Design of battery electric vehicles in accordance with legal standards and manufacturers' and customers' requirements

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1 Introduction

The process, methods and tool to design conventional vehicles has been developed, tested and optimized over more than 100 years. For battery electric vehicles (BEV), there is no such experience. In powertrain and energy storage systems (battery vs. fuel tank), but also in chassis and electronics, there are significant differences. Due to this, new design rules for construction need to be developed because developing electric vehicles according to the requirements for driving performance of conventional vehicles is not beneficial for the electric car concept. For example maximum traction power highly depends on temperature, manoeuver duration and State-of-Charge (SoC) of the battery. To design an electric vehicle considering user acceptance, efficiency and economic viability, the layout criteria need to be adapted to the characteristics of, amongst others, powertrain and energy storage.

1.1 Electric Vehicles available today

Table 1 shows currently available electric vehicles. Aside from the Tesla Model S and the upcoming Chevy Bolt all of todays electric vehicles have a New Electric Driving Cycle (NEDC) Range off less the 300 km and are not suitable for long range travelling.

2 Temperature Operating Conditions

In order to make sure that the vehicle is applicable in all relevant markets, it must be designed for a wide operable temperature range. Platform and construction sets, which are used for conventional and electric vehicles, define the boundary conditions for platform-parts of battery electric vehicles, even if they are not sold in countries with extremely high respectively low temperatures. The operable temperature range for internal combustion engine vehicles reaches from temperatures up to +50 °C (for example in the middle east) and below -20 °C (limit-temperature for diesel-fuel in winter), where it is assumed that the vehicle is well tempered. Petrol cars normally start up even at temperatures lower than -20 °C.

2.1 Critical Temperatures for BEVs

For most powertrain parts, extreme temperatures mainly result in mechanical requirements which are due to bearing clearance and viscosity of lubricant and coolant. However, the temperature effect on the battery system is even more dramatic. High battery temperatures result in exponentially faster battery degradation, at low temperatures the power output for driving and the power input for charging are highly limited. [Fraunhofer, 2015] quantifies the power reduction at low temperature with factors of 5 – 7. The power limitation of the most recent electric vehicles is even more severe, such that long-time exposure to great cold without preheating the battery renders the vehicle inoperable. The charging process is also strongly affected by extreme temperatures: At battery temperatures below 0 °C, charging time increases extremely, such that the charging power is first used for heating up the battery (for cars with an electric battery heating system) and the charging process starts after the battery has reached temperatures above 0 °C.

Table 1: Overview of Battery Electric Vehicles

	BMW i3 (2016)	Chevy Bolt (2017)	Hyundai Ioniq (2017)	Kia Soul (2014)	Nissan Leaf (2015)	Renault Zoe (2017)	Tesla X P90D (2016)	VW e-Golf (2017)
Battery Capacity [kWh]	33	60	28	27	30	41	90	35
Battery Mass [kg]	240	485	260	270	290	300	610	310
Power (Peak/Contin.) [kW]	125/75	150/?	88/?	81/?	80/?	65/43	396/?	100/50
0 – 100 km/h [s]	7,3	< 7	9,9	11,5	11,3	13,5	3,9	9,6
Top Speed [km/h]	150	150	165	145	144	135	250	150
Torque [Nm]	250	360	295	285	254	220	658	290
Consumption NEDC [kWh/100km]	12,6	~13	11,5	14,7	14,7	13,3[1]	17,3[2]	12,7
Range NEDC [km]	300	~ 400	250	210	250	4003	467	282
Mass [kg]	1.245	~ 1.600	1.495	1.565	1.533	1.577	2.468	1.585

1 NEDC city cycle only
2 plus charge losses

2.2 Reduced Traction Power at extreme Temperatures

The power and performance of conventional vehicles is not significantly affected by temperature. Merely after cold starts, there is a revolution per minute (rpm) limit for diesel engines, and due to reduced air mass stemming from warmer inlet air at hot temperatures, there is a small power reduction at hot temperatures for Internal Combustion Engine (ICE) vehicles. As already mentioned, the performance of battery electric vehicles is significantly diminished at extreme temperatures. At low temperatures, the electrolyte freezes, and hence, the power of the battery effectively reaches zero. At high temperatures, the battery power is limited by the battery management system to save battery life and limit the risk of a thermal runaway.

For reducing the power limitation, the thermal management heats at low temperature and cools down at hot temperatures. As visible in table 1, the two long range electric vehicles (Tesla Model S and Chevy Bolt) contain heavy batteries, which results in a high energy and power demand to heat those batteries up to a proper temperature. This power demand competes with air-conditioning and also with the power needed for driving. Especially in situations when the maximum power of the battery is limited, power distribution needs to be prioritised.

2.3 Reduced Range at low Temperatures

Due to the fuel tank with its high energy content and low efficiency of conventional vehicles, there is only a small effect on range at low temperatures. In contrast, the powertrain efficiency of electric vehicles is high, and hence, there is only little waste heat available for heating up the powertrain. For cabin and traction battery climatization, electric powered high voltage heaters with power consumption of about 5 kW are necessary. This additional power need which approximately equals the power needed for traction in city driving cycles, results in a range loss at low temperatures (table 2).

Table 2: BEV range at low temperatures [Autobild2014-1]

Vehicle	Battery Capacity	Range (NEDC)	Range (winter -4 °C)
Tesla Model S	85 kWh	502 km	206 km
Nissan Leaf	24 kWh	199 km	69,1km
BMW i3	21,6 kWh	130 – 160 km	61,4 km
Mitsubishi i-MiEV	16 kWh	150 km	61,3 km
Renault Zoe	22 kWh	100 – 150 km	58,9 km

3 Powertrain Specifications

Maneuvers with long duration and high power demands significantly influence the design of the powertrain, especially when repeated. The electric powertrain can be overloaded without negative effects for short time periods. This boost power is only available for a limited time because of resulting rise of component temperatures. This wide power spectrum ranges, for example, for the Tesla Model S P90D from extreme low power at low SoC (< 15 kW at SoC < 5%), over certificate of conformity power of 69 kW to the peak power of both electric engines of 567 kW.

ICE vehicles do not possess such a wide range of available power; instead there is only the maximum power of the internal combustion engine which is available in nearly every situation. For supercharged engines, sometimes an over boost torque or launch control mode is declared, which can be used for acceleration in low gears. Only in case of a detected malfunction, the power is reduced (for example limp home mode to reach a safe area on highways). Compared to battery electric vehicles, the amount of fuel does not affect the power of a conventional vehicle.

The powertrain of an electric vehicle consists of an electric part, including battery, battery junction box (BJB), power electronics and engine, and a mechanical part, including rotor shaft, gearbox and axle shaft. Both parts can be overloaded. By overloading the mechanical part, the lifetime is reduced depending on the overload size. Overloading the electric part does not reduce the lifetime directly. Without strengthen the thermal management, the component temperatures increase, especially in the high power parts. For instance the rotor of the electric engine and the insulated-gate bipolar transistor (IGBT) of the power electronics are converting high current. These higher temperatures result in a faster aging of those parts. For electric vehicles, the manufacturer often declares a peak and a continuous power because of this ruggedness. For example, the peak power of Tesla Model S P90DL is 6 times the continuous power. While overloading an electric powertrain, the cooling requirements are more challenging because the cooling supply temperature for the components, especially the battery, is much lower than for an internal combustion engine (table 3), and a direct contact between coolant and electric parts needs to be prevented due to electrical conductivity of the standard coolant.

Table 3: Efficiency and Thermal Parameter Tesla Model S90P

	Battery	Power Electr.	Electric Engine	ICE
Temp. Range	0 – 50 °C	< 80 °C	< 120 °C	< 300 °C
Efficiency	~ 97%	85 – 95%	80 – 95%	5 – 40%
Therm. Capacity	300 kJ/K	10 kJ/K	25 kJ/K p. EM	

In table 3 working temperatures, efficiency and thermal capacity of the Tesla Model S90 powertrain are shown. The efficiency of all three parts is much higher compared to a conventional powertrain, so that there is less waste heat. The maximum temperature is lower, too. Since the maximum tolerable temperature of the battery is about 50 °C, an active cooling system is needed. Due to the huge thermal capacity of the battery, the heating is relatively slow. The higher working temperatures of power electronics and engine enable the cooling of these components by means of a radiator. The self-heating of power electronics and engine needs to be monitored carefully due to the small thermal mass, which results in fast heating at high power. Most of the heating is produced in parts which cannot be cooled directly, for example the rotor and IGBTs. Hence, the cooling becomes more complex and inefficient.

In the EU Regulation R85 [ECE R85], the power measurement is described. The peak power must be available only for a short duration, in contrast to the net power, which is averaged over 30 minutes. Table 4 shows the bandwidth of the net and peak power of the Tesla Model S. For smaller vehicles like the BMW i3 and the VW e-Golf the difference between net and peak power is less significant (factor 1,5 ... 2).

Table 4: Net and Peak Power Tesla Model S P90D (with and without Ludicrous Option)

	Net Power (30 min)	Peak Power Electric Engines	Battery Power
Tesla P90D	69 kW	v: 193 kW; h: 375 kW; ∑ 567 kW	345 kW
Tesla P90D L	69 kW	v: 193 kW; h: 375 kW; ∑ 567 kW	396 kW

3.1 Load Cases

Due to the option to overload the powertrain, the measurement results for standard maneuvers depend on the temperature of the drivetrain. For example, after repeating an acceleration maneuver several times the power drops from peak to net power. The maneuvers are given by legislative authority, consumer protection organizations (for example NCAP or IIHS) and automotive magazines. Although the maneuvers of magazines are not obligate, poor test results lead to bad publicity.

3.2 SoC Influence on Driving Performance

The state of charge and temperature of the battery have a significant effect on the available maximum power. At very high respectively very low temperatures, as well as low charge states, the battery power is limited.

3.2.1 State of Charge and Battery Voltage

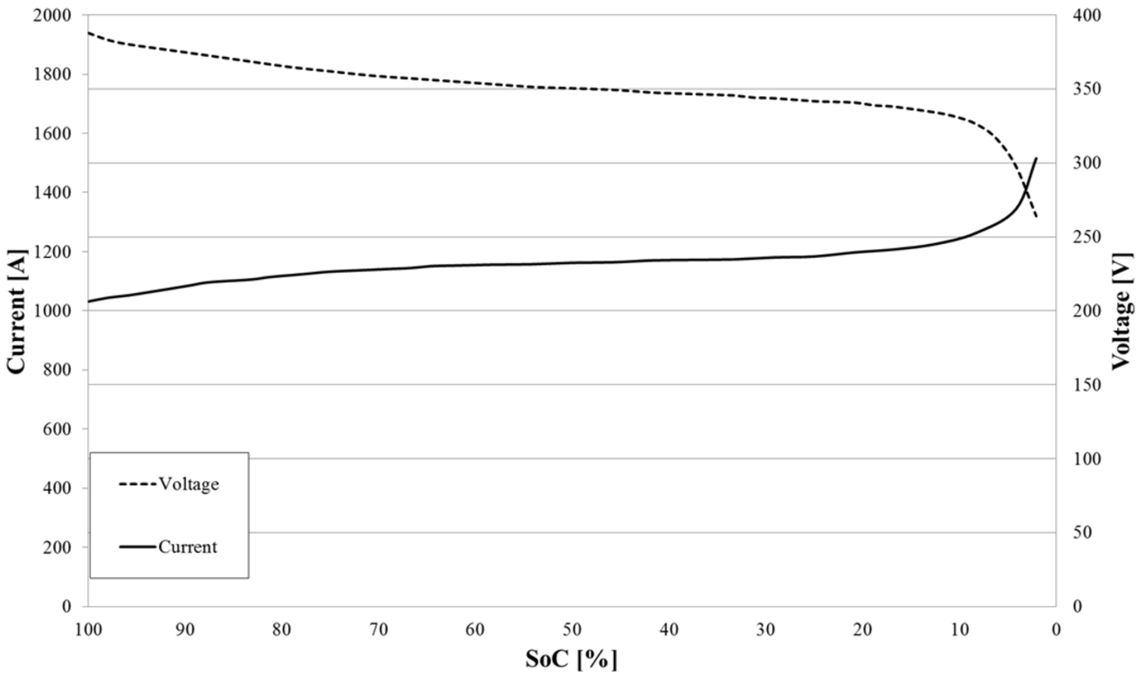

Figure 1: Current Influence on Cell Voltage (OCV) at 400 kW Power (Cell data from [lygte2011])

Lithium-Ion- and Lithium-Polymer-Batteries have a nominal cell voltage of 3,7 V. Nominal voltage is measured at 50% SoC. At higher SoC the voltage increases, at lower SoC the voltage decreases. The usable range is between 2,8 V (10% SoC) and 4,2 V (95% SoC). In most electric components, the current is the limiting value, so that for a given power and decreasing voltage the current must rise (P = U x I). As mentioned, maximum current is limited and consequently the maximum power decreases. The battery peak power of Tesla Model S in table 4 of about 400 kW is only available at high SoCs. The 96s74p (96 cells parallel, 74 cell serial connected) setup applies 400 V at 95% SoC and 270 V at 10% SoC. To supply 400 kW for the powertrain the necessary current rises from an already large value of 1.000 A at 95% to 1.500 A at low SoC (figure 1), which is more than most current-carrying parts (HV-wiring, BJB, power electronics und electric engines) can sustain. In reality, the open-circuit voltage (OCV) in figure 1 drops additionally due to high load. This drop depends on C-factor of the cell, which is the quotient of current and battery capacity:

$$C = \frac{I[A] * [h]}{Q\ [Ah]}$$

For the Tesla Model S85D this means that the maximum speed at very low SoC is reduced to 40 km/h. The C-factor is limiting the maximum power especially for cars with small batteries and/or high electric power. Power reduction due to C-factor, temperature und SoC interact with each other. For this reason, the maximum power of a battery electric vehicle is a function of SoC, temperature and duration. The maximum power is only available at ideal temperature with a fully loaded battery and for a short period of time.

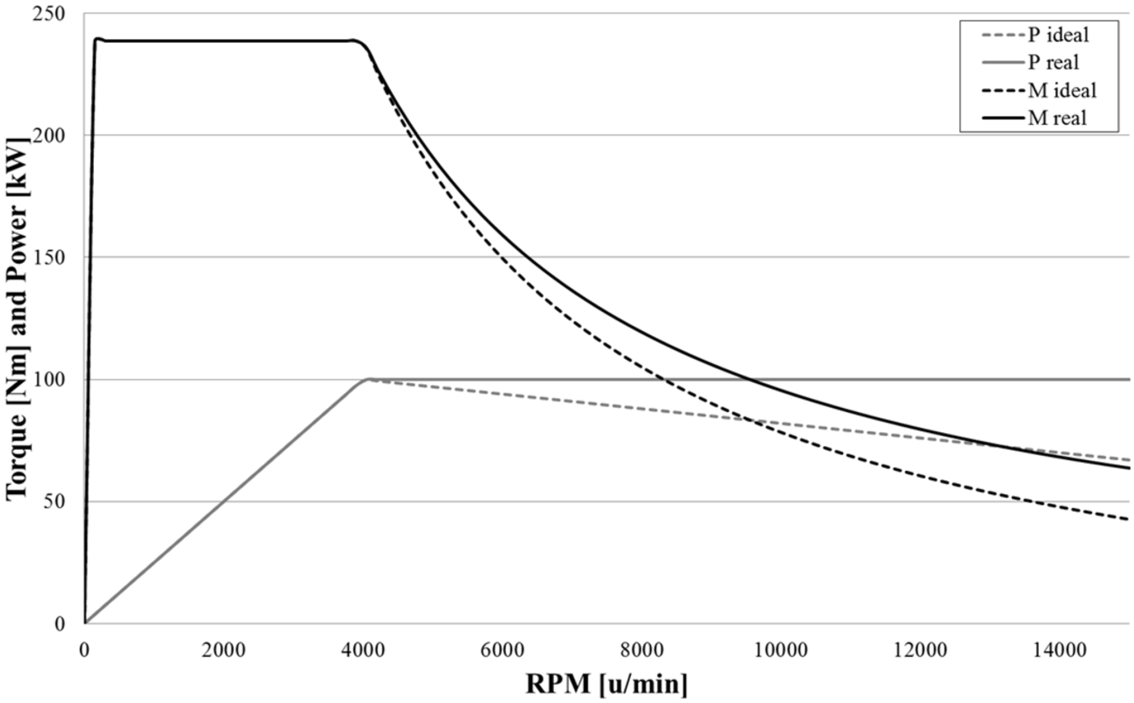

Figure 2: Influence of Electric Engine Efficiency on mechanical Power and Torque

3.2.2 Gear Ratio and Efficiency

In figure 2 the ideal torque and power output curve of an electric motor is shown. Until the rated speed of about 4.000 rpm, the torque is constant (limited by maximum current and torque of the motor) and power raises. At higher rpm the maximum power is the limit and thereby the torque declines ($P = M * n$). In addition to the ideal torque and power characteristics, the real mechanical torque and power output are shown in figure 2: Instead of constant power, the mechanical power is continuously decreasing. The decline is a result of ascending electric losses. For engines with lower efficiency, the decreasing of power at higher rpm is even stronger.

For battery electric vehicles, single speed gearboxes are used. This fixed gear ratio and the graphs shown in figure 2 indicate that power drops with velocity. The gear ratio is given by the maximum speed of the electric machine and the maximum velocity of the car. With rising top speed, the gear ratio gets larger. This implies a reduced start-up torque and thus reduced acceleration performance. In figure 3 the influence of the gear ratio on the acceleration performance is shown. A long gear ratio results in a significant reduced acceleration performance. Due to this reduced performance, cars with high top speed sometimes use 2-speed gear boxes (for example BMW i8 und Rimac Concept One/S).

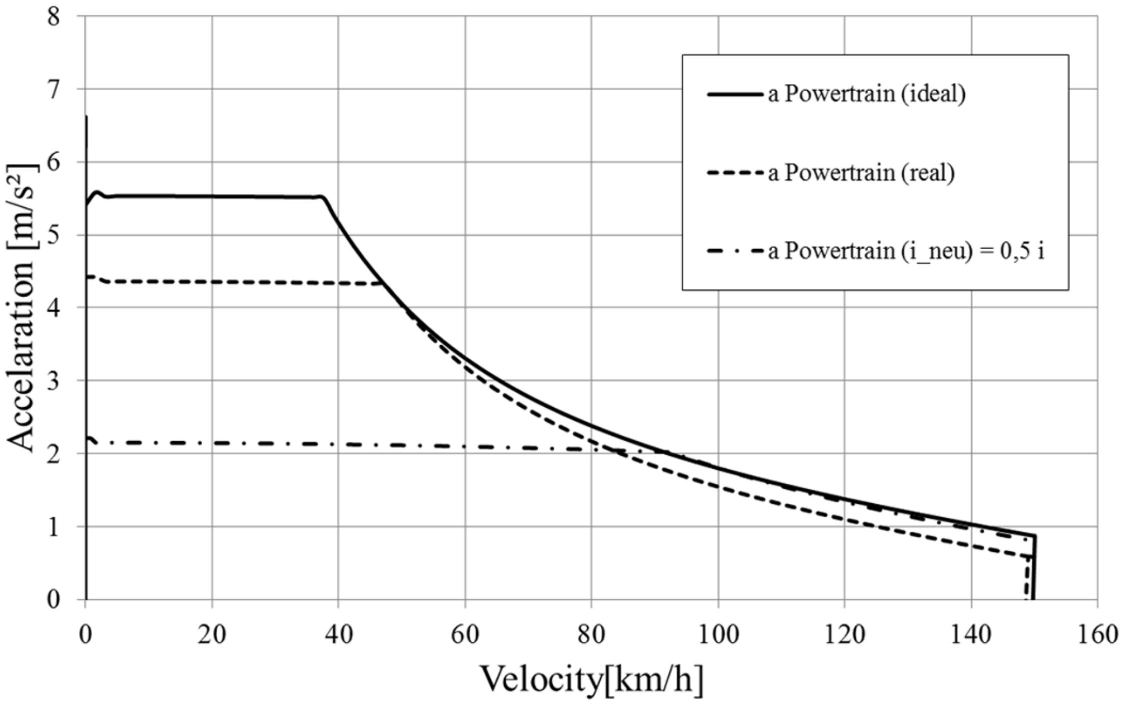

Figure 3: a-v-Chart of a BEV with long and close gear ratio

The start-up torque is important for climbing ability and pass over curbs at low speed, too. Conventional cars with multi speed gear boxes and a short first gear ratio do not have problems with low starting torque, especially with torque converter which rises torque at low speed. Additionally, asynchronous motors (ASM) enable only a low torque at zero rpm, due to a small magnetic field in the rotor while not rotating. ICE vehicles with all-wheel drive having the possibility to shift torque between front and rear axle in a wide range. Electric vehicles do not have a cardan shaft, which means the torque allocation is given by the maximal torque of the machine(s) at the front and rear axle. When using machines with big varying torque at front and rear axle, there is a poor the off-road performance and climbing ability on low friction.

4 Fuel Consumption

For ICE vehicles, the fuel consumption is measured in established driving cycles, which represent the real vehicle usage not at all. The cycles were designed in the 1970s (FTP) and 1990s (NEDC). They do not consider features of modern cars, which increase

fuel consumption, like air conditioning, but also features that increase efficiency, like driving assistance systems. Due to this, customer advocacy, but also OEMs are working on new cycles or at least on adding features and auxiliary load (A/C, active body control, …) to the existing cycles. [MTZ2016-10].

For electric vehicles there are no commonly used special driving cycles. The TÜV Süd developed the TSECC which is rarely used, and in the US, the multi cycle test is used to measure the range of electric cars.

Electric vehicles have the ability to regenerate energy while braking. Classic ICE cars cannot regenerate energy; only with hybridization this is possible. Due to regenerative braking, the dynamics of a cycle and the mass of an electric vehicle do not affect the energy consumption that much. In contrast, the auxiliary load has much more influence on range and efficiency because of the low energy consumption for driving: the Volkswagen e-Golf has an equivalent gas consumption of 1,4 l gas / 100 km. When adding 1 l / 100 km for heating and air-conditioning which is quite normal for ICE cars the total amount of energy is nearly doubled. For a conventional Golf adding 1 l / 100 km for air-conditioning means only a rise in fuel consumption of about 10 – 20%. Additionally, the waste heat of electric vehicles is very small, so that the cabin and battery must be heated electrically. Due to their poor efficiency, the waste heat of conventional vehicles is much higher, such that only at very cold temperatures the cabin is electrically heated for a short time after cold start.

4.1 Variance of Energy Consumption in Costumer Usage

Although conventional vehicles also have a variance in fuel consumption [heise2016], driving cycle and auxiliary load have a much higher influence on the range of electric vehicles. This variance is mentioned in most manuals of electric vehicles. Tesla Motors and BMW offer a website to calculate the maximum range depending on temperature and speed (figure 4)[4]. The graphs in figure 5 show the correlation between speed, energy demand and range of a Tesla Model S. The gain is higher compared to conventional

4 [https://www.tesla.com/en_AU/models, Abgerufen am 09.12.2016], [http://www.bmw.com/com/en/newvehicles/i/i3/2016/showroom/range_charging.html, Abgerufen am 09.12.2016]

vehicles due to the higher efficiency of ICE at high load. At 80 mph (130 km/h) constant speed the battery consumption is twice as high as at 20 mph (32 km/h). As consumption rises, the range decreases: When accelerating from 45 mph to 80 mph, the range is the half. The range reduction in tests of motor journal is much clearer: 185 km at 120 km/h for the 2014er Tesla Model S 85 [Bloch, 2014]. This may be the result of auxiliary load and more dynamic driving.

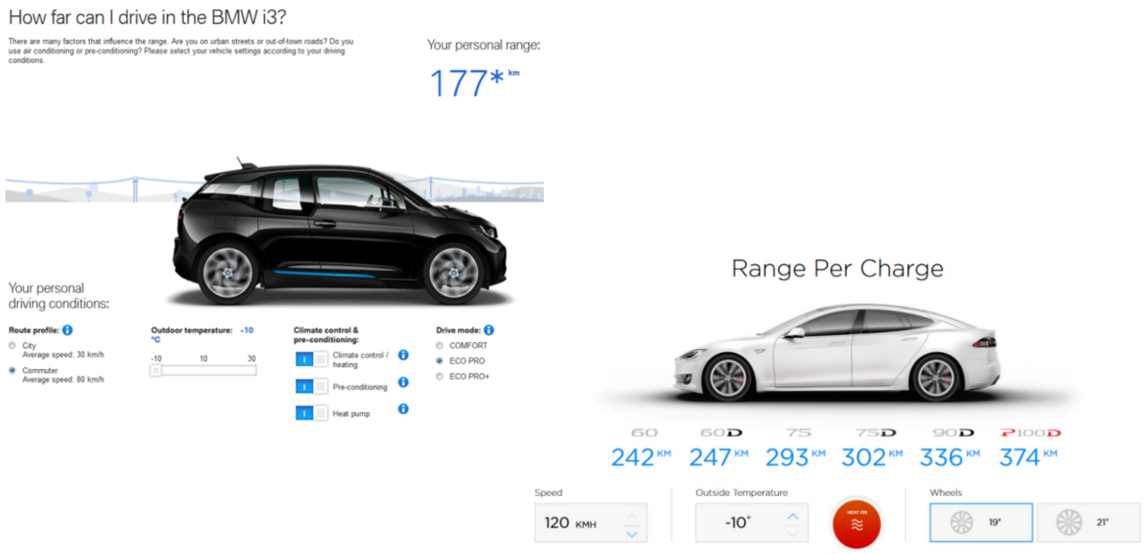

Figure 4: Range Calculator BMW i3 and Tesla Model S

As already mentioned, heating of cabin and battery at low temperatures are significant auxiliary power consumers. Even so electric cabin and engine heating is also used for conventional vehicles (PTC-heater or fuel powered engine-off heaters for Diesel vehicles), the amount of power is much lower due to fast self-heating of ICEs. For long range electric vehicles, battery and cabin heating have an amount of 5 kW each [Schüppel2015]. Due to the high mass and material of large specific thermal capacity (table 3), the battery heater is activated at low temperatures for long periods of time. The self-heating of the battery due to small waste heat is not sufficient for fast and battery-convenient heating. The cycle range may be reduced by heating and temporary capacity loss at low temperatures to more than 50% [Bloch 2011], [Sokolov 2016]. The range loss at second generation or face lift BEV is reduced to about 15% at -7 °C [Bloch 2014]. The range reduction illustrates that the integration of A/C and heating load to cycle tests as planed with the MACTP and EPA AC17 is necessary to give the user range information in real use.

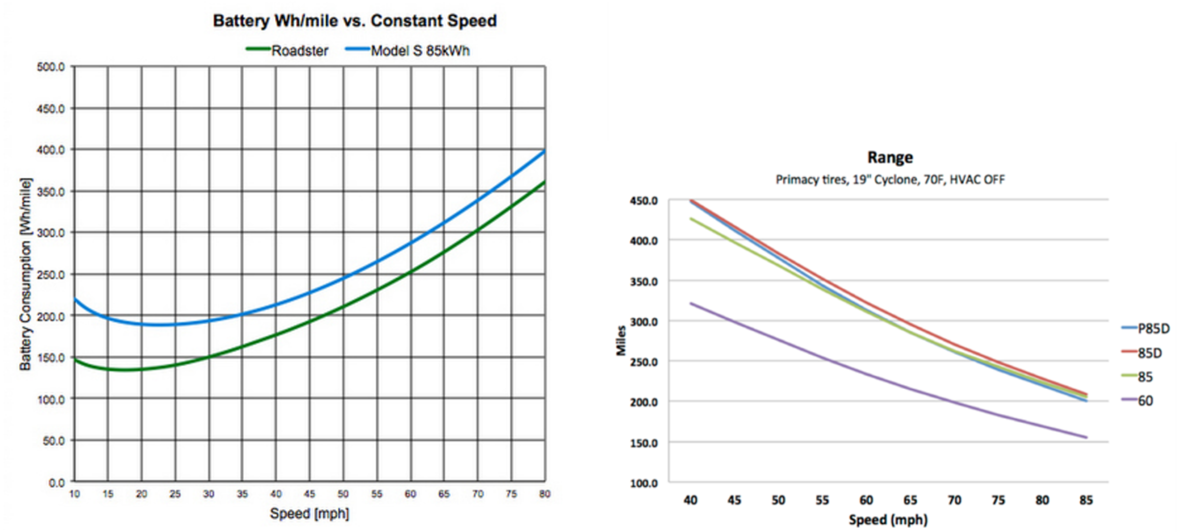

Figure 5: Speed Influence on Energy Consumption and Range [Musk/Straubel 2012][Straubel 2014]

4.2 USA

The EPA developed the 5-Cycle test for electric vehicles. Additionally to the known FTP72 und HWFET cycles a dynamic (US06) and an air-condition cycle (SC03) are driven. To quantify efficiency at low temperatures a FTP cycle at -7 °C is used. The three new cycles (US06, SC03 and cold FTP72) are not yet used [SAE1634]. In future, the new cycles should give customers more detailed information about impact of temperature and driving style on energy consumption.

Today in the US, vehicles with less than 60 miles range are tested with the so called Single Cycle Test (SCT). In the SCT first the FTP72 is repeated until the battery is empty and secondly the HWFET is repeated until empty battery, too. The SCT is very time intense, especially for cars with long range because the full range is driven twice. For vehicles with range higher than 60 miles the Multi Cycle Test (MCT) is used. The MCT consists of 6 weighted cycles and constant speed driving for reducing SoC. The battery is driven empty only once.

4.3 EU

Electric car energy consumption is regulated with the ECE R101 Annex 7 in EU. It is based on the New European Driving Cycle (NEDC) which is driven twice with a fully charged car and afterwards again recharged completely while measuring energy. The result is then extrapolated to a distance of 100 km.

The range is determined the same as in the US SCT Test, which means that a fully charged car is driven in NEDC cycles as long as the battery is empty and the vehicle cannot follow the velocity input. [ECE2014]

4.4 Further Measuring Standards

Japan (JC08) and China (GB/T18386-2005) have different standards for measuring range and consumption. The test procedure in South Korea (SAE J1634) and India (ECE R101) are based on existing methods of US and EU. In table 5 range of the Nissan Leaf in different standards is shown. Due to the high dynamic the range in the US is at least while range in the very slow JC08 cycle is 70% higher.

Table 5: Nissan Leaf (24 kWh Battery) Range in Different Cycles

Nissan Leaf	EU (NEDC)	USA (FTP)	Japan (JC08)	China (GB/T)
Range	199 km	135 km	228 km	160 km

5 Brake Design

Due to low deceleration demands, the regulatory requirements to brakes do not determine the size. Only the maximum pedal force in case of mastervac failure may define the length and the transmission ratio of the brake pedal. State of the art brake systems decelerate much stronger than statutory, so that motor journal and consumer tests are used for brake design.

5.1 Legal Requirements

The legal requirements for brakes are ruled in the UN ECE 13H (EU and Japan) and the FMVSS 135 respectively SAE J 843 (US). In figure 6 the legal requirements and real brake distances are shown. For state-of-the-art brake systems the deceleration request of 5,5 m/s^2 are no challenge.

5.2 Motor Journal and Road Track Test Cases

As shown above the legal requirements are not sufficient for state-of-the-art brake design. Due to this, brakes are dimensioned according to special maneuvers created by motor journals or based on field experience of OEMs. These tests should represent the extreme brake stress of car model life. Besides standard brake tests on dry, wet and icy roads, fading is monitored by repeated high speed tests and long downhill driving (for example the Groß-Glockner Alpenstraße [Bremsenhandbuch2012]).

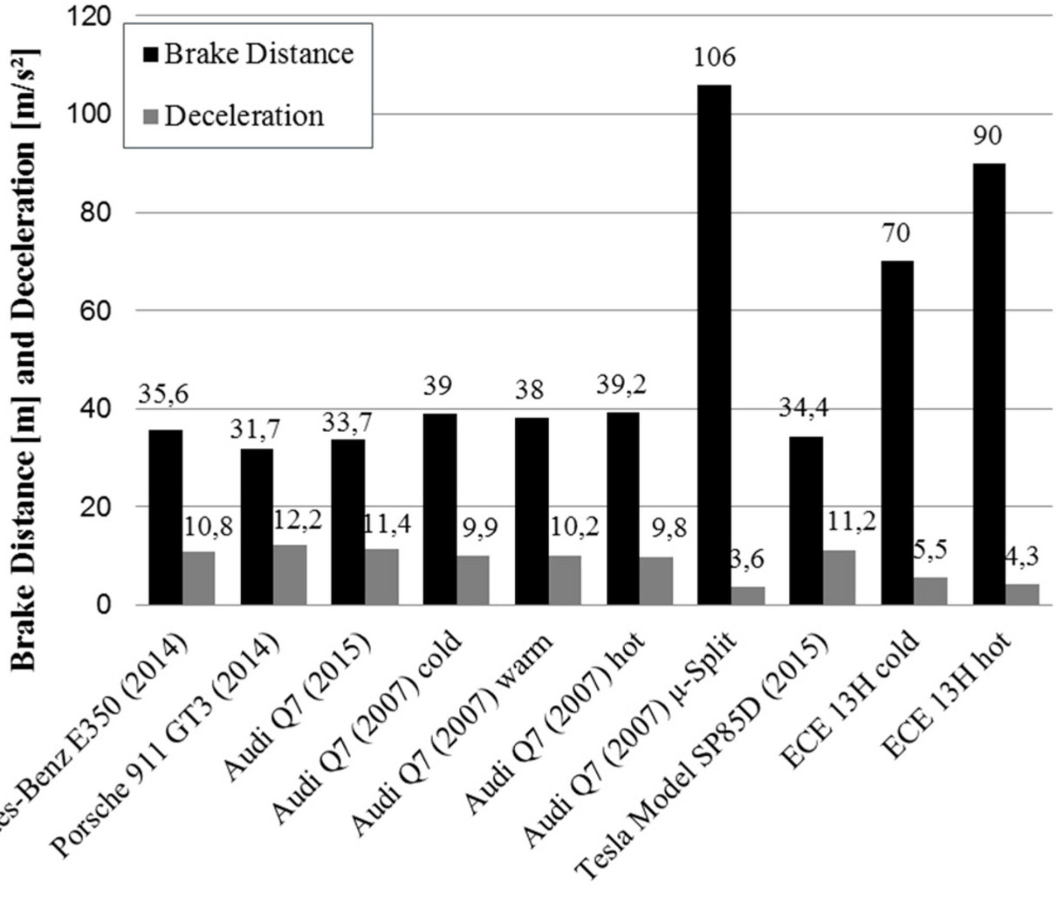

Figure 6: Brake distance (100 – 0 km/h) and deceleration of several cars and ECE requirements [AMS1/2007], [AB2015], [AZ2015]

5.3 Brake Design Differences between electric and gasoline powered Vehicles

Due to recuperation, there are major differences between brake design of conventional and electric vehicles. The drag torque of an ICE depends mainly on the size and losses of the engine, rpm/gear and oil temperature, and is limited to values of about 10-15 kW. Electric vehicles can use their total engine power for braking.

In dynamic situations often the friction brake is used, due to faster and more precise controllability. When braking only the rear axle, the stability in corners or on low-mu may be reduced. Until 3 m/s² (which is not exceeded in normal driving) exclusive electric braking is possible, above the guiding value the mechanical brake is more and more used. [FAT265].

In some uncommon cases the recuperation braking is not available. For example when the traction battery is fully loaded, too cold or hot to charge energy or due to safety issues. If so the mechanical system must decelerate the car on its own. On the other hand in normal driving the mechanical brake is only rarely used, such that action against corrosion and pollution need to be taken.

The challenge is to design a brake system which consists of a mainly used regenerative and a rarely used mechanical brake. The system has to work efficiently and as safely and reliable as the known brake system in conventional vehicles and thus is driven by functional and safety design considerations.

6 Conclusion

The design of conventional vehicles has been developed, tested and optimized over more than 100 years. However, for battery electric vehicles (BEV) there is no such experience. There are major differences between BEV on the one hand and conventional vehicles on the other hand. While some areas, e.g. climatization und E/E architecture, are similarly constructed, other aspects like platform design, architecture, energy storage, and especially the powertrain design differ significantly.

Due to these strong distinctions, nearly all new electric vehicles and construction kits base on a purpose electric design. This leads to the fact that early conversion cars such as Volkswagen e-Golf and Tesla Roadster are replaced or getting replaced with cars which base on pure electric platforms. Besides different design patterns, there are major differences in the performance of Internal Combustion Engine (ICE) driven cars and electric vehicles, for example, the state of charge and the temperature. Whereas the gas tank level of a conventional car has a vanishing impact on the traction power, the full power of an electric engine requires 80% to 100% State-of-Charge (SoC) and temperatures between 10° and 30° Celsius. More dramatically, if the remaining power in the battery cell becomes smaller than 20% SoC, the traction power decreases rapidly. Moreover, at temperatures beyond -20° C the whole functionality of an electric car cannot be guaranteed anymore.

In this work, we compare the design process of electric and regular cars and spot their major differences. It turns out, that in case of electric cars the design of powertrain, braking systems and temperature dependency needs to be entirely revolutionized in order to make electric cars competitive with regular cars. This drastic change needs a complete restructuring of the design process. In particular, an interdisciplinary approach combining competences from different fields of development, such as powertrain, chassis, E/E, thermal management, bodywork, will be beneficial.

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