)	1	0	202	552	257	152	477	621	805	830
	2	0	216	773	86	-201	292	496	792	761
	3	0	207	946	-164	-653	-15	230	625	524
	4	0	170	1064	-407	-1426	-666	-404	77	-411
	5	0	-393	632	-634	-2507	-1648	-1390	-835	-2028
	6	0	-979	156	-930	-3674	-2736	-2497	-1879	-3790
	7	0	-1588	-356	-1287	-4919	-3919	-3710	-3035	-5674
	8	0	-2225	-909	-1714	-6253	-5212	1370	3564	2840
	9	0	-2886	-1502	-2207	-7669	-6604	-75	2159	685
	10	0	-3570	-2129	-2752	-5560	-2692	-1609	659	-1576
∑ of Δ Use and Ownership Costs (Savings) over ICE ($)		0	-10846	-774	-9751	-32710	-22722	-6969	2933	-7837

The model outputs show that approximate production costs vary from more than $2,500 for a mild hybrid to more than $11,800 for a battery electric vehicle versus the baseline ICE vehicle. Despite these increased manufacturing costs, table 6-7 shows that all architectures achieve better Δ costs of ownership than the reference car within the first seven years. Particularly, plug-in hybrids were best in achieving payback. Full hybrids took the longest to achieve payback based on the scenario input parameters selected in this case study. Additionally, the PHEV 50 architecture shows that the cost of a battery replacement after the eighth year of ownership can eliminate savings previously accumulated from electric driving.

In the LCC model, the costs of a battery replacement were added to the costs of ownership as a one-time occurrence. It is possible that future cars that run mostly electric will exhibit two depreciation curves, one for the battery and one for the rest of the car. The first will be based on battery life and ability to hold charge while the latter can be modelled closer to conventional cars. It is likely that costs of a battery replacement will be shared by the manufacturer or subsidized by the government in the future.

Design for value will be a key factor in the introduction of new architectures. As cars with increased electric driving capability enter the market, allowing customers to choose how much electric capacity is installed can provide increased value to both customers and manufacturers. Allowing cars to be functionally scaled by the customer can have a depreciation-lowering effect through individualization. Such a strategy allows OEMs to charge higher premiums for cars where customer value is increased, but at the same time may require additional investment into manufacturing flexibility and distribution.

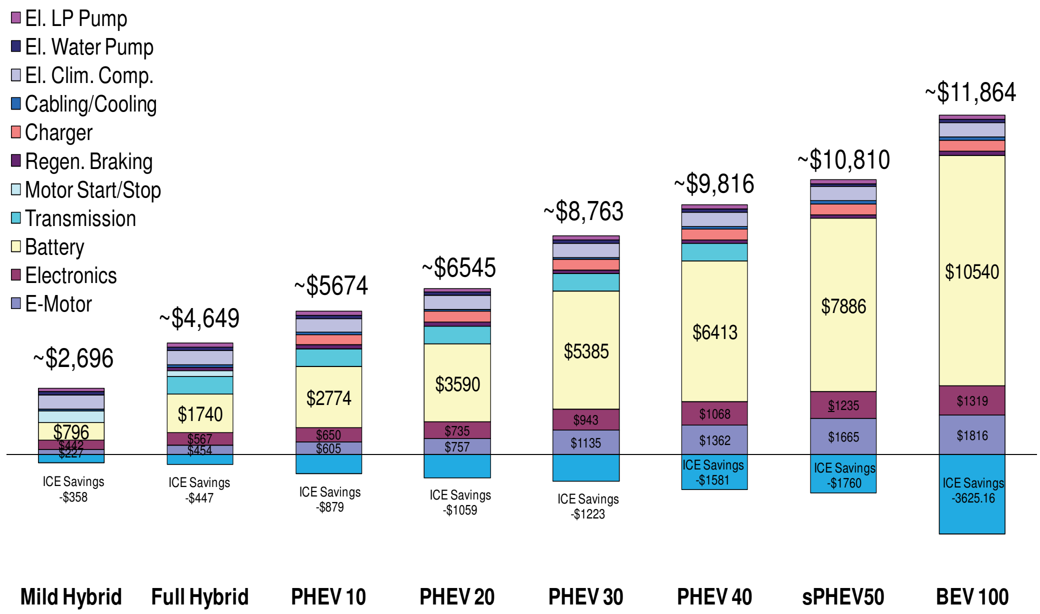


Figure 6-7 Estimated delta manufacturing costs of electrification for a passenger car 2015.

The delta in production costs are dominated by the battery, electric motor and power electronics costs. However, substantial savings can be achieved through downsizing (or elimination) of the internal combustion engine as illustrated in figure 6-7.

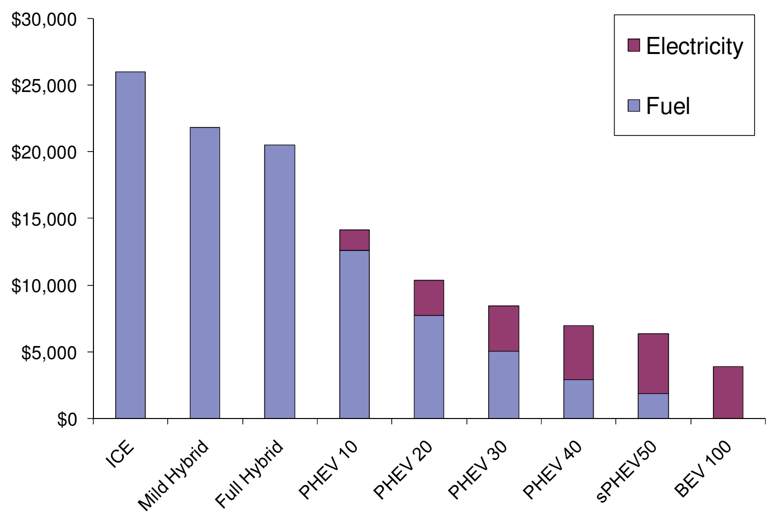


Figure 6-8 Estimated cumulative energy costs from 2015-2024 – for energy prices assumed see table 5.

The higher the electric driving capacity for HEV powertrains, the more dramatic the fuel savings a costumer can expect given the energy and fuel forecasts presented. Figure 6-8 shows the impressive estimated fuel savings effect of new vehicle architectures accumulated through 10 years of ownership from 2015-2024 based on the LCC model's initial conditions.

Despite the dramatic savings some HEVs and PHEVs achieve in fuel costs, comparing accumulated costs of ownership and operation from year to year across all architectures remain within an estimated range of $8000 from each other. This indicates that the fixed cost of ownership, such as depreciation; insurance; taxes and financing, which make up 60-75% of costs, far outweigh the variable costs of ownership. This results in comparable total overall costs as demonstrated in figure 6-9.

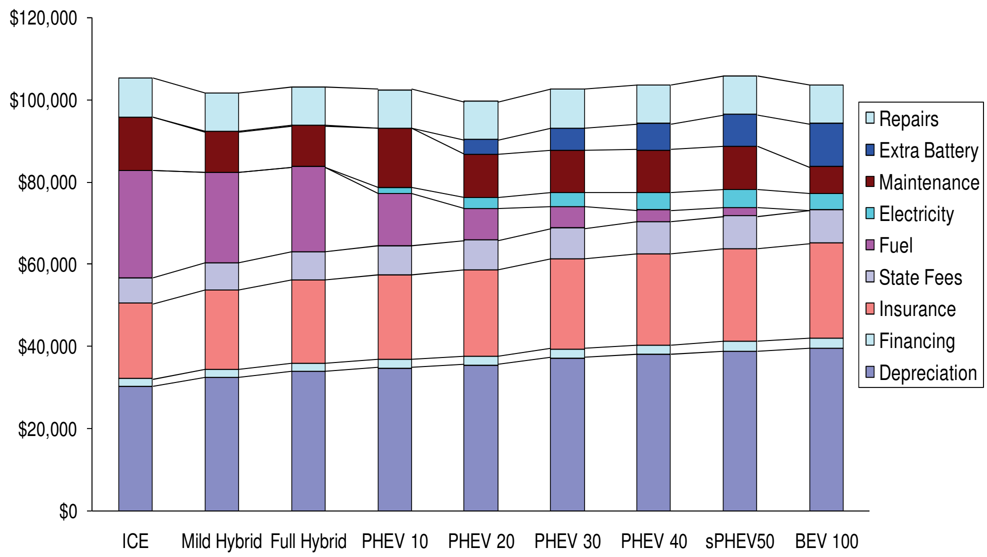


Figure 6-9 LCC Model estimated 10 year Cost of Ownership and Operation for various architectures from 2015 -2024

The biggest factors in ownership and operation costs are depreciation and insurance. In the LCC model, depreciation was estimated using current data for cars over the past 10 years. Generally, the more expensive a car is initially, the larger the depreciation will be in the first three years of ownership. It is difficult to judge how depreciation of new car architectures will differ in the future from the data observed for conventional ICE cars. Core questions regarding depreciation will be:

- How will the battery systems depreciate?
- Will battery systems remain the highest cost item in the future?
- Will battery cost be borne by the user, the manufacturer or the government?

Cost of ownership will be influenced by government involvement in terms of incentives or penalties that could add or detract from the initial depreciation price basis. In the model, an accumulated ~$8000 over the 10-year period is collected in government fees. If the government decides to tax only conventional cars, users of alternative cars could gain the ability to see payback as early as the first year of ownership. The most recent US federal economic stimulus package law, includes provisions of up to $7500 in incentives for cars with extended electric driving capability (refer to section 3.2).

The issues of maintenance and repair must be further examined. The LCC model assumes an equal maintenance and repair fee for all vehicle types. However, consumer cost reduction benefits to extended electric driving are known to include a reduced number of engine oil changes and brake-related repairs for hybrid vehicles and the full elimination of engine maintenance cost in the BEV case. Unknown are maintenance costs due specifically to electric systems that might include individual battery cell or module replacements. These small variations were not explicitly modelled in this case study.

6.4 Use Case Scenario Building and Optimization

The LCC model allows for the building of use case scenarios in order to examine sensitivities of inputs variables to the overall model results. Consider a potential hybrid vehicle worst-case scenario by changing three assumptions: yearly distance travelled city/highway driving percentage and fuel price.

The new pricing assumptions are changed from Table 6-6 to reflect fuel prices that remain low starting at $2.10/gallon in 2015 and growing on average 8% to $4.20/gallon in 2024 (projected electricity prices remain unchanged). The driving profile is set to 80% highway and 9000 annual miles travelled during a total of 240 days per year[18].

[18] Note that fuel prices in this scenario are priced well below May 2011 levels of $4.10 a gallon to show life cycle cost sensitivities to extreme fuel prices. The lower the fuel price the harder it is for a hybrid car to amortize the added costs of electrification compared to a reference ICE baseline car.

Table 6-8 LCC model results for new scenario

	ICE	Mild Hybrid	Full Hybrid	PHEV 10	PHEV 20	PHEV 30	PHEV 40	sPHEV50	BEV 100
Δ Production Costs over ICE ($)	0	2696	4649	5674	6545	8763	9816	10810	11864

Years of Ownership		ICE	Mild Hybrid	Full Hybrid	PHEV 10	PHEV 20	PHEV 30	PHEV 40	sPHEV50	BEV 100
Δ Use and Ownership Costs (Savings) over ICE ($)	1	0	457	865	1001	1148	1604	1853	2082	2211
	2	0	730	1405	1585	1809	2565	2982	3370	3550
	3	0	980	1899	2091	2370	3407	3972	4508	4723
	4	0	1208	2346	2615	2629	3924	4619	5290	5227
	5	0	912	2245	3155	2582	4112	4916	5711	5053
	6	0	591	2099	3616	2433	4177	5074	5981	4715
	7	0	245	1912	4003	2188	4126	5103	6114	4227
	8	0	-128	1684	4314	1845	3954	4998	6105	3584
	9	0	-528	1413	4546	1399	3658	4755	5948	2778
	10	0	-956	1097	4694	845	3230	10780	13523	12345
∑ of Δ Use and Ownership Costs (Savings) over ICE ($)		0	3511	16965	31619	19249	34758	49052	58632	48413

Table 6-8 shows results for this new scenario where only the mild hybrid architecture was able to return lower costs of ownership compared to the reference conventional car within the 10-year period. The results show that electrification benefits are influenced significantly by changing these three input variables.

In order to analyze the input variable sensitivities more closely, we turn to optimization theory. An objective function **f**(**x**) is defined to be the *average* Δ cost of ownership and operation (ΔCOO) across 10 years for a selected architecture. In this case we analyzed the PHEV10, a plug-in hybrid with 10 miles (16 km) of electric range. Based on table 6-8 under the PHEV column, the original value to the optimization's objective function is:

$$Objective\ Function\ f(\boldsymbol{x}) = \frac{\left(\sum_{1}^{10} \Delta\ Cost\ of\ Ownership(\boldsymbol{x})_{PHEV10}\right)}{10\ years}$$

The optimization's goal is to find the minimum value of the objective function by finding values for selected variables subject to a set of constraints. This problem takes on the following form: minimize **f**(**x**) = 0, subject to **h**(**x**) =0; **g**(**x**) ≤ 0; x $\in X$, where **x** is a vector of criteria of interest f_i, $i=1,...,n$ that represents the cost difference between the PHEV10 architecture and the reference vehicle. The set of variable values **x** that satisfy all constraints is known as the feasible design domain, *S*.

The set of design variables **x** is defined as follows: annual vehicle miles travelled; one-time government incentive; percentage of city travel; and starting electricity and fuel prices. These variables are subject to the following constraints:

Vehicle miles travelled ≤ 15000 (miles)
One-time government incentive ≤ 2500 ($)
Percentage city travel ≤ 20%
Starting fuel costs ≤ 2.10 ($/gal)
Starting electricity ≥ .108 ($/kWh)
Δ*Cost of ownership for each year from 4 to 10 ≤ 0*

This last constraint ensures that the PHEV10 remains less expensive to own after the fourth year of ownership relative to the reference vehicle. All other parameters not mentioned in this scenario are left unchanged from section 4.1

The constraint sets above do not allow for higher fuel prices, lower electricity prices, nor a change in the percent city driving profile than was assumed in the scenario. Changes are only allowed in "vehicle miles travelled," assuming the customer can use the car for leisure travel, and the introduction of a maximum one-time government incentive of $2500. The optimization problem was run using the Microsoft Excel© solver data analysis toolset and the results are presented in table 9 below.

The initial value of the objective function based on Table 6-8 is $3162, which is the average COO for the column labelled PHEV10 for the 10-year period. This value is the initial state for **f**(x) as shown atop table 6-9. The optimization end state or minimum value results in a negative ΔCOO of -$755. The PHEV10 found at this end state shows lower COOs than the reference car after the first year of ownership! The list of variables that achieve this minimum has a direct or binding influence on the objective function. If any variable were to change, the objective function result will change to a higher value.

The column labelled "sensitivity reduced gradient" in Table 6-9 summarizes this discussion by presenting the "reduced gradient" state that the "average ΔCOO" value would be for a one-unit decrease of variable x, keeping all other variables constant. This value is referred to in economics literature as a *shadow price* [BERTSIMAS et al. 2000, pp. 354-360].

Table 6-9 Optimization results

Target Cell (Minimize)

Objective Name	Original Value	Final Value
PHEV10-Average 10yr-Delta COO	$3,162	-$755

Adjustable Cells

Design Variable Name	Units	Original Value	Final Value	Sensitivity Reduced Gradient	Reduction Amount	Status
Fuel Cost (Year of Purchase)	$/gal	2.10	2.10	-$2,093	-1 $/gal	Binding
Government Incentive	$	0	2500	-$1	-$1	Binding
Annual Vehicle Miles	miles	9000	15000	-$0.21	-1 mile	Binding
Percent City MilesTraveled	percent	20%	20%	-$31	-1%	Binding
Electricity Cost (Year of Purchase)	cents/kWh	0.108	0.108	$20	-1 cent /kWh	Binding

For example, a $1 decrease in the price of fuel (i.e. from $2.10 to 1.10) results in an average ΔCOO = (-$755 – (-$2,093)) = $1,338 over the ten years. As expected, a reduction in fuel price results in a PHEV10 that is on average $1338 more expensive to own and operate year to year than the reference car. Conversely, an increase in fuel price of $1 results in an average ΔCOO = (-$755 + (-$2,093)) = $2,848, making the vehicle more profitable to own. Thus, the benefits of electric driving are increased when fuel prices rise faster relative to electricity prices.

Following a similar logic for the other adjustable variables: for every dollar of government incentive/or penalty, the PHEV10 customer will benefit/suffer an average of a dollar in ΔCOO. And, for each additional/lesser mile travelled, the PHEV10 customer will save/lose an average of $0.21 COO per year over the reference car. For every 1% percent of increase/decrease in city driving, the PHEV10 customer will benefit/suffer $31 over the reference conventional car on average over the 10 years. Finally, for every cent the starting electricity price decreases/increases, the PHEV10 customer will benefit/lose $20 over the conventional car. Again, all sensitivity shadow prices mentioned in this discussion assume all other variables remain unchanged.

In summation, optimization tools offer a way to study variable sensitivities in the LCC model. The insight gained from this second scenario is that alternative architectures cannot be guaranteed to always offer better cost of ownership and operation than conventional cars. We have identified four key variables which COOs depend upon the most: fuel and electricity cost; annual vehicle miles travelled; percent city miles travelled and government incentives. Of these variables, cost of ownership is most sensitive to the user's city/highway driving profiles and the price of fuel.

6.5 Summary of Lifecycle Cost Theory and Modeling

Understanding the factors that affect lifecycle costs early in the planning stages of product development can bring with it valuable insights for anticipating customer needs. In this chapter, lifecycle cost modelling for the design of new vehicle architectures demonstrated that architectures hold higher purchase cost in exchange for savings over the lifecycle of the product.

Limitations to the LCC model in the early development stages are primarily due to epistemic and aleatory uncertainty. Epistemic (reducible) uncertainty is abundant in the early development stages where detailed information is not available for modelling the system architecture. Assumptions that are made initially must be revised at a later stage when more information is available. Aleatory (irreducible) uncertainty stems from statistical variations or "noise." Aleatory risk can only be limited by changing the system itself. Identifying sources and magnitudes of uncertainty allows developers to realize where modelling efforts and information can be improved.

The results of the practical examples in sections 6.3 and 6.4 show that vehicle architectures with increased electric range capability bring with them considerable manufacturing costs that will result in higher retail prices for customers. The increased capacity to drive in electric mode can effect a large displacement of fuel costs with considerable savings over the ownership period. Benefits from electric driving are greatest when fuel prices increase at a faster rate than electricity prices. However, when fuel prices are low, electrification becomes less attractive. Finally, improvements to the ICE technology resulting in fuel consumption improvements not related to hybridization can make the business case for HEVs and EVs less of a bargain as the reference vehicle would provide greater efficiency to the customer for less investment.

The fixed costs of ownership need to be examined more closely for potential consumer cost savings. These costs remain present regardless of electrification. However, typical trends such as "increased purchase price leads to higher depreciation" must be examined in more detail in the case of cars that rely heavily on electric systems.

Design for value can only be exercised if the entire lifecycle costs are understood. In the early stages of product development, the greatest benefit of a LCC analysis materializes in identifying key costing parameters and trends that can provide more information to the product architecture selection. The actual numerical cost values are of lesser importance than determining the leading costing parameters and their sensitivities to change. The insights provided by a LCC analysis in a multi-disciplinary environment can lead to new business models and strategies that will allow the successful introduction of new vehicle architectures in the market.

7 Evaluation Case Study

The tools developed in previous chapters are applied to the pre-selection of urban vehicle architectures in the evaluation case study that follows. The vehicle architectures considered are intended to fulfill future mobility requirements for urban areas that have grown in both their physical boundaries and population.

The trend to urbanization is not an uncommon problem. The population division of the United Nations Department of Economic and Social Affairs estimates that by 2025 Europe will have at least two megacity agglomerations defined by a population of 10 million people or more - representing 4% of the European population. Another 4% of the population will be living in 3 city agglomerations ranging from 5 to 10 million habitants, and 15% living in some 50 cities from 1 to 5 million inhabitants. Finally, 10% of the European population will live in over 86 cites between 500,000 and a million inhabitants and 67% living in over 377,009 smaller urban areas of up to 500,000 inhabitants [UN POPULATION DIVISION 2010]. In summary, more than 30% of the European population could benefit from vehicle architectures designed specifically to fulfill urban requirements.

7.1 Pre-selection of a New Mobility Car Architectures

As a guide in pre-selecting vehicle architectures suitable for future urban mobility, we turn to the methodology steps described in section 4.4 as listed below:

1. **Develop a goal oriented design statement** – In section 7.1.1 the requirements that allow for the creation of a goal oriented design statement are considered. Perhaps the most important input, is determining what type of customer is intended for the vehicle architecture and what concrete goals need to be achieved by the overall system.

2. **Develop an architecture solution space with the aid of matrices** – In section 7.1.2 the broad structural solution space developed in section 5.5 is taken as the starting point and then filtered to specific architecture types. A compatible requirement sets is constructed using the scheme developed in section 5.6 that match the goal oriented design statement.

3. **Determine lifecycle cost projections and filter out dominated solutions –** The bounded solution space is further reduced in section 7.1.3 by looking at lifecycle cost projections within defined use cases. The Lifecycle cost model parameters discussed in chapter 6 are utilized and trade studies are generated to help visualize the information.

4. **Select vehicle architectures for detailed study that best fulfill goals** – This final step presented in section 7.2 resorts to decision making methodologies for the selection of architectures for further study. MDM representations of candidate

architectures can be constructed to facilitate modularization strategies during follow on concept development.

The pre-selection of architectures occurs in the pre-development phases of the product development cycle. At this early stage, developers have limited information available and the aim is not to choose one particular solution, but rather to develop a solution space of sensible vehicle architectures suitable for further development that match the global requirements. The intent of this early stage process is to determine the boundary conditions and define only the technical "corner points" of the vehicle architecture design.

7.1.1 Urban Vehicle Requirements and Design Goal Formulation

The reduction of green house gas emissions and energy conservation are at the top of the agenda for new mobility in urban environments. Personal safety, noise pollution reduction and efficient integration in both conventional and future fuel flexible transportation infrastructure are additional important goals an urban vehicle must also support.

In this case study, the choice field for future urban vehicles is limited to the combustion engine, hybrid electric and electric architecture pathways depicted in Figure 1-4 (no fuel cell technologies are considered consistent with the previous chapters). The basic car segment considered is the "compact car luxury" segment for which the 2010 MINI line of cars is taken as the baseline ICE for this evaluation study presented in table 7-1 [MINI 2010].

Table 7-1 MINI specifications for 2010 models in Germany – used as reference vehicle specifications

	MINI One (55kW)	MINI One (72kW)	MINI Cooper
Engine type	1,6 Liter, 4 Cylinder/16V	1,6 Liter, 4 Cylinder/16V	1,6 Liter, 4 Cylinder/16 V
Max Engine output / RPM	55 kW (75 PS) at 6.000 RPM	72 kW (98 PS) at 6.000 RPM	90 kW (122 PS) at 6.000 RPM
Max. Torque/RPM	140 Nm at 2.250 RPM	153 Nm at 3.000 RPM	160 Nm at 4.250 RPM
Acceleration 0-100km/h	13,2 s	10,5 s [12,3][3]	9,1 s [10,4][3]
Top Speed	175 km/h 109mph	186 km/h [181][3] 116mph [112mph]	203 km/h [197][3] 126mph [122mph]
Acceleration 80-120km/h	13,5 s/16,7 s	12,1 s/15,3 s [n/a][3]	9,6 s/12,1 s [n/a][3]
Fuel Consumption City[1]	7,2 l/100 km	7,2 l/100 km [8,7][3]	6,9 l/100 km [8,7][3]
Fuel Consumption Highway[1]	4,4 l/100 km	4,4 l/100 km [5,1][3]	4,6 l/100 km [5,1][3]
Fuel Consumption Combined[1]	5,4 l/100 km	5,4 l/100 km [6,4][3]	5,4 l/100 km [6,4][3]
CO2-Emission[1]	127 g/km	127 g/km [150][3]	127 g/km [150][3]
Curb Weight EU[2]	1.135 kg	1.135 kg [1.175][3]	1.140 kg [1.180][3]
Max. Permissible weight	1.510 kg	1.510 kg [1.550][3]	1.515 kg [1.555][3]
Tank Volume (ca.)	40 Liter	40 Liter	40 Liter
Dimensions (LxWxH)	3.699 x 1.683 x 1.407 mm	3.699 x 1.683 x 1.407 mm	3.699 x 1.683 x 1.407 mm
Transmission	6-speed Manual	6-Speed Manual or Automatic Steptronic	6-Speed Manual or Automatic Steptronic
Drag Coefficient	0,33	0,33	0,33
Frontal Area	1,97 m2	1,97 m2	1,97 m2
Rolling Resistance Coefficient	0,01	0,01	0,01
Base Price (Germany)	€ 15.300,-	€ 16.600,-	€ 19.300,-

[1] More information on Fuel Consumption at www.mini.de

[2] These values refer to a car with 90% filled tank, a 68kg Driver and 7 kg lugagge weight with standard equipment

[3] All figures relate to vehicles with manual transmission. Figures in [ ] are for vehicles with automatic transmission

Specific requirements for a future urban vehicle must take in consideration current and upcoming regulatory requirements, customer needs, competitor market offerings and the manufacturers own business strategy as addressed in chapter 3. As a guide for laying out concrete guidelines for this case study, a condensed requirements catalog is presented in tables 7-2 and 7-3 developed by the author with the assistance of automotive engineers at the BMW research and innovation center. The requirements catalog is influenced strongly by the manufacturer's traditional brand positioning for the MINI that evolved through time within the brand vehicle offerings. Requirements can also be adjusted from anticipated future customer or regulatory needs directly.

Table 7-2 Design requirements guideline catalog prioritized based on customer profile needs. This example table was generated in collaboration with BMW hybrid vehicle concept developers.

		Customer Profile Priority (0-Not Relevant, 1 - Low Priority, 2 - Priority, 3 - High Priority)								Overall Design Priority	
Requirements	**Criteria**	**Resource Concious**	**Environm. Friendly**	**Thrifty**	**Trend-setter**	**Driver (Sporty)**	**Practical Person**	**Inner City Customer**	**Outer City Customer**	**Score = ∑ (Multiplier x Priority)/8**	
	Multiplier	**1**	**3**	**1**	**1**	**1**	**3**	**2**	**3**		
E-Drive Use Case	City Driving (0 - 60 km/h)	3	3	3	2	1	2	3	3	5	High Priority
	Highways (60-120 km/h)	3	3	3	2	0	0	1	2	3	Low Priority
	Expressways (80-160km/h)	2	2	3	1	0	0	1	2	3	Low Priority
Performance (Low Velocity)	Response 0-4 sec acceleration	2	2	3	3	3	1	3	1	4	Priority
Performance (High Velocity)	acceleration 0-100 km/h maximum velocity maximum sustained velocity in 10% grade	1	1	1	3	3	1	1	2	3	Priority
Range	Overall vehicle range	3	3	1	2	2	3	1	3	5	High Priority
All Electric Range	All Electric range (one battery discharge)	3	3	3	3	0	1	3	2	4	Priority
Catalog Fuel and Emmisions	CO2 Well to Wheel emmisions European (CO2 & l/100km catalog value) FTP 72 (CO2 & l/100km catalog value)	3	3	3	2	2	3	3	3	5	High Priority
Emissionen	Other Emissions: HC, NOx, CO	0	2	0	0	0	0	2	1	2	Low Priority
Weight	Curb Weight Axial Weight Distribution	1	2	1	1	0	0	1	1	2	Low Priority
Comfort	Climate Comfort Acustic Comfort Cargo Load Space Capacity Maximal load bearing capacity Time to full charge Performance reduction at low charge	2	1	1	3	2	3	3	3	4	Priority
Costs	Cost of Ownership Cost of Operation Retail Price Manufacturing costs	3	3	3	1	2	3	3	3	5	High Priority
Overall System Concept Quality	Vehicle life duration High temperature performance (>45 deg C) Low Temperature performance (< -10 deg C) Vehicle Crash Safety	2	2	2	2	3	3	3	3	5	High Priority

The requirements guidelines show that the development criteria for vehicle architecting constitute an "n-dimensional" problem. The span of design areas can be further broken down into more detailed criteria as information becomes available. During the initial the pre-development process stages, more detailed information is normally available when dealing with a pre-existing architecture platform of cars. In traditional evolutionary design, the previous generation architecture is used as a benchmark along with close competitor's products to justify requirement weighting and prioritization.

In order to define a new mobility concept that breaks from the traditional evolution of a conventional architecture, a closer look at customer profiling (see section 3.4.4) can help prioritize design areas of emphasis. The columns following the criteria in table 7-2 describe a prioritization scheme that shows areas where design emphasis must be placed to meet the needs of a particular customer profile. In addition to the six customer profiles, inner city and outer city customer needs are added to the profiling scheme, as the vehicle is designed to operate in an urban setting.

The prioritization scheme presented in table 7-2 can be further expanded to weigh all sub-criteria independently. The greatest design emphasis in this case study is placed on the "environmentally friendly" and "practical person" customer profiles living within an urban environment. Requirements covering these profiles are thus reinforced by the multiplier weighting scheme found in the top row in table 7-2.

The design should additionally attract other customer profiles which are considered with a lower weighting. The overall score for the prioritization of each requirement is determined by averaging the product of the priority assigned score and the multiplier weight for each profile. Design requirement categories with an overall rounded score of 5 are designated as a high priority, whereas a score of 4 are designated priority requirements and finally a score of 3 or less are designated as low priority requirements.

Table 7-3 shows an exemplary mapping from the customer prioritization profiling scheme to a strategic market positioning guidelines. This mapping was generated in a follow on step to the customer profile analysis. This resulting guideline is used by the manufacturer to define the broad goals of a brand (or line) of cars with respect to competitors or future competitors in the market.

There are three differentiation areas in Table 7-3 that map to the priorities set. Areas of no differentiation require that the vehicle architecture perform as close as possible to the standard offering in the future market. The middle column refers to areas of differentiation where the architecture must be amongst the top 3 offerings in the future market. Finally, the requirement areas of strong differentiation are given extra design emphasis for which the most consumer value is to be generated. These areas are denoted as "best in class" requirements that must top any other offerings in the future market.

Table 7-3 Strategic market positioning of urban vehicle brand against future competitors

Preliminary Vehicle Design Guidelines for an Urban Vehicle Architecture

Requirements	Criteria	Standard or Lesser Value Acceptable standards for a particular vehicle class and segment	Differentiation Measure Within the top 3 main competitors in segment (Better than acceptable standards)	Strong Differentiation Segment Leadership (Benchmark) Best in Segment
E-Drive Use Case	City Driving (0 - 60 km/h)			●
	Highways (60-120 km/h)	●		
	Expressways (80-160km/h)	●		
Performance (Low Velocity)	Response		●	
	0-4 sec acceleration		●	
Performance (High Velocity)	acceleration 0-100 km/h		●	
	maximum velocity		●	
	maximum sustained velocity in 10% grade	●		
Range	Overall vehicle range			●
All Electric Range	All Electric range (one battery discharge)		●	
Catalog Fuel and Emmisions	CO2 Well to Wheel emmisions			●
	European Cycle (CO2 & l/100km Katalogwert)			●
	FTP 72 (CO2 & l/100km Katalogwert)			●
Emissionen	Other Emissions: HC, NOx, CO		●	
Weight	Curb Weight	●		
	Axial Weight Distribution	●		
Comfort	Climate Comfort	●		
	Acustic Comfort			●
	Cargo Load Space Capacity	●		
	Maximal load bearing capacity	●		
	Time to full charge		●	
	Performance reduction at low charge		●	
Costs	Cost of Ownership		●	
	Cost of Operation			●
	Retail Price			●
	Manufacturing costs		●	
Overall System Concept Quality	Vehicle life duration			●
	High temperature performance (>45 deg C)		●	
	Low Temperature performance (< -10 deg C)		●	
	Vehicle Crash Safety			●

With the information provided by the requirements analysis above, a goal oriented design statement can be drafted that identifies preliminary objectives, design variables, parameters and constraints for the pre-selection of vehicle architectures as outlined in section 4.4. The design statement in Figure 7-1 shows a concise design statement for this simplified evaluation case study.

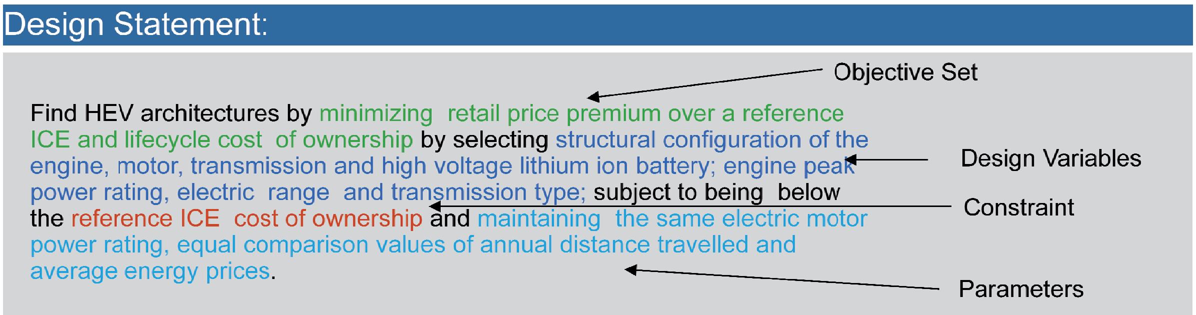


Figure 7-1 Evaluation study design statement including the objectives, key design variables, constraints and parameters taken from optimization theory [DE WECK, OLIVIER et al. 2004b]

The objective set in the design statement can be comprised of multiple objectives, however the more objectives considered the more complex the analysis will be. In this case study, the objective set focuses on minimizing lifecycle costs separating this goal in two parts:

1. *Electrification costs* – defined as the retail price difference between a reference vehicle and those exhibiting an electric or hybrid powertrain

2. *Cost of ownership* – includes all estimated ownership and operation costs for a vehicle architecture selection

The most important overall objective in this case study is selected to be cost, while other goals such as weight, performance in acceleration, fuel consumption, emissions and others are included as design parameters to the model.

Design variables highlighted in Figure 7-1 include vehicle configuration choices based on the structural solution space generated in chapter 5, the engine power rating and the all-electric range. To keep to the current MINI 2010 engine offerings highlighted in Table 7-1, the engine selection is limited to the current 55kW, 72kW and 90kW MINI engine set. The all electric range is designated to 10, 20, 30, and 40 miles - which correspond to 16, 32, 48, 64 kilometers respectively.

The constraints to this analysis involve items that limit the design boundaries and can be expressed as inequalities. In this case, the vehicle architecture under consideration must have less costs of ownership than the reference vehicle within a fixed limit of a 5 or 10 year ownership period.

Finally, some parameters remain fixed throughout the optimization run. In this evaluation study the electric motor power rating is fixed for all vehicles at 45kW sustained power and 70kW peak power as explained in section 7.1.2. Further parameters include the customer's yearly distance traveled (set at 12,000 miles {19,200km}) and energy prices (set at 1.42 Euros per liter and 0.80 Euro cent per kWh). A sensitivity analysis helps observe how strongly the overall objective results are affected when unit changes to parameters are made.

7.1.2 Application of Matrix Analysis

The starting point for the pre-selection of architectures in this study uses a case-based approach with aid of compatibility matrices (see 5.6.4 and 5.6.5). The solution space comprises more than 5450 vehicle configurations linked to 91 requirement choice combinations pertaining to the electric system within the ICE-HEV-BEV spectrum (refer to figures 5-17, 5-21, 5-22).

7.1.2.1 Reduction of the Requirement Choice Set

Determination of electric motor power requirements for the urban vehicle helps refine the solution space. Table 7-2 assigns a high priority to electric driving and overall range. Because battery electric vehicles lack overall range, the future urban vehicle is best served by a hybrid architecture that can perform extended electric driving. A plug-in hybrid vehicle best fits the selection criteria for this particular case. Thus, the requirement choice set of 91 options can be filtered to 24 possible choice combinations that are applicable for PHEVs.

To further filter the requirement set the necessary power requirements are assessed. Figure 7-2 shows the average power requirements necessary for an electrical powertrain system to navigate the key US regulatory city (FTP72) and highway (US06) cycles. These cycles are

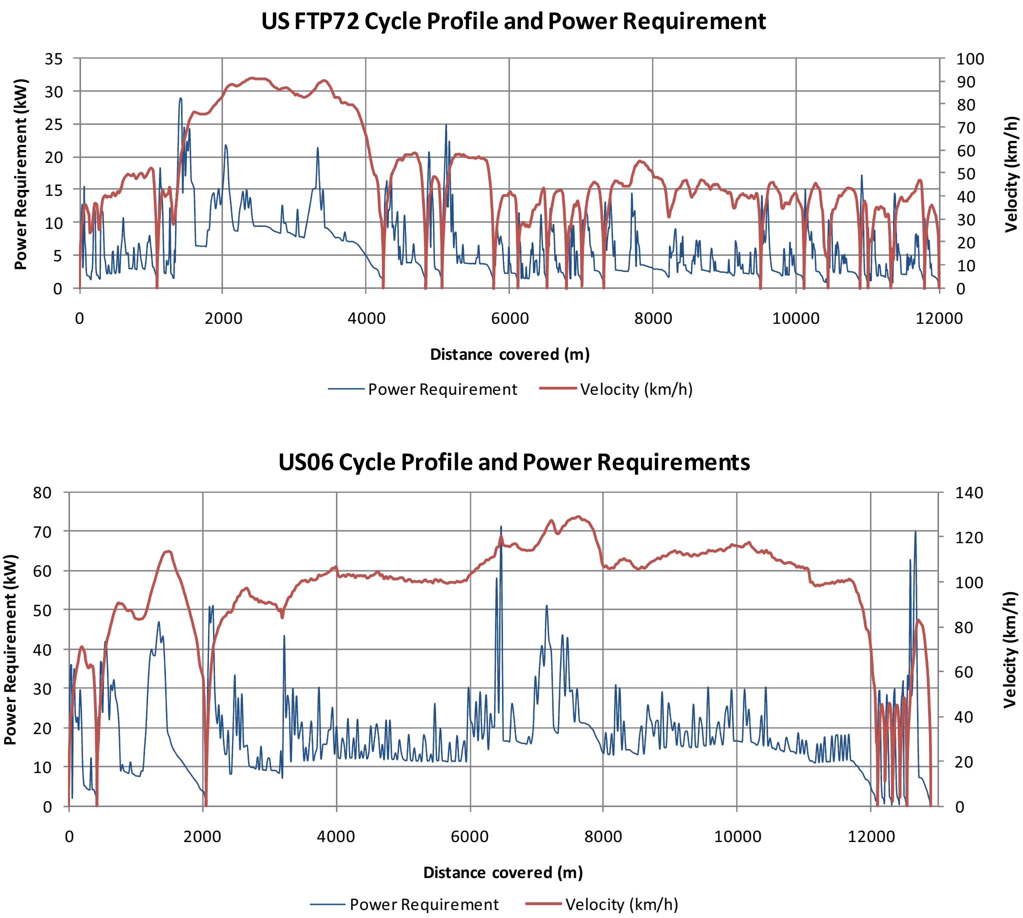


Figure 7-2 Power requirements for the electric powertrain derived from simulations using the FTP72 cycle for city driving and the US06 for highway driving – An electric motor with peak power of 70kW and sustained power of 45kW is suitable for both cycles and is selected for the subsequent analysis.

used as a reference point in dimensioning the electric power train.

The target electric powertrain is dimensioned to drive both regulatory cycles in an “all electric” mode. The cumulative electric power requirement for such a powertrain requires at an electric motor(s) with a peak power of 70 kW, a sustained power output of 45kW and an all electric range of over 13km as given by the information in Figure 7-2. This information is used to further filter the requirement choice set (from Figure 5-22) to a PHEV concept with four possible architectures choices of varying electrical range as listed below:

Table 7-4 Reduction of the requirement choice set yields12 selections from a possible 24 combinations described below by means of compatibility matrix clustering (refer to section 5.6.4)

Concept	Architecture	Electrical Index	All Electric Range in miles (AER)	Power to Energy Ratio (P/E)	Depth of Battery Discharge (%DOD)
PHEV	Through-the-Road	0.3 - 0.8	10 - 20	5 - 10	50 - 70%
	Parallel		20 - 30		
	Combined		30 - 40		>70%
	Series				

In order to enjoy long term economies of scale, the engine selection is assumed to keep to the three engine output sizes of 55kW, 72kW and 90kW currently in production by MINI (see Table 7-1). The electrification index selection requirement can be verified to lie between 0.3 and 0.8. This index is calculated by taking the ratio between the peak required electric power of 70kW and the total overall vehicle power (combustion engine plus electric motor output) yielding values of 0.56, 0.49 and 0.43 respectively.

The selection of an electric range determines the battery energy requirement. The energy requirement is estimated by using the relationship in equation 31:

$$Required\ Battery\ Energy\ (kWh) = \frac{Desired\ Electric\ Range\ (miles)}{(\%DOD)x\ Electric\ Consumption\ \left(\frac{miles}{kWh}\right)} \qquad (31)$$

As an example, if the desired electric range is assumed to be 20 miles, the average electric consumption of 3 miles/kWh, and the battery DOD is set to 65%, the required installed battery energy according to equation 31 results in 10.3kWh of installed battery energy. The ideal power to energy ratio of the battery design can also be calculated assuming that the battery must deliver 15% more power (80kW) than that of the peak electric motor output of 70kW to cover for efficiency losses within the battery and inverter unit. The calculated ideal battery power to energy ratio for this example yields:

$$Calculated\ P/E\ Ratio = \frac{Required\ Battery\ Power\ (kW)}{Required\ Battery\ Energy\ (kWh)} = \frac{80.5\ kW}{10.3\ kWh} = 7.81$$

In practice, the power to energy ratio is set by the battery manufacturer cell type selected for the design. The calculated P/E ratio requirement can help determine which battery cell to purchase from a wide market variety of battery chemistries and configurations (refer to section 4.2.2).

The depth of discharge (DOD) window is an important parameter to determine battery use life as discussed in section 6.5. A DOD window of 65% allows for roughly 2,750 battery charging cycles assuming a lithium ion battery technology good for approximately 5-6 years of use (refer to Figure 6-6).

For the purposes of the follow on design space exploration study, the power to energy ratio is set to 5 and the depth of discharge to 65% for PHEV10 – 20 and 75% for PHEV 30-40 as typical parameters for PHEV and BEV high energy battery cells. The electric index has three variations (0.56, 0.49 and 0.43) as previously explained and the electric range is allowed to vary in four increments of 10 miles (16 km) up to 40 miles (64 km).

7.1.2.2 Reduction of the Structural Choice Set

The structural combinations list is reduced to include only the "concept" field "PHEV" from the morphological matrix logic from Table 5-3. This first filtering step reduces the structural set from 5451 to 2634 valid choice sets.

Next, the architecture field is taken to include only four choices {through the road, parallel, combined and series} in accordance to the requirement set filtering described in Table 7-4. This focused architecture choice set further reduces the number of valid choice selections to 2436.

In order to continue to reduce the selection choice set to a manageable set of less than 100 configurations, several assumptions must be made. For purposes of this evaluation study five further assumptions are made that reduce the structural choice set to only 64 selections:

1. Engines are selected to be placed at the front axle of the vehicle. Hence under the choice field "Engine, Drive" (Table 5-3) front engine placement is selected allowing for both front wheel drive and four wheel drive - all other choices are filtered out.
2. The "engine orientation" field is reduced to only those options where the engine is placed parallel to the axle keeping with the longstanding MINI Cooper tradition.
3. Only "automatic transmissions" are considered
4. The configuration must have at least one electric motor directly mounted in the transmission, one of the axles or as wheel-motors.
5. The "battery placement" selection is set to a "sandwich" placement only.

Table 7-5 shows the resulting choice fields that are available for combination. Only 62 of 288 possible combinations are valid configurations once the compatibility matrix methodology is applied.

Table 7-5 Reduction of the requirement choice set yields62 selections from a possible 288 combinations described below by means of compatibility matrix clustering (refer to section 5.6.4)

1. Concept	**2. Architecture**	**3. Engine Placement**	**4. Engine Orientation**	**5. Engine Transmission**
~~Micro Hybrid~~	Through-the-Road	Front, 4WD	Parallel to axle	~~Manual~~
~~Mild Hybrid~~	Parallel	~~Front, RWD~~	~~Perpendicular to axle~~	Automatic
~~Full Hybrid~~	~~P-Split~~	Front, FWD	~~No Engine~~	CVT/ECVT
PHEV	Combined	~~Rear, 4WD~~		~~No Transmission~~
~~BEV~~	Series	~~Rear, RWD~~		
	~~BEV~~	~~No Engine~~		

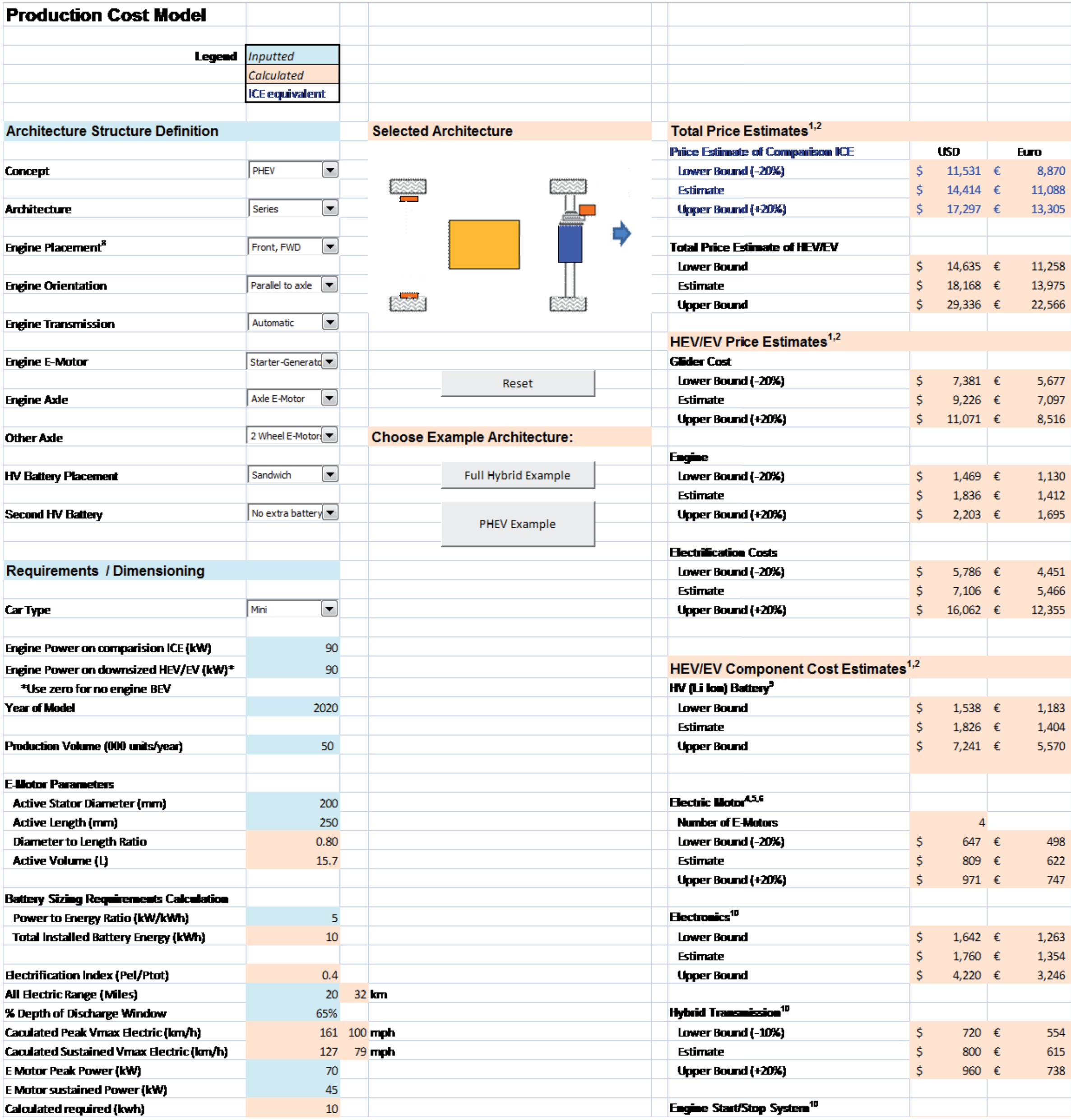
6. Engine E-Motor	**7. Engine Axle**	**8. Other Axle**	**9. HV Battery Placement**
Pre-Transmission	Axle E-Motor	Axle E-Motor	Sandwich
Starter-Generator	2 Wheel E-Motors	2 Wheel E-Motors	~~Drive Axle~~
~~No Engine~~	No E-Motors	No E-Motors	~~Other Axle~~
			~~Tunnel~~
			~~No HV Battery~~

7.1.3 Lifecycle Cost Modeling

The cost model presented in chapter 6 is incorporated in a computer spreadsheet program used to evaluate both the manufacturing and user lifecycle costs. The reduced set of 62 PHEV urban vehicle configurations are examined systematically at electric ranges of 10 miles (16 km), 20 miles (32km), 30 miles (48km) and 40 miles (64km) and with combustion engines of 55kW, 72kW and 90kW peak power. It follows from this information that the total numbers of iterations per optimization run results in a set of 744 combinations (62 x 12).

Figure 7-3 presents an excerpt of the production costs input page of the spreadsheet model. The left hand side of the spreadsheet module uses a series of dynamic drop down menus where the user can select the powertrain configuration. The selection choices present only valid combinations using the compatibility matrix methodology as a logical basis for providing the user choices. As the architecture is selected, a general graphical representation appears under the field “selected architecture” seen in the middle of the figure.

The bottom left portion of the spreadsheet defines architecture requirements used in dimensioning and production cost calculations. To the right from the graphical representation, the total price estimates for the vehicle architecture are calculated and compared to a reference conventional ICE architecture denoted by a blue font. Light blue fields in the spreadsheet represent inputted parameters; whereas the light brown fields represent calculated values. The costing estimates are provided with upper and lower limit bounds resulting from a combination of items with explanatory equations as well as three point estimates (refer to 6.1.3).



Production Cost Model

Legend	
	Inputted
	Calculated
	ICE equivalent

Architecture Structure Definition	
Concept	PHEV
Architecture	Series
Engine Placement[8]	Front, FWD
Engine Orientation	Parallel to axle
Engine Transmission	Automatic
Engine E-Motor	Starter-Generato
Engine Axle	Axle E-Motor
Other Axle	2 Wheel E-Motor
HV Battery Placement	Sandwich
Second HV Battery	No extra battery

Selected Architecture

Reset

Choose Example Architecture:

Full Hybrid Example

PHEV Example

Requirements / Dimensioning		
Car Type	Mini	
Engine Power on comparision ICE (kW)	90	
Engine Power on downsized HEV/EV (kW)*	90	
*Use zero for no engine BEV		
Year of Model	2020	
Production Volume (000 units/year)	50	
E-Motor Parameters		
Active Stator Diameter (mm)	200	
Active Length (mm)	250	
Diameter to Length Ratio	0.80	
Active Volume (L)	15.7	
Battery Sizing Requirements Calculation		
Power to Energy Ratio (kW/kWh)	5	
Total Installed Battery Energy (kWh)	10	
Electrification Index (Pel/Ptot)	0.4	
All Electric Range (Miles)	20	32 km
% Depth of Discharge Window	65%	
Caculated Peak Vmax Electric (km/h)	161	100 mph
Caculated Sustained Vmax Electric (km/h)	127	79 mph
E Motor Peak Power (kW)	70	
E Motor sustained Power (kW)	45	
Calculated required (kwh)	10	

Total Price Estimates[1,2]		USD		Euro
Price Estimate of Comparison ICE				
Lower Bound (-20%)	$	11,531	€	8,870
Estimate	$	14,414	€	11,088
Upper Bound (+20%)	$	17,297	€	13,305
Total Price Estimate of HEV/EV				
Lower Bound	$	14,635	€	11,258
Estimate	$	18,168	€	13,975
Upper Bound	$	29,336	€	22,566

HEV/EV Price Estimates[1,2]				
Glider Cost				
Lower Bound (-20%)	$	7,381	€	5,677
Estimate	$	9,226	€	7,097
Upper Bound (+20%)	$	11,071	€	8,516
Engine				
Lower Bound (-20%)	$	1,469	€	1,130
Estimate	$	1,836	€	1,412
Upper Bound (+20%)	$	2,203	€	1,695
Electrification Costs				
Lower Bound (-20%)	$	5,786	€	4,451
Estimate	$	7,106	€	5,466
Upper Bound (+20%)	$	16,062	€	12,355

HEV/EV Component Cost Estimates[1,2]				
HV (Li Ion) Battery[3]				
Lower Bound	$	1,538	€	1,183
Estimate	$	1,826	€	1,404
Upper Bound	$	7,241	€	5,570
Electric Motor[4,5,6]				
Number of E-Motors		4		
Lower Bound (-20%)	$	647	€	498
Estimate	$	809	€	622
Upper Bound (+20%)	$	971	€	747
Electronics[10]				
Lower Bound	$	1,642	€	1,263
Estimate	$	1,760	€	1,354
Upper Bound	$	4,220	€	3,246
Hybrid Transmission[10]				
Lower Bound (-10%)	$	720	€	554
Estimate	$	800	€	615
Upper Bound (+20%)	$	960	€	738
Engine Start/Stop System[10]				

Figure 7-3 Excerpt of a spreadsheet calculation tool for production costs based on the cost modeling equations presented in chapter 6. The model takes an architecture configuration and component requirement sizing as input on the left hand side to estimate pricing and manufacturing costs on the right.

The example presented in Figure 7-3 is that of a Plug-in electric vehicle, in a series configuration with two wheeled electric motors in the rear axle. The vehicle is given a production volume of 50,000 units per year as a basis for its component cost estimation and is designed for 20 miles (32km) electric driving per charge. The estimated costs of additional electrification components for this example amount to $7,106 (or 5,466 Euros at and exchange rate of 1.3 dollars per euro).

The costs of ownership and operations are further calculated by the spreadsheet program following the cost model in section 6.2.3. Figure 7-4 shows a screenshot of the model's input parameters such as year of purchase, year of sale, yearly vehicle distance travelled, percent

User Cost Model

Legend	
	Inputted
	Calculated
	ICE equivalent

User Information			
Year of Purchase	2020		
Year of Sale	2040		
Yearly Vehicle Miles Traveled	15,000	24,000	km
Number of Days Driven per Year	290		
Average Miles per Daily Drive	52		
Percent City Miles Traveled	80%		
Percent Highway Miles Traveled	20%		
Electric Range (km)	32.0		
Percentage Electric Driving	48%		

Government/State	
Inflation Rate	3%
Value Added Tax (VAT) - Sales Tax	19%
One time Government Incentive	$ 2,500
Yearly Government Incentive	$ 150
Yearly Tolls Saved	$ -

Financing		
Payment Start Date	2/1/2020	
Percent Down Payment	10%	
Down Payment (HEV/EV)	$ 4,748	€ 3,652
Principal to Finance (HEV/EV)	$ 42,729	€ 32,869
Down Payment (ICE)	$ 3,744	€ 2,880
Principal to Finance (ICE)	$ 33,696	€ 25,920
Annual Interest Rate	4%	
Number of Years	4	
Number of payments per year	12	
Optional Extra Payment (cost per period)	0	

Fuel Consumption Costs			
Cost of Electricity ($ per kW hour)	$ 0.21	€ 0.16	Euros per KWh
Cost of Fuel ($ per gallon)	$ 6.00	€ 1.21	Euros per Liter
Fuel Consumption City (MPG) for ICE	18	13.07	l/100km
Fuel Consumption Highway (MPG) for ICE	28	8.40	l/100km
Fuel Consumption City (MPG)	25	9.41	l/100km
Fuel Consumption Highway (MPG)	36	6.53	l/100km
Electric Consumption City (miles/kWh)	4.11	6.61	km/kWh
Electric Consumption Highway (mi/kWh)	2.49	4.00	km/kWh

Extra HV Battery	
Battery Use Life (Cycles)	2,500
% Depth of Discharge	65%
Mileage to Replacement (Miles)	63,098
Battery Replacements Required	4
Years until Replacement is Required	4

Simulation Input Figures			
Cw	0.33		
Frontal Area (m2)	1.97		
Rolling Friction	0.01		
Electrical Accessories Load	350		
Efficiency DC/DC	0.97		
Glider Curb Weight (Kg)	1000		
+ Engine Weight	188		
+ Battery Weight	82		
+ mechanical 4WD components	0		
+extra auto transmission	0		
+ Electric Motor(s)	80		
+ other electric components	20		
Total Weight	1369		
Mini one (55kw) Catalog Curb weight (kg)	1135	2497	lbs
Mini one (72kw) Catalog Curb weight (kg)	1135	2497	lbs
Mini Cooper (90kw) Catalog Curb weight (kg)	1140	2508	lbs
Specific Energy req for MINI FTP72 (Wh/tkm)	110.4		

Comparison ICE MSRP[2]	USD	Euro
Price Estimate	$ 14,864	€ 11,434
Additional Overhead, Mark-up estimate:	60%	
MSRP	$ 23,783	€ 18,295
Costs of Ownership		
Inflation and VAT at time of purchase	$ 13,657	€ 10,505
Financing Cost	$ 2,188	€ 1,683
Depreciation Cost	$ 24,180	€ 18,600
Annual Fuel Cost	$ 4,643	€ 3,571
Total Fuel Cost	$ 92,857	€ 71,429
Total Cost of Ownership (Comparison ICE)		
Cost at time of Purchase	$ 37,440	€ 28,800
Yearly costs	$ 5,961	€ 4,586
Total Cost of Ownership	$ 156,665	€ 120,511
Years of Ownership	20	

HEV/EV MSRP[2]	USD	Euro
Price Estimate	$ 18,168	€ 13,975
Additional Overhead, Mark-up estimate:	66%	
MSRP	$ 30,159	€ 23,199
Delta Retail (no tax)	$ 6,376	€ 4,905
Costs (Gains) of Ownership		
Inflation and VAT at time of purchase	$ 17,318	€ 13,322
Financing	$ 2,892	€ 2,224
Depreciation	$ 30,662	€ 23,586
Annual Fuel Cost	$ 1,763	€ 1,356
Total Fuel Cost	$ 35,253	€ 27,117
Annual Electricity Cost	$ 415	€ 319
Total Electricity Cost	$ 8,291	€ 6,378
One-time Government Incentive	$ (2,500)	€ (1,923)
Yearly Gov't Incentive and tolls saved	$ (150)	€ (115)
Total incentives and tolls saved	$ (3,000)	€ (2,308)
Battery Replacement Cost	$ 7,302	€ 5,617
Total Cost of Ownership (HEV/EV)		
Cost at time of Purchase	$ 44,977	€ 34,598
Yearly costs	$ 3,705	€ 2,850
Total Cost of Ownership	$ 126,376	€ 97,213
Years of Ownership	20	
Additional Cost of Ownership: HEV/EV vs ICE		
Year of Purchase	$ 7,537	€ 5,798
Yearly Costs	$ (2,256)	€ (1,736)
Year of Sale	$ (30,288)	€ (23,299)

Years to Break Even (Cost in Euros)

Year	Cost of ICE	Cost of HEV	Delta Cost
1	€ 28,800	€ 34,598	€ 5,798
2	€ 33,385	€ 37,448	€ 4,062
3	€ 37,971	€ 40,298	€ 2,327
4	€ 42,557	€ 48,764	€ 6,208
5	€ 47,142	€ 51,614	€ 4,472
6	€ 51,728	€ 54,464	€ 2,737
7	€ 56,313	€ 57,314	€ 1,001
8	€ 60,899	€ 60,164	€ (735)
9	€ 65,484	€ 63,014	€ (2,471)
10	€ 70,070	€ 65,864	€ (4,206)
11	€ 74,656	€ 68,714	€ (5,942)
12	€ 79,241	€ 71,564	€ (7,678)
13	€ 83,827	€ 74,414	€ (9,413)
14	€ 88,412	€ 77,263	€ (11,149)
15	€ 92,998	€ 80,113	€ (12,885)
16	€ 97,584	€ 82,963	€ (14,620)
17	€ 102,169	€ 85,813	€ (16,356)
18	€ 106,755	€ 88,663	€ (18,092)
19	€ 111,340	€ 91,513	€ (19,827)
20	€ 115,926	€ 94,363	€ (21,563)

Years to Break Even (Cost in USD)

Year	Cost of ICE	Cost of HEV	Delta Cost
1	$ 37,440	$ 44,977	$ 7,537
2	$ 43,401	$ 48,682	$ 5,281
3	$ 49,362	$ 52,387	$ 3,024
4	$ 55,324	$ 63,394	$ 8,070
5	$ 61,285	$ 67,099	$ 5,814
6	$ 67,246	$ 70,803	$ 3,557
7	$ 73,207	$ 74,508	$ 1,301
8	$ 79,169	$ 78,213	$ (955)
9	$ 85,130	$ 81,918	$ (3,212)
10	$ 91,091	$ 85,623	$ (5,468)
11	$ 97,052	$ 89,328	$ (7,724)
12	$ 103,014	$ 93,033	$ (9,981)
13	$ 108,975	$ 96,738	$ (12,237)
14	$ 114,936	$ 100,442	$ (14,494)
15	$ 120,897	$ 104,147	$ (16,750)
16	$ 126,859	$ 107,852	$ (19,006)
17	$ 132,820	$ 111,557	$ (21,263)
18	$ 138,781	$ 115,262	$ (23,519)
19	$ 144,742	$ 118,967	$ (25,776)
20	$ 150,704	$ 122,672	$ (28,032)

Figure 7-4 User cost model based on section 6.2.3. The model calculates the years to break even by comparing the costs of ownership of the new architecture to that of a reference vehicle for a defined period of use. In the example above, 7 years are required to amortize the difference in retail price of $7537.

city and highway usage, government incentives and taxes, simulation input figures and fuel consumption costs presented on the left hand side. The reference vehicle information is presented in the center section and the cost of ownership results on the right.

The cost of ownership model relies on a backwards calculating simulation embedded in the spreadsheet. The model determines the fuel consumption figures based on a vehicle weight calculation. The more weight that is calculated to the powertrain, the larger the installed battery energy required. Also, the use of multiple electric motors results in additional weight to the calculation. The overall vehicle weight is thus a function of the architecture configuration and the dimensioning of the powertrain components within it.

The fuel consumption simulation is separated into two components, the charge depleting mode and the charge sustaining mode. The values for the charge depleting mode is based on electric driving energy usage based on the FTP72 cycle for city driving and the US06 cycle for highway driving presented previously in Figure 7-2. The charge sustaining mode uses the MINI cooper current fuel consumption values for 2010 vehicles already outfitted with the start-stop and regenerative braking functions as a first order estimate.

7.2 Selecting Architecture Concepts for Further Development

The pre-selection of architecture concepts entails the screening of 744 selections using a systematic optimization approach alluded to in sections 4.4, 6.4 and 7.1. A computer program recorded the 10 year and 5 year cost of ownership of each iteration run as well as the retail price premium of each architecture over the reference ICE architecture – the reference case is a MINI Cooper with 90kW peak power engine shown in Table 7-1 column 4. These values comprise the objective elements to be minimized.

Table 7-6 Cost model optimization objective, design variables, parameters and constraints

Objectives	**Parameters**	
Minimal Retail Price Premium over ICE	Production Volume = 50,000 per year	Cost of Electricity = $0.21 per kWh (0.16 Euro per kWh)
Minimal Cost of Ownership and Operation	Year of Purchase = 2020	Cost of Fuel = $7 per US gallon (1.42 Euro per liter)
(Measured at 5 yrs, at 10 Yrs)	Year of Sale = 2030 (for 10 yr Cost of Ownership Analysis)	Depth of Discharge = { 65% for El. Range of <= 20 mls; 75% for El. Range of > 20 mls}
Design Variables	Year of Sale = 2025 (for 5 yr Cost of Ownership Analysis)	Reference Vehicle City Fuel Consumption (Gasoline Engine in FTP72) = 18 MPG (13 l/100km)
62 different vehicle configurations on 9 selection c	Electric Motor(s) Peak Power = 70kW	Reference Vehicle Highway Fuel Consumption (Gasoline Engine in US06) = 28 MPG (8 l/100km)
- Concept = PHEV	Electric Motor(s) Sustained Power = 45kW	Urban Vehicle Charge Sustaining City Fuel Consumption (Gasoline Engine in FTP72) = 25 MPG (9 l/100km)
- Architecture = {TTR; Parallel; Combined; Series}	Glider Curb Weight = 1000kg	Urban Vehicle Charge Sustaining Highway Fuel Consumption (Gasoline Engine in US06) = 36 MPG (6.5 l/100km)
- Engine Placement = { Front, 4WD; Front FWD}	Vehicle Miles Travelled = 15000mls per year	Battery Use Charging Cycles = {2500 for 75% DOD; 2750 for 65% DOD}
- Engine Orientation = Parallel to axel	Percent City Driving = 80%	Drag Coefficient Cw = 0.33
- Engine Transmission = {Automatic; CVT/ECVT}	Percent Highway Driving = 20%	Frontal Area (m2) = 1.97
- Engine E-Motor = {Pre-Transmission; Starter-Generator}	One time Government incentive for PHEV = $2500	Rolling Friction = 0.01
- Other Axel = {Axel E-Motor; 2 Wheel E-Motors; No E-Motors}	Yearly incentive for PHEV = $150	Electrical Accessories Load = 350 W
- Engine Axel = {Axel E-Motor; 2 Wheel E-Motors; No E-Motors}	Value added tax = 19%	
- HV Battery Placement = Sandwich	Inflation Rate = 3%	
Engine Peak Power = {55kW; 72kW; 90kW}	Percent Down Payment = 10%	
Electric Range = { 10 mls, 20 mls, 30mls, 40mls}	APR on financing loan = 4%	
	Years of Financing = 4yrs	
Constraints	Number of Payments per year = 12	
Cost of Ownership and Operation (COO) <= Reference ICE Vehicle COO	Exchange rate USD to EUR = 1.3	

Table 7-6 shows a comprehensive optimization description based on the elements being modeled. This table builds upon the design statement from Figure 7-1.

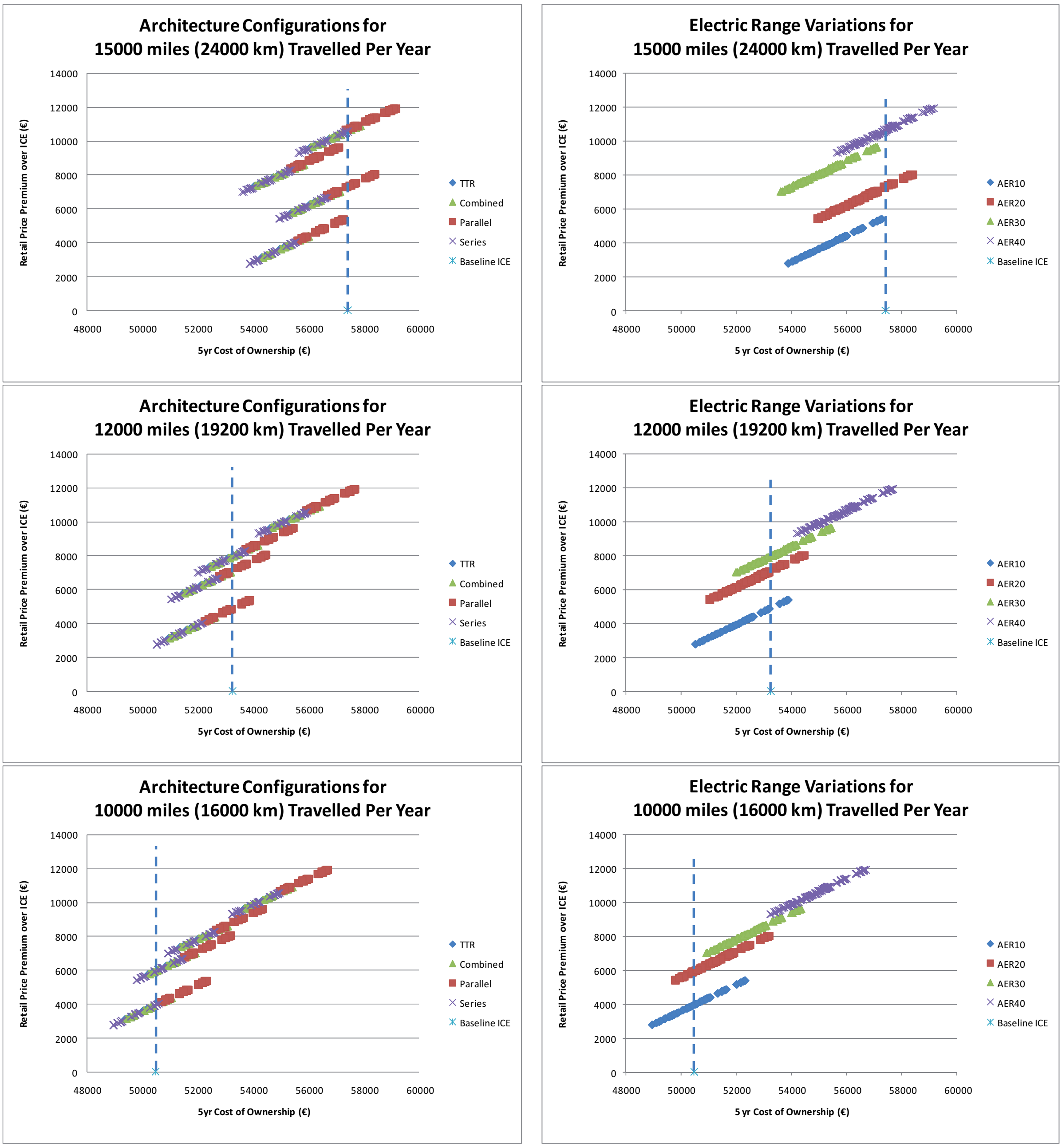


Figure 7-5 Scatter plot optimization results for the 744 variations by plotting 5yr Cost of Ownership (x-axis) versus retail price premium over reference ICE vehicle – all figures in Euros. Only the architectures left of the reference vehicle vertical dotted line achieve payback within 5 years of ownership.

The dominant solutions in the design space shown in Figure 7-5 are those architectures that have both the lowest retail price premium and the lowest 5 year cost of ownership values (lower left corner). The objective space entails solutions that exhibit lower costs of ownership than the reference vehicle - the sole constraint listed in table 7-6. These architectures are found left of the vertical dashed line that represent the costs of ownership of the reference IC engine vehicle.

Optimization results in Figure 7-5 highlight both architecture selection (left column charts) and the electric range variation (right column charts). The design space exploration is done by changing the distance travelled parameter to take on values of 10, 12, and 15 thousand miles (16, 19.2, and 24 thousand kilometers per year respectively) for a total of three optimization runs. The parameter for price of fuel is set to 1.42 Euro per liter ($7 per gallon) and electricity costs at 0.16 Euros per kWh ($0.21 per kWh) throughout the optimization. These prices are conservatively low for 2020 projections considering that they are equivalent to European market prices during the summer of 2010.

The design space results presented are in concurrence with earlier data presented in chapter 6. The number of eligible architectures in the design space increase with the annual distance travelled. In principle, the more the customer drives the PHEV, the larger the savings accumulate in comparison to the reference vehicle. These savings allow for a quicker payback of the initial retail price premium paid for electric powertrain components. However, it is important to highlight that any technological improvements to fuel consumption of the reference ICE that are not related to hybridization would shift the vertical blue line in Figure 7-5 to the left.

Designs set to a larger electric range capability exhibit larger retail cost premiums directly related to larger battery costs. The size of the battery also affects overall vehicle weight. Large battery systems were found to have an adverse effect on cost of ownership with lower consumption efficiency despite the extended electric range capability. The effects of weight on the costs of ownership follow a linear relationship due to the discrete nature of the variable combinations modeled. Figure 7-5 shows a linear upwards trend for each electric range category between 10 miles and 40 miles.

In all cases, vehicles with an electric range of 10miles (16km) were found to have the highest payback rates within the first 5 years of ownership due to the lower retail price premium involved. A smaller battery is better for keeping the manufacturing costs low while still delivering great cost of ownership value throughout the ownership lifetime. The 20 mile (32km) PHEV concepts were found to be competitive in the 12000 miles (19200km) yearly distance travelled cases. Likewise, the 30mile (48km) electric range PHEVs offer very competitive cost of ownership for the 15000 miles (24000km) driven per year case. Finally, vehicles with 40 miles (64km) electric range seemed to be over dimensioned for the distances travelled in this study. This finding shows that there is value to the customer by tailoring the battery size to the expected usage or daily/annual commute expected. Not using the energy capacity stored in the battery completely results in lesser value to the customer.

The left column charts in Figure 7-5 suggest that architecture selection also affects cost of ownership and retail price premium. Particularly, parallel hybrid systems tend to be more expensive to manufacture and lead to higher costs of ownership. The calculations show that parallel hybrids exhibit higher overall weight particularly when the electric motors are placed within the transmission box ahead of the transmission.

Series hybrid configurations were found to be the least expensive to manufacture and own. The manufacturing cost efficiencies can be explained from the simplicity in design. In a series hybrid configuration, the traditional ICE transmission is not necessary in the design. Instead simple reduction gears or planet gear ECVTs are enough in this particular structural design. These savings translate to a lower retail price and reduced costs of ownership. Finally, the through the road and combined architectures generate attractive results that lie between the series and parallel dichotomy.

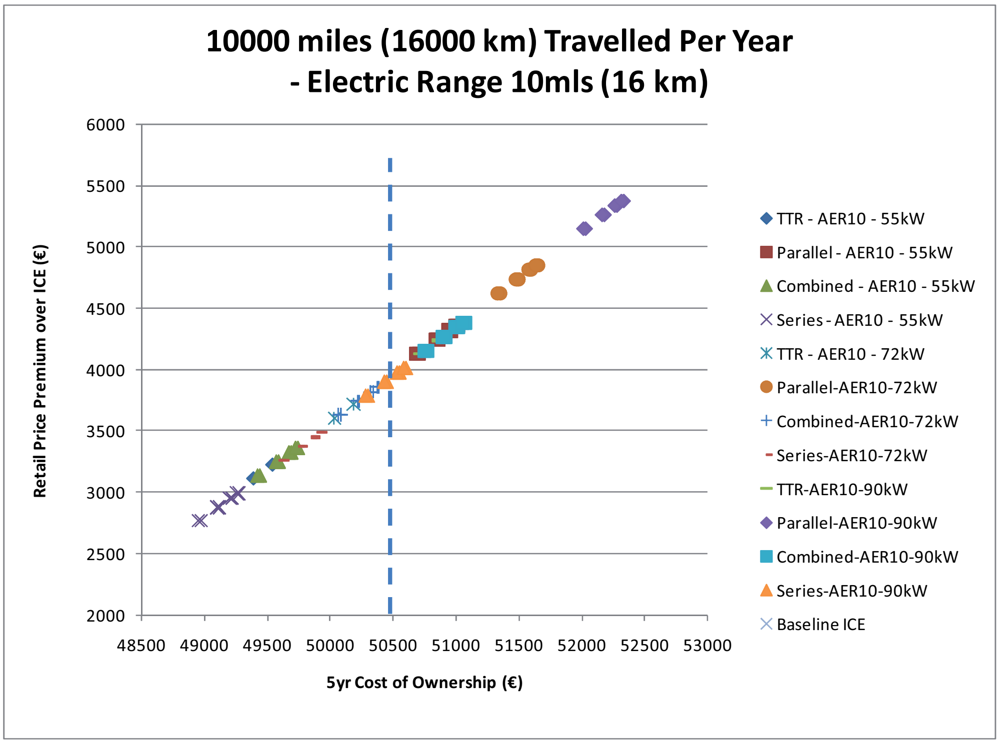


Figure 7-6 Optimization results for vehicle architectures with 10 miles (16km) electric range at 10000 miles travelled per year showing architecture and IC engine selection.

Figure 7-6 presents a more detailed depiction for the 10000 annual driven miles (16000km) case, specifically for PHEV architectures with 10 miles (16km) electric driving range per charge. These architectures are further classified by type and IC engine power size. The dominant designs in this particular case are found to be series hybrids with a 55kW engine. Whereas the least favorable designs in this category are parallel hybrid configurations with a 90kW engine. These results reinforce the disadvantages of hybrids that oversize power requirements to customer use and fail benefit from simplicity in design when merging the electric and combustion engine powertrains.

An interesting result in Figure 7-6 is finding that series hybrid configurations with larger 72 kW engines dominate parallel hybrid configurations with smaller 55 kW engines. Similar occurrences can be seen when comparing series and parallel architectures with 90kW and 72kW engines. This demonstrates that simpler architecture structures bring more value than engine downsizing. Hybrid configurations with simple "through the road" structures, where one axle is powered by the combustion engine and the other powered by the electric system, are found to achieve the second-best overall results. Combined hybrid architectures that can deliver both a series and parallel hybrid mode through a simple coupling mechanism also rates comparably well with the through the road architecture configurations.

The overall results of this case study suggest that series, combined and through the road hybrids with high electrification ratios but with a moderate electric range of 10 miles (16km) are best suited for designs where the customer is expected to travel 10,000 to 15,000 miles per year. The payback periods for these vehicles are within 5 years of ownership compared to the reference architecture.

7.3 Evaluation Study Summary

The evaluation case study serves as an example of how cost modeling, case based architecture synthesis, and optimization theory can be applied to facilitate the pre-selection of a future urban vehicle. The scenario is specifically developed to reflect many technical choices and uncertainty facing engineers during the early development process when addressing a completely new product that lacks an evolutionary development history.

The combination of detailed cost and vehicle architecture information are rarely available during the pre-development stages. At this early stage, design freedom is available at relatively low costs compared to changes later on in the development process. This evaluation study shows how early estimation of cost can be tied to product architectures in order to facilitate filtering out dominated solutions during early decision making.

The methodology presented in this case study follows many of the system architecting principles described in section 4.1. The need for a new product begins with the customer’s needs and organizing customer requirements. Not all customers are similar. Therefore, conscious selection criteria for customer profiles similar to table 7-2 help focus the early engineering requirements identification effort. These requirements are then prioritized and translated to technical design considerations that begin to develop what functionality the product is intended to accomplish.

The development of a design statement that incorporates the key elements in optimization theory further defines the design objective at this stage. This particular case study placed emphasis in lifecycle cost minimization with the goal is to maintain manufacturing costs in check while providing tangible value to the user.

Compatibility matrices revisited from chapter 5, are used to establish a choice field generated from a collection of design configurations. In section 7.1.2, the choice field is reduced by filtering out choices that fail to meet the requirements developed for the urban vehicle case study. A plug-in hybrid structure was ultimately selected to address the need for electric driving capability, without compromising the overall travelling range comparable to a conventional ICE car. Further choice field reductions were accomplished by educated assumptions that help manage this n-dimensional problem to a reduced set of parameters.

Finally, the concept selection follows from the optimization results. Because the evaluation case study is generated using discrete design variables, the results are useful in generating a feel for parameter sensitivity. Further optimization work can be carried out by analyzing continuous design variables within ranges that seem promising – refer to the continuous optimization presented at the end of chapter 6.

8 Summary and Outlook

In this concluding chapter, the results obtained throughout this research are briefly reviewed. The discussion outlines the research goals as well as the contributions to research and industry.

8.1 Research Goals and Contributions

Given the current re-introduction of electric based vehicle architectures in the automotive market, the goal of this research work entailed three areas. First, is the analysis of boundary conditions affecting this fundamental market change. Second, is the exploration of possible architectural configurations in the hybrid-electric vehicle product space. Third, the development of a methodology to link lifecycle cost analysis for these vehicle structures early on in the product development cycle to aid in pre-selection of vehicle concepts.

The contributions of this research specifically focus on the automotive market. However, the methodologies used within this automotive framework can also be applied to any product facing architectural competition, be it in an early product introduction phase or as in the case of the automotive industry, following the reinvention of a mature product.

Goal 1 – Analysis of Boundary Conditions in a Shifting Product Market

The analysis presented in chapters 1-3 address the many factors affecting the development of new electric based vehicle architectures. In chapter 1 the various pathways from energy primary sources to vehicle architectures are discussed to establish a framework to focus on the hybrid electric vehicle realm.

Central to this discussion is the definition of vehicle architectures building on the traditional views of product and system architecture from ULRICH, K. T. 1995, PAHL et al. 2006, LINDEMANN, UDO 2007 and others authors cited in chapter 2. The s-curve depiction of how car architectures have entered the market for more than a century shows that the automotive industry already faced architectural competition in its early history. The result of that competition was the establishment of a dominant architecture, the internal combustion engine car.

The factors affecting architectural change discussed in chapter 3 address the changing nature of design boundary conditions that challenge the dominant architecture. These factors include environmental considerations, government regulations, competitors in the market, car buyers preferences, and the manufacturing firm's own business strategy. These factors can also apply to any shifting product market.

Contributions to Research and Industry – The discussion in chapters 1-3 show two primary contributions: the historical representation of architectural competition and the development of a system dynamics model to simulate hybrid and electric vehicle adoption in the market. The first contribution culminates with figure 2-8, depicting architectural competition in a historical frame of reference. This figure, presented for the first time in GORBEA et al. 2008, indicates that complex product architectures evolve in performance following an S-shaped path that is in agreement with the established technological innovations lifecycle theory. The discussion in chapter two highlights the possibilities to extend the life of an existing architecture by incorporating technological advances of other competing architectures types or elements thereof. Another novel idea is that risk to automakers increases during periods of architectural competition by the mere fact that it is uncertain which architecture will ultimately prevail. This architectural risk affects all other risks including strategic, market and functional risk.

The second contribution is the development of a system dynamics model to simulate vehicle architecture adoption. This is a more practical contribution that is relevant to industry professionals. The simulation model is built by linking many of the factors discussed in chapters 1-3 into a mathematical model using the system dynamics methodology. The links within each element in the model are explained in the equations found in appendix 9.1.

An example simulation is presented in section 3.5.3 by applying the system dynamics methodology step by step according to FORRESTER 1994. The simulation is meant to model the US light duty market to determine the potential market adoption of hybrid and electric vehicles. The results of the simulation are in line with studies from various sources presented in Figure 3-12, which predict that by 2020 the US market will have close to 15% of new vehicle offerings involving some level of hybridization and a small offering of electric vehicles below roughly 6% of the market.

The system dynamics methodology presented serves as a practical example to this research. Similar simulation modeling can be applied to model the dynamics of other complex product markets.

Goal 2 -Case-based, matrix modeling analysis of vehicle architecture configurations

This second objective stems from the research question: Can fundamental analysis of links between functions and components lead to a methodology that enables the generation of a cased-based synthesis scheme of valid vehicle architectures?

The research presented in chapter 5 achieves the development of a large structural solution space of vehicle powertrain architecture configurations that follows a discrete case-based approach. The basis of this methodology stems from basic system architecting principles and system engineering methodologies discussed in chapter 4. Important knowledge on hybrid electric powertrains, terminology and configurations discussed in section 4.2 is a necessary building block for the case-based analysis in follow on chapters 5-7.

Contributions to Research and Industry – The main contribution to research in chapter 5 is the novel application of DSM and MDM analysis to represent vehicle architecture links between functions and components. Once the MDM matrix representation is established as a form of abstracting vehicle architecture structures, matrix manipulations such as delta MDMs and sigma MDMs show how information can be collected to support a more generic case-based synthesis approach.

The delta MDMs are used to show point differences between two architecture structures, whereas the sigma MDM is used to aggregate cases of links between functions and components. The latter method generates a key contribution, namely the "sigma design mapping matrix." This DMM can be transformed to a binary matrix that has information of all possible combinations between functions and components documented across all cases considered. This newly formed matrix can be used in the calculation of either the functions DSM or components DSM; given either one is readily available. This contribution to research can be applied to any product architecture family.

The study of links between functions and components leads to information used in establishing a compatibility matrix. The compatibility matrix first suggested by HELLENBRAND et al. 2008, is used as a way to develop a solution space of valid architecture cases and is a further development of Zwicky's morphological matrix methodology. The clustering of the compatibility matrix using DSM clustering algorithms is used in finding valid combinations. Hellendbrand's methodology is validated to generated 5451 architectural combinations of vehicle architectures out of more than 290,000 possible combinations within the morphological matrix (see section 5.6).

The same methodology is applied to a broad set of requirements relevant to electric powertrains successfully. This application can be a valuable contribution in the field of requirements management. The self-developed concept of adding linear linking selection between requirements and structural configurations enabled the creation of a filter to the large structural solution space of valid architecture cases. The evaluation case study shows how the knowledge collected in the compatibility matrices can be applied in a practical design example.

Goal 3 – Incorporation of early lifecycle cost modeling of future architectures

A common observation in the development of new product architectures is the fact that not all configurations can show a financial benefit across their lifecycle when referencing a base architecture. The problem is that a lifecycle cost analysis normally stems from experience within a product market, where fact and figures can be readily extracted. The ability to model and estimate lifecycle costs early in the product development cycle can assist in early pre-selection of concepts. The motivation of this research goal was to develop a means to link the architectural solution space to a lifecycle costing modeling scheme early enough in the development process to allow for the pre-selection of the more promising architectures.

Chapter 6 builds upon established lifecycle cost theory and provides a practical modeling scheme that can be applied for early cost estimation of vehicle architectures. The elements of the model including the manufacturing cost model, the calculation of capital costs and the user costs are applicable not only to vehicles, but to other product architectures as well. The discussion presented in section 6.1.3 is particularly meaningful in developing awareness of the sources of uncertainty that limit the model's accuracy in the early development stages. Finally, the practical example in section 6.4 and the case study in chapter 7 provide examples of how the pre-selection of dominant architectures can be achieved using the tools developed.

The optimization terminology and methodology presented section 4.4, section 6.4 and 7.2 are well known in academia, however, their transfer to industry is rare. The principles of optimization according to known references such as DE WECK, OLIVIER et al. 2004b, PAPALAMBROS et al. 2000 need to be better understood and utilized by industry's product architects.

Contributions to Research and Industry – The contributions to research and industry is the documentation of practical example case studies of cost modeling for a complex product. A number of methods including linear regression, multiple variable linear regression, 3 point estimation, backwards calculation, analogy costing, and other schemes known in the cost estimation literature are applied to vehicle architecting in the chapters 6 and 7. The value of this contribution comes in providing a means to develop an early estimation of cost versus benefit for product architecture concepts. The practical applications of these ideas are not limited to vehicle architectures, but the development of products in general.

8.2 Outlook

Despite the advances in this work, some items remain unsolved and represent opportunities for future research.

The research presented here is limited to the hybrid electric vehicle and battery electric vehicle cases. The exploration of fuel cell electric and other alternative vehicle architectures including the architectural variations of other flexible fuel constructs can be a topic of further research.

As this work concludes, hybrid cars approach a decade of use, particularly models such as the Toyota Prius and the Honda Insight. Little is known about how robust the electrical components of these vehicles have stood the test of time and use. Information on battery longevity, maintenance costs and other costs of ownership can know be collected and measured with exactness and provided as input to the costing model presented in chapter 6.

In contrast, many new component systems such as lithium ion battery chemistries are still under development and are far from reaching a steady state as far as performance, quality and costs are concerned. The follow on cost tracking of these key electric powertrain items needs to be ongoing and can be used to refine the calculations presented in this work.

Many of the architectural combinations presented here as valid combinations are also areas for further study. Promising examples within the plug-in electric vehicle category are the "through the road" hybrid architectures where the one axle is dedicated to the electric system and another to the combustion engine system. Plug-in series hybrid architectures are already in development and the first mass produced lines of cars are expected to enter the market concurrent to the publication of this work. Further research can be applied to develop a system of metrics that can relay information on the pros and cons of incorporating a particular architectural structure.

The matrix based product architecture representation using DSMs and MDM is far from reaching maturity. The methodologies presented here show merely the beginning of these efforts within an international research community that continues to explore the areas of complexity management. Further research to the matrix based representations shown here can include the ability to go up and down levels of abstraction within the architecture model representation of the MDM.

The compatibility matrix, DSM and MDM approach also require further development to allow for non-linear linkages. In an n-dimensional space, not all selections can be represented as a binary link between two elements. Conditional links exist in relationships between elements that are difficult to assess with the matrix based methods presented here. This is a topic of ongoing research within the DSM community.

A final promising field of research comes in developing a link between simulation of complex systems and the modeling of complex system structures. In principle, simulation such as the system dynamics model in section 3.5.3 provides a method to analyze how a system structure behaves through time. MDM modeling in section 5.1.3 looks at structural configuration of complex systems across multiple domains at a fixed point in time. There is a potential to extract benefit in combining these methodologies to analyze how changing a complex system structures can produce changes to the system dynamics.

9 Appendix

9.1 Vehicle Performance Data for Lifecycle S-Curve Calculation

The data listed below on power, weight, fuel consumption and price was collected primarily from the www.conzeptcars.com database. This list was used to create the performance index using equation 1. The plotted results can be seen in Figure 2-7 on page 29. In some cases, general open-source internet research was used to fill in the gaps in the database.

Architecture	*Year*	*Make*	*Model*	*Nominal MSRP ($)*	*Real MSRP (2008 $)*	*Weight (lbs)*	*Power (HP)*	*Power to Weight (hp/lbs)*	*Vmax (mph)*	*L/100km*	*Performance Index Score*
ICE	1885	Benz	Motorwagen	400	15172	400	0.8	0.0020	8	47.0	0.28
ICE	1896	Burnard Jartfer	Quadricycle	200	5480	500	4	0.0080	8	58.8	0.27
ICE	1896	Ford	Quadracycle	450	12331	410	4	0.0098	18	58.8	0.28
ICE	1897	Panhard	ET Levassor	1130	30061	520	4	0.0077	15	58.8	0.23
ICE	1899	Winton	Motor Carriage Phanteon	1000	25076	500	6	0.0120	15	58.8	0.25
Steam	1899	Locomobile	Stanhope Style I	600	15046	640	2	0.0031	20	29.4	0.39
Steam	1900	Stanley	Runabout	750	18259	640	2	0.0031	20	23.5	0.41
ICE	1900	Benz	Duc vis-à-vis Victoria	1050	25563	600	6	0.0100	15	29.4	0.37
ICE	1901	Packard	Model C Runabout	1500	35455	700	12	0.0171	15	29.4	0.37
ICE	1901	Oldsmobile	Surrey	2200	52000	435	6	0.0138	15	15.7	0.38
ICE	1901	Knox	Model A Runabout	485	11464	600	10	0.0167	35	29.4	0.47
Steam	1901	Foster Artzberger	Steam Wagon	1200	28364	1285	6	0.0047	59	19.6	0.48
Steam	1902	White	B Stanhope	1200	27538	1285	6	0.0047	30	19.6	0.43
EV	1902	Studebaker	Runabout	1200	27538	1350	10	0.0074	13	6.7	0.46
ICE	1902	Rambler	Model C	750	17211	1100	6	0.0055	20	29.4	0.39
ICE	1903	Ford	Model A	700	15596	1240	8	0.0065	45	19.6	0.49
EV	1903	Columbia Electric	Mark LX Runabout	1200	26736	1200	1	0.0008	14	5.9	0.44
EV	1903	Baker Electric	Runabout	850	18938	1400	0.75	0.0005	14	4.3	0.47
Steam	1904	Stanley	Spindle-seat runabout	1500	32446	700	8	0.0114	45	33.6	0.40
EV	1904	Baker Electric	Stanhope	1600	34609	1500	1.75	0.0012	20	4.3	0.45
ICE	1904	Oldsmobile	Model R Curved Dash Runabout	650	14060	1100	4	0.0036	24	33.6	0.38
EV	1904	Baker Electric	Newport Electric	1500	32446	1100	0.75	0.0007	15	4.3	0.44
ICE	1905	Ford	Model C	1240	26041	850	10	0.0118	25	19.6	0.44
Steam	1906	Stanley	F-Touring	1500	30584	1700	20	0.0118	65	39.2	0.42
ICE	1907	Ford	Model K	2800	55427	2000	40	0.0200	45	29.4	0.39
Steam	1908	Stanley	Steamer Model K Semi Racer	1800	34594	1500	30	0.0200	65	29.4	0.48
ICE	1908	Ford	Model N	500	9609	1400	15	0.0107	45	15.7	0.53
ICE	1910	Ford	Model T	850	15398	1540	20	0.0130	40	14.7	0.52
Steam	1911	Stanley	85-Touring	2200	38693	3000	30	0.0100	80	29.4	0.47
EV	1911	Baker	Electric	2300	40452	800	2	0.0025	20	4.3	0.44
Steam	1915	Stanley	Mountain Wagon Condensing	2700	42192	3200	30	0.0094	85	19.6	0.51
ICE	1915	Ford	Model T	470	7344	1540	22	0.0143	45	13.8	0.56
EV	1915	Detroit Electric	Brougham	3000	46880	950	2	0.0021	20	4.3	0.42
Steam	1920	Stanley	735D - Sedan	6700	90313	4450	20	0.0045	80	23.5	0.36
ICE	1920	Mercer	Series 5	4675	63017	2800	40	0.0143	75	23.5	0.44
ICE	1922	Dodge	Series I	985	12515	2450	35	0.0143	60	19.6	0.55
Steam	1923	Doble	Model E	9000	111021	5000	30	0.0060	95	18.1	0.37
ICE	1928	Ford	Model A	570	6065	2375	40	0.0168	75	18.1	0.61
Steam	1930	Doble	Model F	9500	95286	3500	30	0.0086	90	18.1	0.40
ICE	1935	Ford	Model 48	700	6056	2643	85	0.0322	80	18.1	0.67
ICE	1937	Oldsmobile	L-37	925	7544	3396	110	0.0324	85	26.1	0.64
ICE	1941	Oldsmobile	98	1505	10905	3790	110	0.0290	85	26.1	0.62
ICE	1946	Packard	clipper deluxe Eight	1817	11357	3625	165	0.0455	85	26.1	0.67
ICE	1948	Oldsmobile	66	2730	16084	3940	100	0.0254	85	21.4	0.62
ICE	1950	Mercury	Roadster	1980	10996	3320	110	0.0331	86	19.6	0.66
ICE	1952	BMW	501	3000	15704	2955	65	0.0220	86	16.8	0.63
ICE	1954	Sunbeam	Talbot 90	2899	14304	2856	70	0.0245	93	11.8	0.68
ICE	1955	Austin	Healey 100M	3275	15689	1955	110	0.0563	109	10.7	0.81
ICE	1960	MG	A	2450	10124	1900	80	0.0421	100	9.4	0.77
ICE	1960	Lincoln	Continental Mark V	6850	28306	5150	160	0.0311	109	33.6	0.60
ICE	1962	Dodge	Dart	2241	8729	2970	130	0.0438	100	21.4	0.72
ICE	1965	Austin	MINI CooperS	2350	8377	1400	78	0.0557	100	8.4	0.82
ICE	1966	BMW	1800	3230	11178	2400	90	0.0375	100	11.2	0.74
ICE	1967	Volkswagen	karmann-Ghia	2250	7560	1786	53	0.0297	82	11.2	0.69
ICE	1968	Datsun	PL510	1996	6511	2010	96	0.0478	100	9.4	0.79
ICE	1969	Volkswagen	Beetle 1500	1800	5701	1742	53	0.0304	82	9.4	0.71
ICE	1972	Dodge	Challenger	2790	8086	3070	110	0.0358	120	26.1	0.72
ICE	1976	BMW	2002	6855	17652	2403	98	0.0408	118	9.4	0.78
ICE	1976	Buick	LeSabre	4747	12224	4170	110	0.0264	90	29.4	0.61
ICE	1977	Buick	Regal	4710	11775	3550	105	0.0296	98	26.1	0.65
ICE	1978	Mercury	Cougar XR7	5025	12197	3761	134	0.0356	120	23.5	0.72
ICE	1982	BMW	323i	13290	28661	2500	143	0.0572	119	11.8	0.80
ICE	1984	Mazda	RX7	10195	20724	2345	101	0.0431	130	10.7	0.80
ICE	1985	Pontiac	Fiero SE	9000	17762	2790	92	0.0330	103	8.4	0.73
ICE	1987	BMW	325i	26990	50209	2813	168	0.0597	120	9.8	0.77

Architecture	Year	Make	Model	Nominal MSRP ($)	Real MSRP (2008 $)	Weight (lbs)	Power (HP)	Power to Weight (hp/lbs)	Vmax (mph)	L/100km	Performance Index Score
ICE	1990	Nissan	300ZX	29100	49541	3300	222	0.0673	125	11.2	0.79
ICE	1990	Toyota	Celica	12698	21617	2500	200	0.0800	110	10.2	0.88
ICE	1991	Ford	Explorer 2WD	16375	27065	3700	155	0.0419	85	16.8	0.66
ICE	1992	Mitsubishi	Eclipse	10860	17427	2680	92	0.0343	105	10.2	0.73
ICE	1993	Honda	Civic	9400	14645	2120	102	0.0481	120	9.4	0.81
ICE	1993	BMW	325i	29650	46194	3020	189	0.0626	124	9.4	0.79
ICE	1995	Ford	Mustang	14330	21044	3075	145	0.0472	131	10.7	0.81
ICE	1998	Toyota	Rav4	16768	22535	2700	120	0.0444	100	11.2	0.74
ICE	1999	Hyundai	Accent	9100	11873	2090	92	0.0440	90	10.2	0.75
EV	1999	GM	EV-1	33995	44356	2970	137	0.0461	80	2.3	0.69
ICE	1999	Oldsmobile	Cutlass	19800	25835	3080	150	0.0487	100	13.1	0.73
ICE	2000	Chevrolet	Metro	10610	13440	1940	79	0.0407	100	5.3	0.77
Hybrid	1999	Toyota	Prius	19995	26089	2765	70	0.0253	100	4.7	0.70
Hybrid	2004	Toyota	Prius	19995	22505	2855	70	0.0245	100	4.3	0.71
ICE	2005	Ford	Escape	19265	21051	3333	153	0.0459	105	9.0	0.76
ICE	2006	Honda	Civic	14360	15235	2593	140	0.0540	120	6.7	0.84
Hybrid	2006	Honda	Civic Hybrid	21850	23181	2875	110	0.0383	120	4.7	0.78
ICE	2006	Honda	Accord	18225	19335	3056	244	0.0798	110	7.8	0.89
Hybrid	2006	Honda	Accord Hybrid	30140	31976	3501	244	0.0697	135	6.7	0.88
ICE	2007	Honda	CRV	20395	21007	3428	156	0.0455	120	8.4	0.80
Hybrid	2007	Ford	Escape	26365	27156	3594	133	0.0370	105	7.8	0.73
EV	2007	Tesla	Roadster	95000	97850	2500	187	0.0748	130	1.7	0.75
ICE	2008	Toyota	Camry	19620	19620	3307	158	0.0478	120	10.0	0.80
Hybrid	2008	Toyota	Camry Hybrid	25200	25200	3680	147	0.0399	120	7.1	0.77
Hybrid	2008	Toyota	Prius	21950	21950	2932	76	0.0259	100	4.3	0.71
EV	2008	Smart	For Two	56000	56000	1609	41	0.0255	70	1.8	0.58
EV	2006	Th!nk	City	34300	36389	2075	27	0.0130	56	1.5	0.56
EV	2007	Reva	Gwiz	17613	18141	1466	18	0.0123	50	1.4	0.59

9.2 System Dynamics Model Equations List

Table 9-1 Table of equations and initial conditions for systems dynamics model

Model Element(s)	Mathematical Equations(s) / Input Values	Units
Number of ICEs Sold, Number of HEV_PHEVs Sold, Number of BEVs Sold	Number Sold = Integral (Sales) + initial value	Units
Sales of ICEs, Sales of HEVs_PHEVs Sold, Sales of BEVs Sold	Sales = Market Share * Total Demand for Cars	Units/year
Total Demand for Cars	Estimate: 13 million; Minimum: 0; Maximum: 5; Increment: 0.01	Units
Market Share ICE, Market Share HEV_PHEV, Market Share BEV	Market Share = Attractiveness / Total attractiveness of all Architectures	Dmnl
Attractiveness of ICE, Attractiveness of HEV_PHEV, Attractiveness of BEV	Attractiveness = Network Effects on Attractiveness / (Cost of Operation Attractiveness * Cost of Ownership Attractiveness)	Dmnl
Network Effects on Attractiveness ICE, Network Effects on HEV_PHEV Attractiveness, Network Effects on BEV Attractiveness	Network Effects on Attractiveness = EXP(Sensitivity of Attractiveness to Network Effects*(Number Sold/ Threshold for Network Effects)	Dmnl
ICE Sensitivity of Attractiveness to Network Effects	Estimate: 0.001; Minimum: 0; Maximum: 5; Increment: 0.01	Dmnl
HEV_PHEV Sensitivity of Attractiveness to Network Effects	Estimate: 0.1; Minimum: 0; Maximum: 5; Increment: 0.01	Dmnl
BEV Sensitivity of Attractiveness to Network Effects	Estimate: 0.1; Minimum: 0; Maximum: 5; Increment: 0.01	Dmnl
ICE Threshold for Network Effects	Estimate: 13 Million	units
HEV_PHEV Threshold for Network Effects	Estimate: 3 Million	units
BEV Threshold for Network Effects	Estimate: 10 Million	units

Table 9-2 Architecture Adoption Model Equations and initial conditions continued

ICE Cost of Ownership Attractiveness	ICE Cost of Ownership Attractiveness = ((1+%CO2 Government Tax or Incentive)*Avg. ICE Retail Price)/ Avg. ICE Retail Price	Dmnl
HEV_PHEV Cost of Ownership Attractiveness	HEV (PHEV) Cost of Ownership Attractiveness = ((1+%CO2 Government Tax or Incentive)*Avg. ICE Retail Price* HEV_PHEV Retail Price Premium over ICE)/Avg. ICE Retail Price	Dmnl
BEV Cost of Ownership Attractiveness	BEV Cost of Ownership Attractiveness = ((1+%CO2 Government Tax or Incentive)*Avg. ICE Retail Price* BEV Retail Price Premium over ICE)/Avg. ICE Retail Price	Dmnl
Avg. ICE Retail Price	Estimate: 30000 ; Minimum: 5000 ; Maximum: 150000 ; Increment: 1000	$
%CO2 Government Tax or incentive	Estimate: 0.2; Minimum: -0.9; Maximum: 0.9; Increment: 0.1	Dmnl
HEV_PHEV Retail Price Premium over ICE	HEV_PHEV Retail Price Premium over ICE = (1+(Initial HEV % Retail Premium over ICE - (Electric Powertrain Technology Maturity*Initial HEV % Retail Premium over ICE)))	Dmnl
BEV Retail Price Premium over ICE	BEV Retail Price Premium over ICE = (1+(Initial BEV % Retail Premium over ICE - (Electric Powertrain Technology Maturity*Initial BEV % Retail Premium over ICE)))	Dmnl
Initial HEV % Retail Premium over ICE	Estimate: 0.35; Minimum: 0.05; Maximum: 0.55; Increment: 0.1	Dmnl
Initial BEV % Retail Premium over ICE	Estimate: 0.7; Minimum: 0.1; Maximum: 1.5; Increment: 0.1	Dmnl
Electric Power Train Maturity	Estimate: 0.1; Minimum: 0; Maximum: 1; Increment: 0.1	Dmnl
ICE Cost of Operation Attractiveness, HEV_PHEV Cost of Operation Attractiveness, BEV Cost of Operation Attractiveness	Cost of Operation Attractiveness = Cost of Operation / Cost of Operation Sum	Dmnl
ICE Cost of Operation	ICE Cost of Operation = Price per gallon of Gasoline/ Average Gas Mileage of ICE	$/miles
HEV_PHEV Cost of Operation	HEV_PHEV Cost of Operation = Price per gallon of Gasoline / Average Gas Mileage of HEV	$/miles
BEV Cost of Operation	BEV Cost of Operation = Price per kWh/ Average Mileage per kWh of BEV	$/miles
Cost of Operation Sum	Cost of Operation Sum = ICE Cost of Operation + BEV Cost of Operation + HEV_PHEV Cost of Operation	$/miles
Price Per Gallon of Gasoline	$2.99 in year one increasing to $5.63 in year 20 according to EIA	$/gal
Average Gas Mileage of ICE	Estimate: 20; Minimum: 10; Maximum: 100; Increment: 5	miles/gal
Average Gas Mileage of HEV	Estimate: 30; Minimum: 10; Maximum: 100; Increment: 5	miles/gal
Price Per kWh	$0.13 per kWh	$/kWh
Average Mileage per kWh of BEV	Estimate: 4; Minimum: 2; Maximum: 6; Increment: 0.05	miles/kWh

9.3 Vehicle Architectures MDM Representations

This section includes the MDM representations of architectures explored in previous chapters. The first eight vehicle architecture MDMs were the basis of analysis for the delta MDM and sigma MDM calculations presented in chapter five. The last two architectures are example variations that can be arrived at from the analysis in chapter 5 for configurations that are currently not available in the market. It is important to note that in section 5.6 more than 5,450 different configurations were found, each of which can be translated into MDM form. The MDMs that follow are one possible structure of many within the classification category.

The MDMs are comprised of three matrices, a components DSM marked in blue, a functions DSM marked in red and a functions to components DMM marked in green. On the top right of each matrix set is a simple schematic of the key components referenced in the components DSM shown. The diagram shows both component physical connections and the energy flow according to the legend in each diagram. Specific matrix index numbers are assigned to each component and functional element so that they maintain the same index number on each architecture depicted. Functional and component elements not present in the architecture are omitted for simplicity. For a full listing of component and functional elements, refer to Figure 5-11 on page 156.

The component and functions DSMs are not clustered. Both the component and functions DSM can be further clustered to create component and functional modules using DSM clustering algorithms. Examples of clustered component and functional DSM can be referenced in Figure 5-4 on page 148, Figure 5-15 on page 160 and Figure 5-24 on page 175.

Functions-Component MDM Representation of a Conventional IC Engine Architecture

Functions DSM

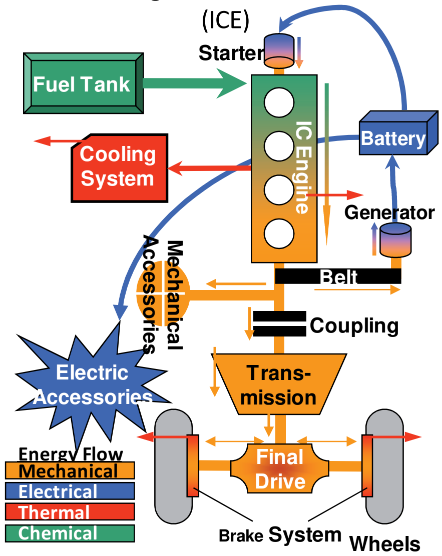
No.	Function / Component	1 Store Fuel	2 Store Electric Energy	3 Convert Fuel into Mechanical Energy	4 Convert Mechanical into Electrical Energy	5 Convert Electrical into Mechanical Energy	6 Deliver (Recover) torque to (from) wheels	7 Convert Moment tranfered (mechanical)	8 Equate Rotational Speed	10 Couple/Uncouple Moment	11 Release Heat to the Environment	12 Transfer Heat (to Cooling system)	13 Transfer Moment to (from) the road	14 Slow or Stop Vehicle (recovering energy)	15 Slow or Stop Vehicle (releasing Energy - by Friction)	18 Consume Electric Energy for Auto Accesory OPS	19 Consume Mechanical Energy for Engine Accesory
1	Store Fuel	■		1													
2	Store Electric Energy		■			1						1				1	
3	Convert Fuel into Mechanical Energy			■	1					1		1					1
4	Convert Mechanical into Electrical Energy		1		■							1					
5	Convert Electrical into Mechanical Energy			1		■						1					
6	Deliver (Recover) torque to (from) wheels						■	1					1	1	1		
7	Convert Moment tranfered (mechanical)						1	■	1	1			1	1			
8	Equate Rotational Speed							1	■				1	1			
10	Couple/Uncouple Moment			1				1		■							
11	Release Heat to the Environment										■						
12	Transfer Heat (to Cooling system)									1	1	■					
13	Transfer Moment to (from) the road						1	1	1				■		1		
14	Slow or Stop Vehicle (recovering energy)													■			
15	Slow or Stop Vehicle (releasing Energy - by Friction)						1				1		1		■		
18	Consume Electric Energy for Auto Accesory OPS															■	
19	Consume Mechanical Energy for Engine Accesory																■
1	Fuel Tank	1															
2	High Voltage Battery		1									1					
4	Internal Combustion Engine			1								1					
9	Generator				1							1					
10	Starter					1											
11	Transmission							1									
13	Final Drive						1	1	1								
18	Clutch Direct Coupling1									1							
21	Cooling System										1						
22	Wheels												1	1	1		
23	Braking-system										1				1		
26	Additional Electric Accessories Load															1	
27	Mechanical Accessories Load																1

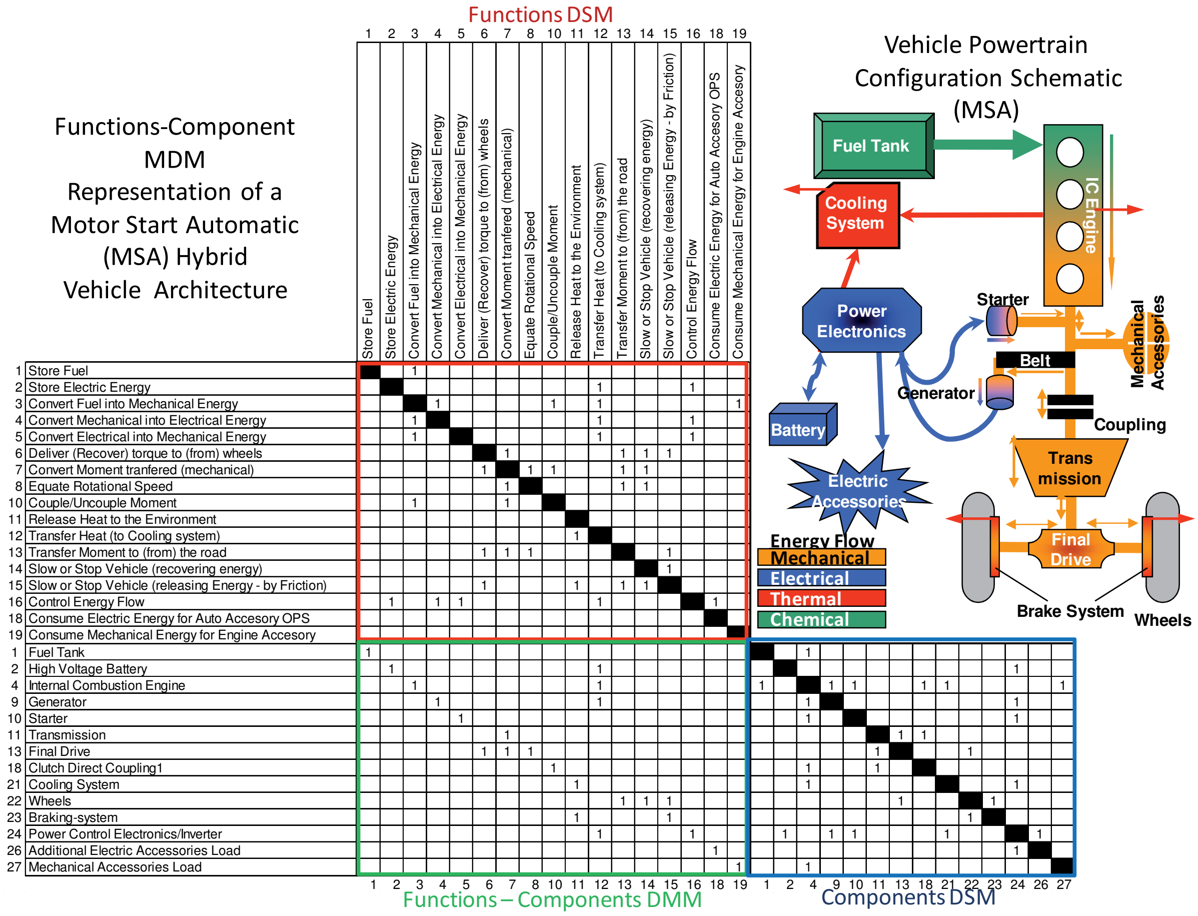
Functions – Components DMM

Components DSM

No.	Component	1	2	4	9	10	11	13	18	21	22	23	26	27
1	Fuel Tank	■		1										
2	High Voltage Battery		■		1	1							1	
4	Internal Combustion Engine	1		■	1	1			1	1				1
9	Generator		1	1	■									
10	Starter		1	1		■								
11	Transmission						■	1	1					
13	Final Drive						1	■			1			
18	Clutch Direct Coupling1			1			1		■					
21	Cooling System			1						■				
22	Wheels							1			■	1		
23	Braking-system										1	■		
26	Additional Electric Accessories Load		1										■	
27	Mechanical Accessories Load			1										■

Vehicle Powertrain Configuration Schematic (ICE)




Functions-Component MDM Representation of a Motor Start Automatic (MSA) Hybrid Vehicle Architecture
Functions DSM
Store Fuel
Store Electric Energy
Convert Fuel into Mechanical Energy
Convert Mechanical into Electrical Energy
Convert Electrical into Mechanical Energy
Deliver (Recover) torque to (from) wheels
Convert Moment tranfered (mechanical)
Equate Rotational Speed
Couple/Uncouple Moment
Release Heat to the Environment
Transfer Heat (to Cooling system)
Transfer Moment to (from) the road
Slow or Stop Vehicle (recovering energy)
Slow or Stop Vehicle (releasing Energy - by Friction)
Control Energy Flow
Consume Electric Energy for Auto Accesory OPS
Consume Mechanical Energy for Engine Accesory
Fuel Tank
High Voltage Battery
Internal Combustion Engine
Generator
Starter
Transmission
Final Drive
Clutch Direct Coupling1
Cooling System
Wheels
Braking-system
Power Control Electronics/Inverter
Additional Electric Accessories Load
Mechanical Accessories Load
Functions – Components DMM
Components DSM
Vehicle Powertrain Configuration Schematic (MSA)
Fuel Tank
Cooling System
IC Engine
Power Electronics
Starter
Mechanical Accessories
Belt
Generator
Battery
Coupling
Trans mission
Electric Accessories
Energy Flow
Mechanical
Electrical
Thermal
Chemical
Final Drive
Brake System
Wheels

Functions-Component MDM Representation of an Integrated Starter Generator (ISG) Hybrid Vehicle Architecture

Functions DSM

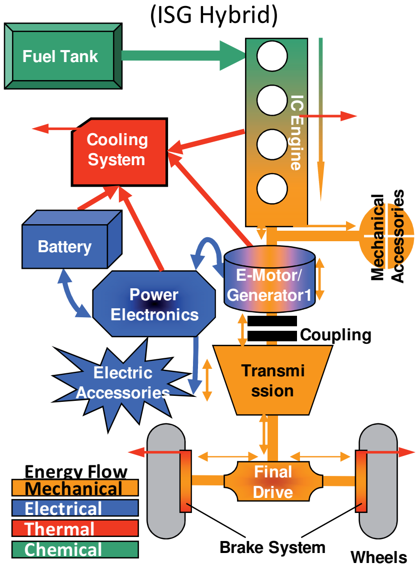
	1 Store Fuel	2 Store Electric Energy	3 Convert Fuel into Mechanical Energy	4 Convert Mechanical into Electrical Energy	5 Convert Electrical into Mechanical Energy	6 Deliver (Recover) torque to (from) wheels	7 Convert Moment transferred (mechanical)	8 Equate Rotation	10 Couple/Uncouple Moment	11 Release Energy as Heat to the Environment	12 Transfer Heat (to Cooling system)	13 Transfer Moment to (from) the road	14 Slow or Stop Vehicle (recovering energy)	15 Slow or Stop Vehicle (releasing Energy - by Friction)	16 Control Energy Flow	18 Consume Electric Energy for Auto Accessory OPS	19 Consume Mechanical Energy for Engine Accessory
Store Fuel	■		1														
Store Electric Energy		■									1				1		
Convert Fuel into Mechanical Energy			■	1							1						1
Convert Mechanical into Electrical Energy				■							1				1		
Convert Electrical into Mechanical Energy			1		■				1		1				1		
Deliver (Recover) torque to (from) wheels						■	1					1	1	1			
Convert Moment transferred (mechanical)						1	■	1	1			1	1				
Equate Rotation							1	■				1	1				
Couple/Uncouple Moment				1			1		■				1				
Release Energy as Heat to the Environment										■							
Transfer Heat (to Cooling system)										1	■						
Transfer Moment to (from) the road						1	1	1				■		1			
Slow or Stop Vehicle (recovering energy)													■		1		
Slow or Stop Vehicle (releasing Energy - by Friction)						1				1		1		■			
Control Energy Flow		1		1	1						1		1		■	1	
Consume Electric Energy for Auto Accessory OPS																■	
Consume Mechanical Energy for Engine Accessory																	■
Fuel Tank	1																
High Voltage Battery		1									1						
Internal Combustion Engine			1								1						
E-Motor/Generator1				1	1						1		1				
Transmission							1										
Differential Gear						1	1	1									
Clutch Direct Coupling1									1								
Cooling System										1							
Wheels												1	1	1			
Brake-system										1				1			
Power Electronics/Inverter											1				1		
Additional Electric Accessories																1	
Mechanical Accessories																	1

Functions – Components DMM

	1	2	4	5	11	13	18	21	22	23	24	26	27
Fuel Tank	■		1										
High Voltage Battery		■						1			1		
Internal Combustion Engine	1		■	1				1					1
E-Motor/Generator1			1	■			1	1			1		
Transmission					■	1	1						
Differential Gear					1	■			1				
Clutch Direct Coupling1				1	1		■						
Cooling System		1	1	1				■			1		
Wheels						1			■	1			
Brake-system									1	■			
Power Electronics/Inverter		1		1				1			■	1	
Additional Electric Accessories											1	■	
Mechanical Accessories			1										■

Components DSM

Vehicle Powertrain Configuration Schematic (ISG Hybrid)



Functions-Component MDM Representation of a Parallel Double Coupling Hybrid Vehicle Architecture

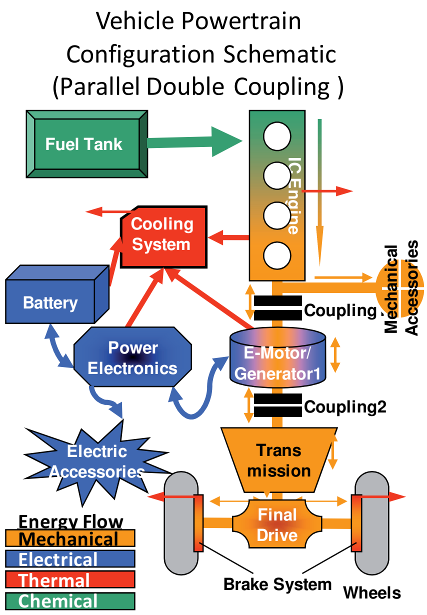
Functions DSM

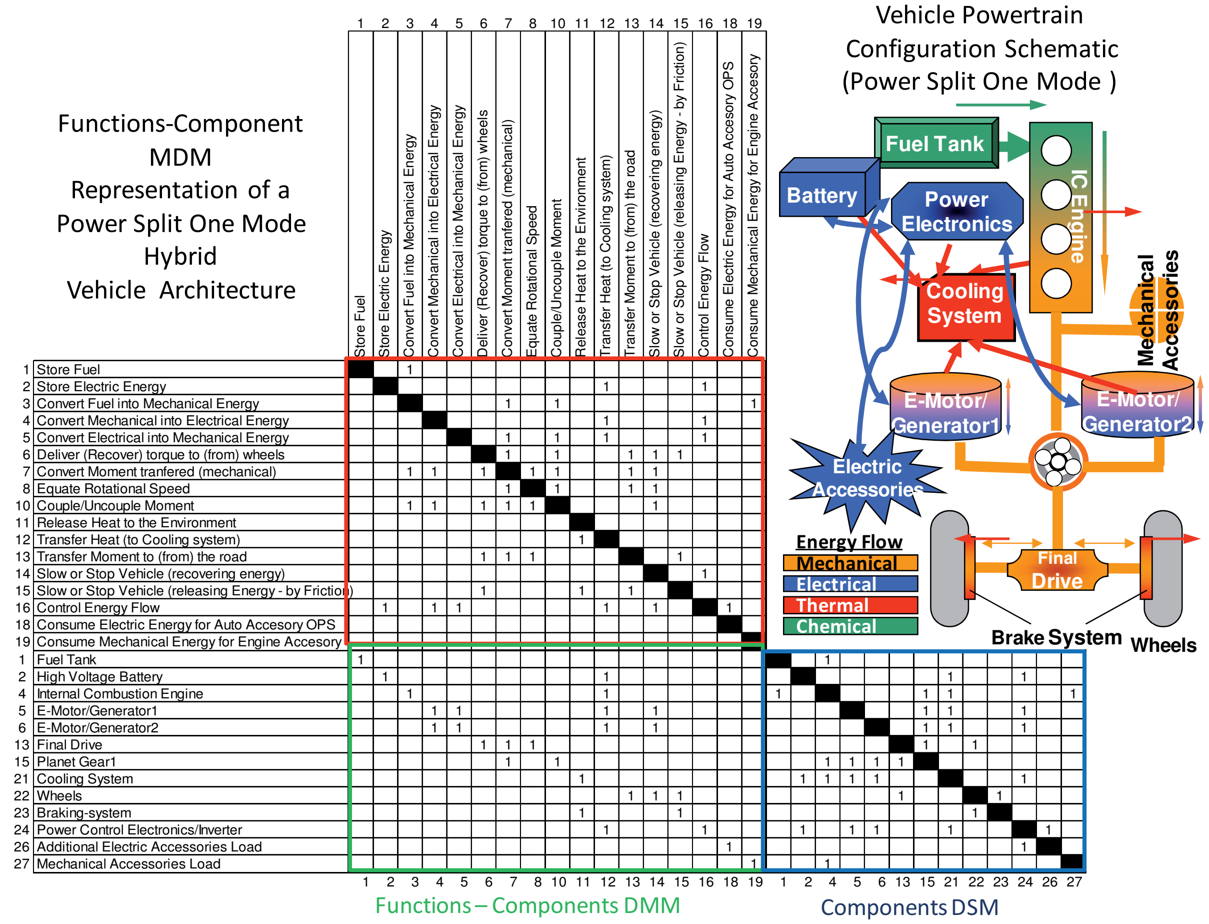
		1 Store Fuel	2 Store Electric Energy	3 Convert Fuel into Mechanical Energy	4 Convert Mechanical into Electrical Energy	5 Convert Electrical into Mechanical Energy	6 Deliver (Recover) torque to (from) wheels	7 Convert Moment tranfered (mechanical)	8 Equate Rotational Speed	10 Couple/Uncouple Moment	11 Release Heat to the Environment	12 Transfer Heat (to Cooling system)	13 Transfer Moment to (from) the road	14 Slow or Stop Vehicle (recovering energy)	15 Slow or Stop Vehicle (releasing Energy - by Friction)	16 Control Energy Flow	18 Consume Electric Energy for Auto Accesory OPS	19 Consume Mechanical Energy for Engine Accesory
1	Store Fuel	■		1														
2	Store Electric Energy		■									1				1		
3	Convert Fuel into Mechanical Energy			■						1								1
4	Convert Mechanical into Electrical Energy				■							1				1		
5	Convert Electrical into Mechanical Energy					■		1				1				1		
6	Deliver (Recover) torque to (from) wheels						■	1					1	1	1			
7	Convert Moment tranfered (mechanical)				1	1	1	■	1	1			1	1				
8	Equate Rotational Speed							1	■				1	1				
10	Couple/Uncouple Moment			1				1		■								
11	Release Heat to the Environment										■							
12	Transfer Heat (to Cooling system)										1	■						
13	Transfer Moment to (from) the road						1	1	1				■		1			
14	Slow or Stop Vehicle (recovering energy)													■		1		
15	Slow or Stop Vehicle (releasing Energy - by Friction)						1				1		1		■			
16	Control Energy Flow		1		1	1						1		1		■	1	
18	Consume Electric Energy for Auto Accesory OPS																■	
19	Consume Mechanical Energy for Engine Accesory																	■

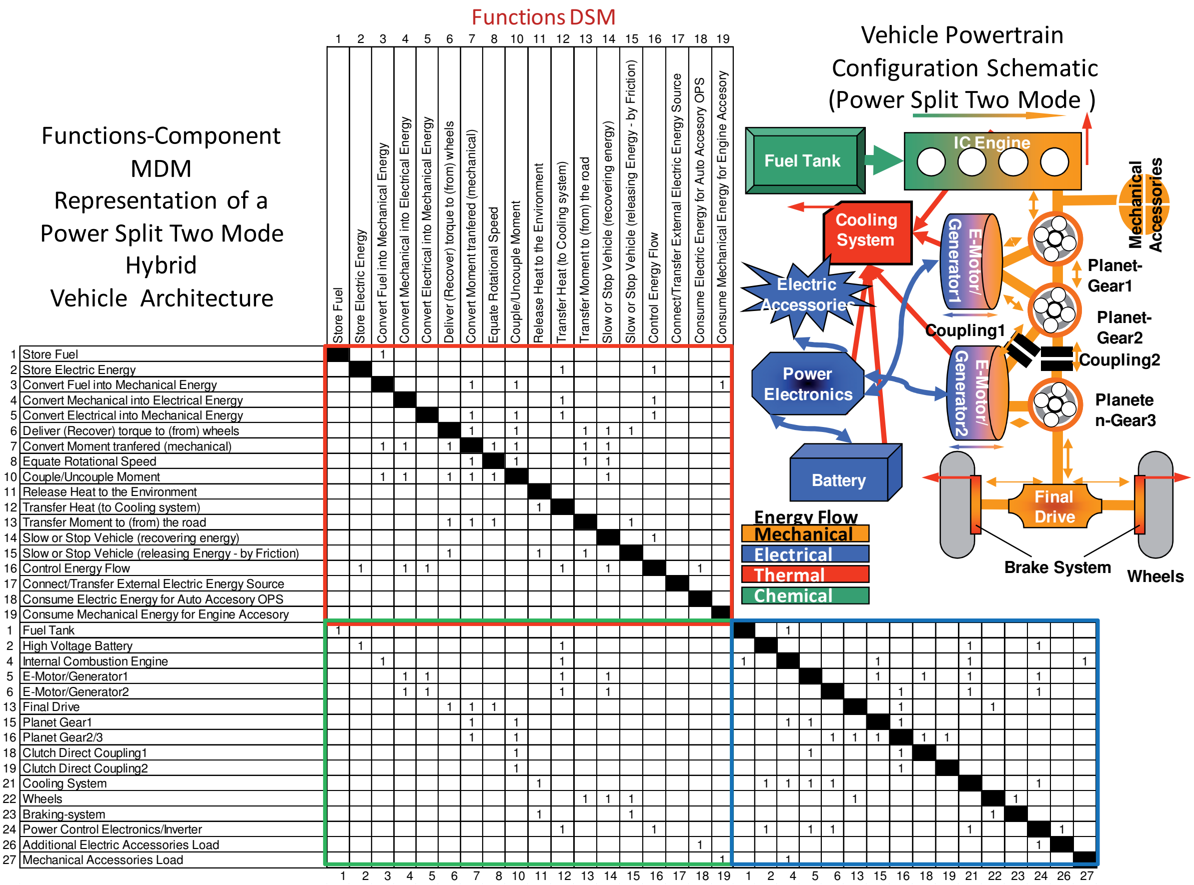
Functions – Components DMM / Components DSM

		F1	F2	F3	F4	F5	F6	F7	F8	F10	F11	F12	F13	F14	F15	F16	F18	F19	C1	C2	C4	C5	C11	C13	C18	C19	C21	C22	C23	C24	C26	C27
1	Fuel Tank	1																	■		1											
2	High Voltage Battery		1									1								■							1			1		
4	Internal Combustion Engine			1								1							1		■				1		1					1
5	E-Motor/Generator1				1	1						1		1								■			1	1	1			1		
11	Transmission							1															■	1		1						
13	Final Drive						1	1	1														1	■				1				
18	Clutch Direct Coupling1									1											1	1			■	1						
19	Clutch Direct Coupling2									1												1	1		1	■						
21	Cooling System										1									1	1	1					■			1		
22	Wheels												1	1	1									1				■	1			
23	Braking-system										1				1													1	■			
24	Power Control Electronics/Inverter											1				1				1		1					1			■	1	
26	Additional Electric Accessories Load																1													1	■	
27	Mechanical Accessories Load																	1			1											■

Functions – Components DMM   Components DSM




Functions-Component MDM Representation of a Power Split One Mode Hybrid Vehicle Architecture
Vehicle Powertrain Configuration Schematic (Power Split One Mode)
1 Store Fuel
2 Store Electric Energy
3 Convert Fuel into Mechanical Energy
4 Convert Mechanical into Electrical Energy
5 Convert Electrical into Mechanical Energy
6 Deliver (Recover) torque to (from) wheels
7 Convert Moment tranfered (mechanical)
8 Equate Rotational Speed
10 Couple/Uncouple Moment
11 Release Heat to the Environment
12 Transfer Heat (to Cooling system)
13 Transfer Moment to (from) the road
14 Slow or Stop Vehicle (recovering energy)
15 Slow or Stop Vehicle (releasing Energy - by Friction)
16 Control Energy Flow
18 Consume Electric Energy for Auto Accesory OPS
19 Consume Mechanical Energy for Engine Accesory
1 Fuel Tank
2 High Voltage Battery
4 Internal Combustion Engine
5 E-Motor/Generator1
6 E-Motor/Generator2
13 Final Drive
15 Planet Gear1
21 Cooling System
22 Wheels
23 Braking-system
24 Power Control Electronics/Inverter
26 Additional Electric Accessories Load
27 Mechanical Accessories Load
Functions – Components DMM
Components DSM
Fuel Tank
Battery
Power Electronics
IC Engine
Cooling System
Mechanical Accessories
E-Motor/ Generator1
E-Motor/ Generator2
Electric Accessories
Energy Flow
Mechanical
Electrical
Thermal
Chemical
Final Drive
Brake System
Wheels



Functions DSM
Functions-Component MDM Representation of a Power Split Two Mode Hybrid Vehicle Architecture
Vehicle Powertrain Configuration Schematic (Power Split Two Mode)
1 Store Fuel
2 Store Electric Energy
3 Convert Fuel into Mechanical Energy
4 Convert Mechanical into Electrical Energy
5 Convert Electrical into Mechanical Energy
6 Deliver (Recover) torque to (from) wheels
7 Convert Moment tranfered (mechanical)
8 Equate Rotational Speed
10 Couple/Uncouple Moment
11 Release Heat to the Environment
12 Transfer Heat (to Cooling system)
13 Transfer Moment to (from) the road
14 Slow or Stop Vehicle (recovering energy)
15 Slow or Stop Vehicle (releasing Energy - by Friction)
16 Control Energy Flow
17 Connect/Transfer External Electric Energy Source
18 Consume Electric Energy for Auto Accesory OPS
19 Consume Mechanical Energy for Engine Accesory
1 Fuel Tank
2 High Voltage Battery
4 Internal Combustion Engine
5 E-Motor/Generator1
6 E-Motor/Generator2
13 Final Drive
15 Planet Gear1
16 Planet Gear2/3
18 Clutch Direct Coupling1
19 Clutch Direct Coupling2
21 Cooling System
22 Wheels
23 Braking-system
24 Power Control Electronics/Inverter
26 Additional Electric Accessories Load
27 Mechanical Accessories Load
Fuel Tank
IC Engine
Cooling System
Mechanical Accessories
E-Motor/ Generator1
Planet-Gear1
Electric Accessories
Coupling1
Planet-Gear2
Coupling2
Power Electronics
E-Motor/ Generator2
Planeten-Gear3
Battery
Final Drive
Energy Flow
Mechanical
Electrical
Thermal
Chemical
Brake System
Wheels

Functions-Component MDM Representation of a Series Hybrid Vehicle Architecture

Functions DSM

		1 Store Fuel	2 Store Electric Energy	3 Convert Fuel into Mechanical Energy	4 Convert Mechanical into Electrical Energy	5 Convert Electrical into Mechanical Energy	6 Deliver (Recover) torque to (from) wheels	7 Convert Moment tranfered (mechanical)	8 Equate Rotational Speed	11 Release Heat to the Environment	12 Transfer Heat (to Cooling system)	13 Transfer Moment to (from) the road	14 Slow or Stop Vehicle (recovering energy)	15 Slow or Stop Vehicle (releasing Energy - by Friction)	16 Control Energy Flow	18 Consume Electric Energy for Auto Accesory OPS	19 Consume Mechanical Energy for Engine Accesory
1	Store Fuel	■		1													
2	Store Electric Energy		■								1				1		
3	Convert Fuel into Mechanical Energy			■	1						1						1
4	Convert Mechanical into Electrical Energy				■						1				1		
5	Convert Electrical into Mechanical Energy			1		■	1	1	1		1				1		
6	Deliver (Recover) torque to (from) wheels				1	1	■					1	1	1			
7	Convert Moment tranfered (mechanical)				1			■				1	1				
8	Equate Rotational Speed								■			1	1				
11	Release Heat to the Environment									■							
12	Transfer Heat (to Cooling system)									1	■						
13	Transfer Moment to (from) the road						1	1	1			■		1			
14	Slow or Stop Vehicle (recovering energy)												■		1		
15	Slow or Stop Vehicle (releasing Energy - by Friction)						1			1		1		■			
16	Control Energy Flow		1		1	1					1		1		■	1	
18	Consume Electric Energy for Auto Accesory OPS															■	
19	Consume Mechanical Energy for Engine Accesory																■

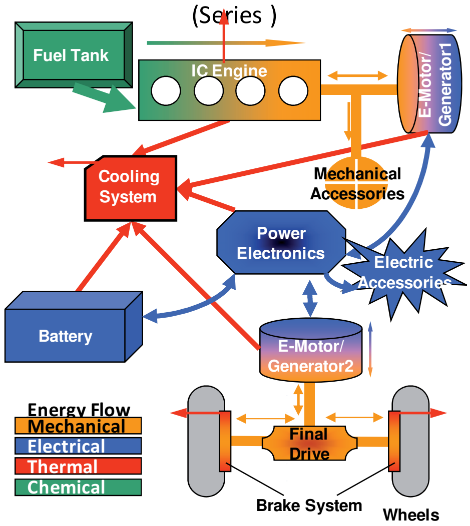
Functions – Components DMM

		1	2	3	4	5	6	7	8	11	12	13	14	15	16	18	19
1	Fuel Tank	1															
2	High Voltage Battery		1								1						
4	Internal Combustion Engine			1							1						
5	E-Motor/Generator1				1	1					1		1				
6	E-Motor/Generator2				1	1					1		1				
13	Final Drive						1	1	1								
21	Cooling System									1							
22	Wheels											1	1	1			
23	Braking-system									1				1			
24	Power Control Electronics/Inverter										1				1		
26	Additional Electric Accessories Load															1	
27	Mechanical Accessories Load																1

Components DSM

		1	2	4	5	6	13	21	22	23	24	26	27
1	Fuel Tank	■		1									
2	High Voltage Battery		■					1			1		
4	Internal Combustion Engine	1		■	1			1					1
5	E-Motor/Generator1			1	■			1			1		
6	E-Motor/Generator2					■	1	1			1		
13	Final Drive					1	■		1				
21	Cooling System		1	1	1	1		■			1		
22	Wheels						1		■	1			
23	Braking-system								1	■			
24	Power Control Electronics/Inverter		1		1	1		1			■	1	
26	Additional Electric Accessories Load										1	■	
27	Mechanical Accessories Load			1									■

Vehicle Powertrain Configuration Schematic (Series)



Functions-Component MDM Representation of a Battery Electric Vehicle (BEV) Architecture

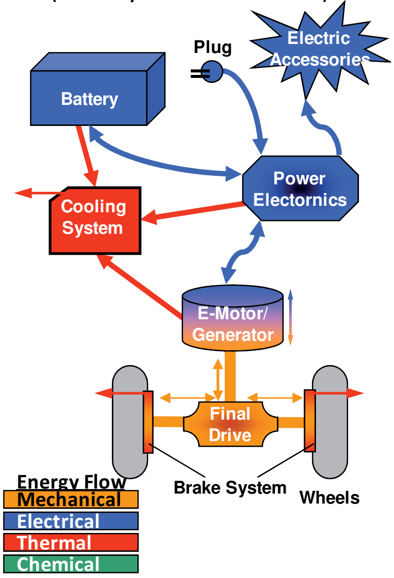
Functions DSM

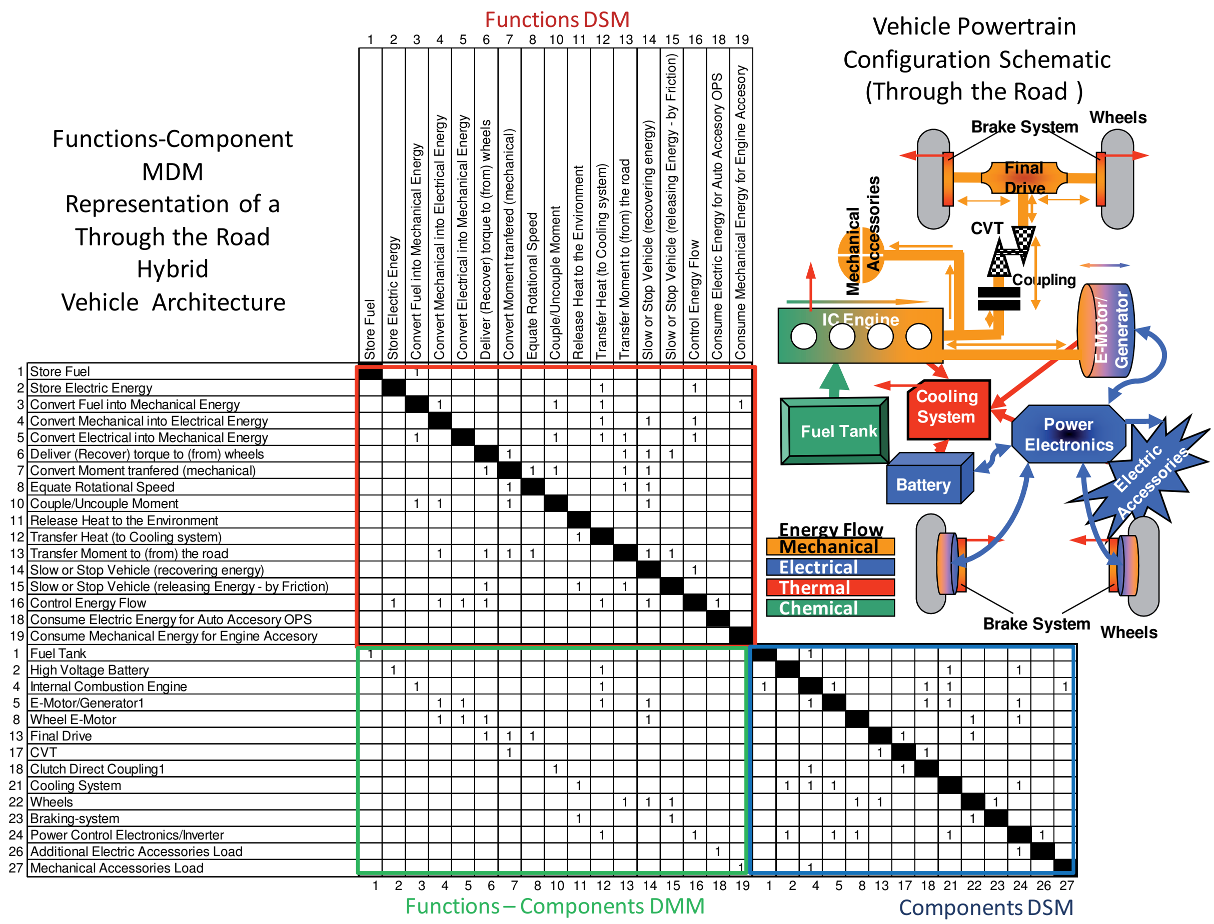
		2 Store Electric Energy	4 Convert Mechanical into Electrical Energy	5 Convert Electrical into Mechanical Energy	6 Deliver (Recover) torque to (from) wheels	7 Convert Moment tranfered (mechanical)	8 Equate Rotational Speed	11 Release Heat to the Environment	12 Transfer Heat (to Cooling system)	13 Transfer Moment to (from) the road	14 Slow or Stop Vehicle (recovering energy)	15 Slow or Stop Vehicle (releasing Energy - by Friction)	16 Control Energy Flow	17 Connect/Transfer External Electric Energy Source	18 Consume Electric Energy for Auto Accesory OPS	2	5	13	21	22	23	24	25	26
2	Store Electric Energy	■							1				1	1										
4	Convert Mechanical into Electrical Energy		■						1				1											
5	Convert Electrical into Mechanical Energy			■	1	1	1		1				1											
6	Deliver (Recover) torque to (from) wheels		1	1	■					1	1	1												
7	Convert Moment tranfered (mechanical)		1			■				1	1													
8	Equate Rotational Speed						■			1	1													
11	Release Heat to the Environment			1				■																
12	Transfer Heat (to Cooling system)							1	■															
13	Transfer Moment to (from) the road				1	1	1			■		1												
14	Slow or Stop Vehicle (recovering energy)										■		1											
15	Slow or Stop Vehicle (releasing Energy - by Friction)				1			1		1		■												
16	Control Energy Flow	1	1	1					1		1		■		1									
17	Connect/Transfer External Electric Energy Source	1												■										
18	Consume Electric Energy for Auto Accesory OPS														■									
2	High Voltage Battery	1							1							■			1			1		
5	E-Motor/Generator1		1	1					1		1						■	1	1			1		
13	Final Drive				1	1	1										1	■		1				
21	Cooling System							1								1	1		■			1		
22	Wheels									1	1	1						1		■	1			
23	Braking-system							1				1								1	■			
24	Power Control Electronics/Inverter								1				1			1	1		1			■	1	1
25	Plug w/ Charging device													1								1	■	
26	Additional Electric Accessories Load														1							1		■
		2	4	5	6	7	8	11	12	13	14	15	16	17	18	2	5	13	21	22	23	24	25	26

Functions – Components DMM

Components DSM

Vehicle Powertrain Configuration Schematic (Battery Electric Vehicle)




Functions-Component MDM Representation of a Through the Road Hybrid Vehicle Architecture
Functions DSM
Functions – Components DMM
Components DSM
Store Fuel
Store Electric Energy
Convert Fuel into Mechanical Energy
Convert Mechanical into Electrical Energy
Convert Electrical into Mechanical Energy
Deliver (Recover) torque to (from) wheels
Convert Moment tranfered (mechanical)
Equate Rotational Speed
Couple/Uncouple Moment
Release Heat to the Environment
Transfer Heat (to Cooling system)
Transfer Moment to (from) the road
Slow or Stop Vehicle (recovering energy)
Slow or Stop Vehicle (releasing Energy - by Friction)
Control Energy Flow
Consume Electric Energy for Auto Accesory OPS
Consume Mechanical Energy for Engine Accesory
Fuel Tank
High Voltage Battery
Internal Combustion Engine
E-Motor/Generator1
Wheel E-Motor
Final Drive
CVT
Clutch Direct Coupling1
Cooling System
Wheels
Braking-system
Power Control Electronics/Inverter
Additional Electric Accessories Load
Mechanical Accessories Load
Vehicle Powertrain Configuration Schematic (Through the Road)
Brake System
Wheels
Final Drive
Mechanical Accessories
CVT
Coupling
IC Engine
E-Motor/ Generator
Fuel Tank
Cooling System
Power Electronics
Battery
Electric Accessories
Energy Flow
Mechanical
Electrical
Thermal
Chemical
Brake System
Wheels

Functions-Component MDM Representation of a Series Hybrid Vehicle Architecture with 4 Wheel Motors

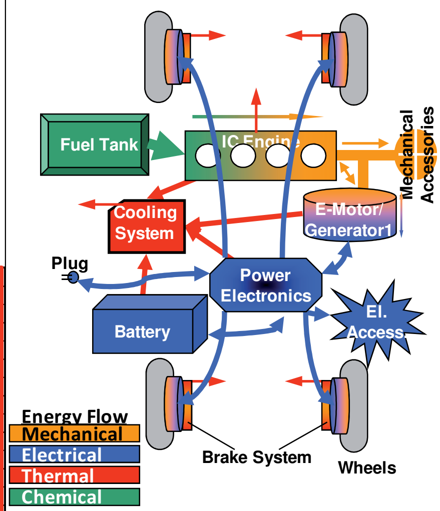
Functions DSM

	Function	1 Store Fuel	2 Store Electric Energy	3 Convert Fuel into Mechanical Energy	4 Convert Mechanical into Electrical Energy	5 Convert Electrical into Mechanical Energy	6 Deliver (Recover) torque to (from) wheels	11 Release Heat to the Environment	12 Transfer Heat (to Cooling system)	13 Transfer Moment to (from) the road	14 Slow or Stop Vehicle (recovering energy)	15 Slow or Stop Vehicle (releasing Energy - by Friction)	16 Control Energy Flow	17 Connect/Transfer External Electric Energy Source	18 Consume Electric Energy for Auto Accesory OPS	19 Consume Mechanical Energy for Engine Accesory
1	Store Fuel	■		1												
2	Store Electric Energy		■						1				1			
3	Convert Fuel into Mechanical Energy			■	1				1							1
4	Convert Mechanical into Electrical Energy				■				1		1		1			
5	Convert Electrical into Mechanical Energy			1		■			1	1			1			
6	Deliver (Recover) torque to (from) wheels						■			1	1	1				
11	Release Heat to the Environment							■								
12	Transfer Heat (to Cooling system)							1	■							
13	Transfer Moment to (from) the road				1		1			■	1	1				
14	Slow or Stop Vehicle (recovering energy)										■		1			
15	Slow or Stop Vehicle (releasing Energy - by Friction)						1	1		1		■				
16	Control Energy Flow		1		1	1	1		1		1		■		1	
17	Connect/Transfer External Electric Energy Source												1	■		
18	Consume Electric Energy for Auto Accesory OPS														■	
19	Consume Mechanical Energy for Engine Accesory															■

Functions – Components DMM / Components DSM

	Component	F1	F2	F3	F4	F5	F6	F11	F12	F13	F14	F15	F16	F17	F18	F19	C1	C2	C4	C5	C8	C21	C22	C23	C24	C25	C26	C27
1	Fuel Tank	1															■		1									
2	High Voltage Battery		1						1									■				1			1			
4	Internal Combustion Engine			1					1								1		■	1		1						1
5	E-Motor/Generator1				1	1			1		1								1	■		1						
8	Wheel E-Motor				1	1	1				1										■		1		1			
21	Cooling System							1										1	1	1		■			1			
22	Wheels									1	1	1									1		■	1				
23	Braking-system							1				1											1	■				
24	Power Control Electronics/Inverter								1				1					1			1	1			■	1	1	
25	Plug w/ Charging device													1											1	■		
26	Additional Electric Accessories Load														1										1		■	
27	Mechanical Accessories Load															1			1									■

Vehicle Powertrain Configuration Schematic (Series with 4 Wheel Motors)



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