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Johannes Liebl *Hrsg.*

Der Antrieb von morgen 2017

Hybride und elektrische Antriebssysteme

11. Internationale MTZ-Fachtagung Zukunftsantriebe

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Johannes Liebl
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Vorwort

Durch künftig immer strengere Gesetze zu CO_2-Emissionen und neu gestaltete, anspruchsvollere Prüfzyklen mit realen Fahrsituationen erleben wir einen Paradigmenwechsel. Die Elektrifizierung schreitet weiter voran. Antriebsstränge müssen noch stärker im Systemverbund Verbrennungsmotor, Getriebe und Elektrifizierung ausgelegt werden. Deshalb haben wir die seit über zehn Jahren etablierte MTZ-Tagung „Der Antrieb von morgen“ mit dem Beirat behutsam, aber spürbar neu ausgerichtet. So treffen wir am 25. und 26. Januar 2017 erstmals am Verkehrsknotenpunkt Frankfurt zusammen, werden noch internationaler. Thematisch legen wir den Fokus auf die Antriebssynthese, während Komponenten und Fahrzeugintegration die Basis bilden. Denn die Wirkzusammenhänge werden komplexer. Die Digitalisierung nimmt zu. Unterschiedliche Märkte wollen bedient werden. Viele Anforderungen, die gleichzeitig auch interessante neue Chancen eröffnen.

Das spiegelt sich deutlich in den Vorträgen wider, die Sie dieses Jahr erwarten: Systemdenken, intelligentes Management und neue Entwicklungsmethoden spielen die entscheidenden Rollen.

Unverändert bleiben der familiäre Charakter und die Unterstützung von Schaeffler und Volkswagen. Diese langjährigen Partner haben die diesjährige Neuausrichtung mitgestaltet und gefördert. Ein herzliches Dankeschön dafür! Im Namen aller Beteiligten lade ich Sie ein, bei der 11. Internationalen MTZ-Fachtagung „Der Antrieb von morgen“ dabei zu sein. Wir freuen uns schon heute auf den aktiven Dialog mit Ihnen!

Für den Wissenschaftlichen Beirat
Dr. Johannes Liebl
Herausgeber ATZ | MTZ | ATZelektronik

Editorial

More stringent legislation on CO_2 emissions and new, tougher test cycles involving real-life driving situations are leading to a paradigm shift within the industry. Advances are being made in the field of electrification and powertrains are increasingly being designed as integrated systems consisting of combustion engines, gearboxes and electric motors. As a result of these changes and with the help of the Scientific Advisory Board, we have cautiously taken the well-established MTZ conference “The Powertrain of Tomorrow”, which has been held for more than 10 years, in a noticeably new direction. We will be meeting for the first time in Frankfurt and the conference will have an even more international focus.

The main theme will be the synthesis of powertrains, with an emphasis on components and integration in vehicles, because the interdependencies are increasingly complex. Digitization is becoming more widespread, a range of different markets are opening up and we are facing many challenges that also represent interesting new opportunities. This is clearly reflected in the lectures that you can attend at the congress. A system-based approach, intelligent management and new development methods will be the key features.

The friendly atmosphere of the event remains unchanged. Our longterm partners Schaeffler and Volkswagen have supported and helped to define the new direction taken by the congress and we would like to thank them very much. I would like to invite you to attend the 11th International MTZ Conference “The Powertrain of Tomorrow”. We are looking forward to some interesting discussions!

On behalf of the Scientific Advisory Board
Dr. Johannes Liebl
Editor-in-Charge ATZ | MTZ | ATZelektronik

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Strategic optimization of powertrain technology portfolios by means of market simulation

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1 Research and Engineering Objective

Climate change is one of the most critical challenges of the 21st century. In order to reduce anthropogenic CO_2 emissions, the European Union (EU) has set emission reduction targets for each industry sector. Due to the fact that a major part of anthropogenic CO_2 emissions can be traced back to the transportation sector, stringent targets regulating new vehicle CO_2 fleet emissions were adopted. In 2020, new vehicles should emit less than 95 g/km CO_2 on average. Reducing those targets even further is currently under discussion. Possible targets for 2025 range between 68 g/km and 78 g/km and 2030 targets ranging from 50 g/km to 70 g/km.

In case of target exceedance, high penalties have to be paid by the vehicle manufacturers. In order to fulfil the targets and to avoid penalty, penalties as well as damage corporate reputation, manufactures need to adjust their product portfolio and deploy new technologies in their vehicle fleet. On the one hand, conventional power-trains need to become more efficient, but on the other hand it is necessary to introduce new alternative power-trains to the market, especially regarding to more stringent targets in 2025 and potentially 2030.

The customer acceptance and awareness of new technologies and alternative fuel vehicles (AFV) is questionable and influenced by various political measures ranging from direct subsidies to reduced taxes or non-monetary incentives like free parking. At the same time, high investments need to be made for technology development. This situation leads to high financial risks, increasing even further considering the comparably long development period of new power-trains.

In order to meet these challenges appropriately it is necessary to estimate the impact of product portfolio decisions as well as public measures in advance of development.

2 Methodology and Model Structure

The econometric simulation model presented in this paper enables vehicle manufacturers to optimise their product portfolio against the background of the EU CO_2 regulation and heterogeneous customer demands by using a hybrid modelling approach incorporating system dynamics (SD) and agent-based modelling (ABM).

The technological profoundness of the model even allows utilising the model to investigate portfolio decisions of automotive suppliers. As a result, potential failures in product and technology planning can be identified and avoided as well as risks of false investments can be mitigated. The structure of the holistic market model is shown in Fig. 1.

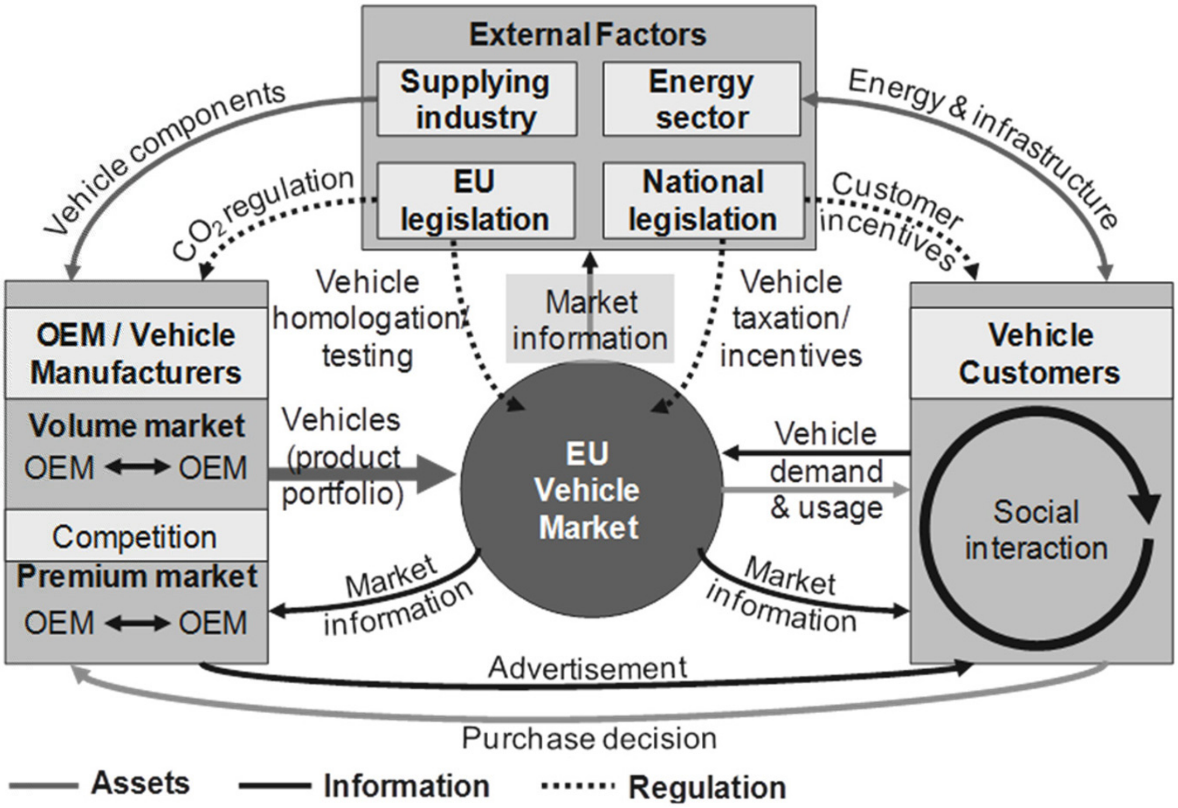

Fig. 1: Relationships of actors within the holistic market model [own illustration]

The challenge of representing the complex interactions of the EU vehicle market is to adequately model both macro effects (e.g. cost degression of EV components) and micro processes (e.g. customers' vehicle choice). In order to fulfil all identified requirements and to depict the underlying market structure the model is composed out of three modules, namely a vehicle manufacturer, a customer, and a market environment module. It is designed as a hybrid model combining advantages of two different modelling approaches [1]. Hence, system dynamics is used for the vehicle manufacturer and the market environment module as well as for relations between modules. To simulate market behaviour an agent-based model as a microscopic approach is used. Agent-based modelling allows considering numerous different customers and is therefore well suited to simulate large and heterogeneous groups. For the crucial task of determining vehicle choice, a sophisticated discrete-choice model was integrated. Extensive data is used to parameterize technological and economical vehicle data as well as customers' socio-demographic characteristics.

The model is validated using sensitivity analysis and comparison with historic data. The target variable for the optimisation is the sales revenue of the focused OEM. Economical and technological leverages that may be applied by the focused OEM are utilised namely its profit margins and technology deployment strategy. The outcome is influenced by application of various scenarios, e.g. regarding customer incentives and taxation.

The model is currently parameterised for application against the EU framework conditions. However, in principle, the model can be adapted for any global automotive market.

2.1 Module Vehicle Manufacturers

The product portfolio and the customer structure of OEM in the European Vehicle Market are obviously very heterogeneous. However, simplification is a crucial element of modelling. Hence, two types of manufacturer, premium and volume OEM are differentiated. Each OEM type is represented by two model OEM, each to account for competitive effects on a basic level. Thus, four OEM are modelled in total, with one premium and one volume OEM in focus as well as one OEM each serving as a reference and competitor.

Each OEM may offer up to eleven power-train configurations (ICEV, MHEV, FHEV, PHEV, each as petrol and diesel alternative, CNG, BEV, and FCEV) in eight segments and three variants with different system power and pricing. Hence, this setup leads to product portfolio of up to 264 vehicle configurations. This structure allows flexible testing of various strategies. Technological improvements may be applied using a predefined technology package approach with a maximum of five steps. Each technology package contains different technologies applicable either immediately or in the future for every specific segment and power-train configuration.

Every vehicle is described by twenty-five attributes relevant for customers purchase decision, tax/incentive or OEM profit calculation. These attributes are mostly defined by database information, or if such vehicles do not exist (e.g. FCEV derivates), attributes are determined by comparison to similar vehicles, manufacturer announcements and assumptions. New vehicle components (e.g. battery, electric motor, etc.) are subject to significant economies of scale and economies of scope. Hence, manufacturing costs for these components are calculated endogenously.

Both, the final technological and economical vehicle attributes are calculated within the model. While technological parameters are equal for all customers, purchase prices and fuel costs have to be adapted for each EU member state represented in the model.

Command variable for the optimisation process is the profit under defined boundary conditions, e.g. full target compliance or certain operating margins. The optimisation process leads to an experimental design where multiple experiments are carried out in parallel. Afterwards the results are manually analysed and new experiments are set up.

2.2 Module Vehicle Customers

To simulate market behaviour, an agent-based modelling approach is used. One single agent represents multiple customers. Each agent is defined by a set of more than 30 attributes of which 15 describe the agent's socio-demographic background. Basic customer information originates from the large-scale mobility survey "Mobilität in Deutschland" conducted in Germany in 2008 and 2009 [2]. Country-specific information was analysed and data was adapted to fit the respective national averages of the modelled EU countries.

Although every customer has its own background and preferences, it is possible to identify customer clusters with similar background and preferences. One first distinctive feature may be the kind of future vehicle use, which is either solely private or at least partly business-related. Thus, different types of customers base their purchasing decision for a new vehicle on different criteria. Within the model, four basic types of customer groups are considered: private customers, fleet customers and company car customers with and without fuel card (fuel paid by employer).

This consideration leads to two different implemented methods to calculate purchase decision probabilities. In order to find the most efficient vehicle for fleet customers, the total costs of ownership (TCO) approach is used [3]. In contrast, (random) utility theory is a broadly accepted approach to describe purchase decisions not strictly bound to economic reason and therefore ideal for private customers [4] [5].

Besides customer characteristics and vehicle parameters, marketing and word-of-mouth play an important role during the purchase decision process [6]. Within the model, both mechanisms are implemented. This approach allows a more realistic representation of the real-world innovation diffusion process. Especially in the case of innovative products, such as electrified vehicles, social interaction (word-of-mouth through various channels) plays a key role in spreading information within society. A sufficient amount of information is crucial to adapt a certain product [7]. As there is no relevant information available neither regarding advertisement success nor social interaction, the effect of these mechanisms needs to be calibrated.

Lastly, customers tend to be influenced by past decisions and strive for alignment with market trends. As an example, petrol and diesel market shares in various EU member states cannot be solely explained by rational behaviour. To nevertheless address this issue, a mechanism is implemented slightly influencing the purchase decision if a power-train technology within the choice set is new or underrepresented in the respective market.

2.3 External Factors

While OEM and customers determine market development, external factors strongly influence the behaviour of these market participants. For example, tax regulations have led to significant differences in power-train market shares in the past.

For this reason, the 13 EU-member states with the largest new vehicle market are implemented in detail, representing about 95 % of the total EU new vehicle market. The remaining countries are consolidated under simplifications. The detailed vehicle and fuel related taxation system, i.e. regarding new vehicle registration/purchase, annual vehicle taxation, fuel, and electricity taxation is implemented for each of this states. Furthermore, fuel availability for alternative fuels, e.g. the density of public charging points, is calculated endogenously and separately for every country depending on simulated market development. Future fuel and energy prices are subject to scenario-based assumptions.

Manufacturing costs of electric motors, power electronics, batteries, H_2-tanks, and fuel cell systems are highly dependent on production numbers. As the model is limited to the EU and production numbers are balanced on a worldwide scale, it is assumed that economies of scale and learning effects are only partly influenced by European sales while the rest is forecasted exogenously by scenario assumptions.

3 Exemplary Results

In the following, some exemplary results are presented to show the model capabilities. However, due to the non-quantifiable nature of the market diffusion effects, it becomes necessary to calibrate the model before usage and perform validation experiments. This process is described in a first step.

3.1 Calibration and Validation

Calibration and validation are a complex process in agent-based modelling tools and cannot be independently performed. For this reason, a sophisticated calibration and validation approach is used, see Fig. 2.

Calibration is done by comparison to historic new vehicle registration data. Until today, vehicles with an alternative power-train concept are underrepresented in the European new vehicle market. In order to avoid stochastic effects to determine endogenous parameters the European market as a whole is inappropriate for the aforementioned comparison. For this reason, calibration of endogenous parameters is performed by comparing historical data of the French new vehicle market starting in 2010 to the predicted values calculated by the model. The French new vehicle market is suited well for this comparison for two reasons. Firstly, the French new vehicle market is comparably large and therefore adequately representative for the European market as a whole. Secondly, there is an acceptable amount of new vehicle registrations with alternative power-trains.

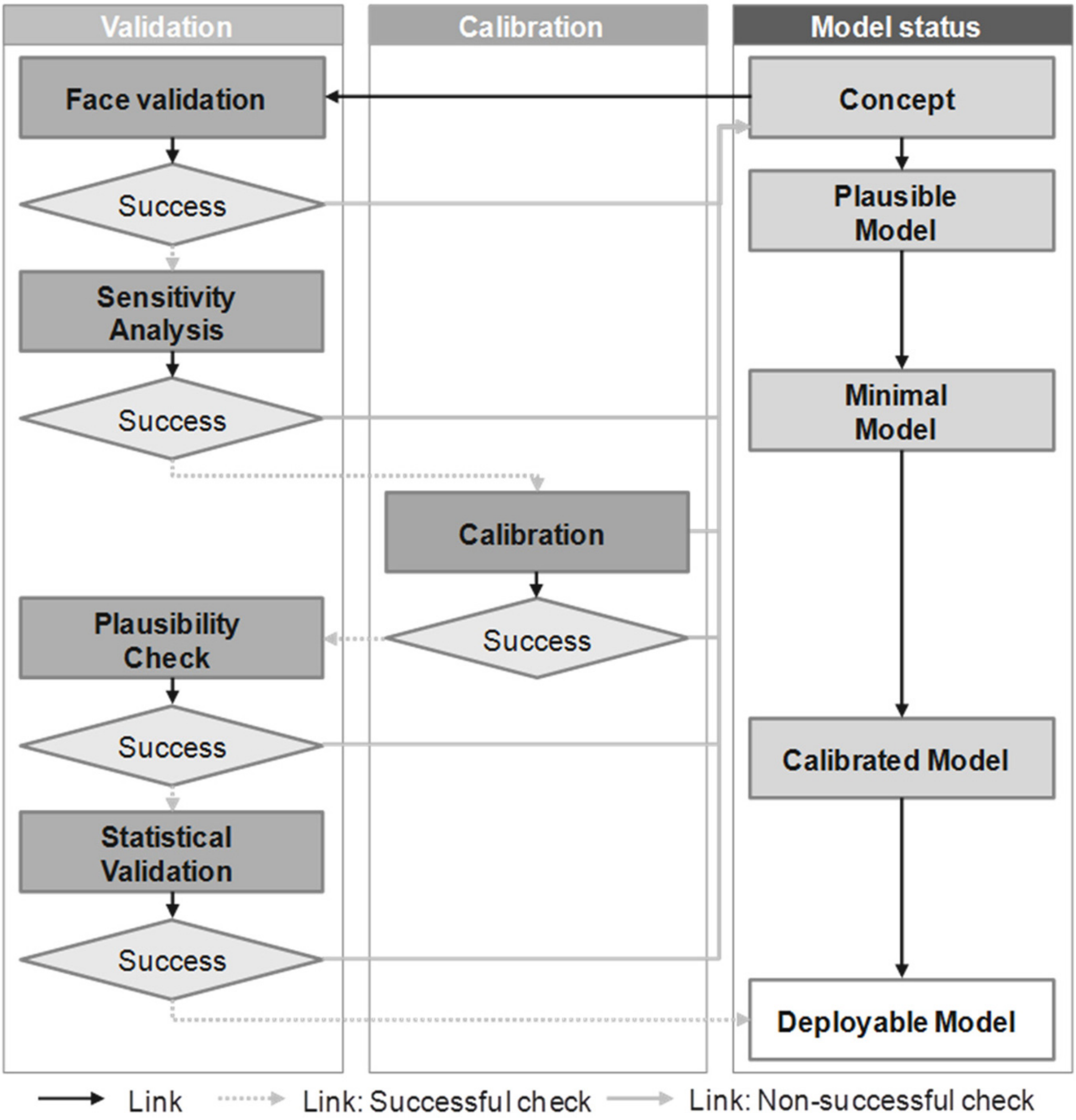

Fig. 2: Calibration and validation process used for the model [own illustration based on [8]]

Validation of the final model is performed in multiple steps. For the statistical validation, a quantitative comparison to historic data of the Norwegian new vehicle market is conducted. The Norwegian Market is well-suited since vehicles with electrified powertrains, especially battery electric vehicles, are widely accepted in Norway and have a significant market share in new vehicle sales. Furthermore, the Norwegian legislation utilises virtually all imaginable monetary and non-monetary incentive measures. Therefore, the validity of the customer decision process can be shown.

The quantitative results of the calibration and validation process are shown in Fig. 3.

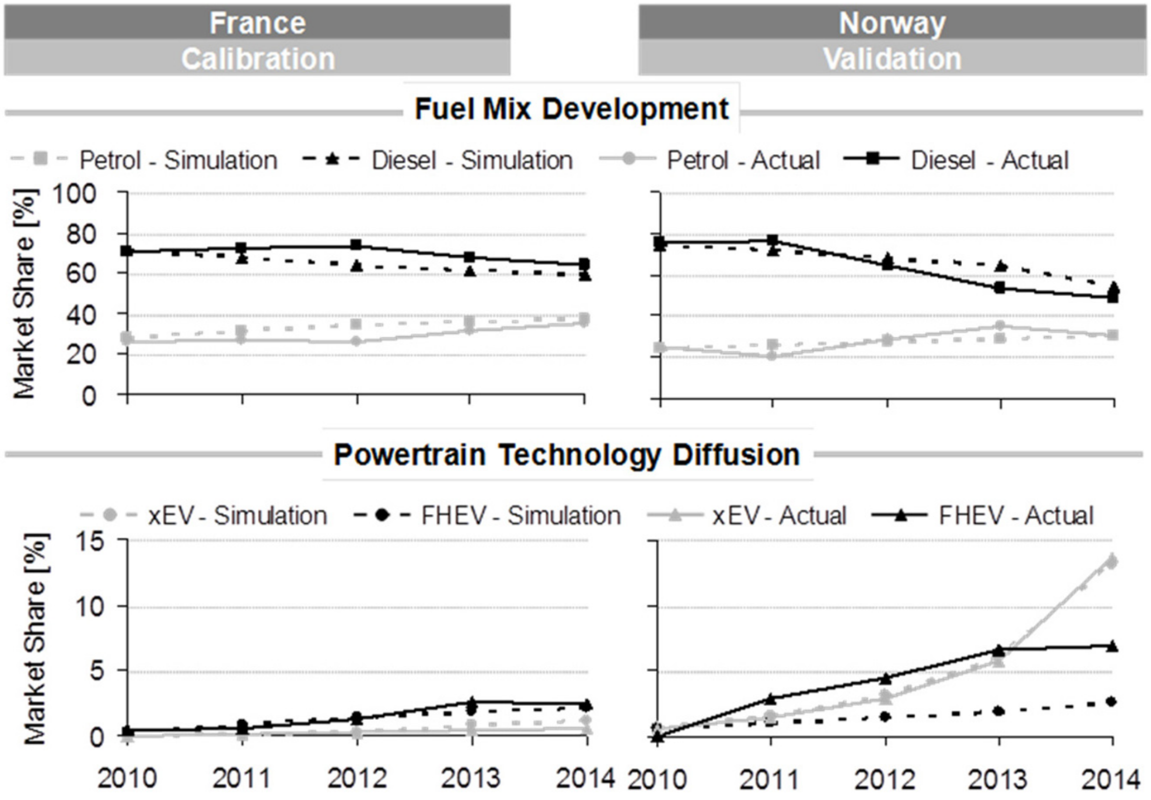

Fig. 3: Results of the calibration and validation process [own illustration]

French values are met very well during calibration. Although the diesel market share is slightly underestimated, the general development is simulated correctly. The same can be said for alternative power-trains.

Norwegian market share for conventional vehicles fits reasonable well, while the market share of FHEV is underestimated. However this gap closes in the model results within an extended simulation period, which can be led back to a slightly underestimated speed of innovation diffusion for FHEV in Norway. In contrast, the xEV market development forecast shows a very good match with only marginal errors.

In conclusion, the calibration and validation process of the above described model can be called valid for the European new vehicle market if no special effects have to be considered. The calibrated model allows simulations of the EU vehicle market until 2030.

3.2 Exemplary Market Forecast

The results in the base reference scenario (i.e. without significant optimisation measures), shown in Fig. 4, indicate a strong loss of importance of the conventional ICEV already in the early 2020s. PHEV and BEV gain significant market shares after 2020/2021 when more vehicles with these power-train configurations are offered and awareness among customers increases. The current trend towards diesel engines will stop as the CO_2 reduction potential of petrol engines is greater. In the long term conventional ICEV will remain only as a niche application with the advent of 48 V MHEV.

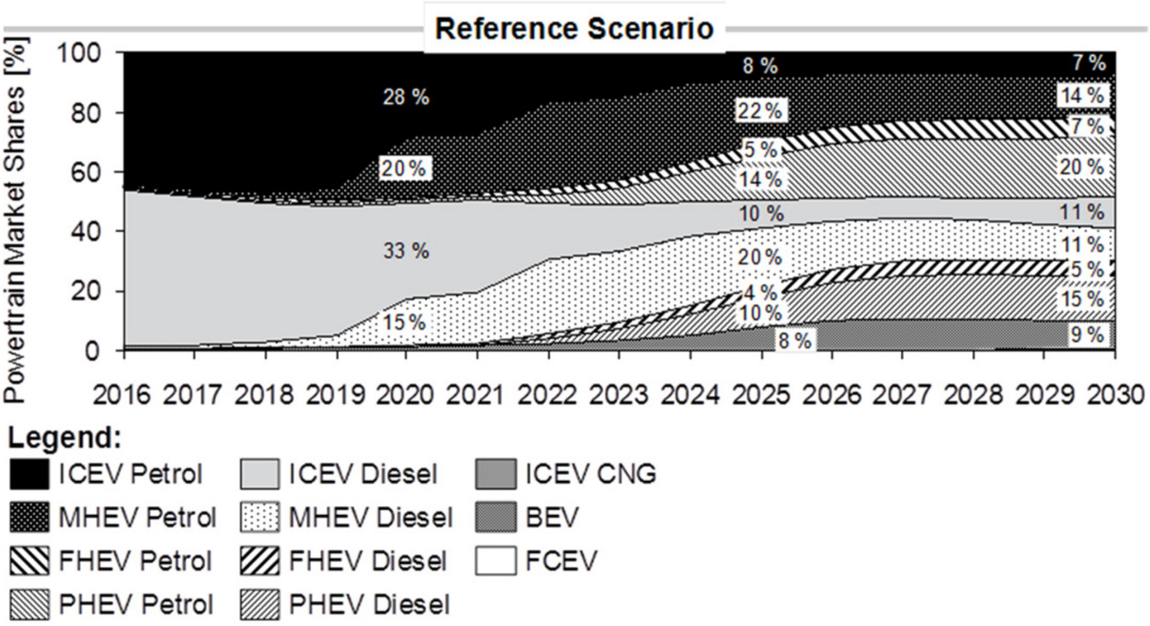

Fig. 4: Power-train technology market share in reference scenario for the complete market [own illustration]

3.3 OEM-specific results

OEM results are highly dependent on scenario assumptions and current product portfolio. However, some general observations can be made. The first observation concerns general power-train portfolio strategies. Results show that many volume manufacturers achieve their best results with a strategy focused on lower levels of electrification, i.e. MHEV and FHEV. This can be traced back to a higher cost sensitivity of the customers and a larger percentage increase in purchasing prices for higher electrified vehicles compared with premium OEM. Premium OEM in turn have their best performance with a widespread application of PHEV with optimised electric range. Secondly, it can be observed that from 2025 onwards additional portfolio measures might be necessary for some OEM. That means that even with a large portfolio of AFV, target compliance may not be achieved since the market uptake is too slow. This would lead to high penalty payments if the OEM does not decide to eliminate inefficient derivates from the portfolio. Furthermore, it can be stated that the sophisticated technological data used in the model is crucial for the success of the optimisation. Implementation of both AFV and other technological measures strongly influences both CO_2 emissions and vehicle mass, as shown in Fig. 5. Since the current EU CO_2 legislation is a mass-based standard, vehicle mass has to be considered as an additional factor. In addition to the above mentioned technical analysis of OEM performance further economical results can be derived from the simulation model, e.g. OEM revenue, profit or penalties.

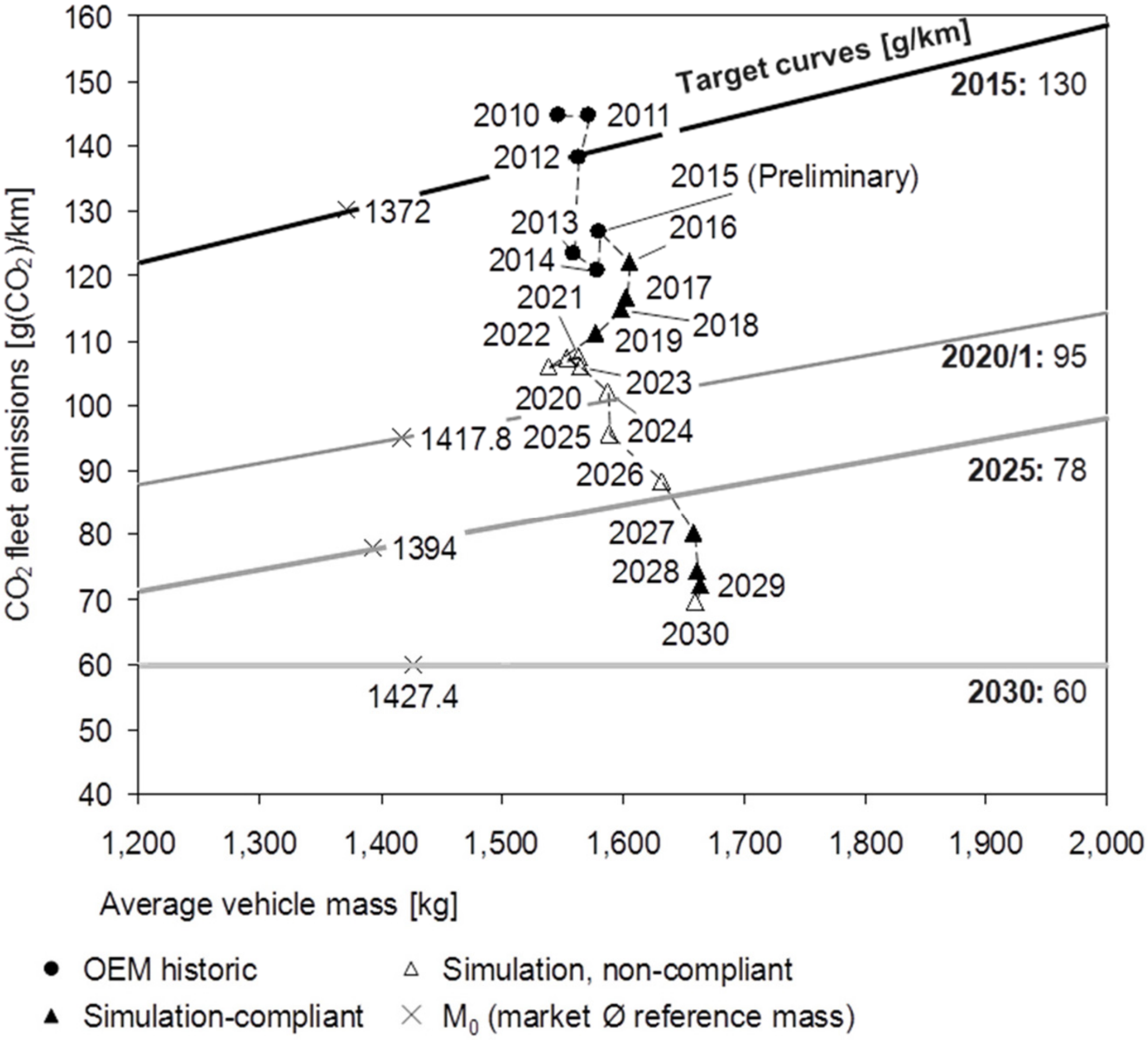

Fig. 5: OEM-specific CO_2 / mass development for an exemplary premium OEM in the reference scenario without sufficient portfolio measures leading to target non-compliance in multiple years (assumptions: 2025 78 g/km with slope equal to 2020, 2030 60 g/km with slope = 0) [own illustration]

4 Discussion

The limitations of the presented simulation tool can be led back to the limitations of all modelling approaches, implying a simplification of the conditions in reality with the risk of over-simplification. A large amount of imaginable effects and causal relations have been tested for their market impact. Relevant effects and relations have been included in the model. However, for reasons of complexity, it is not possible to include all effects in detail. Another limitation arises from the limited availability of data regarding costs and socio-demographics. Nevertheless, risks of false assumptions are covered by application of scenarios.

Finally, new mobility services up to high level automated vehicles may significantly change today’s new vehicle market. This effect is currently only considered as a scenario assumption. Amongst others, this would affect total greenhouse gas emissions as well as manufacturers sales numbers. To provide even more comprehensive insights, the model could be extended or complemented by respective modules. In this case, the choice model for customers' needs could be expanded to other modes of transportation.

5 Conclusions

The EU automotive industry is facing large challenges through decarbonisation efforts, especially the CO_2 legislation, which implicates high financial risks due to an unknown future customer demand.

Therefore, the objective was to create and validate a holistic market modelling toolkit for the EU automotive market, which enables to simulate and optimise technical as well as economical product portfolio strategies of vehicle manufacturers. For this purpose, two modelling paradigms, system dynamics and agent-based modelling are applied and combined into a sophisticated hybrid modelling and simulation framework with the purchase decision model derived from a large customer survey. Calibration and validation were carried out qualitatively and quantitatively within a process specifically designed for multi-agent models. The simulation results show a very good match with the actual, historical development. With the validated model, various experiments were performed with the whole EU new vehicle market until 2030. It was shown that an accelerated deployment of both conventional and alternative power-train technologies is necessary to meet future legislative demands. The widespread and early introduction of electrified power-trains is unavoidable to be continuously successful. Mild-hybrids will play a key role in future power-train portfolios, e.g. in form of 48 V-hybrids.

Besides an enhancement of the model runtime, extension of the model scope towards new mobility concepts will be a focus of further research.

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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

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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	