

A Study and Analysis on the influence of Electric Vehicle (EV) parameters on EV Customer Wishes

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Summary

This paper presents the study related to the influence of Electric Vehicle (EV) parameters on EV customer wishes like charging time and range/XMin (range acquired during 5/10/15Min charging stops on autobahn). In general, these customer wishes are majorly influenced by factors like DC charging infrastructure power and battery capacity. But, the area of EV's battery and vehicle parameters influence on EV customer wishes was not explored. The objective of this paper is to understand the interactions within the EV parameters like drag co-efficient (cW), mass, rolling resistance, battery internal resistance, capacity, battery maximum temperature, C-Rate and to study the influence on EV customer wishes. This study also helps in finding the most influencing vehicle and battery parameters, which also provides direction of improvement for EV manufacturers. Simple equivalent circuit based battery model with RC Networks was developed to perform sensitivity analysis by varying vehicle and battery parameters independently. Battery thermal behavior and cooling power requirements were also modeled to arrive at accurate simulation results. For simulation purpose vehicle parameters required for the calculation of EV energy consumption for standard drive cycles are obtained from FASTSim, a vehicle powertrain systems analysis tool supported by U.S Department of Energy.

Keywords: Electric Vehicle (EV), charging, battery, range, simulation

1 Introduction

Our Environment is getting polluted by Co2 emissions in a very big scale. Many options/solutions can be laid on our desk to rescue the environment. But, one of the solutions that can be quickly realized and can create major impact on our environment is adaptation to Electric Vehicles (EV) from conventional gasoline or diesel engines [1]. But, EV market penetration is very sensitive to factors like customer acceptance/satisfaction, flexible charging infrastructure and market demand [2]. This paper focuses on one such factor called customer satisfaction by identifying and studying the parameters that influence EV customer wishes. EV charging use cases can be broadly categorised into three groups depending on their

charging patterns, trends and driving environment like city drive, autobahn. Fig. 1 Shows the charging time variation with three different charging use cases like overnight, public and autobahn charging [2]. Among all the use cases, Autobahn or long range charging sets high bar on fulfilment of EV customer wishes. The definition of customer wish differs with charging use-case. For instance, during autobahn or long range driving, customer wishes for more range during 15 Min charging stop translating it to Range/15Min. On the other hand, charging time is not a prominent customer wish for overnight and public charging use cases.

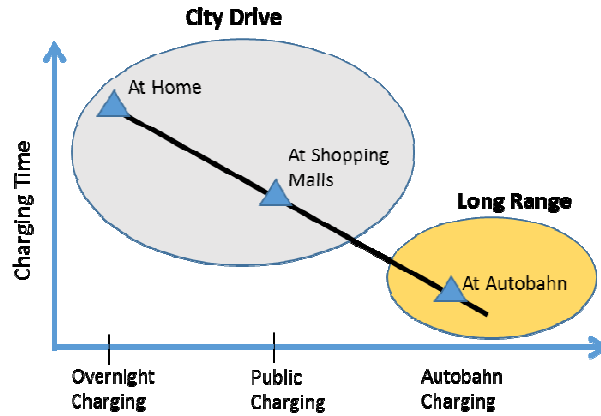


Figure 1: Charging Time Vs Charging Use Cases

During Autobahn charging, customer look forward for less number of charging breaks, least charging duration and high Range/X Min meaning drive range acquired from X Min charging. X can be defined by intended charging break duration. Table 1. Illustrates the customer wishes mapping for ICE and EV customers during Autobahn driving. The study and analysis results produced in this paper are focused towards Autobahn charging scenario where customer wish for long range with minimal charging breaks and duration widely called as range anxiety [3].

Table 1: Customer Wishes Mapping

ICE	EV
No. of travel breaks	No. of charging breaks
Break Duration	Charging Duration
Range/refuel	Range/X Min charging

2 Objective

In general, above mentioned EV customer wishes are majorly influenced by factors like DC charging infrastructure power and battery size. But, the area of battery and vehicle parameters influence on EV customer wishes was never explored. The objective of this paper is to understand the interactions within the battery, vehicle parameters and EV customer wishes like Range/Xmin charging and no.of charging breaks.

2.1 Assumptions

Vehicle drag co-efficient (cW), mass, and rolling resistance are considered as vehicle parameters [4]. This study also considers internal resistance, capacity and C-Rate as the Battery parameters [5]. Energy consumption values of compact and luxury cars like Nissan Leaf [6] and Tesla Model S [7] which are essential for the analysis are obtained from FASTSim [4], vehicle powertrain systems analysis tool supported by U.S Department of Energy. For simulation purpose, this paper also considers equivalent circuit based battery model with RC Networks [5, 8]. Simulation parameters like battery characteristics, thermal characteristics (coolant inlet temperature, heat transfer co-efficient, battery initial and maximum

temperatures) are considered from literature [9,10,11,12,13]. To perform scenario simulations, Charging System Fast Simulations (CSFS), a simple time-based Excel Tool developed at Daimler AG. CSFS tool provides flexibility in creating and simulating charging case scenarios via inputs like infrastructure power, battery characteristics, coolant flow rates and inlet temperatures definitions. This tool communicates charging use-cases to the component models developed in Matlab and writes back the simulation results to CSFS.

2.1.1 Compact and Luxury Car Segment Specifications

To investigate parameter influence, two car segments with different battery capacities are considered. Compact car segment with 30kWh similar to Nissan Leaf [6] and luxury car segment with 90kWh similar to Tesla Model S [7] are considered. Table 2. And Table 3. summarizes vehicle and battery specifications of compact and luxury car segments that are used for present study. Specifications of compact car segment are taken from FASTSim Tool developed by U.S Department of Energy and Luxury car segment specifications are taken from various literature references [4,14,15].

Table 2: Vehicle Specifications of Compact and Luxury Car Segments

Vehicle Specifications	Compact Car (30 kWh)	Luxury Car (90kWh)
Drag Co-efficient (cW)	0.29	0.27
Rolling Resistance (Crr)	0.008	0.008
Vehicle Mass	1575 kg	2250 kg
Frontal Area	2.19 m ²	2.25 m ²
Tyre Radius	0.316 m	0.483 m
Gear Ratio	7.93	9.73

Table 3: Battery Specifications of Compact and Luxury Car Segments

Battery Specifications	CompactCar kWh)	Luxury Car (90kWh)
Battery Energy (Phy)	30 kWh	90 kWh
Battery Energy (Use)	27 kWh	78 kWh
Cell Capacity	42.5 Ah	127 Ah
Uasble Factor	89 %	86 %
Configuration	2p96s	2p96s
Energy Density	0.125 kWh/kg	0.14 kWh/kg

2.1.2 Highway drivecycle for Energy Consumption

Total range of any electric vehicle is tightly coupled to its energy consumption (kWh/100km) [16]. For example, to investigate EV customer wish like Range/X Min, accuracy of energy consumption is very important. Therefore, calculating accurate energy consumption (electric) values of compact and luxury car segments is a vital step for the present study. Hence, FASTSim Tool developed by U.S Department of Energy is used as reference to calculate energy consumptions. As explained in Fig. 1, the necessity of shorter charging times becomes prominent during Autobahn/Highway driving scenario. As a result, highway drivecycle from FASTSim Tool is used for calculating energy consumption. Fig. 2 represents highway drivecycle in the form of driving time Vs vehicle velocity (kmph).

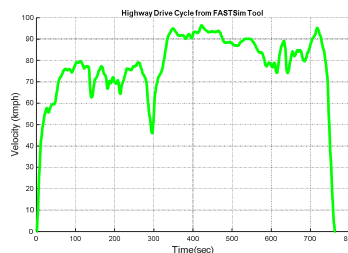


Figure 2. Highway Drivecycle from FASTSim Tool

2.1.3 Energy Consumption using Charging System Fast Simulation Tool (CSFS)

Charging System Fast Simulation (CSFS) Tool is a simple time-based Excel Tool developed at Daimler AG. Seamless integration of user inputs like vehicle specifications and drivecycle information is possible with CSFS Tool. Excel platform is used as the front-end for the tool and back-end comprises of simple component models (like battery, motor) in matlab environment. This tool provides user-friendly interface to calculate/analyse

- Energy consumption for specific vehicle and drivecycle
- Range acquired / X Min charging for specific DC infrastructure power

As a first step, validation of CSFS Tool with FASTSim Tool is performed to ensure accuracy of energy consumption values. Vehicle and battery parameters mentioned in Table 2. & Table 3 are provided as inputs for CSFS Tool. Highway drivecycle (from Fig. 2) is also provided as additional input to CSFS Tool. Table 4. shows the energy consumption validation results for compact and luxury car segments. It is observed that CSFS Tool consumption values deviate with $\approx -5\%$ from consumption values of FASTSim Tool. Efficiency differences of edrive unit can be a possible reason for the deviation. Fig. 3 shows the battery consumption power profiles extracted from FASTSim and CSFS tools of compact car segment. It is evident from Fig. 3 that energy consumption calculated out of FASTSim and CSFS tools are very similar.

Table 4: Energy Consumption Validation

Tools	Compact Car	Luxury Car
FASTSim Tool	13.1 kWh/100km	21.6 kWh/100km
CSFS Tool	12.3 kWh/100km	20.6 kWh/100km

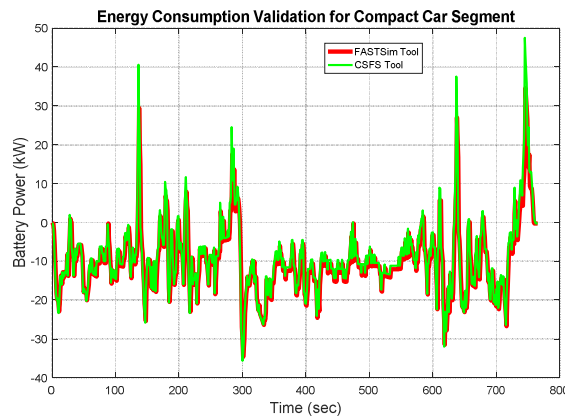


Figure 3. Battery power validation of compact car segment

2.1.4 Use Case: Highway Driving

As discussed in earlier sections, highway driving scenario is a suitable use-case for the present study. Highway drive scenario from Stuttgart to Berlin, Germany which spans across distance of 630km [9] is considered as use-case for the present analysis. For the present study, the altitude information of drivecycle. Stuttgart to Berlin is just considered as an example of highway driving. Let us consider, two EV users with compact and luxury car segment. If both users start their travel from Stuttgart to Berlin at same instance, user with luxury car takes less travel time comparatively to compact car user. Total travel time and number of charging stops are influenced by several factors like

- Energy consumption: High energy consumption means more number of charging stops
- Battery Size: small battery means high travel time due to more number of charging stops
- DC charging infrastructure power: High infrastructure power means less charging and travel times
- Charging Duration (X Min): High charging duration give more range to travel, therefore less travel time

On the other hand, it is also important to understand the consequence of variations in vehicle specifications on total travel time and number of charging stops. To understand above interactions in more detail, sensitivity analysis is performed and results are presented and discussed in below sections. Sections 3 and 4. speaks about the influence of vehicle and battery parameters on range acquired during X Min charging at various DC infrastructure powers. Later, section. 5 summarizes the investigations on parameter influence on Range/X Min and illustrates the variations in total travel time, number of stops during highway scenario (for example, Stuttgart to Berlin).

3 Influence of Vehicle Parameters

Range of electric vehicle is sensitive to its energy consumption [16]. On the other hand, vehicle and battery parameters influences energy consumption. For instance, high vehicle drag co-efficient leads to high energy consumption of the vehicle. As a result, range of the EV decreases with high energy consumption. Equation 1. Illustrates the relation between EV range and EV energy consumption. Upcoming sections illustrates the influence of vehicle and battery parameters on acquired range. As mentioned in section 2.1.4, influence of DC infrastructure powers and charging duration X Min will also be analyzed in the same sensitive plots. Table 5. Shows the variants of DC infrastructure powers and charging durations considered for the sensitivity analysis.

$$EV\ Range\ \propto\ 1 / EV\ energy\ consumption \quad (1)$$

Table 5: Assumptions for Sensitivity Analysis

Sensitivity Inputs	Variant A	Variant B	Variant C
DC Infrastructure	50 kW	150 kW	350 kW
Charging Duration	5 Min	10 Min	15 Min

3.1 Drag co-efficient (cW)

Table 6. Shows the drag co-efficient (cW) values and corresponding energy consumptions (calculated from CSFS Tool) considered for sensitivity analysis. cW values of 0.29 and 0.27 are considered to be baseline values[6,7]. Cw variation of $\pm 15\%$ is considered for sensitivity. It is believed that customer doesn't arrive at EV charging station at 0% State of Charge (SOC). So, assumption is made that the rest range available is 50km from which initial SOC for charging has been derived. Fig. 4 Illustrates the influence of drag co-efficient, DC charging power and charging duration on range acquired in X Min DC charging. In case of luxury segment, from Fig. 5 It is observed that at higher infrastructure powers like 350kW, the influence of charging times 5/10/15 Mins on EV range is prominent in comparison to low infrastructure powers like 50 kW and 150 kW. For the luxury segment car with existing battery (90kWh), 350kW charging power fills up 80% of battery in <5Min. As a result, it is assumed that 350kW charging is possible at reduced cell resistance and battery capacity. Battery capacity and cell resistance are reduced by half for 350kW charging of luxury segment. Fig. 4 shows the influence of drag co-efficient on EV range. In case of compact car, maximum charging time is observed to be 7.7 Min at 350kW, this is due to small size of the compact car segment battery (30kWh).

Table 6: Drag co-efficient variation and energy consumptions

Compact Car (30 kWh)	Luxury Car (90kWh)
0.25; 11.46 kWh/100km	0.23; 19.83 kWh/100km
0.29; 12.28 kWh/100km	0.27; 20.62 kWh/100km
0.33; 13.1 kWh/100km	0.31; 21.41 kWh/100km

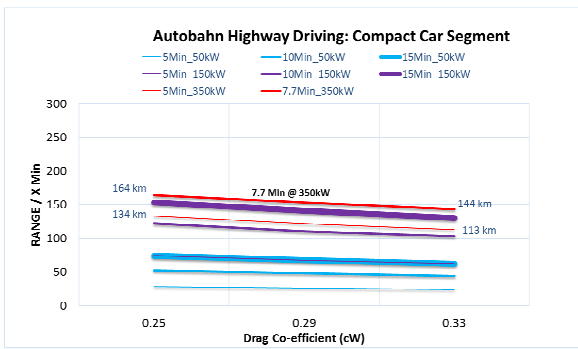


Figure 4. cW Vs Range/X Min: Compact Segment

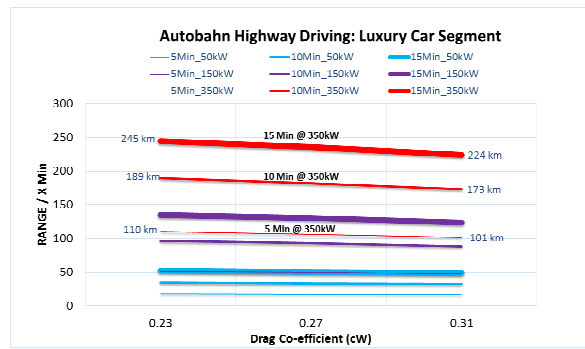


Figure 5. cW Vs Range/X Min: Luxury Segment

3.2 Vehicle Mass

Table 7. Shows the vehicle mass (kg) values and corresponding energy consumptions considered for sensitivity analysis. Vehicle mass of 1575 and 2250kg are considered to be baseline values. Vehicle mass variation of $\pm 15\%$ is considered for sensitivity. Energy consumption variations with drag co-efficient (cW) and vehicle mass variations are quite similar. Hence, the influence of vehicle mass on EV range/X Min charging remains similar to cW influence.

Table 7: Vehicle mass variation and energy consumptions

Compact Car (30 kWh)	Luxury Car (90kWh)
1339 kg; 11.74 kWh/100km	1913 kg; 19.81 kWh/100km
1575 kg; 12.28 kWh/100km	2250 kg; 20.62 kWh/100km
1811 kg; 12.83 kWh/100km	2588 kg; 21.43 kWh/100km

3.3 Rolling Resistance

Table 8. Shows the vehicle rolling resistance values considered for sensitivity analysis. Rolling resistance of 0.008 is considered to be baseline value for compact and luxury car. Rolling resistance of $\pm 15\%$ is considered for sensitivity. Energy consumption variations with drag co-efficient (cW), vehicle mass and rolling resistance variations are quite similar. Hence, the influence of rolling resistance on EV range/X Min charging remains similar to cW and vehicle mass influence.

Table 8: Rolling resistance variation and energy consumptions

Compact Car (30 kWh)	Luxury Car (90kWh)
0.0068; 11.64 kWh/100km	0.0068; 19.75 kWh/100km
0.008; 12.28 kWh/100km	0.008; ; 20.62 kWh/100km
0.0092; 12.92 kWh/100km	0.0092; 21.5 kWh/100km

4 Influence of Battery Parameters

4.1 Battery Internal Resistance

Battery internal resistance sensitivity is done for 15%, 10% increase and decrease in internal resistance

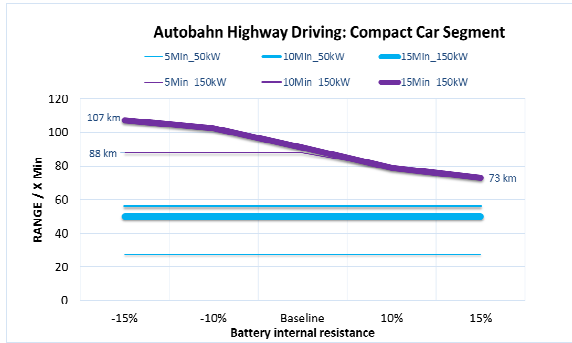


Figure 6. Resistance Vs Range/X Min: Compact

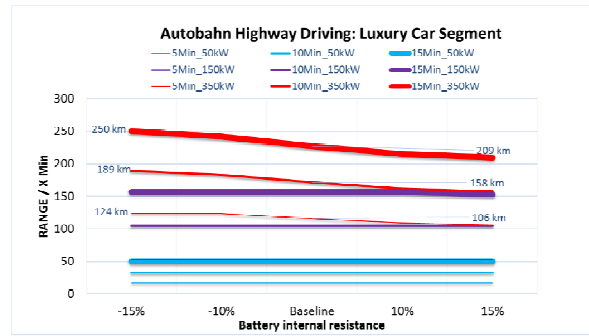


Figure 7. Resistance Vs Range/X Min: Luxury

from the base value. In case of luxury segment, from Fig. 7 it is observed that at higher DC infrastructure powers like 350 kW, the influence of charging times 5/10/15 Mins on EV range is prominent in comparison to 150 kW and 50 kW infrastructure power. With the increase in resistance, temperature reaches maximum value i.e, 45^o C [13] and current derating starts much earlier which in turn decreases the energy put in X min and hence the range decreases. With 150 kW infrastructure power, temperature doesn't reach maximum value [13] in all the cases except +15% increase in resistance and 15 min charging case and hence the range obtained is less than only 4 km when compared to other cases. 50 kW infrastructure power doesn't have influence as the temperature is less than maximum limit even though the resistance is changed. In case of compact car only 50 kW and 150 kW are considered as the battery size is small (30 kWh). In case of 150 kW, with the increase in the resistance, cut-off voltage is reached much earlier and hence there is no difference between 10 min and 15 min charging. With 10 % and 15 % increase in resistance, the energy put is same in 10 min and 15 min charging (as shown in Fig. 6) and hence the range attained is same. Battery internal resistance doesn't have influence with 50 kW.

4.2 Battery Maximum Temperature

Battery maximum temperature sensitivity is done for 15%, increase and decrease in maximum temperature from the base value. Table 9. Illustrates the battery maximum temperature variations considered for the present study. In case of luxury segment, from Fig. 9 it is observed that at higher infrastructure powers like 350 kW, the influence of charging times 5/10/15 Mins on EV range is prominent in comparison to 150 kW and 50 kW infrastructure power. With the increase in maximum temperature limit, more energy can be put in X min due to the increase in the current derating limit w.r.t temperature and hence the range increases. In case of 150 kW infrastructure power, range obtained is same for the baseline and 15 % increase in maximum temperature limit. Battery maximum temperature doesn't have influence with 50 kW infrastructure power on range obtained in X min charging. In case of compact car (as shown in Fig. 8) only 50 kW and 150 kW are considered as the battery size is small 30 kWh. In case of 150 kW, with the increase in the maximum temperature limit, cut-off voltage is reached much earlier and hence there is no difference between 10 min and 15 min charging. In compact car segment, with 10 and 15 min charging as the maximum temperature limit increases, current derating doesn't take place and cut-off voltage is reached must faster and hence energy put decreases which in turn decreases the range obtained. Battery maximum temperature doesn't have influence with 50 kW infrastructure power on range obtained in X min charging even in the compact car segment.

Table 9: Battery maximum temperature variation of Compact and Luxury Segments

Compact Car (30 kWh)	Luxury Car (90kWh)
38	38
45	45
52	52

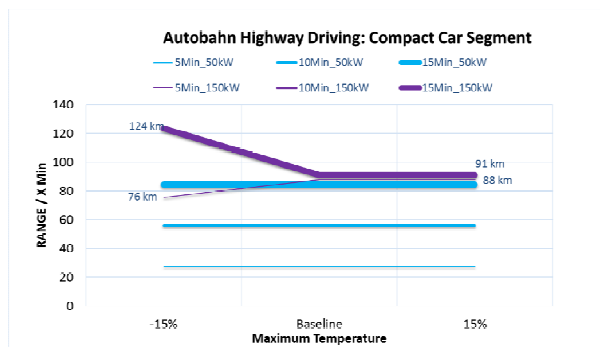


Figure 8. Max.Temperature Vs Range: Compact

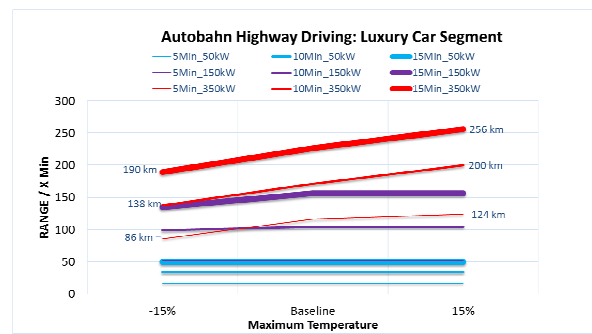


Figure 9. Max. Temperature Vs Range: Luxury

4.3 Battery C-Rate

Base line average C-rate for compact car and luxury car are given in Table 10. In case of luxury segment, from Fig. 11 It is observed that at higher infrastructure powers like 350kW, the influence of charging times 5/10/15 Mins on EV range is prominent in comparison to 150 kW infrastructure power and C-rate doesn't have influence with 50 kW infrastructure power as the infrastructure current itself is limited to 124 A. As the C-rate increases the net current entering the battery increases and hence the range increases. . In case of compact car the range increases with the increase in C-rate for both 50 kW and 150 kW infrastructure powers Fig. 10 Shows the influence of C-rate on EV range.

Table 10. Average C-rate for compact car and luxury car

Segment	50 kW	150 kW	350kW
Compact car	0.93C	2.79C	--
Luxury car	0.93C	0.93C	2.18C

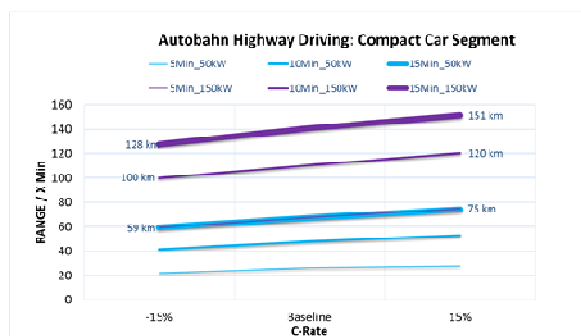


Figure 10. Battery C-Rate Vs Range: Compact

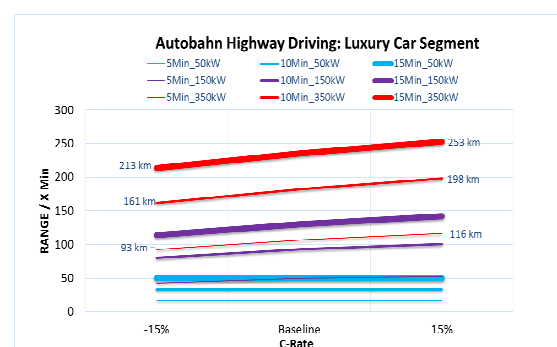


Figure 11. Battery C-Rate Vs Range: Luxury

5 Simulation Results and Observations

Sensitivity analysis provided under section. 3 and section. 4 clearly states that influence of independent variation in vehicle and battery parameters at low DC infrastructure powers like 50 and 150kW is not prominent. Whereas, influence is quite prominent at higher infrastructure powers. Results from above analysis helps in identifying the optimal car for highway driving from Stuttgart to Berlin. Fig. 12 Illustrates the use-case to identify optimal car for highway driving. It is assumed that optimal or best-case car for highway driving should satisfy below criteria

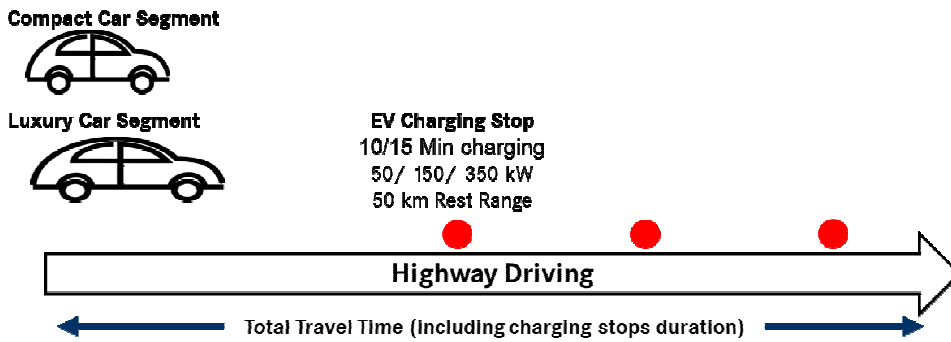


Figure 12. Highway Driving Use-Case to identify optimal car

- Minimal number of charging stops (15 Min / 10 Min stops for luxury and compact car)
- Minimal travel time/duration

5.1 Identification of Best-Case (Optimal) Car for Highway Driving (Stuttgart to Berlin)

EV with less energy consumption can be considered as optimal or Best-case car for highway driving as the number of charging stops and travel time involved is minimal. For this study, three categories: best-case (optimal), Baseline (existing), worst-case are studied. Table 11. Illustrates the parameter variations considered to define three categories. For instance, assumption is made that Stuttgart to Berlin highway have DC charging infrastructure of just 50kW, EV user with Best-Case compact car need to do 3 charging stops, whereas same user with the Worst-Case compact car need to do 15 charging stops which is quite not acceptable by EV customer. This trend is evident from ‘50kW Infra_Stops’ of Fig. 13 On the other hand, it is also observed that there is significant decrease in the number of charging stops for high DC infrastructure powers like 150 kW and 350kW. Fig. 14 Shows that the number of charging stops for optimal or best-case car are minimal when compared to other two categories baseline and worst-case.

Table 11. Parameter variations for Best, Baseline and Worst-case categories

Parameters	Best-Case	Baseline	Worst-Case
Vehicle Mass	-15%	--	+15%
Drag co-efficient	-15%	--	+15%
Rolling Resistance	-15%	--	+15%
Battery C-Rate	+15%	--	-15%
Battery cell resistance	-15%	--	+15%

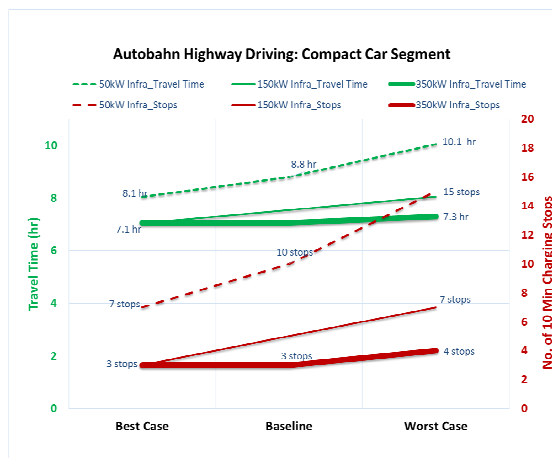


Figure 13. Highway driving: Compact car

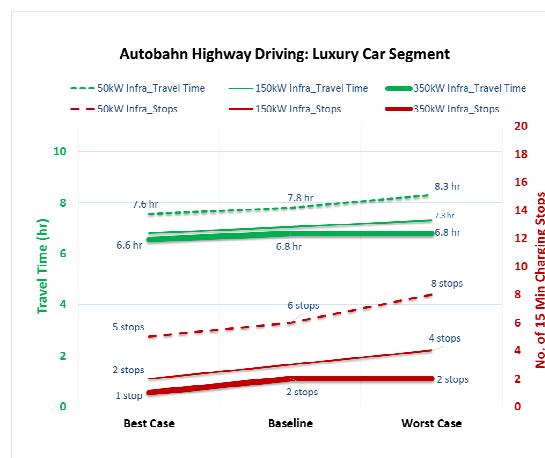


Figure 14. Highway driving: Highway car

6 Conclusions

The results presented in this paper provides an overview on the influence of EV vehicle and battery parameters on EV customer wishes like Range/X Min charging. Such analysis will help the component suppliers and vehicle designers in defining optimal EV parameters to fulfill EV customer wishes. Analysis presented on Highway driving clearly stated the differences between existing (baseline) EV specifications and optimal (best-case) EV specifications. Highway driving analysis analysis will also provide a better direction to the pre-development or research teams in finding the optimal EV and also in designing better DC infrastructure network on highways.

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