

*EVS27**Barcelona, Spain, November 17-20, 2013*

## **Trends in Vehicle Concept and Key Technology Development for Hybrid and Battery Electric Vehicles**

Benjamin Frieske<sup>1</sup>, Matthias Kloetzke<sup>1</sup>, Florian Mauser<sup>1</sup><sup>1</sup> *German Aerospace Center (DLR), Institute of Vehicle Concepts, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany  
Benjamin.Frieske@dlr.de*

---

### **Abstract**

This paper examines the state-of-the-art and trends in vehicle concept as well as key technology development in the context of electric mobility in a time frame from 2002 until 2012. Thus, an extensive vehicle concept database was designed, covering detailed technical specifications of more than 200 electrified vehicles in 3 different world regions, also considering different stages in vehicle development. By analyzing and comparing over 75 different market- and technology-oriented parameters per vehicle, sophisticated statements for the state-of-the-art and development trends of Hybrid and Battery Electric Vehicles are identified. Results in this paper illustrate trends for Hybrid and Battery Electric Vehicle concept development with a focus on vehicle development stages, vehicle segments and powertrain architectures. On the other hand, state-of-the-art and trends for the development of two electric mobility key technologies are pointed out: Batteries and electric machines. Statements here are made for developments in terms of battery and electric machine technology, installation place, as well as technical parameters like energy capacity and power density. Key results illustrate e.g. a trend towards the use of front and rear axle motors, a more than doubled average electric machine power density with over 1,0kW/kg and an average BEV battery capacity of 19Wh per kg vehicle mass in 2012.

*Keywords: Battery, BEV (Battery Electric Vehicle), HEV (Hybrid Electric Vehicle), Power Density, Powertrain, Synchronous Motor*

---

### **1 Introduction**

Electrification of the automotive powertrain is one of the main trends in current vehicle development [1]. Adding supplemental energy storage and energy converter devices to conventionally powered passenger cars allow Original Equipment Manufacturers (OEMs) to significantly increase the efficiency of energy usage of the overall vehicle [2]. As a means to meet ambitious CO<sub>2</sub> reduction targets defined by politics, to avoid penalty fees and to account for

changes in the awareness of customers concerning environmental issues, a variety of different propulsion concepts are being developed. With a multitude of possible powertrain configurations realized (e.g. different degrees of electrification, powertrain topologies, components used), these vehicle concepts and technologies compete in a highly dynamic world market [3]. However, it is uncertain which solution will prevail in the future [4].

To identify development trends, a comparison of detailed technical data of passenger cars over the

time is needed. While a few sources on vehicle performance data already exist, they do not meet the required level of detail and mainly focus on passenger cars in series production as well as vehicles powered by a conventional internal combustion engine [5]. Thus, detailed knowledge about market- and technology-oriented aspects of electrified passenger cars considering a wide timeframe is missing.

The Vehicle Concept Database developed by the German Aerospace Center (DLR) addresses this lack of information. The aim of this study is to compare and analyze the development of market- and technology-based parameters for over 200 electrified vehicles over the last 10 years in detail, thus identifying historical trends as well as the current state-of-the-art. This allows for statistically unique and sophisticated statements in the development of the vehicle concept itself as well as different key technologies for Hybrid Electric Vehicles (HEV) and Battery Electric Vehicles (BEV).

## 2 Methodology

For the analysis carried out in this paper, an extensive vehicle concept database was designed, covering all electrified passenger cars over the years 2002-2012 in detail. Mild-HEV, Full-HEV, Plug-In HEV, Range-Extended Electric Vehicles (REEV) and BEV are considered for this analysis. Besides HEV, REEV and BEV in series production, it was the goal to include also concept cars, design studies and close-to-production prototype vehicles in the database. This allows for comparing e.g. the components used in an early stage of vehicle development with those actually introduced into the market a few years later. Furthermore, the analysis covers three different geographical regions (Europe, USA, Asia) to identify similarities and differences in vehicle concept and technology development trends in an international scope.

The vehicle concept database comprises more than 215 parameters per vehicle. Thereof, 75 were prioritized for the analysis in this paper. They are grouped into market-based parameters as well as technical parameters for different key technologies of electric mobility [6]:

Examples within the 20 prioritized market parameters include name of manufacturer, year of introduction, place of introduction (e.g. motor show), target market, target cost, vehicle segment and vehicle development stage, as well as general

parameters concerning the vehicle concept itself like the degree of electrification, energy consumption per 100km in NEDC, CO<sub>2</sub> emissions per km, size in mm and weight in kg.

In addition to that, a total of 55 technical parameters in 2 different electric mobility key technology fields are covered. In this analysis, statements will be made for 'batteries' and 'electric machines'. The DLR Vehicle Concept Database comprises a total of 5 different technology fields: energy storage technologies (e.g. batteries), energy converter technologies (e.g. electric machines), power electronics, thermal management for electric machines and power electronics as well as lightweight design. Also the powertrain topology (e.g. serial, parallel, power-split) of each electrified vehicle is mapped in detail. The technical parameters were identified and prioritized by literature research and carrying out interviews with experts in their respective technology field. Prioritized parameters for batteries and electric machines as key technologies include for example the following:

### Batteries:

- Technology (Li-Ion, Ni-Cd, etc.)
- Installation site (trunk, underbody, etc.)
- Nominal energy (kWh)
- Nominal voltage (V)
- Specific energy (Wh/kg)
- Specific power (W/kg)

### Electric Machines:

- Technology (synchronous, induction, etc.)
- Installation site (gearbox, in-wheel, etc.)
- Effective power (kW)
- Power density (kW/kg)
- Nominal torque (Nm)

Results of the analysis focus on various topics that are relevant for identifying the state-of-the-art in vehicle concept as well as key technology development. Within this paper, the following evaluations comprise the development of electrified concept cars in relation to series production vehicles throughout the years 2002-2012, the development of Hybrid Electric and Battery Electric Vehicle powertrain architectures, the development of battery technology, energy capacity and installation site in relation to the degree of electrification as well as the development of electric machine technology, weight, power, and installation site in relation to the vehicle segment in different world regions.

### 3 Trends in Vehicle Concept Development

#### 3.1 Concept Cars and Series Vehicles

Between 2002 and 2012, more than 350 electrified vehicles were presented by small, medium and large enterprises in the automotive industry throughout the world. Thereof, about 130 vehicles have already reached series and small series status in the vehicle development stages and were/are ready for market penetration. Another 220 electrified light-duty vehicles were presented in an early concept or prototype status, mainly by OEMs and very often to give potential customers an impression of what to expect in terms of design and innovative technological development in the near future. A clear trend for the increasing importance of electrified vehicles in the last ten years can be derived by comparing the sheer quantities of Hybrid Electric Vehicles and Battery Electric Vehicles that were newly presented at e.g. motor shows throughout the world.

As Figure 1 shows, the number of Hybrid and Battery Electric Vehicles in concept and prototype stage (blue area) worldwide was constantly increasing from 2003 on, arriving at a peak of 44 vehicles in the year 2011. Following with a time lag of 2 to 4 years, a similar trend can be seen in the development of series vehicles (red area), showing a peak in 2009 with 29 vehicles. The number then remains on a constantly high level until 2012, where it is slightly decreasing to a total of about 50 newly presented vehicles in this year.

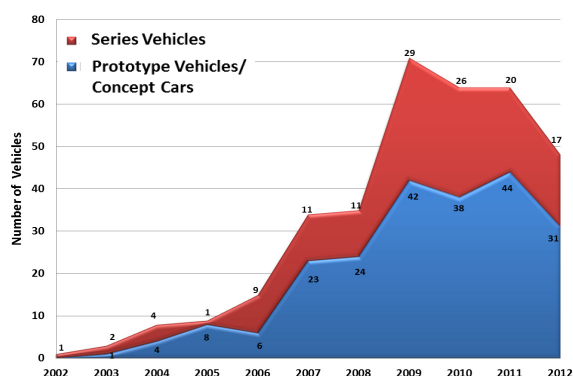


Figure 1: Number of Concept Cars and Series Vehicles for Electrified Light-Duty Vehicles between 2002 and 2012

#### 3.2 HEV and BEV per Vehicle Segment

When investigating in which vehicle segment Hybrid and Battery Electric Vehicles in concept and series stage were introduced throughout the last ten years in different world regions, interesting statements can be made. The following results build up on the European vehicle segmentation (A: very small cars; B: small cars; C: medium cars; D: upper-medium cars; E: executive cars; F: luxury cars; S: sports cars; M: multi-purpose vehicles; J: sport utility vehicles (SUVs)).

A regional comparison of vehicle segments shows for example that European manufacturers in particular focus on the upper and sports class (segments E+F+S) when introducing Hybrid Electric Vehicles. Asian OEMs on the other hand introduce HEVs mainly within the middle class segment (C+D), also including the Toyota Prius as Full- and Plug-In Hybrid Electric Vehicle. US-American manufacturers prefer the SUV segment (J) for HEV market penetration, with a total of 45 concept and series vehicles presented. Due to a high curb weight, large luxury cars as well as Sport Utility Vehicles offer in general a large potential for improvements in terms of the overall energy efficiency and fuel consumption through electrification of the powertrain [7]. Very small and thus light cars (e.g. segment A) are by far the least important segment for HEVs with only 5 vehicles documented in the database so far, as shown in Figure 2.

For Battery Electric Vehicles on the other hand, the small and very small segment (A+B) is by far the most relevant one to OEMs worldwide, with a total of 70 vehicles already introduced into the market or presented in concept and prototype stage. Reasons for this in particular are very high production costs of today's batteries in combination with a high net weight and relatively low energy density per kWh [8]. Thus, pure electric driving ranges of max. 150km to 200km are affordable for average customers, which today predestine small BEVs for (mega-) city operation.

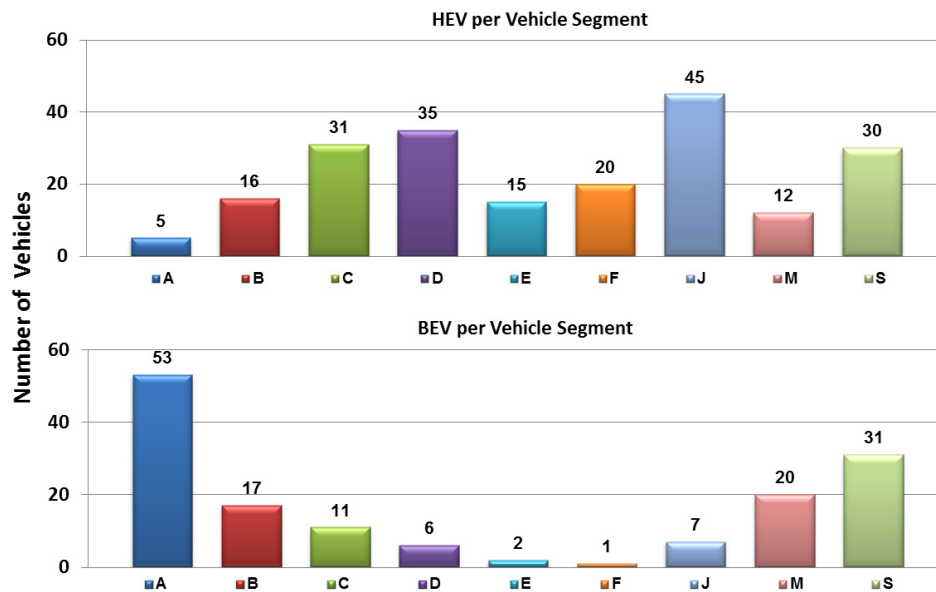


Figure 2: HEV and BEV Concept and Series Vehicles per Vehicle Segment

Another important segment for BEVs is the sport class (S) with 31 vehicles included in the database. During the last 10 years, high performance sports cars like the Mercedes-Benz SLS AMG Electric Drive, the Audi R8 E-Tron as well as the Tesla Roadster were presented at international motor shows throughout the world. However, most of these vehicles are concept or prototype cars, which serve as technology platforms, test vehicles or were presented for image and marketing reasons.

### 3.3 HEV Powertrain Architectures

Three different configurations of hybrid powertrains are possible, depending on the layout of the hybrid system and the interaction of the respective components and modules (mainly internal combustion engine, electric machine, generator, transmission and battery system): parallel, serial or combined (here: “power-split”), as shown in Figure 3. Each powertrain architecture has distinct characteristics in terms of e.g. weight, volume, cost, complexity, efficiency, driving dynamics and comfort to the customer [9].

A serial hybrid powertrain consists of a generator that is coupled most often to the conventional internal combustion engine (ICE). The ICE in a serial hybrid does generally not work as propulsion device for the vehicle. Instead, the generator on board is used as an energy converter

that powers an electric machine connected in series. The electric machine again inducts the power generated either into a battery system or directly to the electric motor which finally propels the vehicle. The fundamental advantage of the serial hybrid system is that the ICE installed in the car can be reduced in size and operated only in need of charging the battery. This significantly reduces local emission of greenhouse gases. Realizing high efficiency ranges as well as optimal engine operating points is possible. Range-extended Electric Vehicles like the Chevrolet Volt are per definition in general serial Hybrid Electric Vehicles, although for efficiency reasons, the ICE does propel the vehicle at high velocities, making it a “combined” HEV in reality.

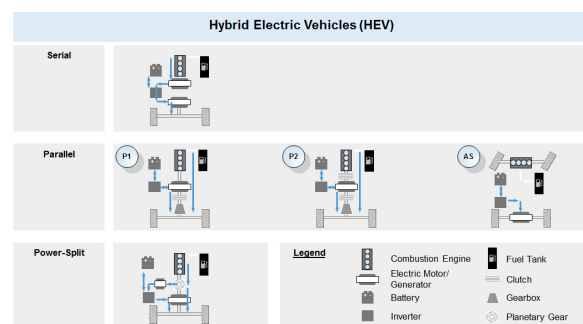


Figure 3: Possible HEV Powertrain Configurations [10]

A parallel hybrid powertrain can both use a conventional combustion engine as well as an electric motor for propelling the vehicle. The electric machine installed in the car works both as a generator and as a motor. The combination of ICE and electric motor enables high overall degrees of efficiency and, furthermore, allows adding the torque generated by both engines for means of driving dynamics. However, the ICE can generally not be operated in the most effective operating point for a constant amount of time. Various designs of a parallel hybrid powertrain can be realized and differ mainly by the quantity and the arrangement of hybrid components installed in the vehicle (e.g. using additional clutches (P1, P2) or separate axles for the ICE and electric motor (axle-split, AS)).

The “combined” hybrid powertrain in this paper is defined as “power-split” type as it is used in the Toyota Prius. In general, it is a combination of the serial and the parallel hybrid topology. Two electric machines are used here to support the internal combustion engine. The essential feature of power-split hybrids is that a planetary gear set serves as transmission device. Thus, the generated power of the ICE is split into a mechanical and an electrical path. The electrical path allows the energy to be transmitted to a secondary electric machine that is directly coupled to the motor shaft and thereby to be converted into mechanical power. A power-split hybrid allows for continuously variable transmission ratios and the engine to work in optimal operating points.

Every powertrain topology has specific advantages and disadvantages which will not be discussed in detail here. Nevertheless, a dominant design has not been formed yet and it is doubtful if this will happen in the near future. Considering that the development of hybrid electric systems will be an intermediate step, that hybrid technologies serve as transitory technologies on the way to purely battery electric driven vehicles, it is reasonable to assume that different hybrid vehicle concepts will exist in the future automotive markets [11].

When investigating which type of powertrain architecture was used in Hybrid Electric Vehicles from 2003 to 2012 worldwide, a clear trend cannot be identified so far. Anyway, regional differences do exist: On a global scale, the most used powertrain architecture throughout the years

was the parallel one, followed by the combined, architecture.

When analyzing and comparing the use of HEV architectures in different world regions, it is shown that European OEMs heavily focus on the parallel HEV powertrain architecture (Figure 4). Asian carmakers on the other hand use mainly the combined system, Toyota being the main driver (Figure 5).

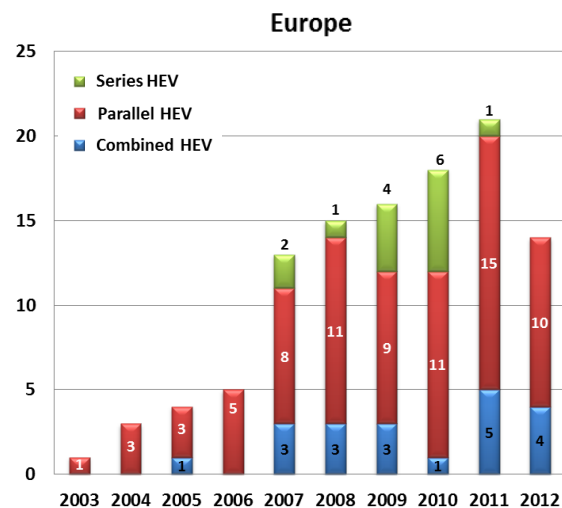


Figure 4: Use of Different HEV Powertrain Architectures in Europe for Concept Cars and Series Vehicles between 2003 and 2012

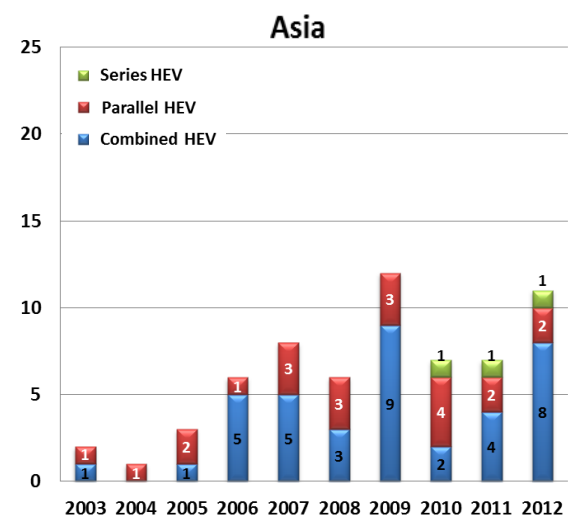


Figure 5: Use of Different HEV Powertrain Architectures in Asia for Concept Cars and Series Vehicles between 2003 and 2012



### 3.4 BEV Powertrain Architectures

Also for Battery Electric Vehicles, different options of designing the powertrain including the quantity and layout of the relevant systems and components can be realized, as shown in Figure 6.

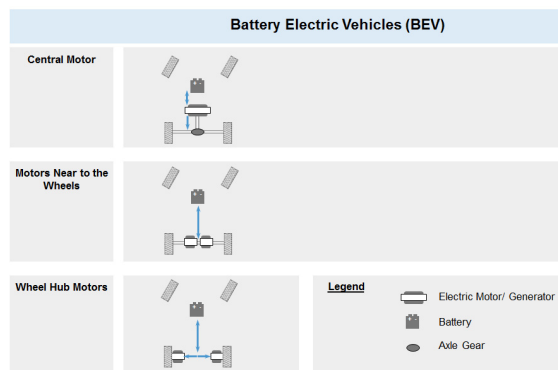


Figure 6: Possible BEV Powertrain Configurations [10]

Usually, the electric machine in the vehicle is installed as central motor. Here, the transmission of power is done with the aid of an axle transmission and a differential.

Electric machines can optionally also be installed on the vehicle's axle near to the wheels. When using this powertrain topology, normally two electric motors are used to propel the vehicle and also two transmissions are installed on board while the differential is not required anymore.

Another way of designing the powertrain of Battery Electric Vehicles is to install wheel hub or in-wheel motors. In general, these electric machines are directly integrated into the wheel hub. This allows for completely replacing transmissions and differentials. However, compared to the central motor, the unsprung masses are substantially increased, theoretically reducing driving dynamics and comfort [12].

Results of the use of different BEV powertrain configurations will be discussed in chapter 4.5 when analyzing the electric machine installation place over the years 2002 to 2012.

## 4 Trends in Key Technology Development

### 4.1 Battery Technology

The biggest technological challenge in the electrification of future vehicle concepts lies in the development of powerful and at the same time cost efficient battery systems [10].

Compared to fossil fuels (12,000Wh/kg, gasoline fuel), the energy density of today's batteries (100-150Wh/kg, Li-Ion battery) is significantly lower [13]. To achieve reasonable electric ranges, large battery packs have to be installed which negatively affects the net weight and production costs of today's Battery Electric Vehicles. For a range of 100km only 7.3kg of gasoline fuel needs to be stored in the vehicle, but 188kg for a Nickel-Metal-Hydride (NiMH) battery and 136kg for a Lithium-Ion (Li-Ion) battery.

To solve this problem, a variety of different electrolyte, anode and cathode materials are being investigated by current battery research. Battery systems based on Li-Ion technology have the biggest potential from near- to mid-term. The characteristics of the whole battery can directly be influenced by developing and adjusting the cell chemistry. For example, Lithium-Nickel-Cobalt batteries have a high energy density but low power density. Lithium-Titanate has a good cycle stability and high power density but is very expensive. Lithium-Iron-Phosphate (LiFePO<sub>4</sub>) is also seen as promising cathode material for near- to mid-term application because it can be produced at relatively low costs, has a high power density and good safety properties [14].

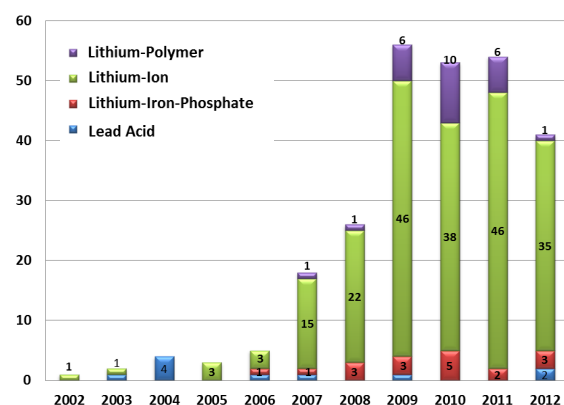


Figure 7: Use of Battery Technologies in Concept Cars and Series Vehicles between 2002 and 2012

As shown in Figure 7, the trend in HEV and BEV battery technology in the years 2002 to 2012 is clearly towards Li-Ion technology, starting with a large gain in 2007 and remaining at a constantly high level until 2012. Within Li-Ion battery technology, Lithium-Polymer is gaining importance from 2009 on, arriving at a peak of 10 concept and series vehicles in 2010. From 2008 on, between 2 and 5 vehicles already use Lithium-Iron-Phosphate batteries every year.

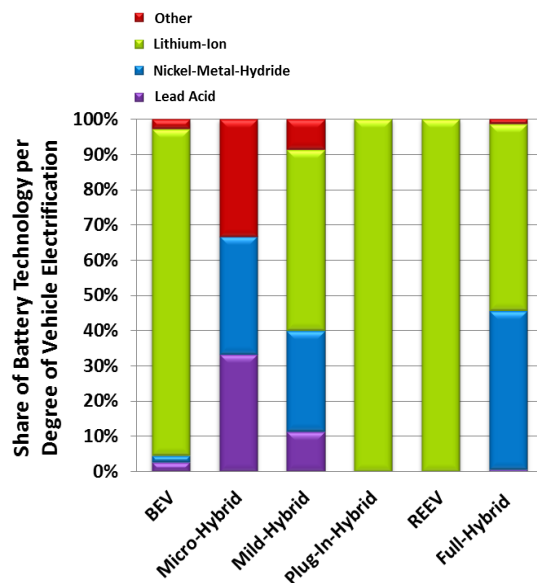


Figure 8: Use of Battery Technologies per Degree of Vehicle Electrification for Concept Cars and Series Vehicles in the Years 2002 to 2012

When investigating which battery technologies were used for different Hybrid and Battery Electric Vehicle concepts throughout the years, a clear differentiation can be derived, as Figure 8 shows.

While Full-Hybrid Electric Vehicles have an almost equal share of Li-Ion and NiMh battery technologies, Range-extended Electric Vehicles and Plug-In-Hybrids focus completely on the more efficient and high energy density Li-Ion technology. Considering Mild- and Micro-HEVs, also lead acid and other battery technologies are being used. For Battery Electric Vehicles (BEV), Li-Ion is by far the preferred battery technology and has shares of almost 95%.

In general, a clear trend can be seen in the use of Lithium-Ion batteries, especially for BEV, Plug-In HEV and REEV. However in the long term, it is not yet sure which battery will be the most

competitive in the future automotive market. Intensive research is for example carried out also for Lithium-Sulfur and Lithium-Air batteries, which could be ready for mass market production within the next 15 years, allowing for even higher energy densities up to 400-500Wh/kg compared to about 150Wh/kg today.

## 4.2 Battery Installation Place

Besides the R&D activities carried out to improve the technical characteristics of battery systems, also (crash-)safety, thermal management and recycling issues are in the focus of current research. Another main aspect when integrating the battery into the vehicle is the battery packaging. Different possibilities exist for where to install the battery within the vehicle.

The Vehicle Database shows that OEMs by far prefer to equip their electrified vehicles with energy storage devices in the underbody of the car (Figure 9). From 2006 on, the number of vehicles with underbody batteries increases constantly, showing an abrupt rise in 2009 and then remaining on a high level until 2011. Other packaging solutions for batteries – like center tunnel, trunk, rear and front of the vehicle – have significantly lower shares.

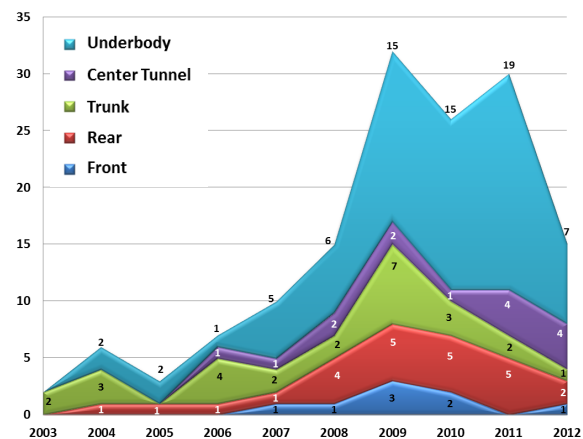


Figure 9: Use of Battery Installation Places for Concept Cars and Series Vehicles between 2003 and 2012

## 4.3 Battery Capacities

Considering the battery capacity of all electrified vehicles in the last 10 years, a trend towards bigger batteries, more electrification and thus more pure electric driving range can be investigated, as shown in Figure 10.

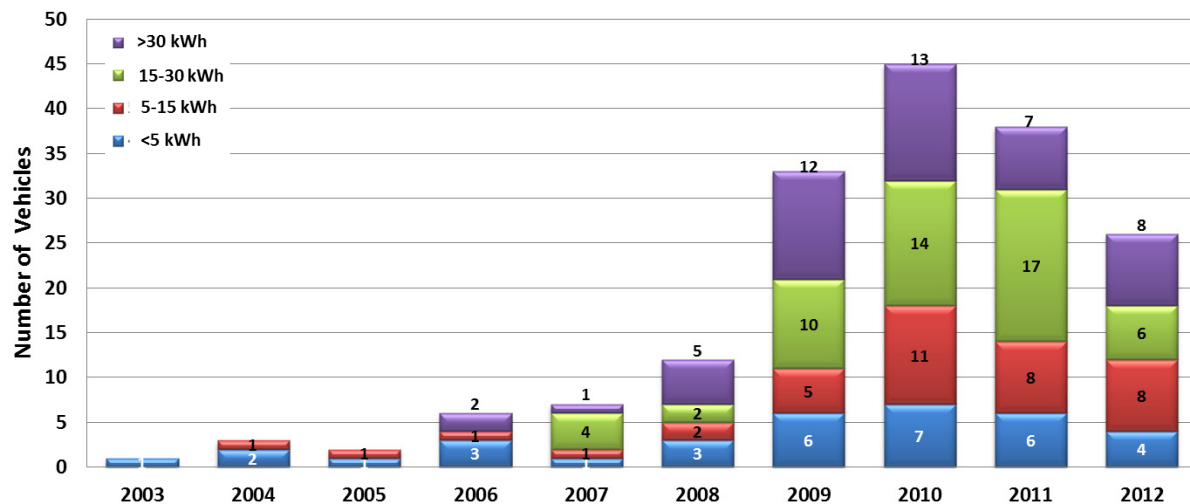


Figure 10: Use of Battery Capacities (in kWh) for Concept Cars and Series Vehicles between 2003 and 2012

Batteries with a size up to 5kWh are mainly used in Mild- and Full-HEVs, allowing for short electric ranges up to 10km and additional hybrid functions like boost, sailing and recuperation. Plug-In HEVs have a larger battery stored on board, allowing for pure electric ranges up to 50km. These batteries mainly have capacities around 15kWh. Range-extended Electric Vehicles and Battery Electric Vehicles use batteries with capacities above 15kWh to achieve electric driving ranges between 50km and 200km.

An interesting trend can in particular be seen when analyzing the specific battery capacity over time in relation to the vehicle mass, and thus deriving the feasible electric driving range of Hybrid and Battery Electric Vehicles (Figure 11). Over the years 2006-2012, the arithmetic mean of the specific battery capacity in relation to the vehicle mass for Battery Electric Vehicles ( $\text{Wh/kg}_{\text{Curb-Weight}}$ ) was fluctuating heavily within the early years ( $35\text{Wh/kg}_{\text{Curb-Weight}}$  in 2006,  $22\text{Wh/kg}_{\text{Curb-Weight}}$  in 2007,  $31\text{Wh/kg}_{\text{Curb-Weight}}$  in 2008,  $21\text{Wh/kg}_{\text{Curb-Weight}}$  in 2009). From 2009 on, OEMs then tended to install battery capacities in relation to the vehicle mass around  $20\text{Wh/kg}_{\text{Curb-Weight}}$ .

The trend line for BEVs suggests a capacity of around  $19\text{Wh/kg}_{\text{Curb-Weight}}$  vehicle mass over the next few years, meaning that a pure electric driving range of about 150km will be realized in NEDC test cycle.

A similar trend can be derived for Plug-In HEVs, although the battery capacities per vehicle mass are not as volatile as for BEVs. However, the trend line over the years from 2007 on is decreasing, settling down at about  $8\text{Wh/kg}_{\text{Curb-Weight}}$ . In a NEDC test cycle, this would translate to about 50km of pure electric driving range for Plug-In HEVs.

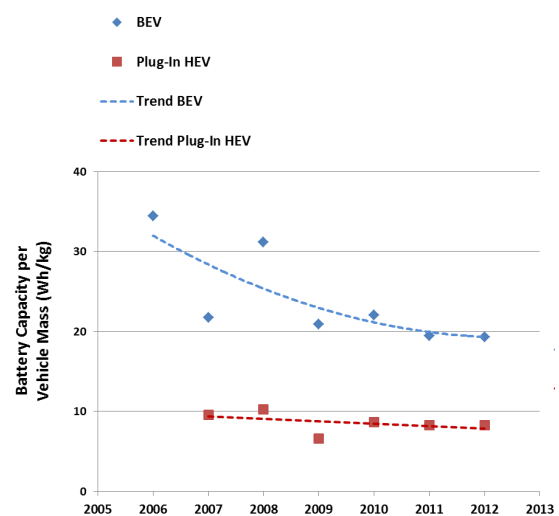


Figure 11: Development of Battery capacity per Vehicle Mass (in Wh/kg)

#### 4.4 Electric Machine Technology

The most important electric machine types in the automotive industry today are poly phase machines (synchronous as well as asynchronous), each having specific advantages and disadvantages. The synchronous machine today is mainly excited by permanent magnets, achieving a very good overall



power density, degree of efficiency (90-95%) and a relatively small, compact design [15]. Disadvantages arise in particular because of the high cost of rare earth materials (e.g., neodymium) that are used for the production of permanent magnets. High cost and limited access to rare earth materials which are available primarily in China are the main drivers for research and development of externally excited electric machines [16]. Besides asynchronous (induction) machines, promising research is also carried out e.g. for switched reluctance machines.

Especially externally excited motors will gain significance in the future if costs for rare earth materials continue to increase. Compared to permanently excited synchronous motors, e.g. induction machines have very good characteristics in terms of reliability, but disadvantages concerning power density, efficiency, volume/weight and controllability. It could be that asynchronous machines will be an alternative in future primarily for small, cheap cars. OEMs in the past and today use induction motors on the one hand in very small city vehicles like the Renault Twizy or Th!nk City for cost reasons, but on the other hand also in high-performance cars like the Tesla Roadster, the Model S or the Audi R8 e-tron concept vehicle.

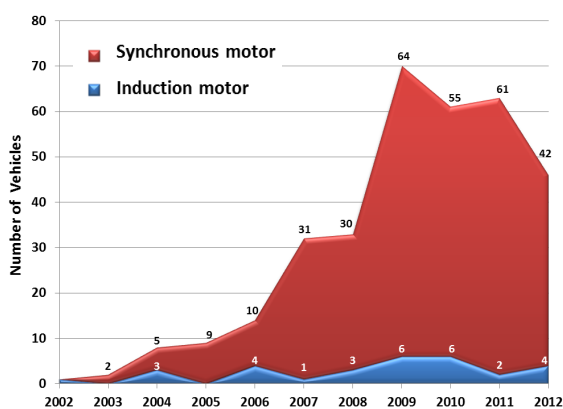


Figure 12: Use of Electric Machine Technology for Concept Cars and Series Vehicles between 2002 and 2012

Analysis of the Vehicle Concept Database shows that synchronous machines are by far the preferred motor type used in HEVs and BEVs over the last ten years (Figure 12). Starting in 2006, a very strong increase can be seen, arriving at a peak of 64 vehicles in the year 2009 and staying on a continuously high level until 2012. Induction motors are used far less over the years, staying at a low level of up to 6 vehicles per year.

There are very few Hybrid Electric Vehicles existing that are propelled by this type of machine (e.g. Chevrolet Silverado Hybrid, 2004), over 80% of vehicles using an induction motor are Battery Electric or Range-extended Electric Vehicles.

#### 4.5 Electric Machine Installation Place

As mentioned in the chapter about different possible Hybrid Electric and Battery Electric Vehicle layouts and powertrain configurations, various places on where to install the electric motor inside the car exist: The traction machine can be installed as one single central motor, as front-, rear- or axle-split-motor, as well as inside the wheel-hub (in-wheel motor) with usually 2 or 4 motors installed, allowing for superior driving dynamics in terms of e.g. torque vectoring and all-wheel drive [17].

When analyzing the installation place of electric machines in Hybrid and Battery Electric Vehicles on a global scale, it can be seen that the central motor is losing importance compared to the axle motor (Figure 13). Starting in 2005, especially the front axle motor is constantly gaining shares, arriving at a peak in the year 2009 (21) and 2011 (20).

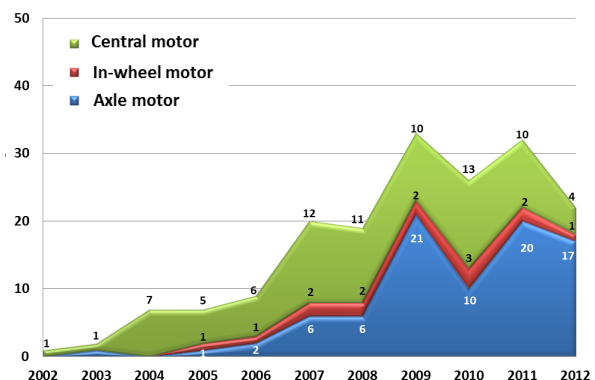


Figure 13: Use of Electric Machine Installation Places and Powertrain Architectures for Concept Cars and Series Vehicles between 2002 and 2013

The in-wheel motor remains at a constant but low level at about 1 to 2 vehicles each year. It is mainly used in high performance prototype cars like the Brabus Project Hybrid (2011, 2 in-wheel motors with 160 kW peak power and 800 Nm torque output each) or the Infinite Emerg-e (2012, 2 in-wheel motors with a total 300 kW power and 1000 Nm torque output) as well as large luxury cars like the Citroen C-Métisse (2006, 2 in-wheel motors with 15kW continuous power and 400Nm torque output each).

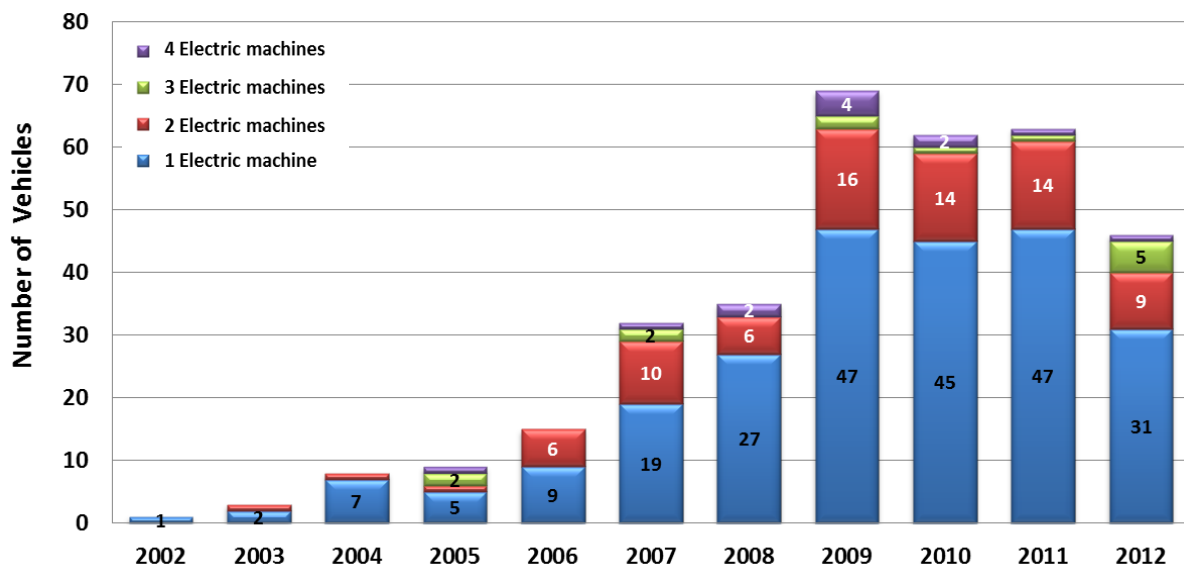


Figure 14: Number of Electric Machines in Concept Cars and Series Vehicles between 2002 and 2012

As the axle motor is gaining significance from 2009 on, also the number of installed electric machines inside the car is rising. From 2009 on, OEMs tend to use 2 electric machines in the car more often, although the use of one single electric motor is still by far the preferred solution, regardless of the installation place as central motor or axle motor, as shown in Figure 14.

#### 4.6 Electric Machine Power Densities

The future technological development of electric motors will mainly be characterized by the attempt to further increase the overall degree of efficiency and power density. Increasing the power density of an electric machine means that the size and weight of the traction motor can further be reduced. The aim of the U.S. Government for example is to raise the power density up to 1.6kW/kg and 5.7kW/l in the midterm [18]. Another challenge for current research is that in the past electric machines have mainly been developed for industrial applications. The specific requirements in the automotive environment concerning durability, temperature resistance and freedom of maintenance need to be incorporated into the development of electric motors for future vehicles.

An analysis of the power density of all HEV and BEV from 2006 to 2012 shows an increasing trend (Figure 15), starting at about 0.5kW/kg in 2006 and arriving at over 1kW/kg in 2011/2012. This is especially interesting when analyzing that the net weight of electric motors was more than

doubled in the last 6 years, starting from 30kg in 2006 and arriving at about 62kg in 2012.

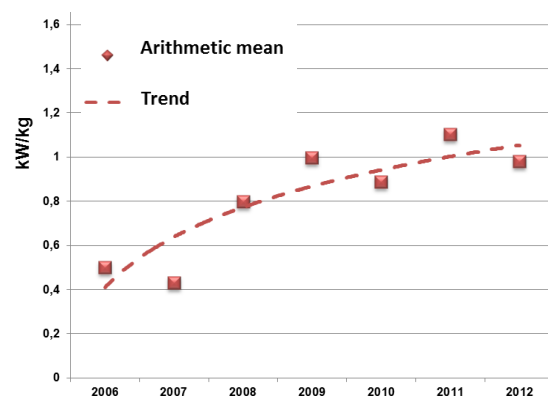


Figure 15: Development of Electric Machine Power Densities (in kW/kg) for Concept Cars and Series Vehicles between 2006 and 2012

## 5 Conclusion

The presented work demonstrates a unique approach to identify state-of-the-art and trends in electric mobility vehicle concept and key technology development. The DLR Vehicle Concept Database comprises over 200 electrified concept and series vehicles that were presented at motor shows or introduced into different world markets over the last 10 years so far. Technical parameters for each vehicle are gathered for 5 different key technologies, generating sophisticated statements and detailed comparisons of developments in advanced research for Hybrid and Battery Electric Vehicles. Key results illustrate e.g. a trend towards the use of front and rear axle

motors, a more than doubled average electric machine power density with over 1,0kW/kg in 2012 compared to 2006 and an average battery capacity for BEVs of 19Wh per kg vehicle mass in 2012, which means that about 150km electric range is achievable in the NEDC test cycle. Regional differences exist e.g. in the use of different HEV powertrain architectures, so that a global state-of-the-art could not be identified so far. European OEMs focus strongly on the parallel HEV powertrain topology while Asian manufacturers prefer the “combined” HEV architecture. The database will continually be updated in the future, and it is expected that around 400 vehicles will be included and analyzed at the end of the year 2014.

## Acknowledgments

The DLR Vehicle Concept Database is being built up in the scope of the project “Research on Perspectives, Technologies and Material Intensities of Electric Mobility”.

The project is funded by the German Federal Ministry of Education and Research within the STROM-program (“Key Technologies for Electric Mobility”).

## References

- [1] McKinsey & Company, *Boost! Transform the Automotive Powertrain - a Portfolio Challenge*, McKinsey & Company, 2011
- [2] United States Environmental Protection Agency (EPA), *Joint Technical Support Document – Final Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards*, 2010
- [3] O. P. R. van Wliet et. Al., *Techno-Economic Comparison of Series Hybrid, Plug-In Hybrid, Fuel Cell and Regular Cars*, Journal of Power Sources, ISSN 0378-7753, 195(2010), 6570-6585
- [4] H.E. Friedrich, B. Frieske, *Trends in der Fahrzeugtechnik vor dem Hintergrund politischer Vorgaben und erwarteter Marktentwicklung*, Deutsches Zentrum für Luft- und Raumfahrt, Sindelfingen, 2012
- [5] ADAC, <http://www.adac.de/infotechatr/autodatenbank>, accessed on 2013-02-11
- [6] F. Mauser, *Modellierung von konzeptionellen und technologischen Markttrends für elektrifizierte Antriebskonzepte*, Deutsches Zentrum für Luft- und Raumfahrt, Stuttgart, 2013
- [7] M. Raghavan, *Propulsion System Electrification*, 13th World Congress in Mechanism and Machine Science, Guanajuato, México, A18-353, 2011
- [8] A. Khaligh, Z. Li, *Battery, ultracapacitor, fuel cell, and hybrid energy storage systems for electric, hybrid electric, fuel cell, and plug-in hybrid electric vehicles: State of the art*, IEEE Trans. Vehicular Technol., 59(2010), 2806-2814
- [9] P. Hofmann, *Hybridfahrzeuge – Ein alternatives Antriebskonzept für die Zukunft*, ISBN 978-3-89190-2, Wien, Springer Verlag, 2010
- [10] Spath et. Al., *Elektromobilität und Beschäftigung- Wirkungen der Elektrifizierung des Antriebsstrangs auf Beschäftigung und Standortumgebung*, ISBN 978-3-8396-8755-0, Stuttgart, Fraunhofer Verlag, 2012
- [11] S. Schmid et. Al., *Market Prospects of Electric Vehicles: Modelling Competition of Alternative and Enhanced Conventional Vehicle Technologies*, Institute of Vehicle Concepts, Stuttgart, 2011
- [12] B. Gombert et. Al., *Wheel-Hub Motors – Criteria of Construction and Vehicle Integration*, ATElektronik worldwide, ISSN 2192-9092, 5 (2010), 4-10
- [13] M. Decker et. Al., *Zukünftige Themen der Innovations- und Technikanalyse*, KIT Scientific Reports 7605, 2012
- [14] J. Fergus, *Recent developments in cathode materials for lithium ion batteries*, Journal of Power Sources, 195(2010), 939-954
- [15] B. Bose, *Power electronics and motor drives: advances and trends*. ISBN 978-0-12-088405-6, London, Elsevier Inc., 2010
- [16] T. Wallington et. Al., *Sustainable Mobility: Lithium, Rare Earth Elements, and Electric Vehicles*, Lecture Notes in Electrical Engineering, ISSN 1876-1100, 191(2013), 155-166
- [17] K. Jalali et. Al., *Development of an Advanced Torque Vectoring Control System for an Electric Vehicle with In-Wheel Motors using Soft Computing Techniques*, SAE International Journal of Alternative Powertrains, 2(2013), 261-278
- [18] United States Department of Energy, *EV Everywhere Grand Challenge – Electric Drive Status and Challenges*, 2012

## Authors



**Benjamin Frieske** (Dipl.-Kaufm. - t.o.) received his diploma in Technically Oriented Business Administration with honors from the University of Stuttgart. He has profound knowledge in the fields of Strategy, Technology and Innovation Management in the aerospace and automotive industry. His professional experience comprises activities at EADS North America (Washington D.C.), Fraunhofer IAO (Stuttgart) and Volkswagen AG (Wolfsburg). Since 2010, Mr. Frieske is working at the DLR Institute of Vehicle Concepts in the area of technology assessment of alternative powertrains.



**Matthias Klötzke** (Dipl.-Ing.) studied Aeronautics at the University of Stuttgart with specialization in aircraft & lightweight design and aircraft systems. His professional experience comprises activities in the automotive industry at Daimler AG (Toolmanagement) in Stuttgart as well as in industrial projects as research assistant at the IFB (Institute of aircraft design, Stuttgart). Since 2010, Mr. Klötzke works at the DLR Institute of Vehicle Concepts in the department of Vehicle Systems and Technology Assessment as a Research Associate.



**Florian Mauser** (Wirtsch.-Ing. - B.Sc.) studied Business Administration and Engineering at the University of Albstadt-Sigmaringen. His first professional experience comprises activities in the automotive industry at Robert Bosch GmbH in Reutlingen. He wrote his thesis at the DLR Institute of Vehicle Concepts in the department of Vehicle Systems and Technology Assessment about market trends for hybrid and battery electric vehicles. Since summer 2013, Mr. Mauser is working at Eissmann Group Automotive in the department of Technical Development as Technical Product Manager.