MEC-E5006

Vehicle Mechatronics

Title: **Project Round Two**
LDoS: **Dec 15, 2018**

All-Electric Vehicle Model

Design a heavy electric vehicle powertrain and a hill holder assistant for the vehicle. The mass of the vehicle **without** batteries and motor(s) is **10500 kg**. The required level of abstraction is similar to the model in Exercise 2. Note that the first step is to get the work started early enough. Return a zip-file that contains all files related to your answer. It should have at least: a pdf that explains how you modelled the vehicle and answers the bolded subjects beneath, a Simulink model of the vehicle and Matlab scripts if you made any.

Step 1

- Pair up with your group mate and carry out **initial overall design**.
- Analyze the vehicle's **max power** need.
- Fix the **gearbox ratio(s)** and the **power of motor(s)**.
- Fix the **battery voltage**.
- Create a sketch / plan / flowchart of the **simulation model** of the vehicle.
- Submit your answers by **Nov 30**.

Answer

Table 1 presents the parameters that roughly provides the initial overall design of our vehicle. The following computations are done in order to get an idea about those parameters which cannot be directly stated but calculated pretty conveniently.

Total Mass

$$m_\mathrm{t} = m_\mathrm{v} + m_\mathrm{pl} + m_\mathrm{batt} + m_\mathrm{m}$$

Aerodynamic drag

$$F_\mathrm{aero} = \frac{1}{2} C_\mathrm{d} \rho A v_\mathrm{max}^2$$

Rolling frictional force

$$F_\mathrm{RR} = f_\mathrm{RR} m_\mathrm{t} g \cos\beta$$

Slope effect

$$F_\mathrm{slope} = m_\mathrm{t} g \sin\beta$$

Intertial force

$$F_\mathrm{iner} = m_\mathrm{t} a_\mathrm{max}$$

Tractive force

$$F_\mathrm{trac} = F_\mathrm{iner} + F_\mathrm{aero} + F_\mathrm{RR} + F_\mathrm{slope}$$

Table 1 – Initial Overall Design

Vehicle Data	
Vehicle mass (m_v) [kg]	10500
Payload (m_pl) [kg]	5000
Battery mass (m_batt) [kg]	663.5
Motors' masses (m_m) [kg]	3048
Aerodynamic drag co-efficient (C_d)	0.36
Air density (ρ) [kg/m^3]	1.17
Vehicle frontal area (A) [m^2]	12.00
Rolling resistance co-efficient (f_RR)	0.014
Slope (β) [deg]	0
Transmission efficient rate (η_trans)	0.9
Dynamic tyre diameter (D_dyn) [mm]	686.5
Gravity acceleration (g) [m/s^2]	9.81
Gear ratio (i_g)	5
Maximum speed (v_max) [m/s]	14.63
Auxiliary Load (P_aux) [kW]	10
Cells in series (C_s)	192
Cells in parallel (C_p)	6
Cell nominal voltage (V_nom) [V]	3.6
Cell nominal capacity (C_nom) [Ah]	40

Table 2 – Additional Design Data

Computed Vehicle Data	
Total mass (m_t) [kg]	19212
Aerodynamic drag (F_aero) [N]	6318
Rolling frictional force (F_RR) [N]	2639
Slope effect (F_slope) [N]	0
Intertial force (F_iner) [N]	37023
Tractive force (F_trac) [N]	45980
Max power (P_max) [kW]	217
Max wheel torque ($T_\text{w,max}$) [Nm]	4580 Nm
Max wheel speed ($n_\text{w,max}$) [rpm]	1391
Motor's maximum torque ($T_\text{m,max}$) [Nm]	1018
Motor's maximum speed ($n_\text{m,max}$) [rpm]	6955
Max battery power ($P_\text{batt,max}$) [kW]	227
Max battery voltage ($U_\text{batt,max}$) [V]	691
Max battery current ($I_\text{batt,max}$) [A]	329

Figure 1 - Wheel Force v/s Road Speeds

Max Power

In order to compute the maximum power, **Figure 1** was consulted. The graph is for light-weight vehicles. Therefore, the maximum force at wheels (F_{max}) for the heavy vehicle here is assumed to be 3000 lbs or $3000 \times \dfrac{4448}{1000} = 13344$ N. The speed at this maximum force ($v_{F\text{max}}$) at wheel value is assumed to be 30 mph or $30 \times \dfrac{44.7}{100} = 13$ m/s.

$$P_{\text{max}} = F_{\text{trac}} v_{\text{max}}$$

Max wheel torque

$$T_{\text{w,max}} = F_{\text{trac}} \times \frac{D_{\text{dyn}}}{2}$$

Max wheel speed

$$n_{\text{w,max}} = \frac{60}{2\pi} \times \frac{v}{\frac{D_{\text{dyn}}}{2}}$$

Motor's maximum torque

$$T_{\text{m,max}} = \frac{T_{\text{w,max}}}{i_{\text{g}} \times \eta_{\text{trans}}}$$

Motor's maximum speed

$$n_{\text{m,max}} = n_{\text{w,max}} \times i_{\text{g}}$$

Max battery power

$$P_{\text{batt,max}} = P_{\text{max}} + P_{\text{aux}}$$

Max battery voltage

$$U_{\text{batt,max}} = C_{\text{s}} \times V_{\text{nom}}$$

Max battery current

$$I_{\text{batt,max}} = \frac{P_{\text{batt,max}}}{U_{\text{batt,max}}}$$

Table 2 presents the values of those parameters which are computed from the initial design parameters. These are the final calculations based on overall design parameters.

(**answers for Step 2 begins from next page**)

Step 2

You are not bound to the design reported in Step 1. Report your design choices of each item and relevant simulation results (battery current, motor speed, torque etc.)

- Analyze the vehicle **energy need**.
- Choose suitable **battery chemistry** and **cell type** (`https://batteryuniversity.com/` is a good source for this).
- **Check battery sizing** in terms of energy and power.
- Estimate the **current density in cabling** and required **battery cable sizes**.
- Develop a **hill holder assistant** that keeps the vehicle at its position in an uphill of 5 degrees.
- **Simulate** the vehicle **energy consumption** (instant and total) in the given cycle.
- Report the **operating range** of your vehicle.
- Report how much **time** it takes to charge the battery to full.
- The simulation model should have at least the following components: **battery**, **vehicle inertia**, **electric motor** (simulating electric motor with lookup tables is ok), **gearbox** (fixed gear(s)), **controller** (PID for example), **brakes** and **regenerative braking**.
- Submit the answers describing your approach including simulation results by **Dec 15**.

Note: a lot of freedom is given for design choices. You are recommended to check components available in the market and choose a good setup and to give justifications for your choices.

Answer

Figure 2 shows the overall electric powertrain design for a heavy vehicle with the aforementioned specifications. The `Vehicle Model` contains the vehicle inertia. The necessary force is computed after comparing the actual vehicle speed with the speed profile. PID controller is used to control the motion of the vehicle. A simple, fixed gear is used. The `Electric Motor` subsystem contains the brakes and `Power` subsystem contain regenerative braking computation values, respectively.

Vehicle Energy Need

The vehicle's minimum energy need ($E_{\text{batt,min}}$) corresponds to having the maximum battery power ($P_{\text{batt,max}}$). The C-rate for the Kokam battery used for this heavy vehicle is 1 (`https://batteryuniversity.com/learn/article/types_of_lithium_ion`). Hence, the vehicle's minimum energy need can be computed as

$$E_{\text{batt,min}} = \frac{P_{\text{batt,max}}}{\text{C–rate}} = \frac{227}{1} = 227 \ \text{kWh} \quad (\textbf{Ans})$$

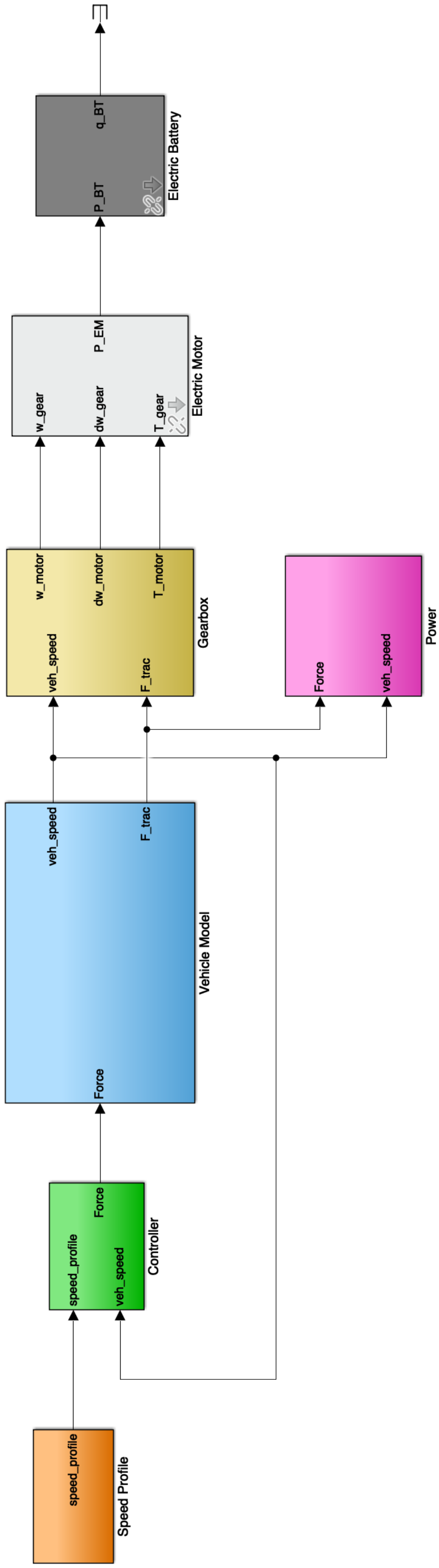

Figure 2 – Simulink Model of Overall Vehicle Structure

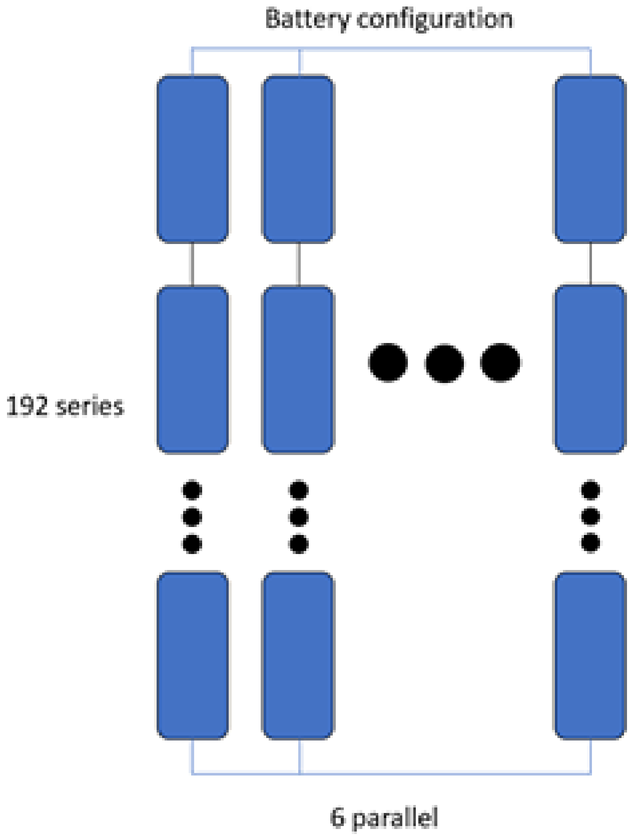

Figure 3 – Battery Configuration

Battery Chemistry and Cell Type

NCA battery chemistry is used mainly because of the fact that, Kokam battery manufacturer uses it and it has good characteristics. Invariably, Li-ion cell is used in this battery. More specifically, Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$) cell is used. **Figure 3** shows the battery configuration for use in the heavy vehicle.

Battery Sizing

From the Kokam website it was found that the nominal voltage and the cell capacities match closely with the QSS toolbox `Battery v3` subsystem, so it was ultimately chosen to be used in the simulation. Based on the simulated values, it was found out that the battery sizing was sufficient enough for this type of application.

Battery Cable Sizes and Current Density in Cabling

Cable sizing was done by finding out the maximum current that goes to the motor, from motor maximum power and the battery voltage. The maximum current was computed to be approximately 329 A. With this value and the used 691 V for battery, it was unanimously decided to use cables from EXRAD (`http://www.evwest.com/catalog/product_info.php?products_id=423`). The following cable was found out to be sufficient where the maximum voltage is 1000 V and maximum current is 500 A: **1/0 AWG Champlain EXRAD XLE 1000V Shielded Cable**. As for current density in cabling, it was computed to be

$$\text{Current Density} = \frac{I_{\text{batt,max}} \ (\text{A})}{\text{Mean area of conductor} \ (\text{mm}^2)} = \frac{329 \ (\text{A})}{77 \ (\text{mm}^2)} \approx 4.27 \ \text{A/mm}^2$$

The current density also turned out to be quite reasonable as well, because typically the value is between 4 A/mm^2 and 6 A/mm^2.

Hill-Holder

Hill holder logic is presented in **Figure 4** and **Figure 5** below. The main motivation in hill holder systems is to ensure that, while starting from a standstill in a hill, the vehicle does not start moving backwards when the driver makes the transition from braking to accelerating. The main idea in the system is that, there are two states: the first one is in which the system is active (**Figure 4**) and, the second one is in which the system is inactive(**Figure 5**). Both states are constantly mirrored against the environment and are triggered as soon as the conditions are right. Unfortunately, due to lack of time, the logic could not be implemented in the simulation. The task also does not explicitly state that it needs to be there in the simulation. Therefore, it was unanimously decided to present the detailed logic of the hill-holder. With further improvements to the presented logic, one could replace the `Wait for 1 s` block with smooth transition, thereby basically constructing a state that mirrors engine torque to brake pressure. This way the transition could be done in relatively smoother manner and more comfort for the driver and passengers could be ensured.

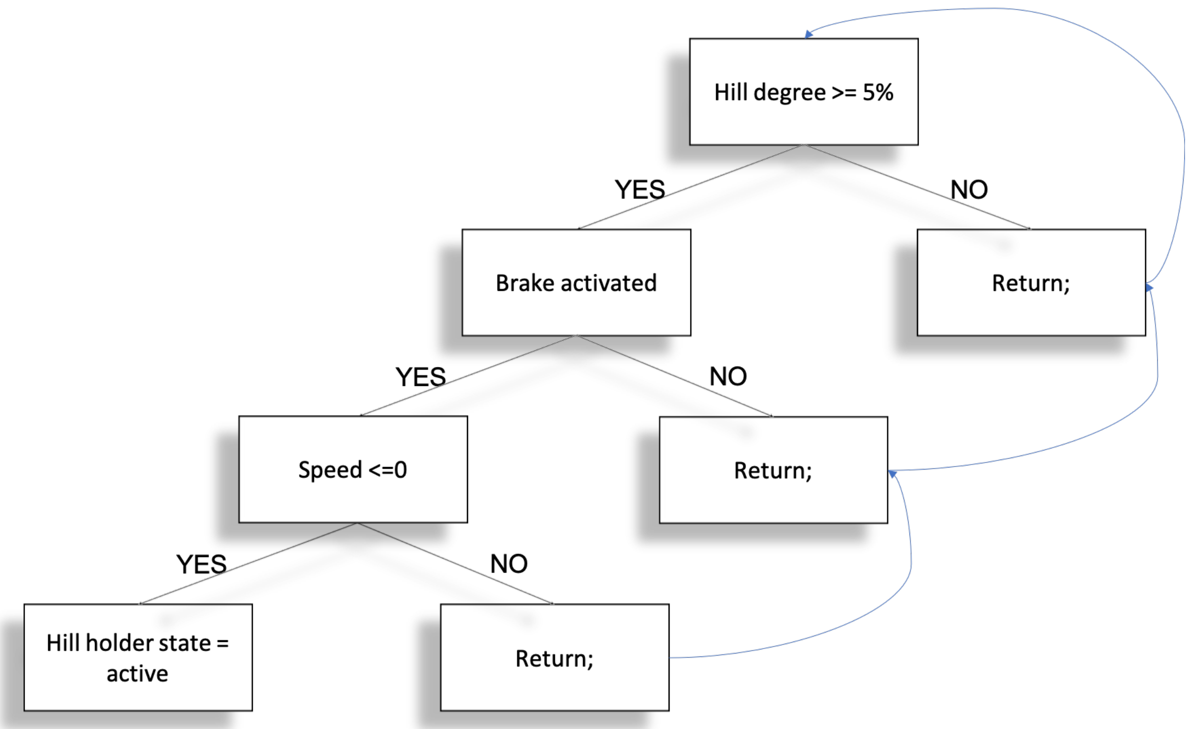

Figure 4 – Activation of Hill Holder

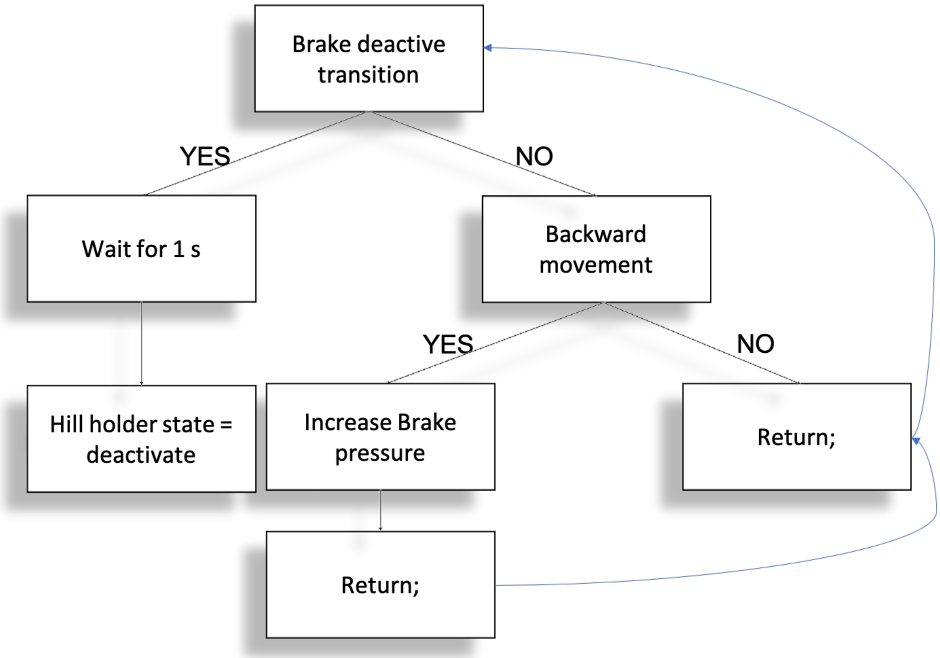

Figure 5 – Deactivation of Hill Holder

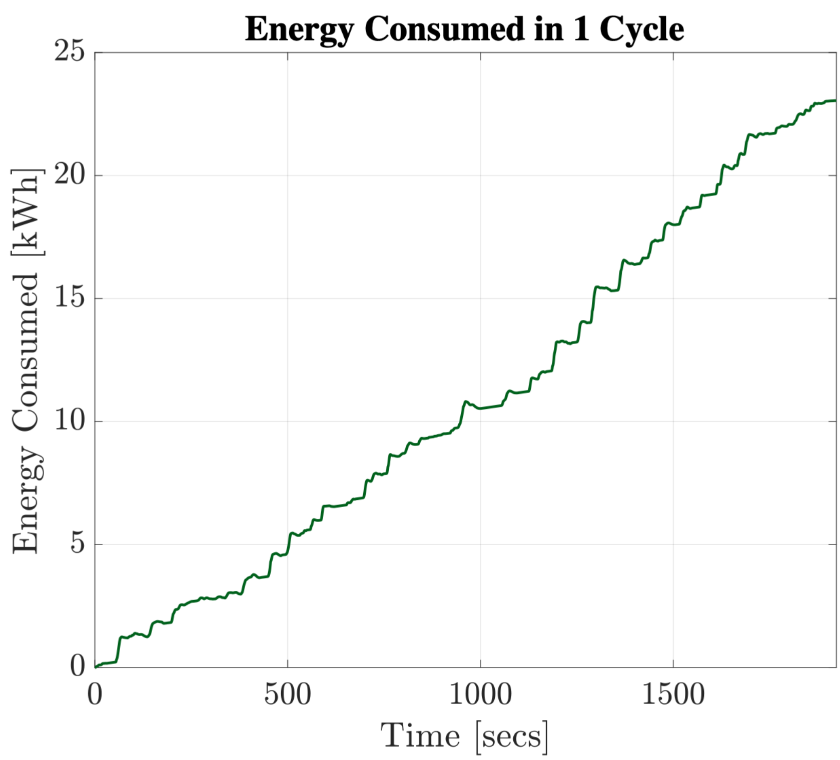

Figure 6 – Energy Consumed during 1 Cycle

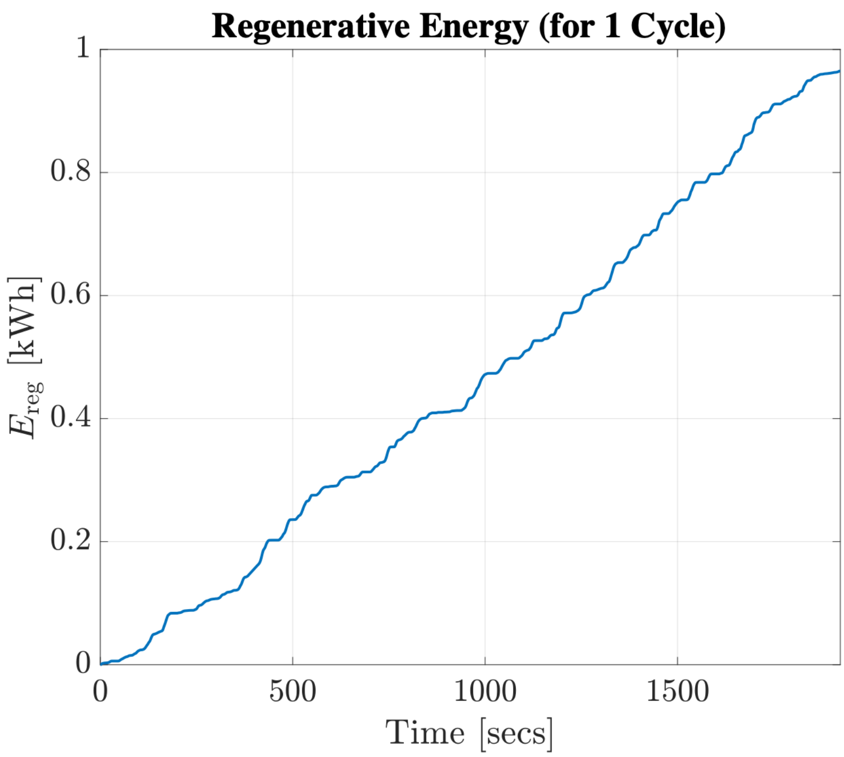

Figure 7 – Regenerative Energy for 1 Cycle

Simulation of Energy Consumption

Figure 6 shows the plot for instantaneous values of energy consumed by the heavy electric vehicle during one cycle as a function of time. **Figure 7** shows the plot for regenerative energy produced by the heavy electric vehicle during one cycle as a function of time. The regenerative energy was computed out to be almost **4.0%** of the total energy consumed by the vehicle. The value for regenerative energy looks reasonable because in heavy vehicles, the maximum regenerative energy as a percentage of total energy consumed is typically 10%. The energy consumption per 100 km (E_{cons}) was computed out to be 182.27 kWh.

Operating Range

The operating range for this heavy electric vehicle can be computed as

$$\text{Range} = \frac{\dfrac{U_{\mathrm{batt,max}} \times \text{Total Cell Capacity}}{1000}\ (\text{kWh})}{E_{\mathrm{cons}}\ \ (\text{kWh}/100\text{km})} = \frac{\dfrac{691 \times 6 \times 40}{1000}\ (\text{kWh})}{182.27\ \ (\text{kWh}/100\text{km})} = 91\ \ \text{km}$$

The target was to drive this heavy electric vehicle as close to 100 km as possible. The mission has been accomplished with the choice of battery, its chemistry, its configuration, battery cable size, current density in battery cabling and regenerative energy.

Charging Time

Typically, a battery with this chemistry takes **3 hours** to completely charge (`https://batteryuniversity.com/learn/article/types_of_lithium_ion`). It is also quite reasonable compared to the fact that, the best one available in the market now-a-days (`https://electrek.co/2018/05/16/daf-all-electric-truck-battery-pack/`) takes 1.5 hours to charge completely, with energy consumption value of 170 kWh/100km. The energy consumption value for his vehicle is slightly higher at 182 kWh/100km. Hence, in order to match up to this mark, the battery has to be slightly bigger and more charging time is, therefore, required.