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Analysis of electric vehicle design and travel based on long trip capabilities

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Abstract

Rethinking electric mobility in terms of pure driving range versus long-trip capabilities is the motivation for this paper. An analysis of battery sizing compared to charging power is carried out in terms of additional time needed to execute a long distance trip with an electric vehicle based on standard consumption, battery size, charging power and limitations due the battery C-rate. The goal is to identify the smallest suitable battery and the "sweet-spot" concerning charging power that will still satisfy the user's need to complete long distance trips by specific charging stops and fast charging with sufficient power to continue the trip. At the same time, some of the limitations of battery technology especially regarding fast charging and durability are taken into consideration. Long-trip capability can be concluded, but also the imperative need for further research to improve fast charging capabilities (up to 100 – 150 kW) of batteries becomes clear.

Keywords: Electric vehicle; fast charging; driving range; trip time; battery capacity; C-rate

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Nomenclature

ADAC	German Automobile Club
DoE	Department of Energy
ELT	Electric Loss Time
I	Current
P	Power
QR	rated reversible electric charge in Amp-seconds
RDC	DC cell resistance in Ohm
SoC	State-of-Charge
UN	Nominal Voltage of the storage device

1. Introduction

The paper presents an analytical investigation to confirm a working thesis that long trips are possible even if the size of the battery is reduced drastically in comparison to market driver trends that would favor larger batteries in order to satisfy marketing perceptions that only vehicles with sufficient range will be accepted by mainstream customers. It is generally known and accepted that vehicles are rarely driven over 100 kilometers in normal day-to-day usage. This means that vehicles designed to satisfy high-range driving capability are basically outfitted with batteries that are consequently oversized for normal daily usage.

The concept of avoiding oversizing batteries is not new, see e.g. the idea of optimizing charging times during a trip as a Key-Note speech [Lit 1] at a recent conference in 2018. Reducing the size of the battery by 40% (from 90 kWh to 54 kWh) would save roughly 5 tons of CO_2 that would have otherwise been needed to manufacture the larger battery. According to the author's notes a longer trip (e.g. from Stuttgart to Venice) is possible by using higher power charging at several mandatory stops along the selected route, and a theoretically assumed C-rate of 6 in order to charge the battery from 5% to 80% SOC within 12 minutes. Further authors published similar work in a recent study [Lit 2], citing in particle a paper on enabling fast charging electrical vehicle considerations [Lit 3] and the need for charging stops on long trips.

Reducing the size of the battery, and maintaining the ability to execute long distance trips is seen as one of the key enablers for increasing the mainstream market uptake of electric vehicles since a direct cost benefit could be expected. This not only has the potential to significantly reduce the price of the electric vehicle but also saves natural resources and energy needed to produce batteries. The analysis in this paper is an idealized investigation that looks in particular at how systematically varying power, battery size and the number of charging stops can influence the overall trip time. It also considers how particular battery cell characteristics such as the internal resistance can limit charging power.

This is a theoretical analysis that was started during the preparation of the proposal CEVOLVER for GV-01-2018 (*Integrated, brand-independent architectures, components and systems for next generation electrified vehicles optimised for the infrastructure*) and has been extended during recent discussions in a SET-Plan Action 7 working group for fast charging and supported partly by CEVOLVER. The GV call allows additional time for charging during the long trip: 60 minutes for 700 km and 90 minutes for 1000 km; the greatest challenge arises with a trip run without a break, which thus serves as the basic reference case, although most likely not realistic.

The analysis shows that long trips are theoretically possible as long as sufficient charging capabilities are available along the motorway and the user has timely access to this infrastructure, as well as sufficient power. It must be noted that it is assumed that high-energy battery cell development is or will improve sufficiently in the next years to ensure that fast charging will not damage the cells even for higher C-Rates. Thus, further research is essential in order to make even small energy-optimized batteries capable of the fast charging that is needed to keep the trip time within acceptable limits, and still ensure their lifetime. Nevertheless, adding rate capability into energy optimized battery designs will have consequences for the weight, volume, lifetime and cost compared to those designs that do not have to handle continuous charging rates in the range of more than approx. 1 C [Lit 5].

2. Methodology

A basic vehicle calculation is carried out in a first step using the physical equation for air-, rolling- and slope resistance to initially estimate the power needed for a standard middle class vehicle such as a VW Golf. In order to adapt the physical data as close as possible to reality, the theoretical data were compared with published real vehicle energy consumption and this additional adjustment was also taken into account in the calculation, so that the results are plausible when comparing to the DoE study and other generally known vehicle data.

The calculations are based on the following set of equations.

	Unit	***Equation***	***Using***
Battery Energy?	kWh	$E_{bat} = s * cons / (90\% + (n-1) * 70\%)$	s: distance [km]
Trip time	h	$t_{trip} = s/v + n * (t_{rec} + t_{add})$	v: average speed [km/h]
Recharge time	h	$t_{rec} = \Delta SOC / C_r$	cons: energy consumption [kWh/km]
t_add	h	t_{add} = Additional time for arrival and departure, (un)plugging, …	n: Number of stops
C-Rate	1/h	C_r = Amp / Amp-h	P_chg: Charging power [kW]
Battery Power to Energy ratio	1/h	$P/E_{nominal}$ = W / W-h	

All trip-time-calculations have been carried out initially with a fully charged battery and for different charging powers between 22 kW and 350 kW. The “additional time” for approaching and leaving the charging station, the insertion of the charging plug, etc. was kept constant at 180 seconds for all scenarios, although the approach allows variations for future investigations.

Two fictive trips that cover a distance of 700 kilometers and 1000 kilometers are used in the investigation as a basis for the standard long trip. The virtual vehicle always starts a trip with 100% State-of-Charge (SoC) and is then “numerically operated” until it reaches 10% SoC. At exactly this theoretical point, the vehicle is “stopped” and the battery is ideally recharged with nominal charging power up to 80% SoC.

On the battery side the charging power, battery size and its charging acceptance determine how much time is needed for charging. Here, the calculations - as a function of charging power - do not include thermal losses that result from the battery system electric resistance as described later. In a more detailed view, (see chapter 3) it can be seen that these losses are important from the system perspective, but they only have a small impact on the overall trip time. Then the rest of the simulated trip and stops are carried out in the same manner, numerically “driving” until 10% SoC is reached, stop for charging and continue the trip as soon as 80% SoC is reached.

Consideration of the additional time for leaving the actual route, plugging in and out, paying etc. has been included as described above. In order to optimize the fast charging process time wise, the charging strategy and SoC limits were chosen in order to charge the battery as completely as possible using a constant current strategy with nominal power (in our example from 10 to 80% SoC ⇔ i.e. 70% of the nominal capacity) in each case.

Typical vehicle characteristics used are specified in the figure below, along with the result shown for a vehicle consuming 14.1 kWh/100km. According to “*Spritmonitor.de*” this value is representative in “everyday use” for electric vehicles like the VW e-up! or the electric version of the Hyundai IONIQ.

Input	Values
Vehicle weight	1550 kg
Starting SoC	100%
Charging scheme (SoC)	10-80%
Drag coefficient	0.24
Front area	2.1 m²
Rolling drag	0.008
Overall efficiency	*Adpt. to "everyday-use"*

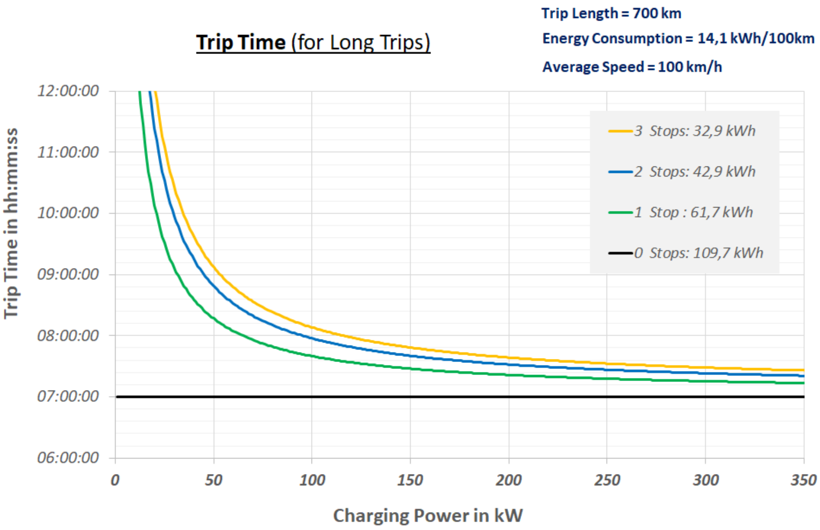

Figure 1: Physical based trip time analysis for different number of stops and various charging power configurations

It can be seen from the figure that such a theoretical 700 km trip would require a battery with nearly 110 kWh if the driver was to attempt such a long drive without breaks at a constant speed. The 0-stop curve also represents the case for conventionally fueled vehicles that either have the range due to the tank size or only has a negligibly short stop for refueling.

However, the German Automobile club (ADAC) and others recommend taking breaks as described in more detail below in Chapter 3 and include the need to limit a trip to a maximum of 10 hours trip time. Analytical variations of the long trips are then based on successively increasing the number of stops that then yield a battery size needed to execute the entire trip (including the stops). Increasing the charging power will initially reduce the overall trip time as seen in *Figure 1*. Further successive increases in charging power level only incrementally reduce the overall trip time asymptotically as shown above. This mainly occurs between 100 …150 kW charging power.

Once the basic relationship of charging power and trip time has been established, it is now important to include the limitation of charging power as a possible consequence of the now established and accepted battery C-Rate. It has become common practice to describe the charging and discharging capability of batteries in terms of the so-called "C-Rate". A definition of C-Rate is the calculated quotient of the charging current and the nominal battery capacity (A/Ah) knowing that in reality reduced charging power has to be considered (losses in between charging point and electrochemical energy storage), which would lead to different charging times due to e.g. caused by thermal and/or chemical de-rating processes. A simplified estimation of charging time based on C-rates is to divide an hour by the C-rate value.

In general, the allowed maximum C-rate is a function of temperature, current direction, load time and SoC. It is limited by the following factors:

A. The battery (electro-) chemistry and the related cell reaction plus side reaction kinetics (all local states within the 3D jelly roll network are involved)
B. The physical design of the cell, including active particle surfaces and electronic plus ionic transport limitations within the overall current path, including the current collectors and welding spots
C. The allowed upper voltage level on cell and battery level
D. The lower and upper battery temperature limits (in order to guarantee safety and lifetime)
E. The thermal design of the cell, the battery pack and the vehicle thermal system that limits the effective cooling power and defines resulting temperature gradients within the cell/battery

State of the art energy optimized batteries limit continuous charging rates to not more than 1.5 C to 2 C (for charging steps in the range of up to 70% to 80% SoC). The biggest challenge for cell producers and integrators is to avoid critical local states within the battery cells at any time for all electrical and thermal loads that could arise in operation. Knowing at the same time that in best case one is only able to measure integral currents and average voltages and temperatures for just some of the cell surfaces integrated in the battery.

All mentioned bullet points above (A to E) are more or less linked to the electric resistance contributions on electrode, cell and/or battery level. For example, the integral internal cell resistance (R_{DC}) defines the instantaneous power losses that depend on the quadratic of the charging current ($P_{losses} = R_{DC}$ x I^2_{charge}).

According to this basic fundamental equation, doubling the charging current thus quadruples these losses. E.g., if charging with “1 C” (e.g. 50 kW) and 1 kW losses, then a “7 C” (thus 350 kW) charging rate would have 7 times the charging current and approx. 50 kW instantaneous losses. If these thermal losses are not managed correctly, then the battery can heat up critically and eventually lead to a degradation of the cells. Finally, in terms of operation strategy, a need for charging power de-rating might arise. Effective cooling would anyway consume relevant additional electric power, which again worsens the charging efficiency.

An elegant means of representing first order effects for the dependency of charging efficiency on electrochemical design, based on DC ohmic losses, is shown in the paper “*Charge Transport in Energy Storage and Conversion Devices*” by V. Döge and Á. W. Imre [Lit 4]. The nominal voltage for a selected battery chemistry along with the DC resistance, with respect to the specific cell capacity of the storage device, determine the **E**lectric **L**oss **T**ime - *ELT* (sec.) as shown in “Figure 2”. The influence of variations in C-Rate can be generalized as shown below. The point at which the C-Rate lines (0.33 C, 1 C, 2 C, 3 C, 7 C) intersect the horizontal *ELT* line are projected down to the x-axis to give an energy efficiency of the battery. Small *ELT* values in general represent lower thermal losses, less overpotential for load phases (helping to stay below the upper voltage limit), higher load dynamics and the potential of fast-charge-ability of the battery. Larger *ELT* values, on the other hand, indicate energy optimized cells but with higher internal battery losses on cell level and bigger (especially thermal) challenges on system level for fast charging.

The *ELT* is defined with the following equation (communicated by the author of [Lit 4]) by using SI units. Q_R represents the rated reversible electric charge (“capacity”) in As, R_{DC} the DC resistance in Ω and U_N is the nominal voltage of the storage device:

$$t_{ELT} = R_{DC} \frac{Q_R}{U_N}$$

Typical condition to determine the R_{DC} and the *ELT* is for room temperature, an SoC of 50%, begin of life and for galvanostatic load steps in the range from 10 s to 30 s. It has to be kept in mind that every other state, like temperature and state of health (expressed by the respective value SoH_R) would lead to another R_{DC} and *ELT* value. The internal resistance will significantly increase for lower temperatures and increase with time and usage and hence used batteries will not offer the same charging performance near the end of usable life for the battery. It is typically necessary to avoid conditions such as high temperature, “Ah” - throughput with high charge C-rates and exceeding cell voltage that can lead to cell degradation. On battery system level additional resistance contributions will arise, based on the passive and active components used to electrically interconnect and operate the used storage cells.

Table 1: Typical ELT values and corresponding power to energy ratios for different secondary lithium battery segments [Lit 4]

Battery segment	Continuous power Reference	10 s peak power reference	Electrical loss time **(ELT)***
High energy	$0 < P_{cont} / E < 2$	$0 < P_{peak}/E < 5$	**80 s < t_{ELT}**
Mid power	$2 \leq P_{cont} / E < 8$	$5 \leq P_{peak}/E < 24$	**20 s < t_{ELT} < 80 s**
High power	$P_{cont} / E \geq 8$	$P_{peak}/E \geq 24$	**0 s < t_{ELT} < 20 s**

Of course it is common knowledge amongst battery experts that the most critical C-rate limitations, besides thermal aspects and integral ohmic overvoltage, arise from the risk of lithium metal plating. Here material selection and electrode design are of great importance. The respective parameters can be adjusted by modifying surface areas,

solid electrolyte interfaces and Li-ion diffusivities within the involved solid and liquid components.
Finally, lithium plating and thermal problems can be avoided by means of improved material selections and physical designs, including electrode packaging plus battery system efforts with respect to temperature conditioning and battery management charging algorithms.

It is important to note that the fast charging limitation is directly linked to the R_{DC} and therefore *ELT* value (simply by Ohm´s law) is the cha rging current related overvoltage that has to be subtracted from the upper voltage limit for calculating the achievable open circuit voltage reference and the correlated SOC window. Example: a 100 Ah cell (graphite/NCM chemistry) with the R_{DC} of 1 mΩ (that means an ELT of appr. 100 s) charged with 2 C at room temperature leads to an overvoltage of 200 mV. Assuming an upper cell voltage level of 4.15 V, this cell can only be charged until the open circuit reference voltage reaches approximately 3.95 V. Afterwards one has to switch to a constant voltage charging process which immediately results in a continuously decreasing C-rate. An OCV voltage of 3.95 V versus 4.15 V finally means to lose about 20 to 30% of SOC window that can be used for 2 C fast charging.

Even though typical *ELT* values for power and energy cells were previously mentioned, on vehicle level it is not possible to quantify exactly if/when a cell, integrated in a pack and installed in the vehicle, is truly capable of fast charging. This is the case since information on thermal coupling, physical cell design, heat rejection from the battery system and the installation situation in the vehicle plays a significant role. Hence, only generalized values are considered in the paper.

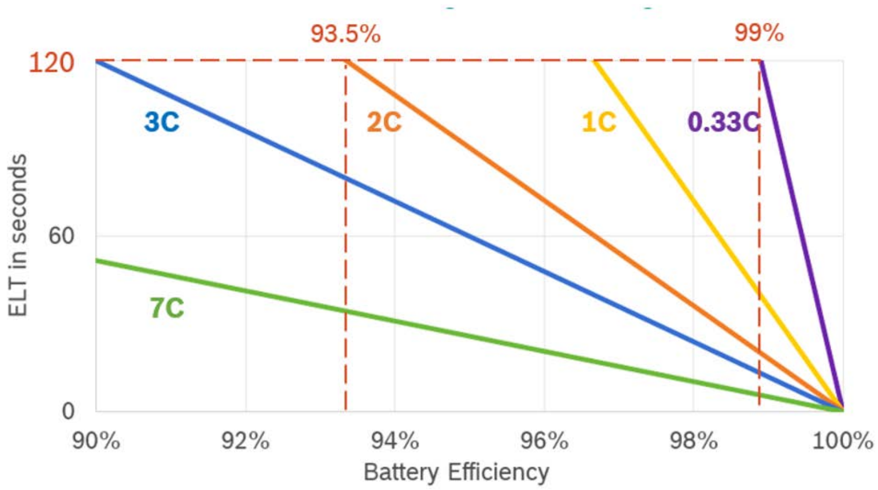

Figure 2: The relationship between Electrical Loss Time (ELT), mean battery efficiency expressed in % and the applied C-rate based on ohmic loss calculation, valid for all kind of electrochemical storage technologies [Lit 4]

As an example cell design that results in a specific *ELT* of 120 seconds (which is a typical value for energy optimized secondary lithium cells) will result in a battery with approximately 93% efficiency when charged at 2 C. If this were a 50 kWh battery, this would mean 7 kW thermal loss when charging a stationary vehicle with 100 kW.

Finally, the travel time calculation was considered using the simplification that no electrochemical- or thermal de-rating of the charging process occurs during the fast charging event; knowing that this cannot be assumed for all current battery systems.

The time saved by ultra-fast charging - e.g. 350 kW - on long-distance trips is time wise therefore not really significant (difference of less than appr. 15 min.) compared to a charging rate of appr. 100 kW to 150 kW, which is often additionally reduced by various de-rating scenarios. The use of high charging power is also less efficient due to the disproportionately increasing losses at higher charging current level. Although these losses just have a small impact on the overall trip time calculation for most of the (begin of live) and RT scenarios (by prolonging charging times in the range of 5 to 10%), C-rates will limit the effective charging power and hence the duration of the break.

3. Analysis

As described above, the calculation shows that a 700 kilometer non-stop trip could be possible with a 109 kWh battery in 7 hours based on a calculated consumption of 14.1 kWh/100 km, see Figure 1 . One or two stops would be realistic for such a long trip. It is assumed that a typical “family-stop” is generally 20 to 30 minutes. A detailed recommendation for planning a trip with breaks is given e.g. in Lit 6 as follows.

Table 2: Recommended break time for long trips [based on Lit 6]

Hours after departure	Recommended break time [min]
1	5
3	10
5	20
7	60
9	10
> 10	Stop driving; staying overnight

Two cases are shown here (Figure 3 and Figure 4): Continuous charging rate is limited by 2 C and 3 C capabilities (although these C-rates clearly both go beyond the current state of the art). It can be seen in Figure 3 that 2 stops combined with approximately 130 kW power and a battery close to 43 kWh would result in around 35 minutes additional trip time for the 700 km trip. Even with 2 C and 2 stops, see Figure 4, the trip would still be within the limits of 60 minute additional time (as set by the GV call text). This would only require somewhat more than 80 kW charging power, but also up to a 30 minute stop. However, it would be closer to the state-of-art for affordable battery cell chemistries.

Furthermore in the diagram it can be clearly seen how the C-Rate limits power. The end of the curve (in the direction of increasing power) is where 2 C and respectively 3 C would be exceeded for that size of battery (and power). Any charging at power below this limit is no problem, but leads to longer charging times.

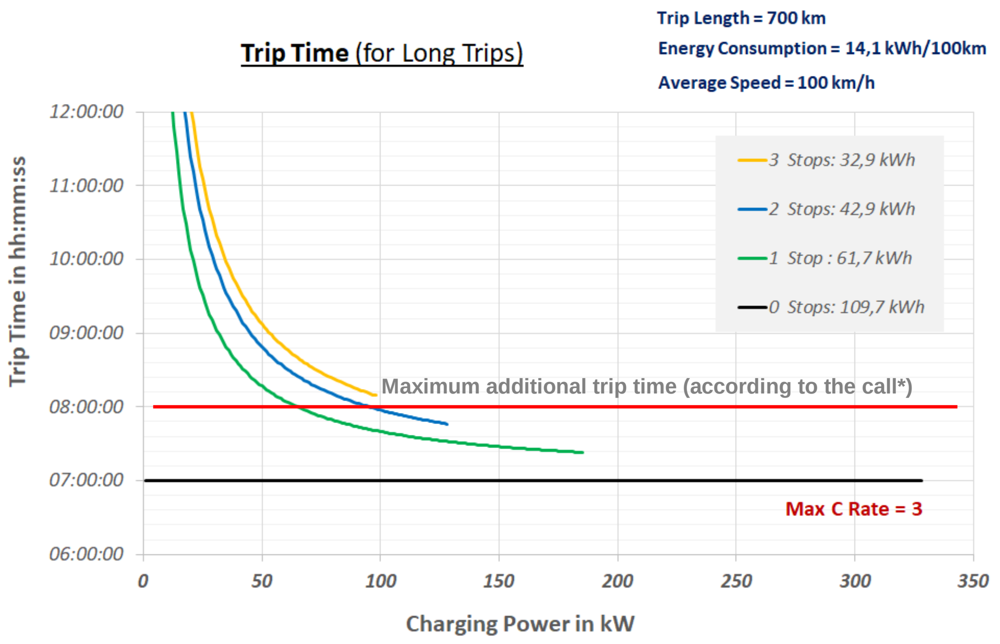

Figure 3: Charge power limited by 3 C versus trip time for 700 km trip (avg. speed 100 km/h)

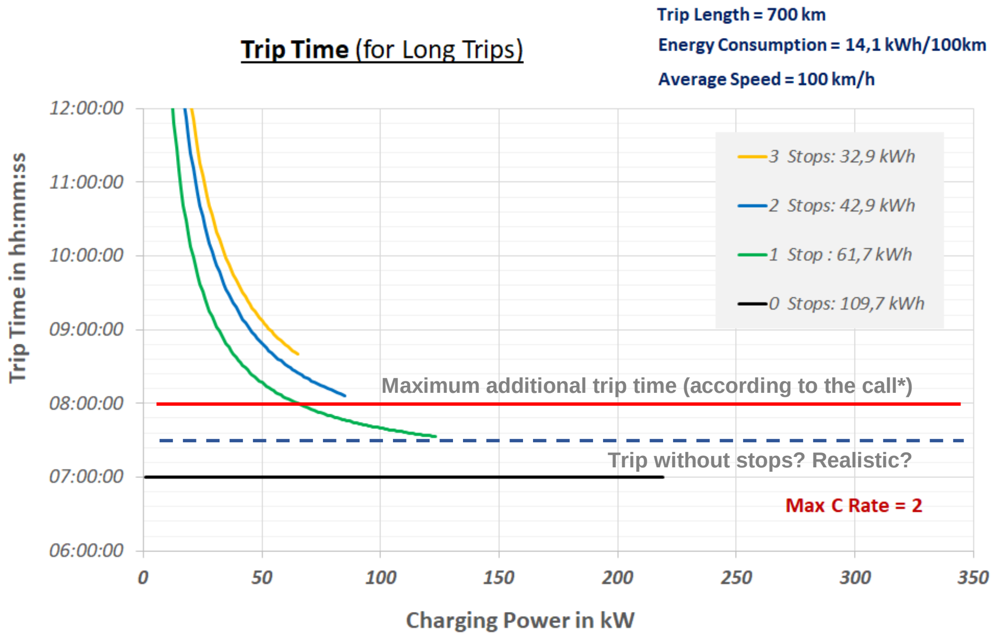

Figure 4: Charge power limited by 2C versus trip time for 700 km trip (avg. speed 100km/h)

In Figure 4 (with 2 C charging limits) the additional question is raised if a trip without stops is realistic. Following the recommendation mentioned previously at least one stop (better two) should be made with at least 20 to 30 minutes breaks. In this case the additional time for two stops and charging becomes only 20 to 30 minutes. In the case of making just one stop, a 61 kWh battery (orange curve) would be needed and result in no additional trip time and a battery capacity that may be better suited for a higher consumption vehicle examples analyzed below.

Thus additional trips of 1000 kilometers have also been analyzed with the methodology, see Figure 5 below. The 1000 kilometer trip is analyzed the in the manner as above. 2 C limits the charging power and three stops would work with a 47 kWh battery.

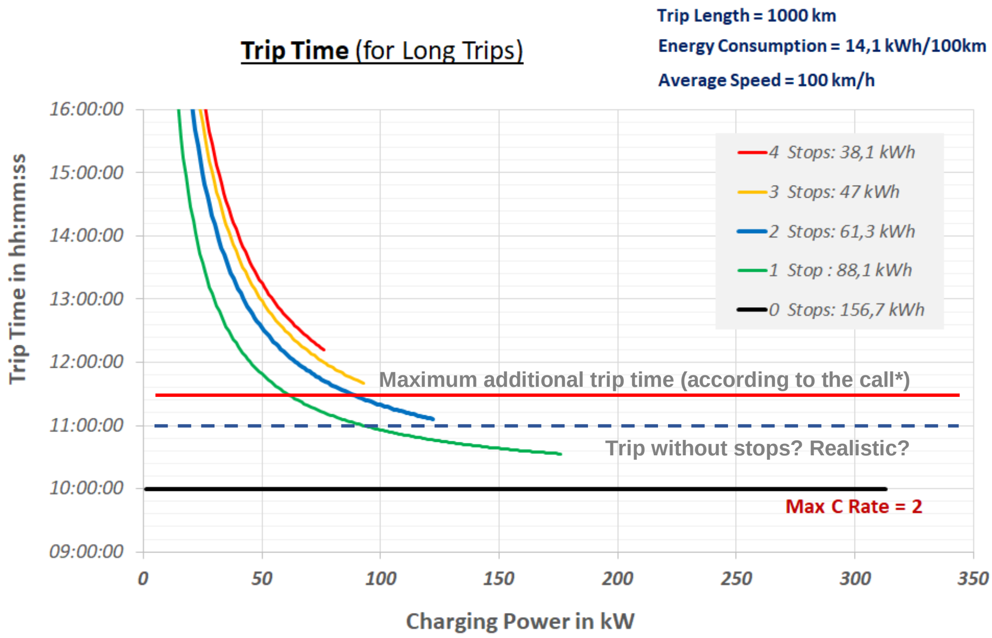

Figure 5: Charge power limited by 2 C versus trip time for 1000 km trip (avg. speed = 100 km/h)

Ideally, a slightly larger battery would be needed with three stops that leads to an additional travel time of less than half an hour compared to the reference trip that includes breaks totaling 1 hour. Charging power estimated for the three stops would be well below 100 kW. The case shown here corresponds to 2 C charging rate. In the case of a 61 kWh battery, it would be theoretically possible to carry out this long trip with just two stops.

Further calculations with higher energy consumption will lead to results with larger batteries and longer stops, but advantageous in terms of satisfying the limitations imposed by the C-Rates. The results of this analysis area shown in the two tables below. The first table represents the 700 kilometer trips and the second table represents the 1000 km trips.

Table 3: Analysis with higher energy consumption for 700 km trip

Energy Consumption	0 Stops		2 Stops		3 Stops		Charging power
kWh/100km	Trip time	Battery Size (kWh)	Trip time	Battery Size (kWh)	Trip time	Battery Size (kWh)	kW
16	07:00	124	08:28	48.7	08:43	37.3	50
16	07:00	124	07:45	48.7	07:56	37.3	100
18	07:00	140	08:38	54.8	08:54	42	50
18	07:00	140	07:52	54.8	08:01	42	100
20	07:00	156	08:48	60.9	09:06	46.7	50
20	07:00	156	07:57	60.9	08:07	46.7	100

Table 4: Analysis with higher energy consumption for 1000 km trip

Energy Consumption	0 Stops		2 Stops		3 Stops		Charging power
kWh/100km	Trip time	Battery Size (kWh)	Trip time	Battery Size (kWh)	Trip time	Battery Size (kWh)	kW
16	10:00	178	12:03	69.6	12:23	53.3	50
16	10:00	178	11:04	69.6	11:16	53.2	100
18	10:00	200	12:17	78.3	12:40	60	50
18	10:00	200	11:11	78.3	11:24	60	100
20	10:00	222	12:32	66.7	12:57	66.7	50
20	10:00	222	11:19	66.7	11:33	66.7	100

Two cases have been highlighted here for the case of a nearly 30% increase in energy consumption. Both cases satisfy the maximum additional trip time requirement compared to the (not realistic) non-stop trip respectively for 700 km and 1000 km. Both cases would indicate that a battery pack between 55 kWh and 60 kWh should be sufficient with charging power of 100 kW and resulting in a C-Rate of approximately 2. This is consistent with the DoE paper [Lit 2] included in the DoE study mentioned above.

Figure 6 has been adapted from the DoE study [Lit 2] and shows the relation between battery size, charging rate, charging power (reduced to a more realistic range of interest) and time to recharge and is consistent with the results presented above.

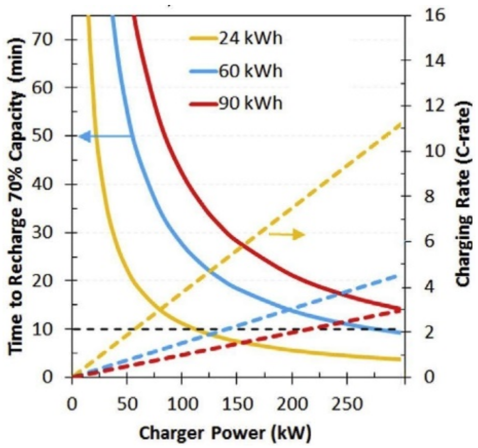

Figure 6: Time of charging and corr. C-rate for diff. batteries as a function of charger power, based on [Lit 2]

Focusing on the targeted 60 kWh battery it can be seen that 100 kW charging power would mean a C-Rate of 1.5 and realistic compared to the state of the art. The solid blue curve shows a charging time between 25 and 30 minutes that is consistent with the analysis shown above. Increasing charging power will help to reduce the charging time, but levels off asymptotically as shown above in Figure 1. An incremental increase in charging power has little effect on the charging time. However, the corresponding C-Rate continues to increase linearly with increasing power. This leads to high inefficiencies as indicated in Figure 2 above.

Even in this modified for, this curve from the DoE study makes it very clear that the C-Rate has clear limitations and must be considered carefully in all the discussions surrounding fast charging. Exceeding the C-Rate is one of the risk factors that can lead to lithium plating, critical warming and hence degradation of the cell capacity and corresponding reduced lifetime of the cell.

4. Conclusions

The analysis presented in the paper has shown that idealized long trips are possible without extended waiting even with smaller batteries. However further advances in cell technology and system set-up are needed in order to reduce the internal resistance and improve thermal design from the cell up to thermal management system on vehicle level. This is absolutely mandatory to improve charging efficiency and to manage thermal losses that occur with increasing charging power.

The significance of C-Rates with regard to the losses that have to be dissipated by the vehicle thermal system has been shown, especially since these become more critical with decreasing the installed battery capacity that lead to higher C-rates at a given charging power. However, this serves as a means of establishing R&D targets for future batteries, especially improving charging C-rates for energy batteries.

From this analysis continuous C-Rates between 2 and 3 would be sufficient for the long trips presented in the paper. Clear benefits for fast charging can be seen up to 100 kW. Finally, the analysis assumes that fast charging stations are readily available at exactly the points where the charge has been depleted to 10%. This will most certainly not be the case for near future, but can serve as a means to support quantifying the fast charging needs regarding infrastructure locations and specification.

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