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Battery Electric Vehicle – One configuration fits all markets

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Summary

This paper assesses the viability of a uniform powertrain configuration considering regional test procedures and incentive requirements in terms of driving range and energy consumption for light duty battery electric vehicles. The results of the simulative evaluation for the uniform powertrain configuration show that the fulfilment of the maximum incentive requirements in the USA, China and Europe is only possible when overachieving the maximum incentive requirements in at least one of the regions.

Keywords: BEV (battery electric vehicle), simulation, regulation, incentive

1 Introduction

A rising share of Battery Electric Vehicles (BEVs) enables manufacturers to cope with stringent CO_2-emission targets as they are counted as zero emission vehicles in many regions [1]. The high costs of BEVs compared to Internal Combustion Engine (ICE) based vehicles is one of the key challenges for their competitiveness [2]. A reduction in BEV powertrain variants gives promise to substantial cost reductions due to economies of scale in the production. For ICE based powertrains, the varying global regulation requirements concerning exhaust gas emissions led to a multitude of component and calibration variants. The requirements are reduced for BEVs due to the non-existence of exhaust gas emissions. This study therefore investigates the possibility of applying a single uniform powertrain variant across different markets. In a first step, the performance of the uniform powertrain will be assessed by determining its energy consumption and driving range according to testing procedures in the USA, China and Europe by simulation. Similar simulation studies for BEVs conducted in the past, have shown a difference in determined energy consumption and driving range depending on the test cycle. In two studies the results for energy consumption and driving range are estimated on single cycle run results [3], [4]. Only one study applies different test weights in line with official regulations [4]. Another study follows the regulatory test procedures, but compares the results between Europe and the USA exclusively [2]. This study expands the scope by investigating the impact of the current and proposed regulatory test procedures of China. By considering the announced Chinese Light Vehicle Testing Cycle (CLTC), possible future changes for this market are approximated. The powertrain is further assessed for its regional viability in terms of driving range to benefit from incentives, representing the market specific requirements. In the next step, the assessment for regional viability is repeated and compared for powertrains with different battery sizes. The potential impact of selected vehicle body parameters is investigated for one powertrain variant with a sensitivity analysis. At last, the powertrain is applied to a typical Sport Utility Vehicle (SUV) variant and the results of the incentive-based assessment are compared to the baseline vehicle.

2 Regulatory framework

Regardless of the non-existence of local emissions, legislators of numerous markets require BEVs to be assessed for their energy consumption and driving range capabilities. The regulation requirements apply country specific vehicle use cases (e.g. test cycles) to provide realistic customer expectations of the vehicle performance, while also enabling the implementation of incentive schemes. The viability of a global powertrain variant will therefore depend on its performance according to regional regulations. Hence, a short outline of the test procedures to determine energy consumption and driving range for BEVs for some of the biggest sales markets is given. Respective test procedures include the Worldwide Harmonized Light Vehicle Testing Procedure (WLTP) for the European Union (EU) [5], the Federal Testing Procedure (FTP) for the USA [6] and the New European Drive Cycle (NEDC) which is currently applied in China [7]. China has derived a new set of driving cycles called China Automotive Testing Cycles which are based on Chinese traffic data and are planned to be implemented for BEVs from 2021. For the Chinese Light Duty Testing Cycle of Passenger Cars (CLTC) a draft standard was released in 2019 [8]. The final standard for the complete procedure is yet to be released. Therefore, assumptions based on the WLTP are used to assess the potential impact of the CLTC cycle on future energy consumption and driving range measurements of BEVs in China.

2.1 Test weight definitions

The regional procedures define different test weights based on the vehicle curb weight (CW). For the FTP, the CW is increased by 136 kg (300 pounds) for testing. In China, the test weight is determined by distinct inertia classes based on the CW increased by 100 kg. The WLTP defines the test weight as the CW increased by 100 kg along with an additional 15 % of the maximum vehicle load. The resulting difference in test mass for the same vehicle leads to different road loads for dynamometer vehicle testing and influence the driving range and energy consumption measurements.

2.2 Cycle differences

The regions apply different test cycles to account for the average regional driving conditions. Based on the varying cycle specifications in terms of velocity, acceleration and idle time, different impacts on driving range and energy consumption for vehicles with different specifications are expected. Especially for BEVs, the time share at high velocity as well as the average and maximum velocity were shown to have a large influence on the energy consumption in another study [3]. This indicates that the highest energy consumption is to be expected for the WLTP and the lowest energy consumption for the CLTC. The NEDC and the FTP, which consists of the Urban Dynamometer Drive Cycle (UDDS) and the Highway Fuel Economy Test Cycle (HWFET), indicate a comparable energy demand for a BEV according to velocity-based metrics. Based on the driving cycle, different testing procedures are used to determine the energy consumption at different battery states of charge (SOC) and temperature conditions of the vehicle components. These procedures can be categorized into consecutive cycle procedures and shortened test procedures (STP). For consecutive cycle procedures, a single cycle is driven repeatedly from a fully charged energy storage until the vehicle cannot follow the cycle anymore due to battery depletion. These procedures directly provide the driving range on basis of the applied cycle. The consecutive cycle procedure is applied using the NEDC in China. The official energy consumption is determined based on the consumed energy to completely recharge the BEV from the grid after the driving range test. STPs were introduced to limit the testing duration for BEVs with higher battery energy and are applied to the WLTP and the FTP, consisting of four driving segments: Two dynamic cycle segments (DS1 and DS2) and two constant speed segments (CSSM and CSSE). The sequence of the segments is displayed exemplarily for the WLTP in Figure 1.

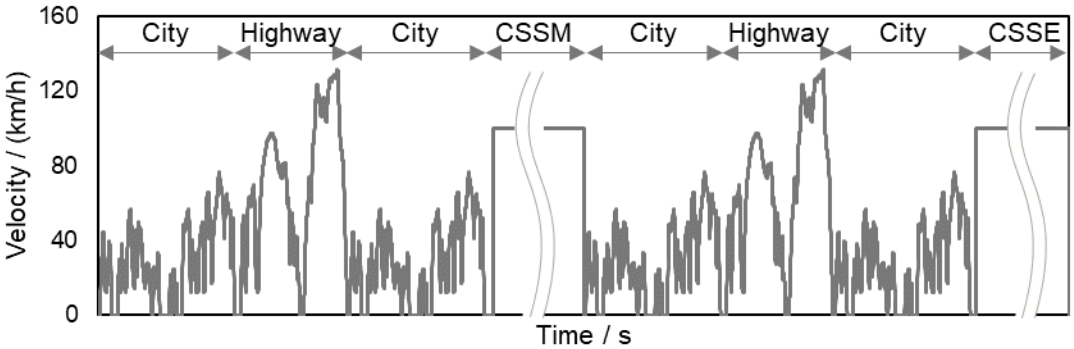

Figure 1: Shortened procedure example for WLTP with respective phases

For the FTP-STP the UDDS and the HWFET are used as the respective city and highway cycles. In the EU, the low and medium phases of the Worldwide Harmonized Light Vehicle Testing Cycle (WLTC) are considered as the city cycle and the high and extra high phases as the highway cycle. In case of the future CLTC based procedure in China, it is assumed that the country will apply a STP with the CLTC Phases 1 and 2 as the city cycle and Phase 3 as the highway cycle respectively. The constant speed segments require a constant velocity of the vehicle above a defined threshold, which also varies between the regulations. Finally, the length of the intermediate constant speed segment is defined by certain distance or useable battery energy (UBE) requirements which must be met at the end of the DS2. The differences in the procedure definitions are summarized in Table 1. The CLTC-STP is assumed to apply a reduced constant speed segment velocity threshold compared to the WLTP-STP based on the lower maximum cycle velocity. The reduction is proportional to the reduction applied for the WLTP-STP in Japan which is based only on the first three phases of the WLTC. The criterion for the start of the CSSE is assumed to be the same as for the WLTP-STP.

Table 1: Differences between regional shortened procedure definitions

	City cycle	Highway cycle	Constant speed threshold in km/h	Requirement at end of DS2
FTP-STP	UDDS	HWFET	105	Distance ≥ 80 % of total STP distance
WLTP-STP	WLTC Low + Medium	WLTC High + Extra high	100	Remaining energy ≤ 10 % UBE
CLTC-STP (assumption)	CLTC P1+P2	CLTC P3	90	Remaining energy ≤ 10 % UBE

2.3 Post processing and ambient condition consideration

The consumed energy and accumulated distance during the dynamic segments are considered in determining the energy consumption. The constant speed segments are used to determine the UBE of the BEV as a basis to calculate the driving range. The official (AC) energy consumption considers the charging losses to recharge the vehicle from the grid. Different weighting of the consumed battery energy during DS1 and DS2 are applied to consider the influence of possible restricted recuperation as well as warm up of components. Equivalent approaches of weighting the consumed energy at high SOC relative to the UBE are used to limit the impact of these influences in the weighted results of the two dynamic segments. In the USA, the measurements are further weighted by applying a factor of 55 % to the city and 45 % to the highway energy consumption. The advertised label values of energy consumption and driving range refer to the 5-cycle-procedure considering additional cycles for aggressive driving (US06) and ambient temperature influences (FTP cold and SC03). The 2-cycle results must be corrected by a factor of 0.7 or an individual factor can be determined by a modified 5-cycle procedure [9]. This study uses 2-cycle-based measurements, with the constant factor of 0.7 being used whenever a label value is stated.

2.4 National incentives to promote BEVs

National measures to incentivize BEV sales can be categorized into credit and subsidy schemes. Credit schemes are forcing manufacturers to supply a certain fleet share of electrified or low emission vehicles, whereas government funded discounts on the sales price are considered as subsidies in the context of this study. China requires 12% of the vehicle fleet of each manufacturer in 2020 to consist of so called New Electric Vehicles (NEV) which include BEVs, Plug-In-Hybrid-Vehicles and Fuel Cell Electric Vehicles (FCEVs). The amount of credits, a single BEV accounts for, depend on its driving range and energy consumption. Starting at a vehicle driving range of 100 km, manufacturers receive increasing credits up to the driving range limit at 350 km, above which the maximum amount of credits are applied. Depending on the energy consumption the amount of credits is factorized, resulting in a different amount of achievable credits for the same driving range [10]. California requires at least 6% of the vehicle fleet of each manufacturer in 2020 to consist of Zero Emission Vehicles (ZEVs) which include BEVs, FCEVs or Range Extended Electric Vehicles. For BEVs, the amount of ZEV credits granted per vehicle depends only on the driving range in the FTP-City, which is not affected by the 5-cycle correction factor. The minimum driving range for ZEV credits is 80.45 km and the amount of credits increases linearly up to a credit cap of four at 563.15 km [11]. China's subsidies for BEVs depend primarily on the driving range and battery capacity. Above a driving range of 250 km, 18,000 CYN and starting from 400 km 25,000 CYN are granted. This subsidy is additionally factorized dependent on energy consumption and battery energy density [12]. In Europe, subsidies are defined by its member states individually. Only the United Kingdom (UK), formerly part of the EU, applies a minimum driving range requirement of 112 km [13]. In this study, the results for energy consumption and driving range will be assessed in relation to the minimum and maximum requirements for incentives in the different regions as summarized in Table 2. Incentives without a driving range or electric energy consumption requirement like tax credits in the USA, do not impose a restriction on the powertrain sizing and are therefore not considered in the scope of this study.

Table 2: Summary of considered incentive requirements

	Min. range threshold (km)	Max. range threshold (km)	Min. energy consumption threshold (kWh/100km)	Max. energy consumption threshold (kWh/100km)
USA-California (FTP city)	80	563	-	-
EU-UK (WLTP)	112	112	-	-
China credits (NEDC)	100	350	$0.0012 \cdot CW+2.5$[1] ($0.005 \cdot CW+13.7$)[2]	$0.0084 \cdot CW+1.75$ ($0.0035 \cdot CW+9.59$)
China subsidy (NEDC)	250	400	90% of min. credits requirement	65% of max. credits requirement

3 Simulation Study

The following section is dedicated to an explanation of the simulation approach, its validation and the results.

[1] Applies for 1000 kg < CW ≤ 1600 kg
[2] Applies for CW > 1600 kg

3.1 Simulation approach and validation

A measurement campaign was conducted on an electric vehicle which is the baseline for the following simulative investigation. The process which was proposed in [14] for a plug-in hybrid vehicle was adapted to be used for a BEV. The powertrain focused vehicle measurements included coast down testing with 1417 kg test weight performed to determine the road load coefficients. Furthermore, cycle testing on the dynamometer included the WLTP-STP and two NEDCs at high SOC. Vehicle instrumentation included current and voltage sensors at the high voltage battery and all auxiliary consumers to determine power consumption. The electric motor was fitted with torque and speed sensors at the output shaft to determine its mechanical power. An external 11 kW AC charger was used to recharge the battery and the consumed energy from the grid was measured. The AC and DC energy consumption as well as the driving range were determined according to WLTP regulation. For the NEDC measurement, the average DC energy consumption of two cycles at different SOC was determined. Based on the UBE and the charging losses determined from the WLTP-STP, the driving range and AC energy consumption were calculated. The sensor-based analysis on the powertrain level from the measurements provided the inputs for the modelling of the vehicle and component behavior in the simulation. A MATLAB/Simulink based powertrain simulation tool is used for the energy consumption and driving range determination according to the regulation. The simulation tool replicates the BEV powertrain through a closed loop simulation approach. A detailed explanation of the used simulation tool can be retrieved from a former contribution on hybrid electric powertrain sizing [15]. Driving resistances were modeled according to the results of the coast down testing. The component behavior is approximated based on library data from components with similar specifications to those of the test vehicle. For the permanent magnet synchronous motor with 125 kW peak power, a combined motor and inverter power loss map depending of speed and torque is used. The high voltage battery consists of 96 lithium nickel manganese cobalt oxide based cells, connected in series with a nominal capacity of 120 Ah each. For these battery cells at 50% SOC, an internal resistance of 0.8 mOhm and an open circuit voltage of 3.6 V is assumed. The single reduction gear with a reduction ratio of 9.665 to 1 is modeled using a torque loss map to account for torque losses depending on the transmission input speed and torque. For the low voltage auxiliary load an average consumption of 200 W during cycle operation without convenience features was extracted from measurements. The DC/DC converter efficiency is assumed at 93 % at this operating point. In addition, the charging process after the driving test was also simulated. The simulation model approach using the generic component input data is validated by comparison between measurements and simulation. Less than 5% difference in driving range and energy consumption between simulation and measurements are observed in the results in Figure 2. Therefore, an adequate level of accuracy for the approach with the estimated component behavior is determined for the investigation.

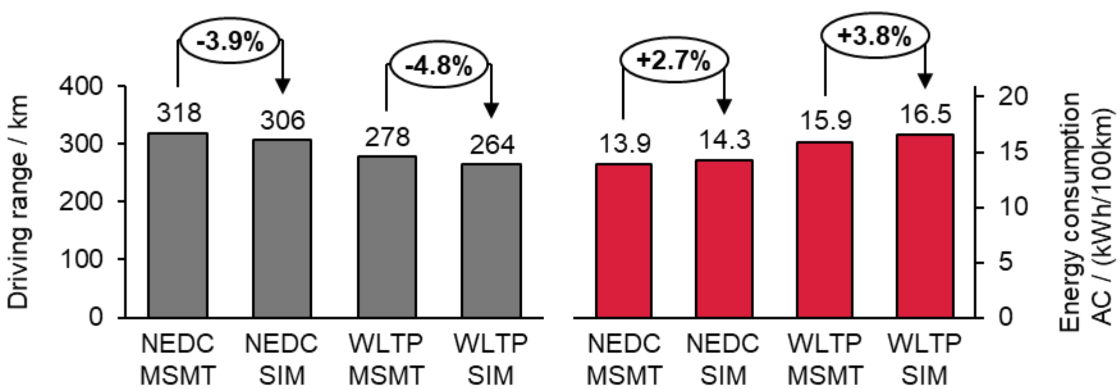

Figure 2: Comparison of driving range and energy consumption (AC) for NEDC and WLTP between measurements (MSMT) and simulation (SIM)

3.2 Simulation Results

Based on the validated model, further simulations were conducted to determine the energy consumption and driving range for the baseline vehicle. For these simulations the different test definitions according to the respective regulations were considered. The resulting test weights for the baseline CW of 1345 kg are: 1470 kg for the NEDC, 1481 kg for the FTP and 1500 kg for the WLTP and CLTC. The weight dependent coast down coefficients F0 and F1 were corrected by the relative change of test weight compared to the measurement values. The procedures were modeled according to the regulations and a uniform system efficiency of the charging process based on the WLTP-STP measurement was used in all calculations. FTP results include the 0.7 factor for 5-cycle equivalent label values. As Figure 3 shows, the baseline vehicle achieves the smallest driving range in the FTP, followed by the WLTP, NEDC and CLTC. The smaller determined driving range in the FTP compared to the WLTP results from the 5-cycle conversion factor and is also described in [2]. Not considering the conversion factor results in a driving range of 307 km, comparable to the result according to NEDC. Considering only the city phases, the smallest driving range results for the FTP city, even without the conversion factor, followed by the WLTP, CLTC and NEDC. This ranking matches the results for the cycle based energy consumption described in [3]. The results for the CLTC indicate that the determined driving range will increase compared to the current determination of driving range according to NEDC. While the CLTC city, assumed as consisting of the first two phases of the CLTC, shows a higher energy consumption than the NEDC city, the opposite is shown for the entire CLTC and NEDC cycles. Since the same inverse relation applies to the average and maximum velocity, the positive correlation between the energy consumption and these velocity-based cycle specifications is supported.

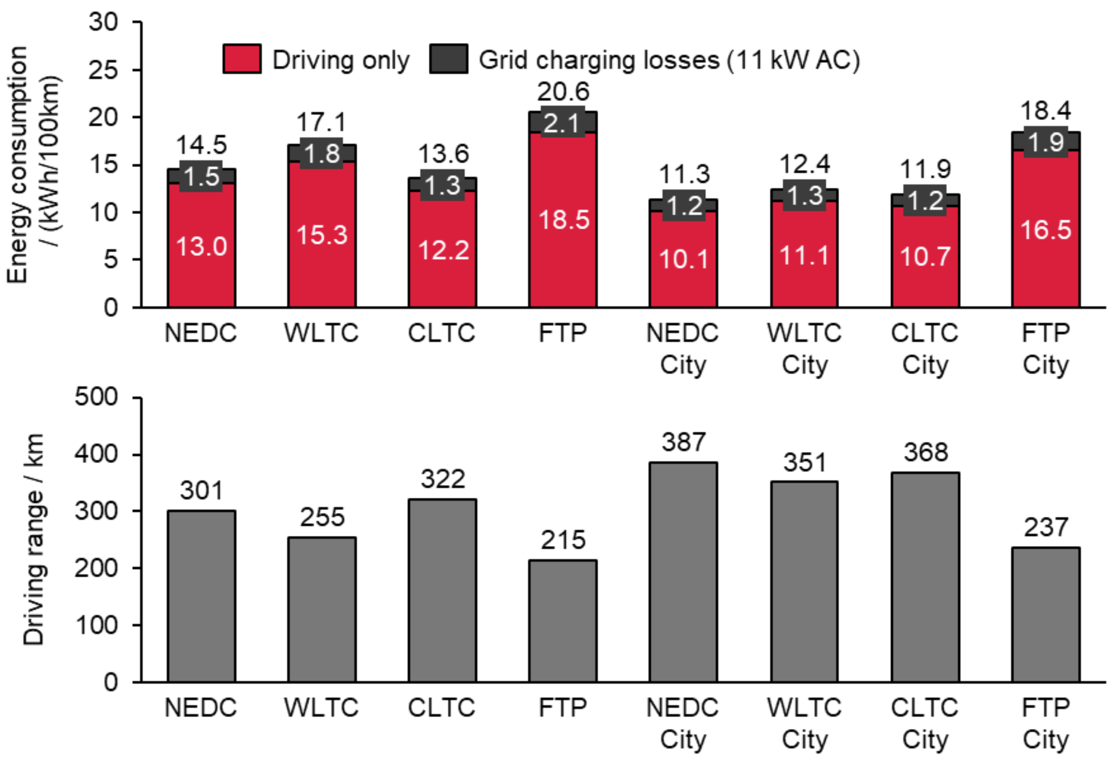

Figure 3: Comparison of simulation results for driving range and energy consumption according to global regulatory procedures for the baseline vehicle

The simulation results show a difference in performance of the same vehicle for the different regional test procedures. In the absence of mandatory limits for energy consumption, these differences represent no obstacle for a uniform powertrain approach. The regional viability will be assessed by comparing the performance to the regional incentive requirements. To provide a technical key performance indicator that quantifies, if a potential benefit exists for increasing the driving range, the incentive fulfilment factor is introduced, see equation (1). Given the determined actual driving range is above the minimum threshold to receive regional incentives, it is set in relation to the regional maximum threshold beyond which additional driving range provides no additional incentive benefit. The minimum and maximum thresholds considered are the ones previously listed in Table 2.

$$Fulfilment\ factor_{region} = \frac{range_{actual,region}}{range_{threshold,maximum,region}} \cdot 100 \tag{1}$$

Figure 4 compares the driving range requirements according to regional test cycles to benefit from the minimum and the maximum amount of incentives to the actual simulated performance of the baseline vehicle. The vehicle fulfils all the market specific minimum requirements and would therefore benefit from incentives in every market. In California the threshold for the highest incentive is underachieved by 39.8%, translating into a fulfilment factor of 60.2%. The fulfilment factors for China, for credits of 86.0% and for subsidies of 75.3%, indicate that achieving a higher driving range would increase the amount of incentives as the maximum requirements are not fulfilled. For China, the driving range based on the CLTC with the assumed WLTP procedure is increased. Therefore, the fulfilment factors for the Chinese credits and subsidies would increase to 92.0% and 80.5% respectively. The benefits do not increase across all regions with additional driving range, as the overachievement of the UK's subsidy requirement shows.

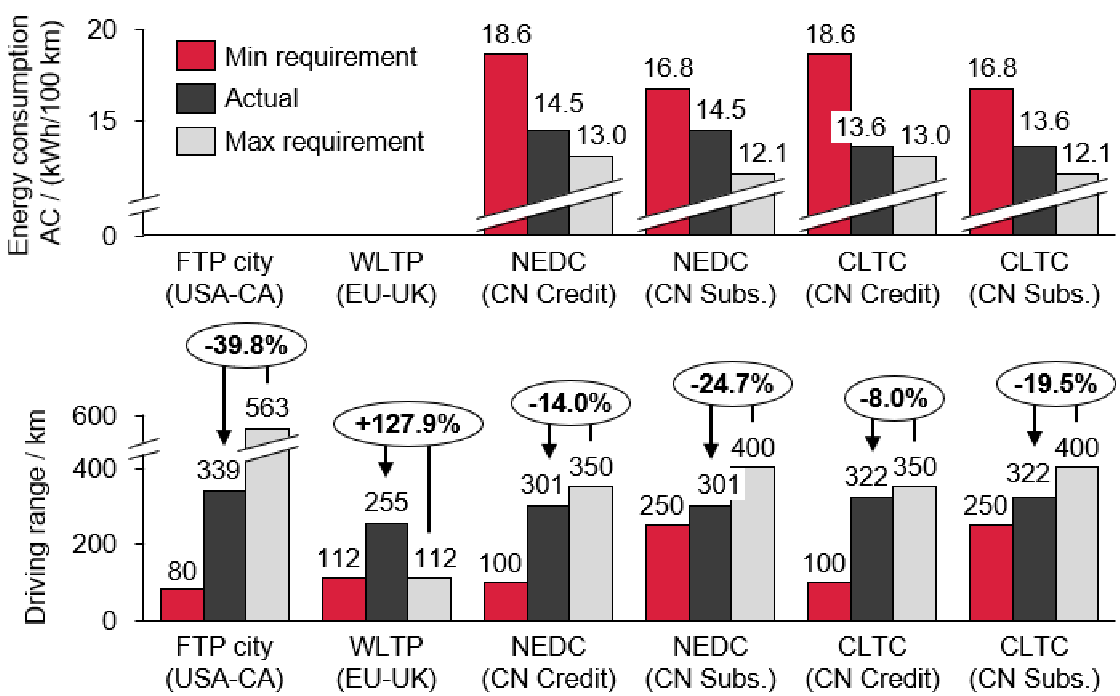

Figure 4: Comparison of incentive fulfilment for the baseline vehicle in California (USA-CA), EU-UK and China (CN)

In terms of energy consumption, the amount of credits and subsidies in China could also be increased by achieving a lower energy consumption. This could be achieved by more efficient powertrain components, optimized charging process as well as reduced road load. Based on these results two different powertrain options with scaled battery energy content to fulfil the minimum (option A) or the maximum (option B) amount of incentives across the regions were investigated. For the scaling of the battery, a constant gravimetric energy density of 176 Wh/kg based on the vehicle measurement results is considered. For option A, a 20 kWh battery is assumed, decreasing the curb weight to 1219 kg. A 60 kWh battery is assumed for option B, increasing the curb weight to 1446 kg. The results for the driving range of the powertrain options compared to the baseline vehicle are presented in Table 3. For option A, the driving range decreases in the FTP city to 173 km or by 49% compared to the baseline. With the increase to 60 kWh battery energy of option B, the FTP city driving range increases by 39 % to 470 km. Comparable relative changes in driving range result in the other cycles.

Table 3: Battery capacity of powertrain options and respective simulation results for driving range

	Battery capacity (kWh)	Driving range FTP city (km)	Driving range WLTP (km)	Driving range NEDC (km)	Driving range CLTC (km)
Baseline	42.2	339	255	301	322
Option A	20	173	128	152	163
Option B	60	470	357	416	449

The resulting fulfilment factors for the two powertrain options are compared to the baseline in Table 4. Option A does not achieve the relatively high minimum requirement for subsidies in China, resulting in a fulfilment factor of 0%. Additional driving range would also provide additional benefit in terms of Californian and Chinese credits as the low fulfilment factors state. This is different for the UK, where the subsidy requirement is already overachieved by 15%. Option B achieves fulfilment factors above 100% in all regions except for California. Additional driving range would only result in a higher amount of credits in California while not granting any additional benefit in the other markets.

Table 4: Fulfilment factor results for baseline and powertrain options

	Fulfilment factor USA-CA FTP city (%)	Fulfilment factor EU-UK WLTP (%)	Fulfilment factor CN Credits NEDC (%)	Fulfilment factor CN Subsidies NEDC (%)	Fulfilment factor CN Credits CLTC (%)	Fulfilment factor CN Subsidies CLTC (%)
Baseline	60	228	86	75	92	81
Option A	31	115	44	0	47	0
Option B	84	319	119	104	128	112

Aiming at the fulfilment of the maximum subsidy target in China, option B is further investigated by applying the powertrain to different chassis. To assess how the incentive fulfilment is influenced by the chosen chassis, a sensitivity analysis of vehicle parameters influencing road load is conducted. The relative change for this analysis in aerodynamic drag coefficient (F2) is between 0.8 and 1.2 and the vehicle curb weight is varied from 1300 kg to 1600 kg. Figure 5 shows the results of the combined sensitivity analysis for relative change in aerodynamic drag and change in vehicle curb weight for option B in the FTP city and NEDC cycle. The driving range decreases in both cases by about 20 km for an increase in curb weight of 100 kg. In contrast the same increase in aerodynamic drag by 30% will decrease the driving range by 38 km in the NEDC compared to 30 km in the FTP city. This observation can be transferred to incentive fulfilment: Accordingly, the Chinese subsidy requirement can still be fulfilled with a 15% less aerodynamic or 100 kg heavier chassis. In California the same chassis changes lead to a decrease in credit fulfilment by three and five percentage points respectively. The investigation of the influence of the vehicle parameters on the incentive requirements dependent on driving range, is concluded by introducing a distinct SUV style chassis as an alternative to the baseline EV chassis. For this analysis the aerodynamic drag force, the curb weight and the auxiliary load were increased to take the differences in vehicle class into account. As a basis for the magnitude of increase in these parameters, a comparison between two vehicle models and their SUV variants was conducted based on manufacturer's data[3].

[3] BMW X5 xDrive40i (2018) vs. BMW 530d xDrive (2017) and BMW X3 xdrive20d (2017) vs. BMW 320d (2018)

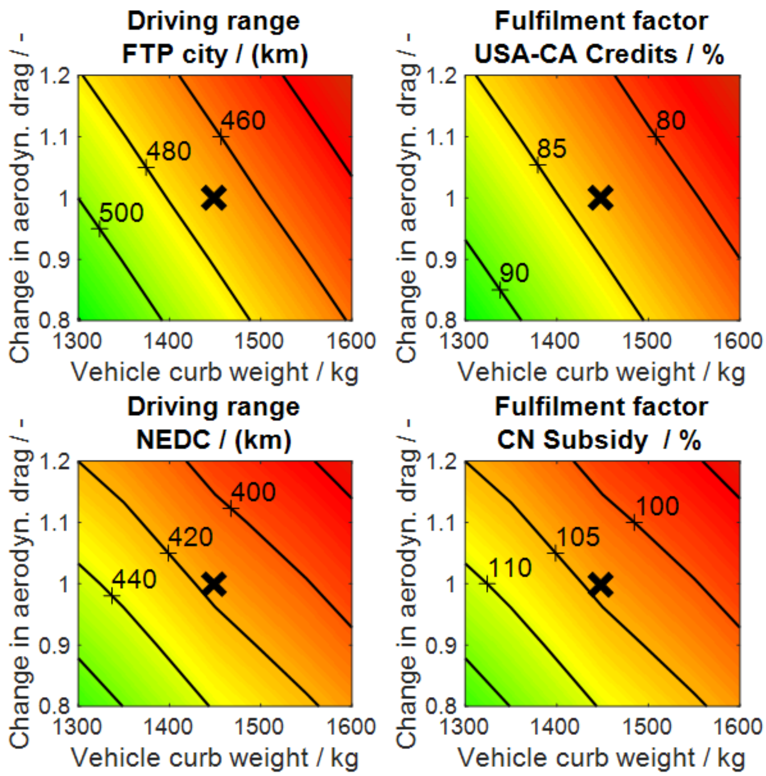

Figure 5: Sensitivity analysis of vehicle curb weight and relative change in aerodynamic drag; the baseline vehicle with the option B powertrain is marked with a cross (NEDC results show an interpolation between the distinct inertia classes)

For the increase in aerodynamic drag, a 20% increase is considered, as the body already shows a comparable drag coefficient to the SUV variants. This reflects the increase in frontal area in the same magnitude as for the other SUV variants. The increase of curb weight of 15% is chosen to be in line with the increase for the reference vehicles between 14% and 17%. As for average auxiliary load during cycle operation, an increase from 200 W to 300 W is considered.

Table 5: Fulfilment factor results for the option B powertrain in the baseline vehicle and SUV

	Fulfilment factor USA-CA FTP city (%)	Fulfilment factor EU-UK WLTP (%)	Fulfilment factor CN Credits NEDC (%)	Fulfilment factor CN Subsidies NEDC (%)	Fulfilment factor CN Credits CLTC (%)	Fulfilment factor CN Subsidies CLTC (%)
Baseline vehicle	84	319	119	104	128	112
SUV	72	276	103	90	111	97

The results for the option B powertrain in the SUV chassis are shown in Table 5. Due to the higher road load, the vehicle achieves a smaller driving range across all regions. The vehicle cannot fulfil the driving range requirement for the maximum subsidy in China anymore and only achieves a fulfilment factor of 90%. The fulfilment factor of 103% states only a small overachievement for the maximum amount of credits in China. With the potential future procedure using the CLTC, the subsidy fulfilment would still not be reached with a fulfilment factor of 97%, while overachieving the maximum credit driving range threshold with a fulfilment factor of 111%. For California, the fulfilment factor declines to 72%.

4 Discussion of Results

The results demonstrate the expected varying characteristics of a uniform powertrain variant in terms of energy consumption and driving range according to regional test procedures. As of now, diverging test results do not contradict the implementation of such a variant, since no regulatory limits on energy consumption are applied for BEVs. The CO_2-emissions from electric energy generation are also not accounted in most of the countries. With more countries like the USA and Japan starting to consider CO_2-emissions of the electrical energy generation within their regulatory frameworks for corporate average fuel economy or CO_2-emission targets, this might be subject to change [16]. Currently, the only way to evaluate the viability of a uniform powertrain variant is the degree of achieving regional incentive criteria. To account for the degree of achievement of those, the fulfilment factor was introduced within this study. The application of the fulfilment factor shows that it will not be possible to obtain the maximum of incentives in all regions without overachieving the criteria for incentives in at least one other country. An example demonstrates the relation: A battery with 20 kWh surpasses the driving range requirements in the UK while not being eligible for subsidies in China. With a 60 kWh battery though, all possible incentives can be obtained in China, while the requirements in the UK would be exceeded. Also, the maximum amount of driving range dependent credits in California would not be reached. The gaps are attributable to the big differences in the absolute driving range requirements to obtain the maximum amount of incentives, e.g. 112 km for the WLTP vs. 563 km for FTP City. In addition, the determined driving range depends on the test cycle characteristics. It could be shown that the driving range for a vehicle with high aerodynamic drag, decreases proportionally more in the NEDC than in the FTP city. For example, assuming a set driving range requirement of 400 km in the NEDC, the driving range in the FTP city of a less aerodynamic vehicle exceeds the one of a more aerodynamic vehicle. Considering incentive requirements, there is no benefit for achieving a driving range in China above 400 km, but additional driving range in the FTP city would grant more credits in California. Given a driving range requirement solely based on achieving the maximum subsidy in China, maximizing the amount of credits in California with a single vehicle configuration could rather be achieved with a less aerodynamic vehicle.

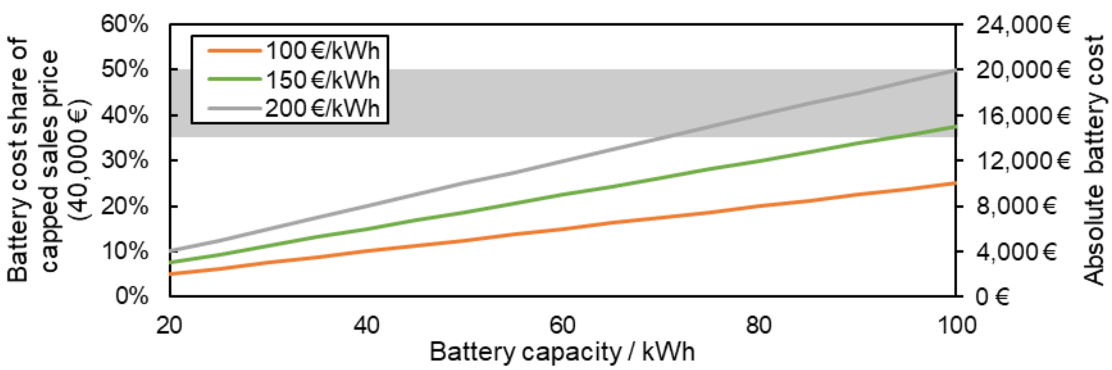

Figure 6: Scenario analysis for the battery cost share of the capped sales price of 40,000 € for subsidies in Germany [17]

The driving range requirements considered for the design of the powertrain by manufacturers will also depend on a multitude of factors like brand appearance and performance of competitors. In this study the incentives were analyzed only in terms of the relative achievement of the maximum possible benefit. The actual monetary benefit of the presented incentives for a manufacturer will depend on its cost structure, the actual fleet composition in the respective markets and other factors like brand appearance. An individual weighting of the incentive fulfilment factors for the different regions is therefore expected. In some countries, only BEVs below a maximum sales price limit are eligible to receive incentives. These incentive conditions impose an additional monetary restriction on powertrain sizing. Since the battery is the most expensive part of a BEV, with estimations varying between 35 and 50% of the vehicle costs [18], an increase in the size of the battery could impact the sales price to an extent that would lead to losing eligibility for subsidies in some markets. As an example, the maximum sales price of 40,000 € for the highest amount of subsidy of 6,000 € in Germany [17] is analyzed. Considering three scenarios for battery prices, Figure 6 shows the increasing battery cost share of the capped sales price to be eligible for subsidies. The marked range of 14,000 to 20,000 € reflects the assumed battery cost share of 35 to 50% of the total vehicle costs. Battery costs within this range imply that the vehicle costs without any sale margins considered, exceed the capped sales price limit of 40,000 €. In a conservative battery price scenario (200 €/kWh) for a battery capacity between 70 and 100 kWh, the battery costs are located in the critical range. The capped sales price limit would therefore be exceeded by the vehicle costs only, losing eligibility for the subsidy.

5 Conclusion

This paper assessed the viability of a uniform BEV powertrain for global application. In the absence of limitations for energy consumption, the fulfilment of incentive requirements was identified as the assessment criterion. The fulfilment of incentive requirements was investigated by simulation of a uniform BEV following the regulatory frameworks of the USA, EU and China. The results of the assessment revealed that a uniform powertrain will only achieve the maximum of incentives across all regions by overachieving at least one of the regions' incentive requirements. The presented incentive fulfilment factors can be used in further studies to assess the actual monetary benefit of a uniform powertrain variant by considering cost and fleet composition data for the target markets. The indicated trend of an increase in driving range with the implementation of the CLTC in China should be further investigated considering the upcoming final test procedure.

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References

1. Z. Yang et Al., *Light-duty vehicle greenhouse gas and fuel economy standards*: *2017 Global update*, https://theicct.org/sites/default/files/publications/2017-Global-LDV-Standards-Update_ICCT-Report_23062017_vF.pdf, accessed on 2020-03-11.
2. S. Kamguia Simeu et Al.*, Factors Influencing Energy Consumption and Cost-Competiveness of Plug-in Electric Vehicles*, WEVJ, *9*(2018).
3. E. Arfa Grunditz et Al.*, Characterizing BEV Powertrain Energy Consumption, Efficiency, and Range During Official and Drive Cycles From Gothenburg, Sweden*, IEEE Trans. Veh. Technol., *65*(2016), 3964–3980.
4. J.X. Teoh et Al.*, Performance Analysis of Electric Vehicle in Worldwide Harmonized Light Vehicles Test Procedure via Vehicle Simulation Models in ADVISOR,* In *2019 IEEE 9th International Conference on System Engineering and Technology (ICSET),* Shah Alam, Malaysia, 2019.
5. *Comission Regulation (EU) 2017/1151 amending WLTP procedures for light duty vehicles with GVW <3500kg*, 2020.
6. Light Duty Vehicle Performance and Economy Measure Committee, *J1634 Battery Electric Vehicle Energy Consumption and Range Test Procedure,* 400 Commonwealth Drive, Warrendale, PA, United States, SAE International: 400 Commonwealth Drive, Warrendale, PA, United States, 2017.
7. National Standard of the People's Republic of China, *GB/T 18386-2017: Electric Vehicles-Energy Consumption and Range-Test Procedures*, 2017.
8. National Standard of the People's Republic of China, *GB/T 1-XXXX: China Automotive Driving Cycle Part I: Light-duty vehicles (Draft for Comments)*.
9. *40 CFR § 600.210-12 (d)(3): Calculation of fuel economy and CO2 emission values for labeling*.
10. Chinese Ministry of Industry and Information Technology*, Measures for the Parallel Management of Average Fuel Consumption and New Energy Vehicle Credits for Passenger Car Enterprises*, http://www.miit.gov.cn/n1146295/n1652858/n7280902/c5824932/content.html, accessed on 2020-03-11.
11. *CCR § 1962.2: Zero-Emission Vehicle Standards for 2018 and Subsequent Model Year Passenger Cars, Light-Duty Trucks, and Medium-Duty Vehicles*. *The California Low-Emission Vehicle Regulations*, pp 219–238.

12. Chinese Ministry of Finance*, Notice on Further Improving the Financial Subsidy Policy for the Promotion and Application of New Energy Vehicles*, http://jjs.mof.gov.cn/zhengwuxinxi/zhengcefagui/201903/t20190326_3204190.html, accessed on 2020-03-11.
13. Government of the United Kingdom*, Low-emission vehicles eligible for a plug-in grant*, https://www.gov.uk/plug-in-car-van-grants, accessed on 2020-03-11.
14. E.P. Morra et Al.*, FEV Hybrid System Benchmark: Zusammenspiel von Versuch, Simulation und Systemauslegung*, In *VPC – Simulation und Test 2016*, ISBN 978-3-658-16753-0, Wiesbaden, Springer Fachmedien Wiesbaden, 2017, pp 99–115.
15. Zhao, J. et Al.*, FEV simulation and optimization tools and their usage for hybrid powertrain sizing*, In *Der Antrieb von morgen 2019*, ISBN 978-3-658-26055-2, Wiesbaden, Springer Fachmedien Wiesbaden, 2019, pp 191–206.
16. Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and Ministry of Economy, Trade and Industry (METI)*, New fuel efficiency standards for passenger cars*, http://www.mlit.go.jp/report/press/jidosha10_hh_000215.html, accessed on 2020-03-11.
17. German Federal Ministy for Economic Affairs and Energy, *Bekanntmachung der Richtlinie zur Förderung des Absatzes von elektrisch betriebenen Fahrzeugen (Umweltbonus)*, 2020.
18. A. Kampker et Al., *Elektromobilität*: *Grundlagen einer Zukunftstechnologie,* ISBN 978-3-642-31985-3, Berlin, Heidelberg, Springer, 2013.

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