Fundamentals of Electric Vehicles

S.A. Sabarirajan
designersabarirajan@gmail.com

Chapter – 1
Vehicle Dynamics

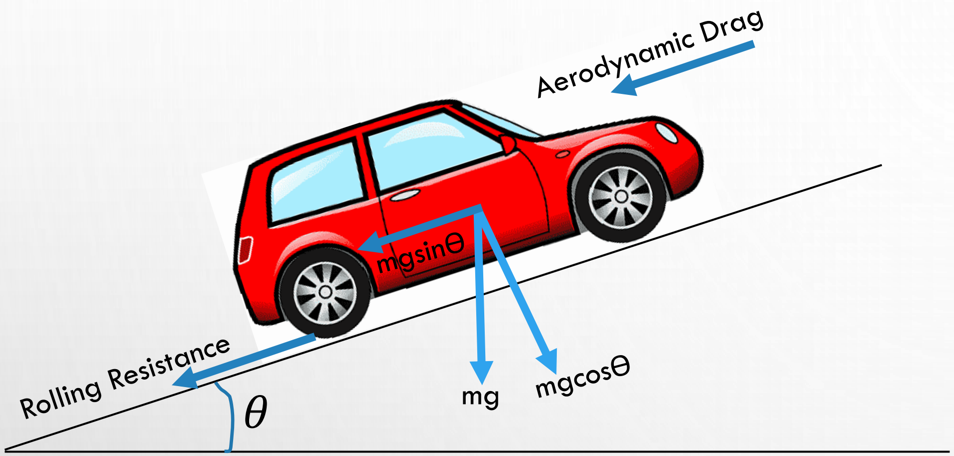
Driving an Internal Combustion Engine or Electrical powered Vehicle

1. How much power required to drive a vehicle?
2. How much energy required to carryout a Road trip?

In order to calculate the power and energy for a vehicle, the below questions to be answered in the first place.

- What is the Composite mass of the vehicle (Including Passengers and goods) – GVW (gross vehicle weight)
- What is the worst condition of road to be considered to design – Rolling Resistance
- What is the worst aerodynamics condition to be considered during design – Aerodynamics Drag
- What is the inclination and banking to be considered – Gradient resistance
- What are the velocities and accelerations at different point of application – Drive Cycle
- What is the maximum speed and maximum acceleration of the Vehicle?

What does the tractive force overcomes:



1. Aerodynamic Drag
2. Rolling Resistance
3. Uphill resistance
4. Acceleration

$$\textbf{Aerodynamic Drag} = \frac{1}{2}\ x\ \rho\ x\ Cd\ x\ A\ x\ v^2$$

Where,

$$\rho = Density\ of\ the\ Air\ @27°C = 1.2\left(\frac{Kg}{M^3}\right)$$

V = Velocity (m/Sec)

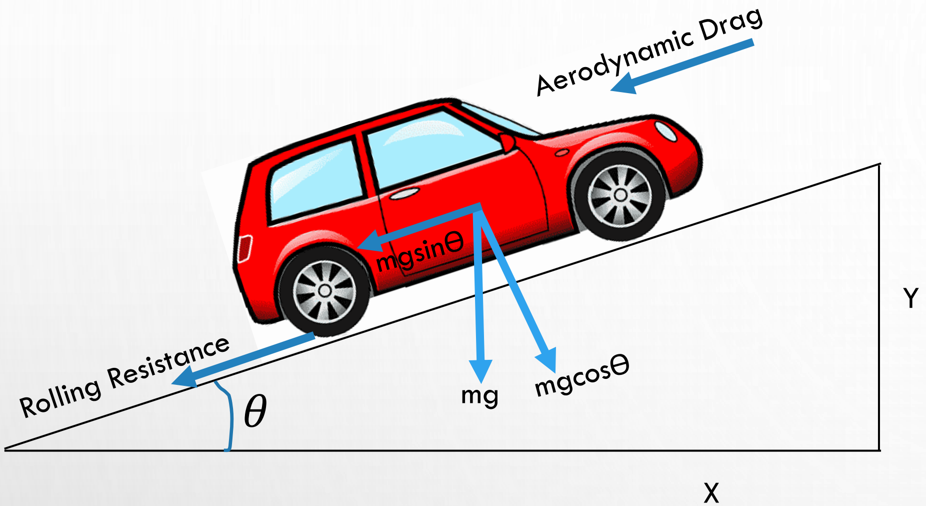
A = Vehicle Frontal Area (or) Projected Area in Sq.m

Cd = Drag Coefficient

$$Aerodynamic\ Drag = \frac{1}{2}\ x\ \frac{Kg}{M^3}\ x\ Cd\ x\ M^2 x\left(\frac{M}{\sec}\right)^2$$

$$\frac{Kg.m}{Sec^2} = Newton = N$$

What does the tractive force overcomes:



Rolling Resistance

$Rolling\ Resistance = mg\ x\ \mu\ x\ cos\theta$

Where,

M=Permissible Load in Kg

$g = gravity\ in \frac{m}{s^2}$

$\mu = Rolling\ Coefficient$

Inclination / Grade :

$$Inclination\ in\ \% = \frac{Height\ of\ grade}{Base\ of\ the\ grade}\ x\ 100\% = \frac{Y}{X}\ x\ 100\%$$

$$Inclination\ in\ Degree = Tan^{-1}\left(\frac{Y}{X}\right)$$

$$If\ Inclination\ is\ 8\% = \left(\frac{Y}{X}\right) = 0.08 = Tan\theta$$

$$\theta = Tan^{-1}(0.08) = 0.08\ radians$$

$$\theta\ in\ degrees = \frac{0.08\ x\ 180}{\pi} = 4.6\ Degrees$$

Uphill Resistance

$uphill\ Resistance = mg\ sin\theta$

So, Tractive force created by powertrain initially overcomes these resistance forces then provides acceleration

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2. Traction Power for a vehicle

Vehicle needs a Traction Power, P_{trac} (watts)applied to it to move and accelerate.

- Traction power in internal combustion Engine (ICE) comes from Petrol / Diesel Engine
- Traction power in EVs comes from Battery through motors and its controllers

Traction Power creates a Force F_{trac} on the vehicle to move forward

- $P_{trac} = F_{trac}$ x v , Where v is Velocity (m/Sec) of the vehicle

The Resulting Torque T (N-m) on the vehicle wheel created by the force is

- T = F_{trac} x r_{Wheel}, r is the radius of the vehicle wheel in m

Torque and Speed (referred to as rpm) are the fundamental parameters of a motor or an engine, and Vehicle velocity is obtained by $v = \frac{Engine\ rpm\ x\ 2\ x\ \pi\ x\ r}{60}$

Traction Force given by

$$Ftrac = Acceleration\ Force + Aerodynamic\ Drag + Rolling\ resistance + Climbing\ Resistance$$

$$Ftrac = (m\ x\ a) + \left(\frac{1}{2}\ x\ \rho\ x\ A\ x\ v^2\ x\ Cd\right) + (\mu\ x\ mg\ x\ cos\theta) + (mg\ x\ sin\theta)$$

Where a is acceleration, and is dv/dt

Energy consumed by the vehicle is integration of traction power

$$Energy = \int\ Ptrac\ dt\ in\ Watt - Sec, and\ is\ converted\ to\ kWh\ by\ Dividing\ 3.6$$

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Vehicle Performance Parameters

Motors, Controllers, Battery and gears – These are elements which drives the performance of the vehicle

Vehicle performances are characterized by Torque, Speed and Power for Nominal (continuous speed and Peak (for short term)

Torque (N-m): Force x Radius of tyre : This would come from Motor – Nominal torque and peak torque (For short time of ten seconds or so)
This torque is used to overcome rolling resistance, aerodynamic resistance and to provide acceleration and Gradient resistance.

Vehicle Speed (Kmph): Cruising speed and Peak Speed, which would come from Motor RPM

$$Speed\ in \frac{M}{s} = Speed\ in\ Kmph\ x\ 3.6$$

$$Speed\ in \frac{M}{s} = rpm\ x\ Tyre\ Radius\ x \left(\frac{2\pi}{60}\right)$$

$$Speed\ in \frac{M}{s} = \frac{rpm\ x\ Tyre\ Radius}{9.55}$$

$$Speed\ in\ Kmph = \frac{rpm\ x\ Tyre\ Radius}{9.55\ x\ 3.6}$$

Motor Rpm	63.66		Vehicle Speed in M/s	2		Vehcile Speed in Kmph	80
Wheel Radius (m)	0.3						
Vehcile Speed m/Sec	1.999938		Rpm	63.66667		Vehicle speed in M/s	288.8087
Vehcile Speed Kmph	0.555538		Vehicle Speed in Kmph	0.555556		Rpm	9193.742

Power in Watts: Nominal Power and Peak Power.

$$Power = Force\ (N) x\ Velocity \left(\frac{M}{s}\right) = \left(\frac{Torque\ (N)}{Radius\ of\ Tyre(M)}\right) x \left(\frac{Rpm\ x\ Rtyre(M)}{9.55}\right)$$

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Power and Efficiency Summary

Mechanical

$Power P = F * v = (ma) * v$ {Translation Movement}

$Power\ P = \tau * \omega = (I\alpha) * \omega$ {Rotational Movement}

In Electric Vehicles, the Force "F" or Torque τ Available for acceleration is residual after deducting all Drags,
Which are

1. Aerodynamics Drag
2. Air Drag
3. Gradient Climbing

Electrical

$Power\ P = V * I$

When V&I are not constant, as in AC Circuits, this gives the instantaneous power

P Measured in "W" Watts

$Since, V = IR$

$$P = \frac{V^2}{R} or\ P = I^2R$$

$$Energy\ E = \int P * dt$$

Where dt is the difference in time . E measured in Joules =Watt-Second

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Chapter – 2
ICE vs Electric Vehicles

Comparison of EV with ICE Vehicles

Common Parts between EV and ICE Vehicle

Body / Frame: Body and Frame of the Existing ICE vehicle

Doors and Power Windows : Existing

Wheels: All wheel components including rim, hub, knuckle and Tires

Suspension system: Existing, Including the lower arm and the struts

Safety System: Airbags and parking sensors

Power steering system: Hydraulic to electric (Existing Steering system, if Electronic)

Power Braking system: Hydraulic to electric (Vacuum pump to actuate the braking system)

Wipers & Fluid Pump: Existing liquid pump

Mirrors: Electronics / Manual Mirrors

Interiors: All Interiors including seats, Seat belts, A/C Vents, Cabin Light and other Interior Components

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Comparison of EV with ICE Vehicles

Parts and Subsystems to be modified for EV

Air conditioning System: Integration of variable speed DC Motor for existing hydraulic actuated AC compressor

Cooling System: Can be reused for Motor & Cooling with electric water pump Integration

Parts and Subsystems to be removed for EV

Engine and its associated connections like Sensors, starter motor etc.

Fuel tank and associated connections like HPP, LPP etc.

Clutch & Transmission to be removed since single speed transmission used.

ECU and other connections like sensors

Fuel pump and other Engine subsystems

Comparison of EV with ICE Vehicles

Parts and Subsystems to be added for EV

Electric Motor : High performance electric motor used for propulsion

Motor Controller: Motor controller for motor drive with closed loop Feedback system

Transmission system: High efficiency transmission system with reduction system for high acceleration

Battery pack with BMS: Reliable battery pack with BMS with CAN communication and support

IoT and Telematics: IoT for vehicle data collection combined with remote monitoring (telematics) and data infrastructure to monitor and manage the vehicle.

DC-DC Converters: Efficient DC-DC Converters for other peripheral components

VCU/MCU: Vehicle control unit or master Control unit for vehicle management and safety

Isolation circuits: Isolation circuits for vehicle and user safety

Charging System: Charging infrastructure, like charging port for onboard charging and external Charging

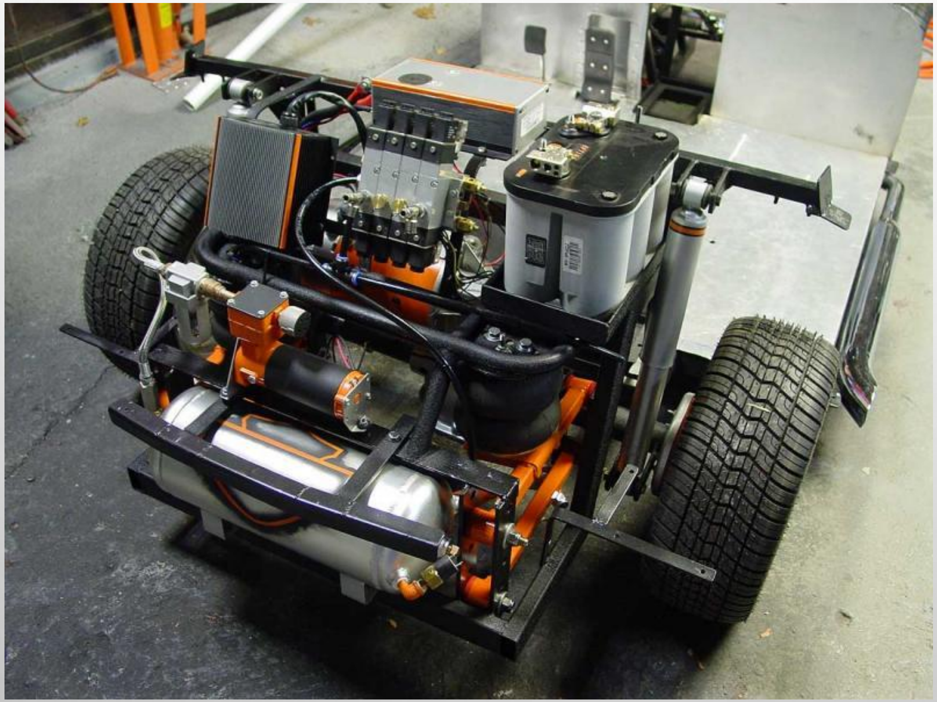
Drive software and Augmented safety system

Comparison of EV with ICE Vehicles

An Electric Vehicle would need to have

Motor and Controller: to drive the vehicle as per requirement, and also to meet the required torque

Battery with Sufficient energy to drive the vehicle for specific range, also should able to give enough power even when the battery gets old and less capacity



Motor and Controller Assembly

https://www.openpr.com/news/1873608/ev-electric-vehicle-motor-controller-market-to-record-an

Comparison of EV with ICE Vehicles

Power, Torque and Speed for EV

Max Torque Requirement: Acceleration (Pick up Time) and Slope driving, both requires high torque

Max Speed Requirement: Max speed of the vehicle determines motor revolution per minute (RPM). Right gear ratio to be chosen to optimize torque and speed (Single gear train used in EV)

Max Power Requirement: Max power required for Higher speeds, Till 60Kmph not significant. 100Kmph or 130Kmph (or even 150Kmph speeds on Highway) would need large power: Power is proportional a Cube of velocity

Gears Multiplies torque

An ICE vehicles engines are producing less torque than the vehicle torque.
Gear are used to multiply the torque by N, Vehicle Torque = N x Engine Torque, with the trade off of speed Vehicle Speed = Engine Speed / N (N = Gear Multiplication Factor)

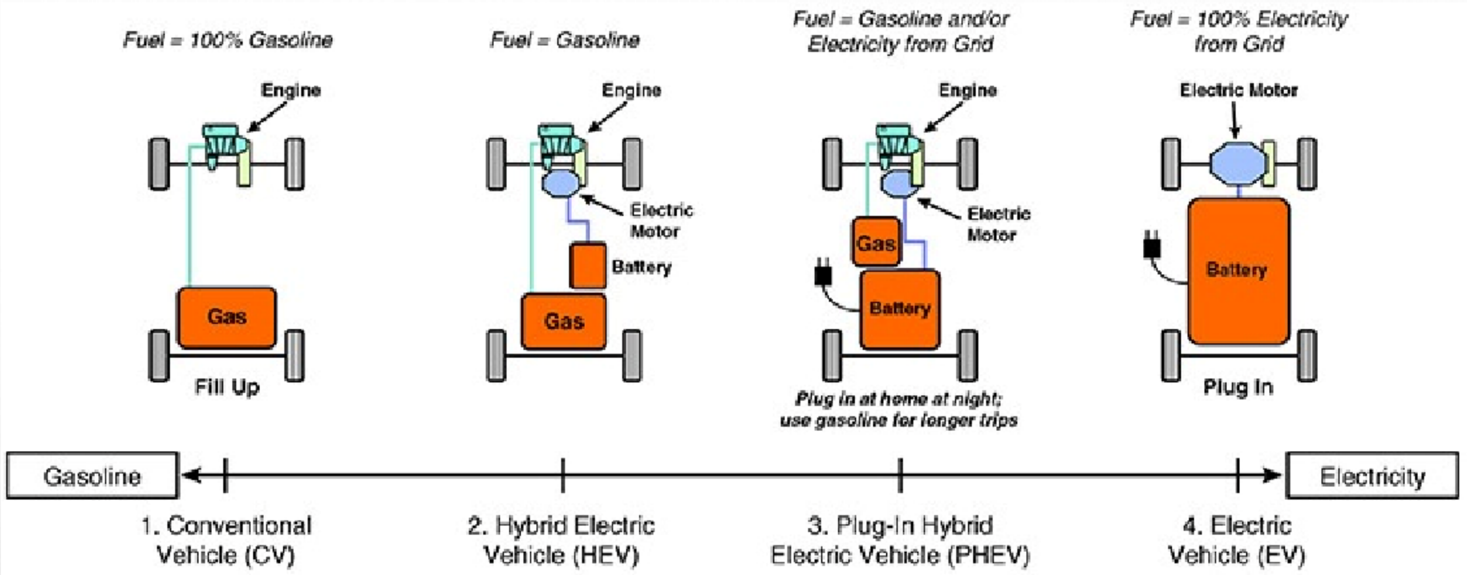
Similarly in EV
Vehicle connected to the motor using gear ratio of N:1
Vehicle torque = Motor Torque x N
Vehicle Speed = Motor Speed / N

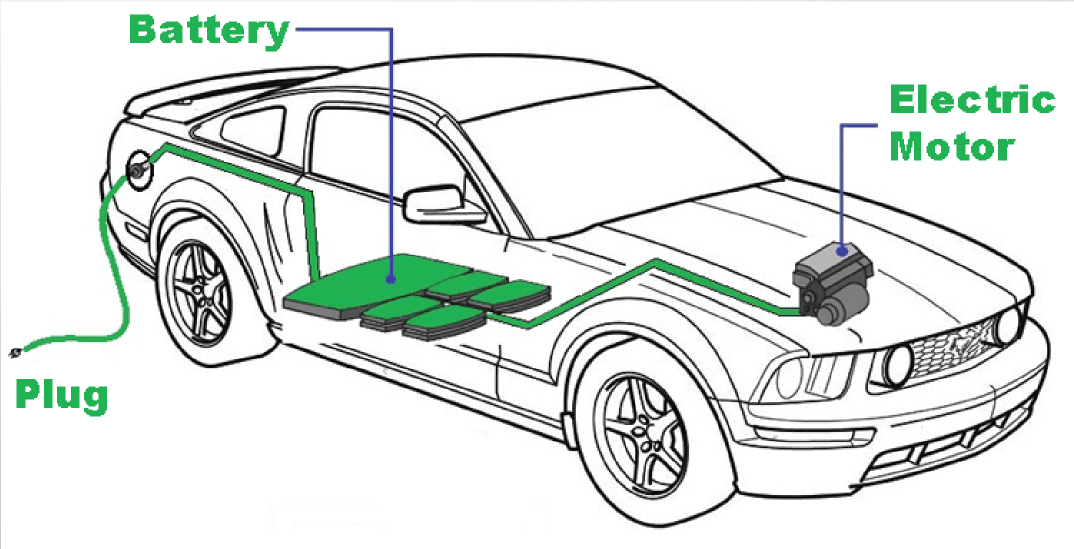
So Motor Torque can be multiplied with the trade of vehicle speed
But EV Motors generally used a single Fixed gear and same would be preferred, as long as one can meet all vehicle requirements.
Power will not change with gear ratio, Thus Motor power and Vehicle power is same

Chapter – 3
Design of Battery Pack

Design Considerations of Battery Pack

- Electrical design
- Mechanical Design
- Thermal Design
- Life
- Durability
- Performance
- Safety





Design Considerations of Battery Pack

Battery Pack

Electrical Design

Deals with Contractors, Connectors, Busbar, Series and Parallel Connections, Junctions Placement etc.

Thermal Management

Deals with Heat generated due to unexpected driving patterns, life of the battery to the entire Intended Life

Mechanical Design

Deals with Vibrations, Noise, external environmental Conditions, restrictions of the cell movement and strength of all components during its life

Battery Management System

Controlling the battery and communicating the status of battery and its properties with other subsystems as well as the occupants

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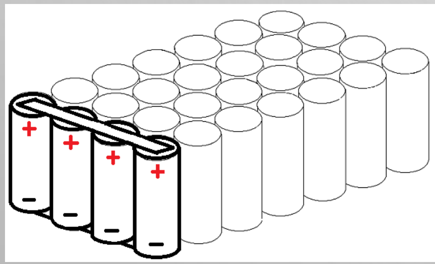
Design Considerations of Battery Pack

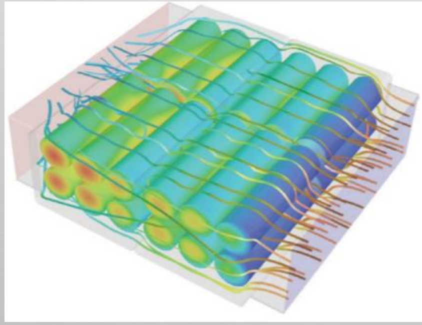
Electrical Design

- ❑ Determine the capacity, Voltage and current
- ❑ High Voltage Isolation
- ❑ Short circuit Scenarios
- ❑ Efficient Power Deliver



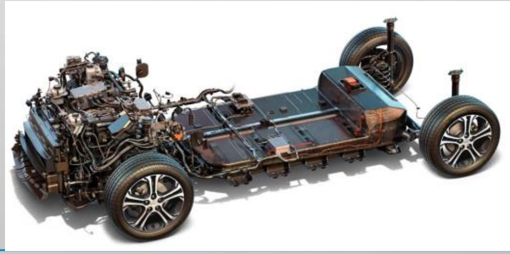
Thermal Design

- ❑ Battery pack Cooling system
- ❑ Improve Pack Efficiency
- ❑ Mitigate thermal accidents
- ❑ Increase cell / pack Life



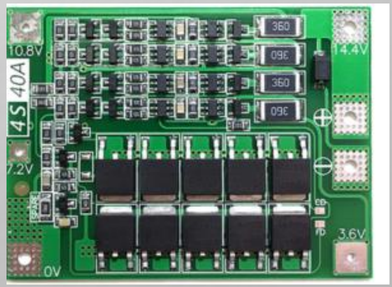
Mechanical Design

- ❑ Safe structure for extreme conditions
- ❑ Cost, Productivity and reliability
- ❑ Ease of assemble and service
- ❑ Aesthetics, compactness and lightweight



BMS Design

- ❑ Maintain Cell / Pack Operation Limitations
- ❑ Prevent concerning Events
- ❑ Control and diagnose thermal systems and events
- ❑ Communications & Diagnostics



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Battery Pack – Configuration Overview

Cell Configuration
- Series
- Parallel
- mPnS Theory

Structure
- Case, Cover, End-Plates, Tie Rods, Cell Holder, base Plate…
- Busbar, Fuses, Wiring and plugs …
- Cooling jackets, Safety valves, Thermistors…

Safety
- Vibration, Shock, Abuse, crash…
- Short circuit, Overcharge/Over discharge…
- Thermal Runway/Thermal Management

Control
- Vibration Control, Aggregates robustness
- Cell monitoring and BMS
- Temperature control and communication

Applications
- Interface
- Telemetry

Mechanical Design Factors

Electrical Design Factors

Thermal Design Factors

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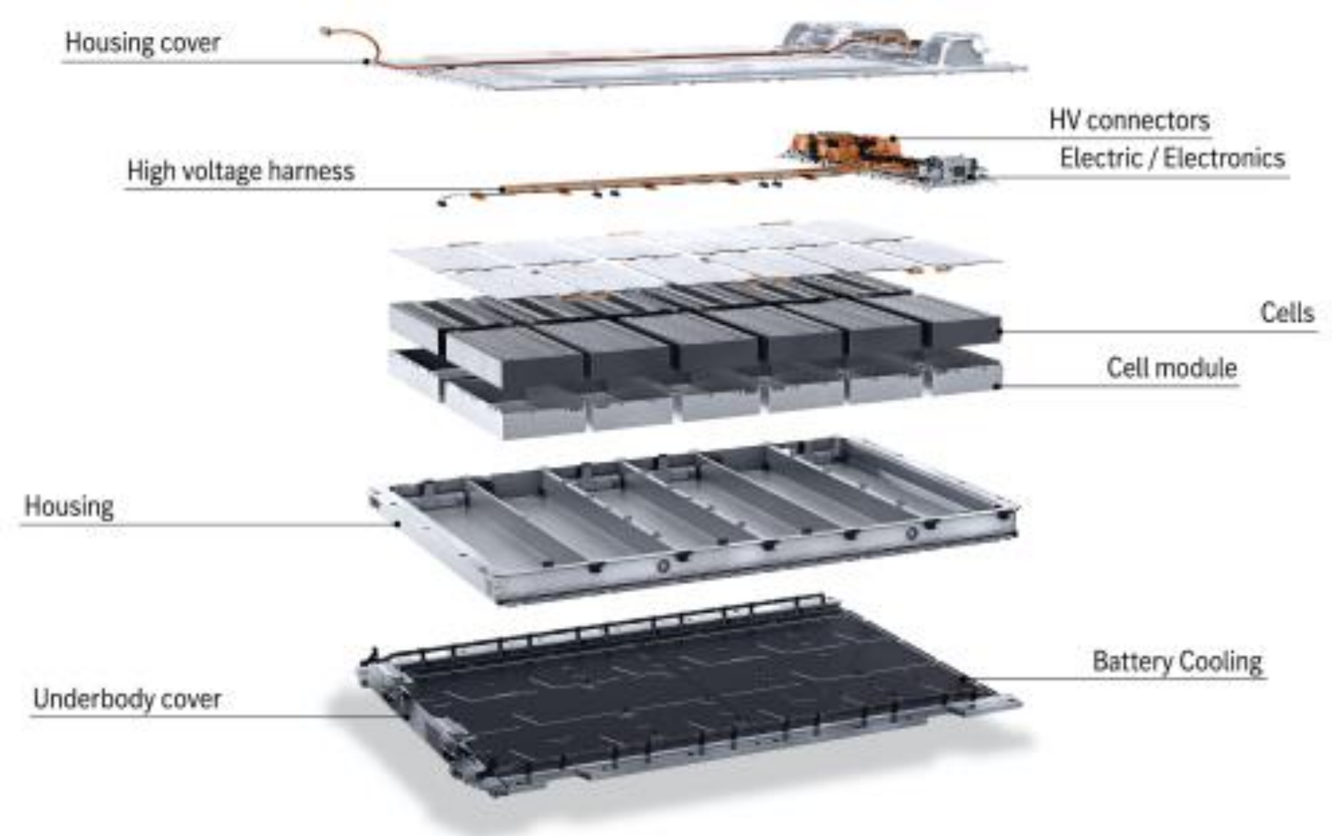
Major Components in Battery pack



Courtesy: Mercedes EQ

- Upper Housing
- Bus bar / Copper Bar
- Connectors / Wiring Harness
- Cells
- Cell adaptor / Module
- Cell Housing
- Insulation Pads
- Cooling Jacket
- Thermistor/voltage sensor
- Underbody Housing
- Battery Management System (BMS)

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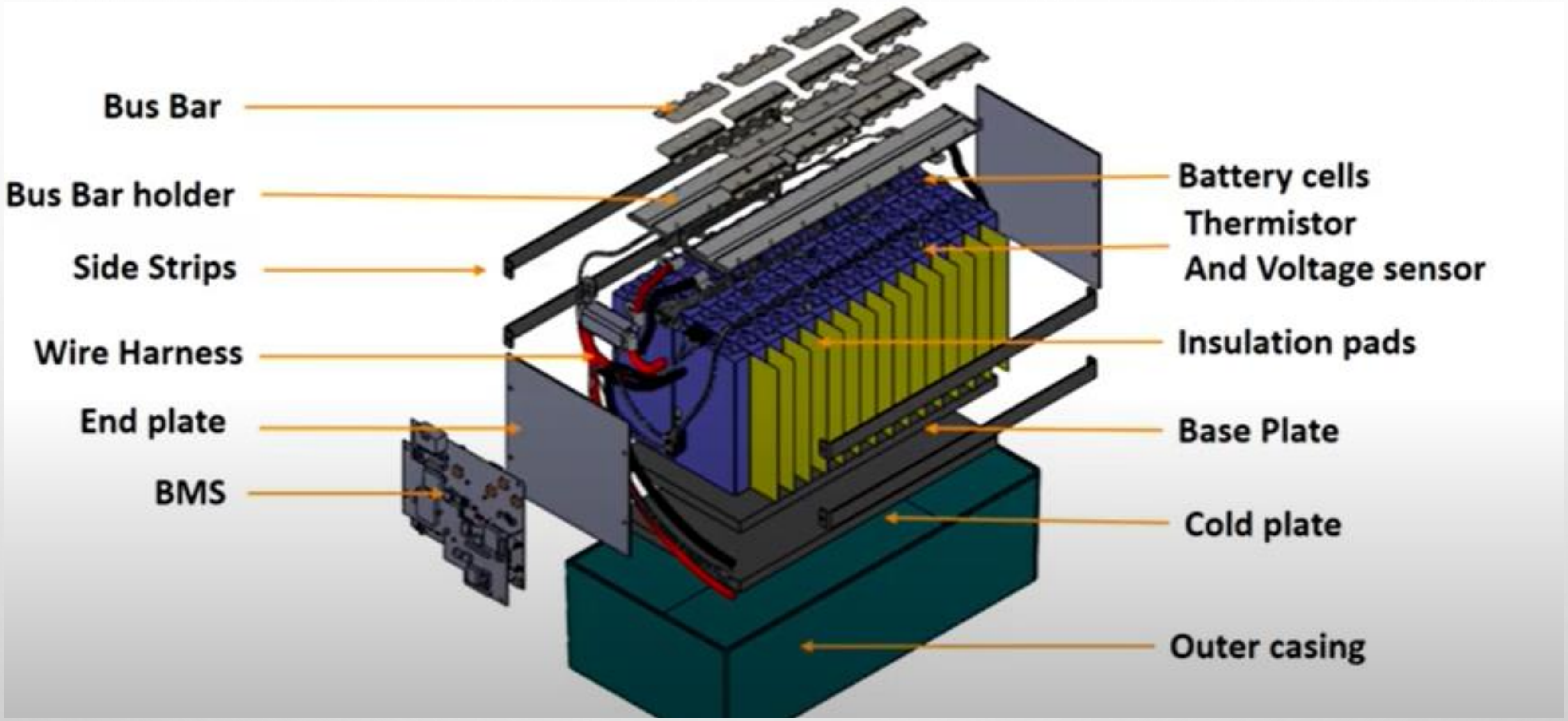
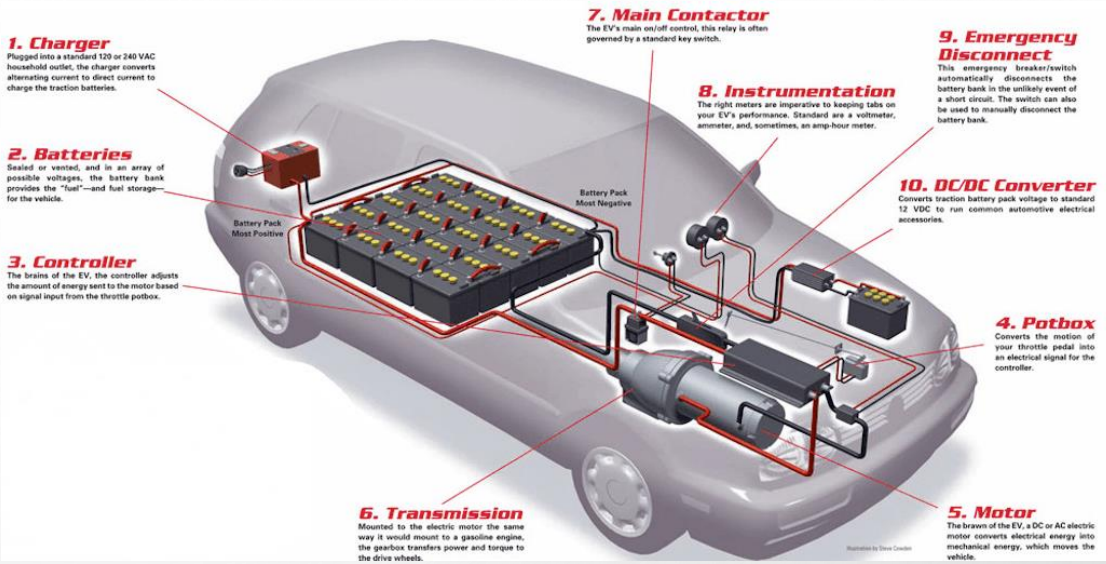
Major Components in Battery pack - Illustration



Courtesy: NPTEL EV

Important Considerations of Battery Pack

- ❑ Material Selection
- ❑ Base plate design for each cell accommodation
- ❑ Cell movement constraint and control
- ❑ Uniform pressure over cell surface
- ❑ Outer case design for overall protection
- ❑ Bus Bar Designing
- ❑ Vehicle level Packaging considering constraints



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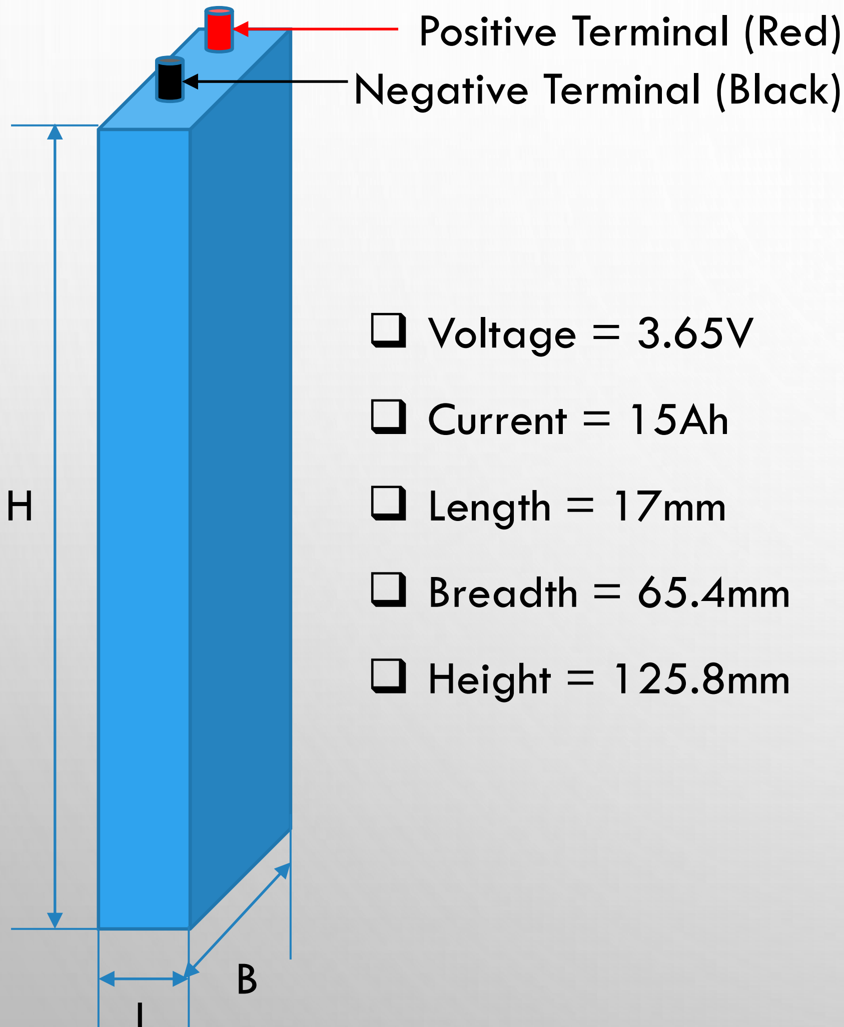
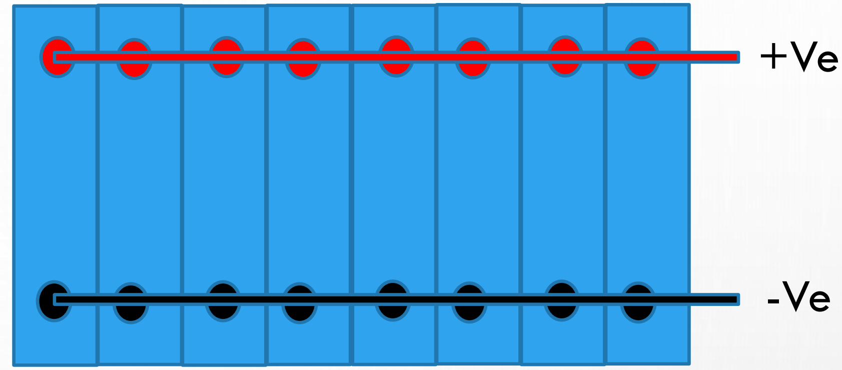
Cell packaging



- Voltage = 3.65V
- Current = 15Ah
- Length = 17mm
- Breadth = 65.4mm
- Height = 125.8mm



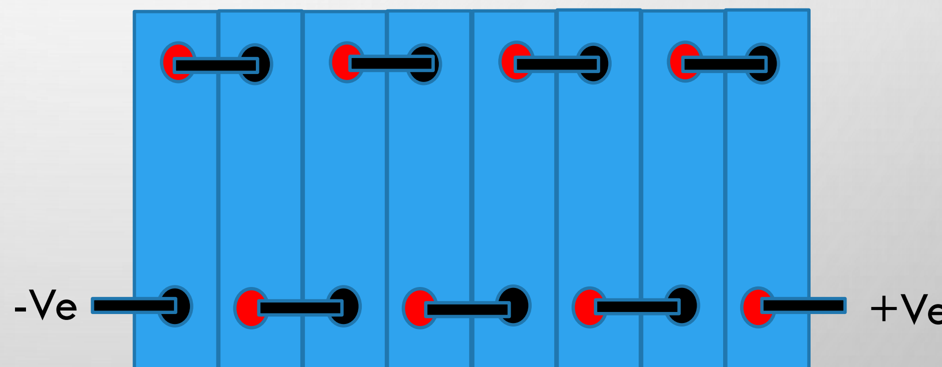
Connection:8P1S

8 Cells in Parallel

$$8Nos\ x\ 15Ah = 120Ah$$

(Capacity of the Battery Pack)

$$Power = 120Ah\ x\ 3.65V = 0.438Kwh$$



Connection:1P8S

8 Cells in Series

$$8Nos\ x\ 3.65V = 29.2V$$

(Voltage of the Battery Pack)

$$Power = 15Ah\ x\ 29.2V = 0.438Kwh$$

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Example Calculation

Consider a vehicle is designed to have a range of 100Kms which consumes 20Wh/km on average from the battery pack to run. Considering DoD (Depth of Discharge) is 80%, Nominal operating Voltage of the Battery pack will be 60V, and power consumed by Auxiliary systems are 5wh/km

Total Power Requirement

$Power\ required\ per\ Km = 20Wh$

$Power\ Required\ for\ 100Kms = 100\ x\ (20 + 5) = 2.5Kwh$

$Considering\ DoD\ 80\% = \frac{2.5}{0.8} = 3.125\ say\ 3.2\ Kwh$

Voltage requirements from Motor Drivetrain = 60V

$Current\ Requirement\ of\ the\ battary\ pack = \frac{32000}{60} = 53.4Ah$

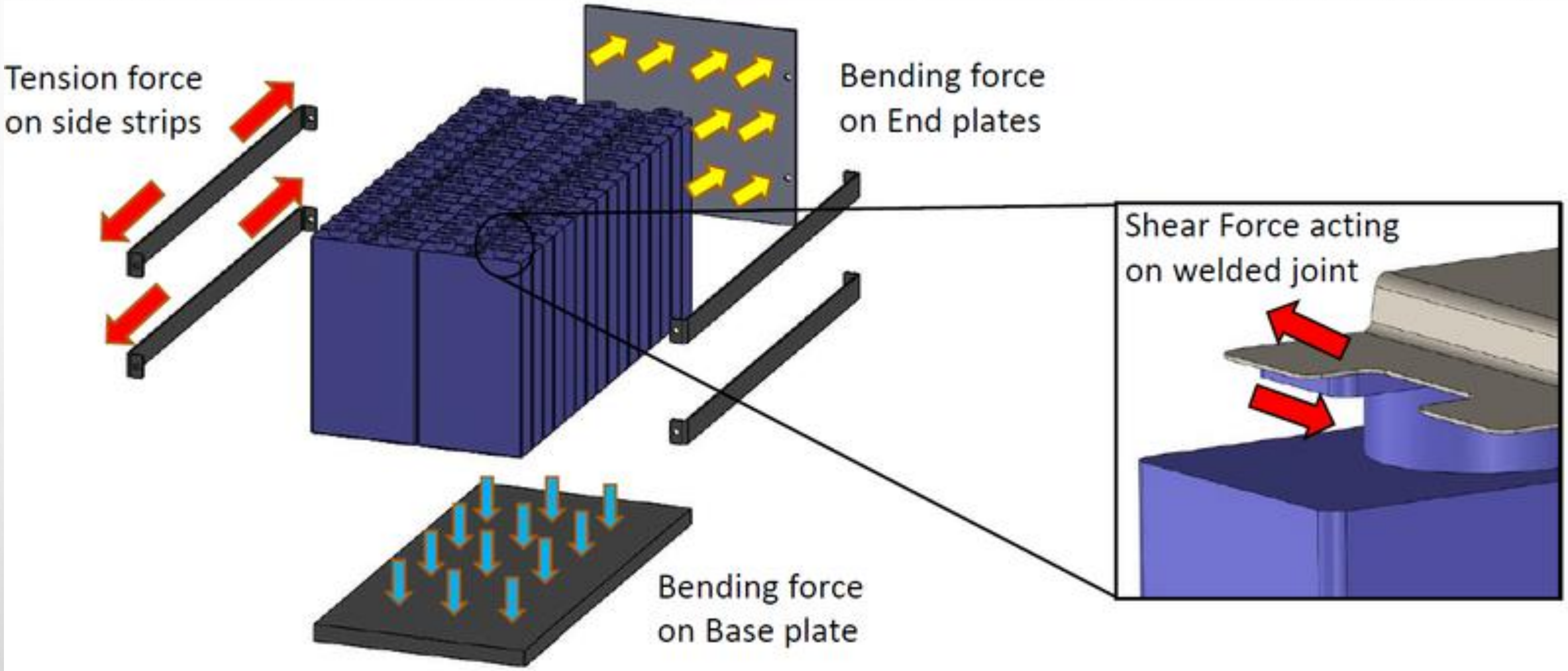
$15Ah\ Battery\ used, so\ no\ of\ parallel\ connections\ required = \frac{53.4}{15} = 3.56\ say\ 4Parallel\ Connections$

$3.65V\ Battery\ used, So\ no\ of\ series\ connections\ required = \frac{60}{3.65} = 16.4\ say\ 16\ Series\ Connections$

Therefore batter pack will be 4P16S
No of cells = 64
No of Rows = 4
Each row =1P8S
No of Cells in one Row = 16

Breadth of the Battery pack = 4 x 65.4 = 261.6mm
Length of the Battery pack = 16 x 17 = 272mm
Hight of the Battery Pack = 125.8mm
Weight of the Battery pack = 64 x 0.32kg = 20.48Kg
$\left(\sim Density\frac{2.2Kg}{M^3}\right)$

Dominant Forces acting on the Battery pack



These main forces on the battery pack to be considered to design the battery pack components, these are the primary forces are taken into the account for initial design considerations.

Length and height of the components can be derived based on the Battery dimensions + Insulation geometry. But thickness of each components are important to decide the strength and cost of the materials.

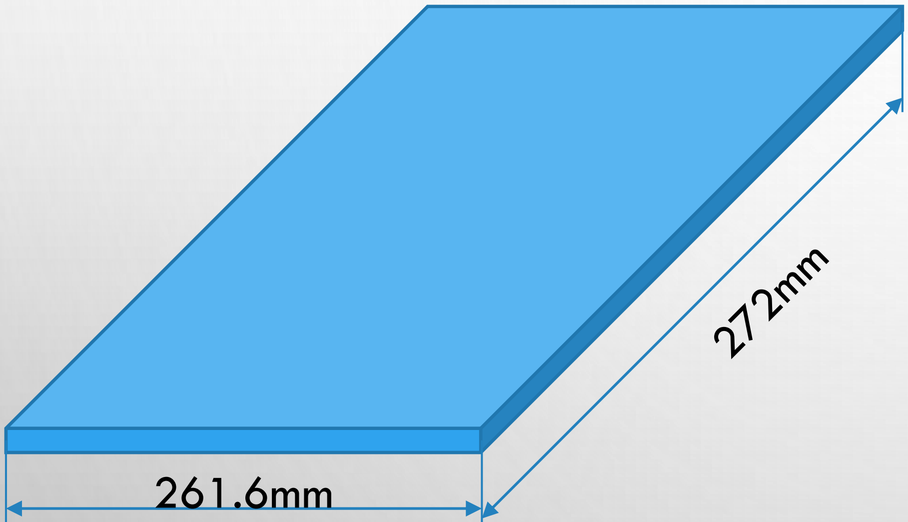
Example Calculation – Base Plate

Assumptions,

Rectangular Plate and Constant thickness

Simply supported on all edges

Uniformly distributed load acting on the plate by battery back



$$\frac{L}{b}Ratio = \frac{272}{261.6} = 1.04$$

$$Length = 272mm + 2mm$$

$$Breadth = 261.6mm + 2mm$$

(tol – 1mm on each Side)

$$Area = 274\ x\ 263.6 = 72226.4mm^2$$

$$Load\ Q = \frac{Total\ force}{Total\ Area}$$

$$Load\ Q = \frac{20.48Kg\ x\ 9.81}{72226.4mm^2} = 2.8\ x\ 10^{-3}\left(\frac{N}{mm^2}\right)$$

$$Load\ Q = 2.8\ x\ 10^3 Pa$$

In order to calculate the thickness, we need to select the material of the base plate

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Example Calculation – Base Plate

Selection of material based on the requirements is playing vital role in designing the Base plate.
We have referred
"M F ASHBY-Methodology, Material selection in Mechanical Design, Butterworth-Heinemann 1999"

Material Index Calculation

For Flat plate thickness – $Maximise \frac{E^{\frac{1}{3}}}{Cm\ x\ \rho}$ $or\ Minimise \frac{Cm\ x\ \rho}{E^{\frac{1}{3}}}$

Parameters are
t = Thickness
E = Modulus of elasticity
Cm = Cost of the Material
ρ = Density

Material	ABS	Aluminum
Density	1.069 g/cc	2.7 g/cc
Youngs Modulus	1.19 Gpa	68.9 Gpa
Cost of the Material	Rs.70/Kg	Rs.280/Kg
Material Index	14.14 x 10^-3	5.17 x 10^-3

Properties of Selected Material	acrylonitrile butadiene styrene
Youngs Modulus	1190 Mpa
Maximum Yield Strength	29.6Mpa – 48Mpa
Poissons Ratio	0.3

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Example Calculation – Base Plate

$$According\ to\ Kirchhoff's\ equation\ for\ bending\ in\ Plates$$

$$Ymax = \frac{-\alpha q b^4}{E t^3}$$

And

$$\sigma Max = \frac{\beta q B^2}{t^2}$$

Where,

Ymax = Maximum Allowable Deflection (Consider 1mm for our calculation)

σmax = Maximum Bending Stress

E = Young's Modulus

B = Breadth

t = Thickness

$$Ymax = \frac{-0.0444\ x\ 0.0028\ x\ 261.6^4}{1190\ \ x\ t^3}$$

$$t = 7.8mm\ say\ 8mm$$

With this Thickness calculating Maximum Stress

$$\sigma Max = \frac{0.2874\ x\ 0.0028\ x\ 262.6^2}{8^2}$$

$$\sigma Max = 8.6Mpa$$

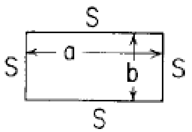
$$\sigma Max < 0.5\text{times of Yield Strength}$$

Potential is there to reduce the thickness by increase the deflection or introducing ribs on the base plate…

To find the Constants of α and β for rectangular plate the with the given ratio of L/b, we are referring

" Roark's Formula for stress and Strain, Warren C.Young, Richard G.Budynas"

Case no., shape, and supports	Case no., loading	Formulas and tabulated specific values
1. Rectangular plate; all edges simply supported	1a. Uniform over entire plate	(At center) $\sigma_{max} = \sigma_b = \frac{\beta q b^2}{t^2}$ and $y_{max} = \frac{-\alpha q b^4}{E t^3}$ (At center of long sides) $R_{max} = \gamma q b$



a/b	1.0	1.2	1.4	1.6	1.8	2.0	3.0	4.0	5.0	∞
β	0.2874	0.3762	0.4530	0.5172	0.5688	0.6102	0.7134	0.7410	0.7476	0.7500
α	0.0444	0.0616	0.0770	0.0906	0.1017	0.1110	0.1335	0.1400	0.1417	0.1421
γ	0.420	0.455	0.478	0.491	0.499	0.503	0.505	0.502	0.501	0.500

Example Calculation – Vibration Analysis

Consider the weight of the battery pack = 21Kg
Weight of Base plate + End plates + Upper Housing + other components = 19Kg
Total weight of the Battery pack assembly = 21+19 = 40Kg
Consider the AVM(Anti Vibration Mountings/Rubber pads) stiffness as per below figure.
We consider the springs on parallel connections since the deflection on springs by the loads are separate.

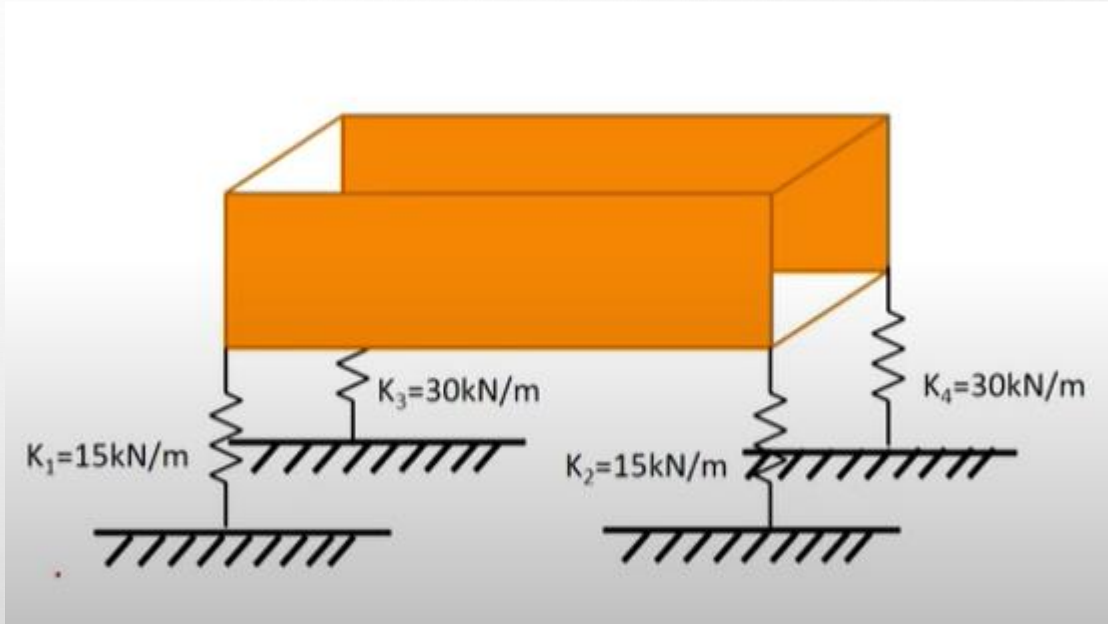
$$\omega n = Angular\ frequency \left(\frac{Rad}{Sec}\right)$$

$$K = Spring\ Stiffnes \left(\frac{KN}{m}\right)$$

$$F = Natural\ Frequency\ in\ Hz$$
$$M = Mass\ in\ Kg$$

$$K = K1 + K2 + K3 + K4 = 90\,\frac{KN}{m}$$

(Since springs are parallelly loaded)



$$\omega n = \sqrt{\frac{K}{M}} = \sqrt{\frac{90}{40}} = 1.5\,\frac{\text{rad}}{\text{sec}}$$

$$F = \frac{\omega n}{2x\pi} = \frac{1.5}{2\pi}\ x\ 100 = 23.8Hz$$

Battery Pack assembly – Physical Testing

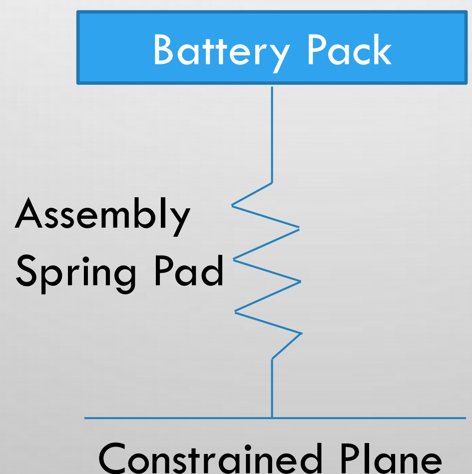
To evaluate and validate the Battery pack assembly, Three different test standards are generally followed

- ❑ Harmonic Vibration Test – AIS 048:2009
- ❑ Shock Abuse Test – AIS 048:2009
- ❑ Ransom Vibration Test – SAE J 2380

Consider the low voltage battery pack is designed for electric bike application. Weight of the battery pack is 10Kg and assembly spring stiffness is 49KN/M. Battery pack design to be considered single spring mass with sinusoidal(harmonic) Acceleration 3G along the vertical axis of the system. Need to find the amplitude of acceleration for 33seconds.

Weight of the Battery Pack = 10Kg
Spring Stiffness = 49KN/M
Acceleration = 3G
Time = 33seconds

$$\omega n = \sqrt{\frac{49}{10}} = 2.213\,\frac{rad}{sec}$$



$$We\ know\ that, F = F0\ x\ sin\omega n\ x\ t$$

$$F0 = 3x9.81x1000 = 29400\,\frac{mm}{\sec^2}$$

$$F = 29400\ x\ sin2.213\ x\ 33$$

$$F = 22.4Hz$$

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Battery Pack assembly – Thermal Calculation

Heat load Determination

Consider battery pack of 2P16S, whose specifications are Nominal Capacity 15Ah and Nominal Voltage 3.65V, Internal Impedance (resistance) 10mΩ. If the module is discharge from 100% to 20% SoC @1C. Calculate the heat generated & energy expelled by the module & compare the energy lost as heat to total module energy in the duration of discharge.

$\underline{Heat\ Generated\ in\ Each\ Cell,}$
$Cell\ current\ = 15Ah$
$Cell\ resistance = 10m\Omega$
$Heat\ generation\ Qcell = I^2R = 15^2 x\ 10 = 2.25W$

→

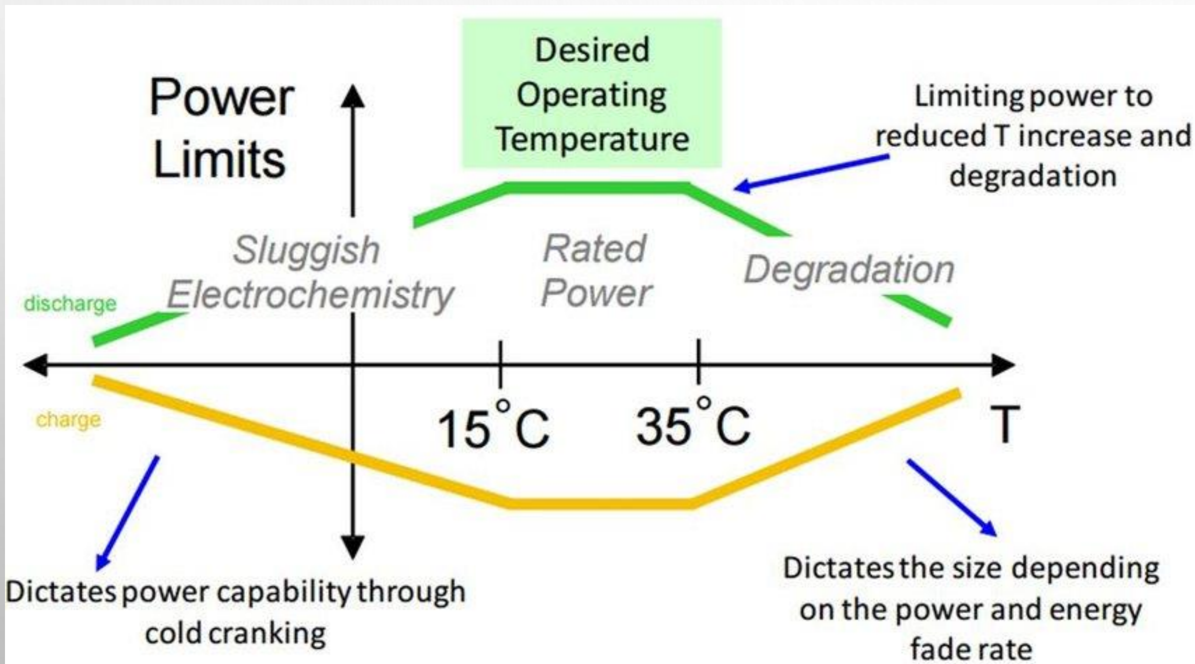
$\underline{Heat\ Generated\ Battery\ Pack}$
$Total\ No\ of\ Cells = 32$
$Heat\ generation\ QPack = Qcell\ x\ N\ = 32\ x\ 2.25 = 72W$

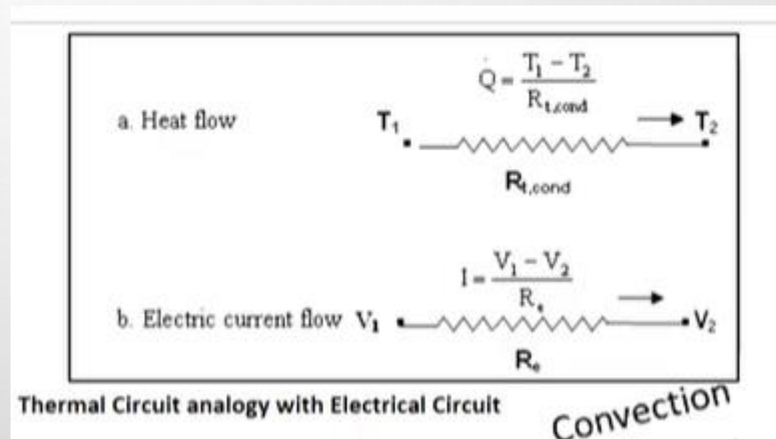
$\underline{Energy\ lost\ by\ pack\ as\ heat}$
$Time\ for\ 100\%\ to\ 20\%\ SoC\ @\ 1C = 3600\ x\ 0.8 = 2880s$
$Heat\ Lost\ Ecell = Qcell\ x\ t = 2.25\ x\ 2880 = 6.48KJ$
$Heat\ Lost\ by\ Pack = Ecell\ x\ N = 6.48\ x\ 32 = 207.36KJ$

$\underline{Comparison\ with\ Total\ Pack\ Energy}$
$Pack\ Energy\ from\ 100\%\ to\ 20\%\ SoC = N\ x\ V\ x\ I\ x\ t = 32\ x\ 3.65\ x\ 15\ x\ 2880 = 5045.75KJ$
$\%\ of\ Energy\ lost\ as\ heat = 4.1\%$

Battery Pack assembly – Thermal Consideration

- ❑ Ensure battery operation under optimal temperature range and within reasonable temperature spread.
- ❑ Monitor state of battery and detect the critical point of battery failures and deliver alarm messages.
- ❑ Suppress thermal runway propagation





Battery Pack assembly – Effects of temperature

Low temperature effects

If the battery is too cold…

- <5°C Cannot be fast charged
- <0°C Battery lose charge, Loss in Power, Acceleration and driving Range in exponential rate

High temperature effects

If the battery is too Hot… (Universal Phenomenon with the average battery)

- >30°C Battery performance degrades
- >40°C can lead to serious and irreversible damage

Optimal temperature for battery in EV +15°C to +30°C

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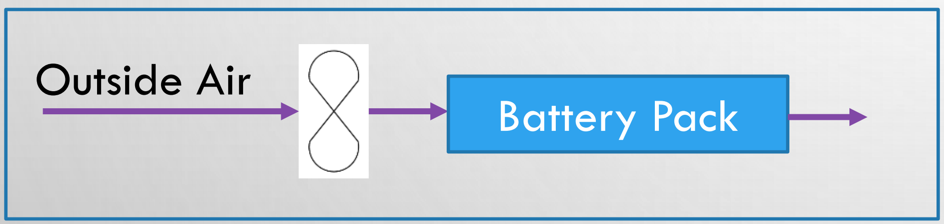
Battery Pack assembly – Sources of Heat

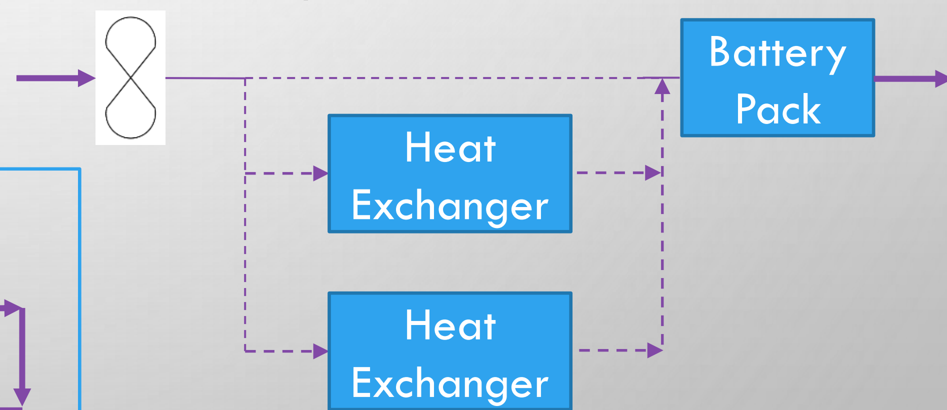
Heat Sources of the battery

- ❑ $Q = I^2R$ Higher current flow gives higher heat flow
- ❑ Faster Battery Charging rates are demanded: Recharge power >200kW & time <30Minutes
- ❑ If Faster Battery Charging employed, highly efficient Thermal Management systems to be employed
- ❑ Local Electrode overpotentials; the entropy of the cell reaction; heat of mixing; side reactions…

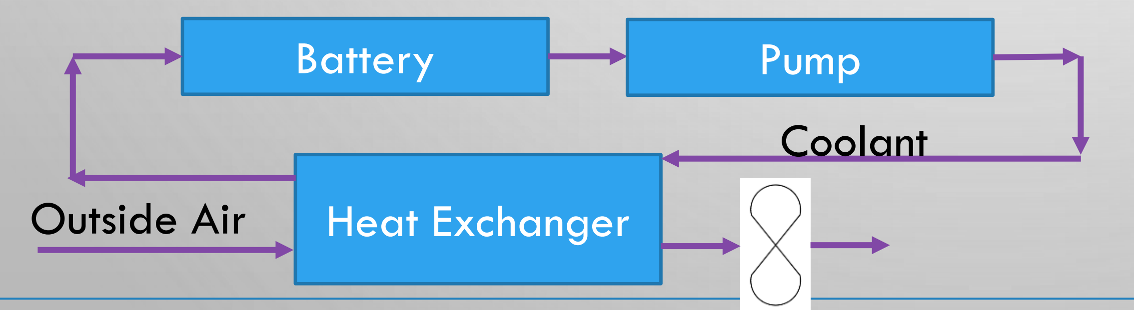
By Medium of air to Regulate battery temperature



By Air & HVAC



By Air & Coolant



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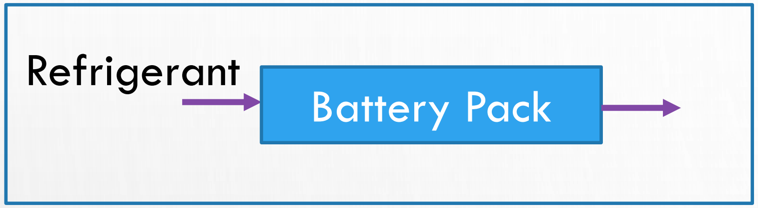
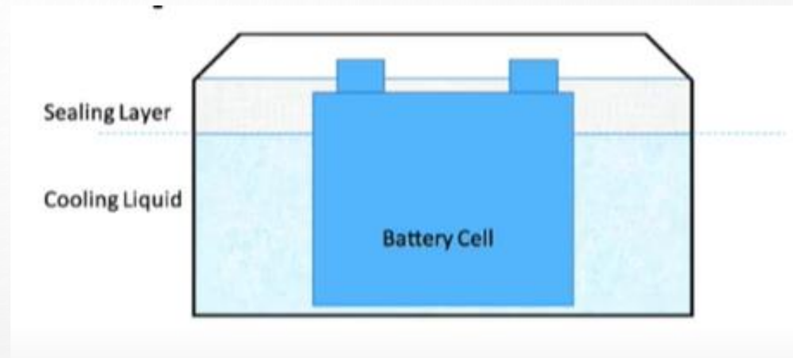
By Medium of Refrigerant to Regulate battery temperature

By Refrigerant only

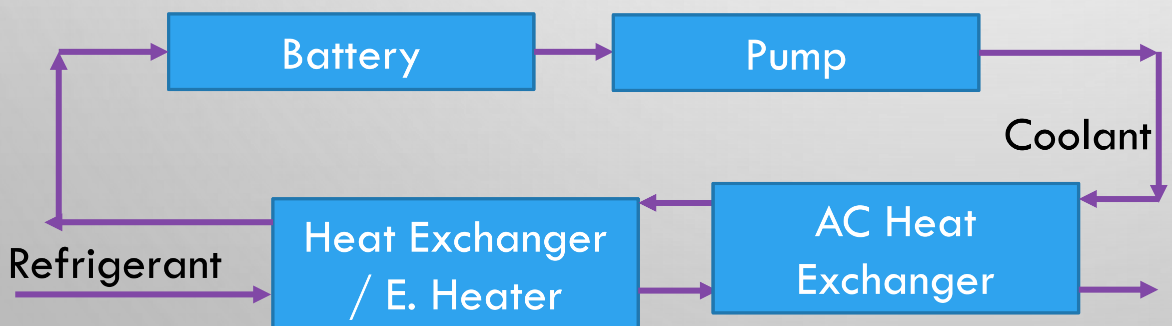


Liquid Immersion



By Coolant & Refrigerant

By Air & Coolant



The choice of Heat transfer medium Includes air, Liquid, Phase Change materials or any combination

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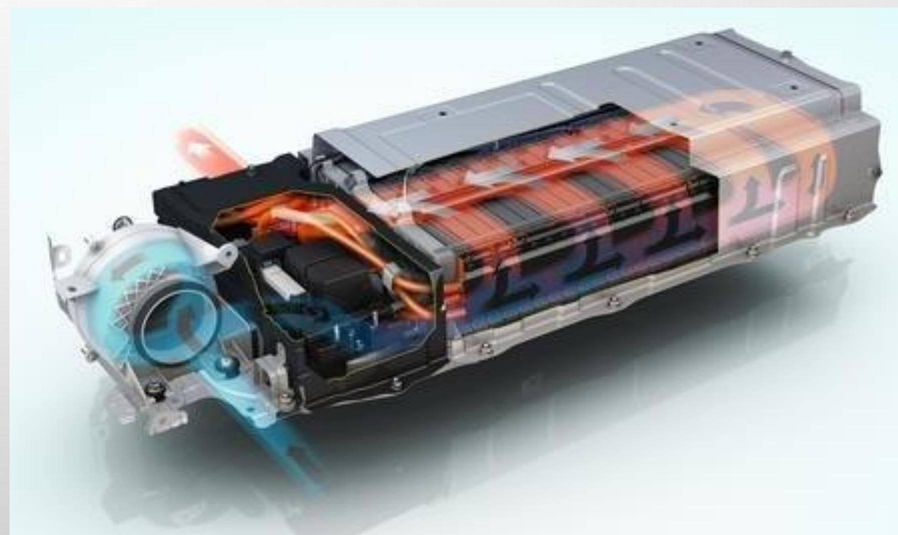
Air cooling Battery Pack References

- Nissan Leaf
- Nissan e-NV 200
- Honda Insight
- Honda FitEV
- Toyota Prius Prime
- Renault Zoe
- Hyundai IONIQ

Nissan Leaf – Battery Pack with Air cooling system



Toyota Prius – Battery Pack with Forced Air cooling system

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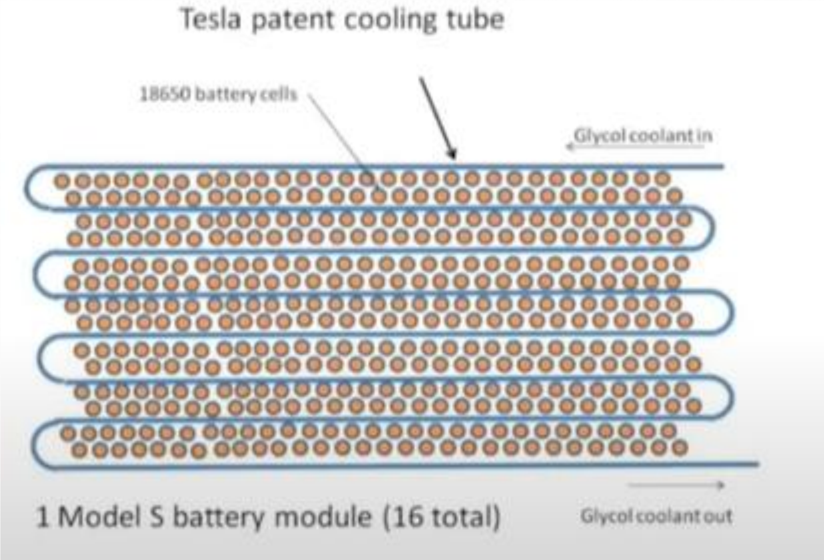
Liquid cooling Battery Pack References

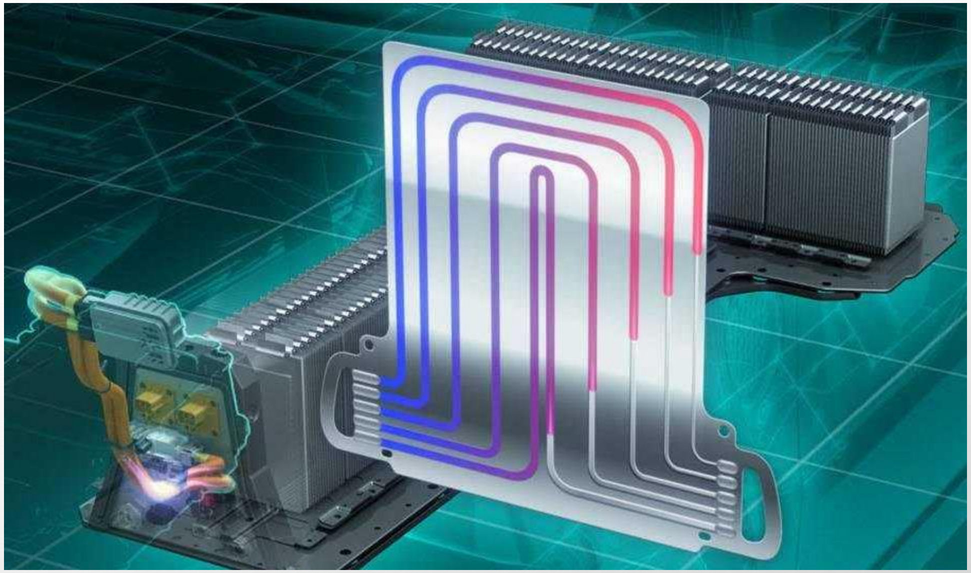
- GM Chevrolet Bolt, Chevrolet Volt
- Tesla Model X, Model S, Model 3
- Ford Focus
- Audi R8 e-Tron
- Toyota –iQ
- Volvo XC90 T8



Tesla Patent : 20110212356
Tesla uses metallic Cooling tubes that snakes through the EV Battery Pack

Liquid cooling Battery Pack References

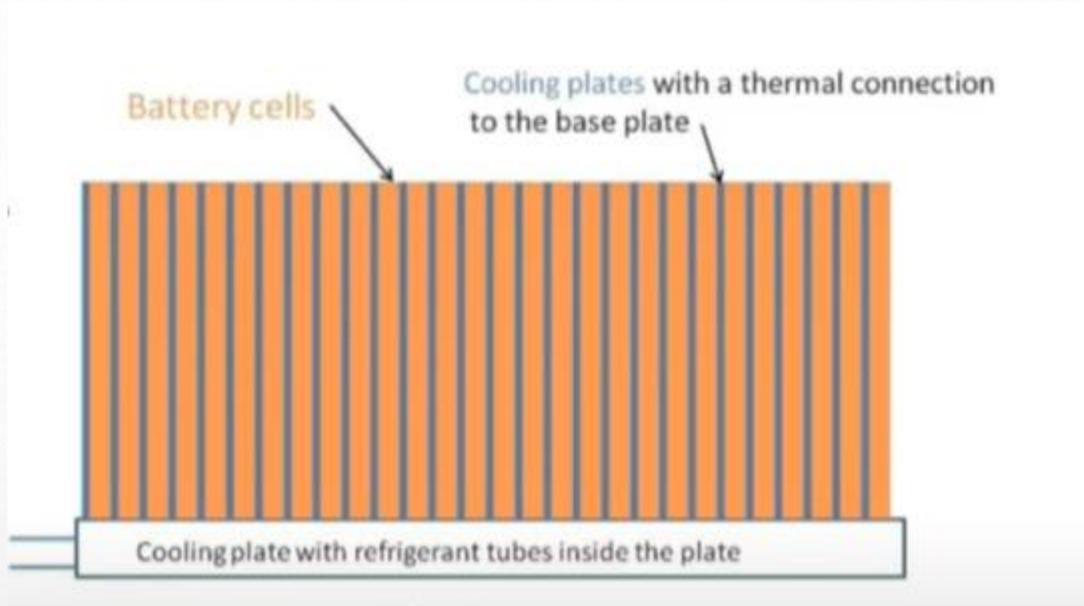
Chevy Bolt Battery Pack is Liquid Cooled via base plate below the cells



Chevy Volt Battery Pack uses cold plates interwoven with battery cells as a Liquid cooling system

Refrigerant direct cooling Battery Pack References

- BMW i3
- Mercedes – Benz S400 Blue
- Proton Saga FXL
- Audi A6 PHEV
- BMW A6 PHEV
- BMW X5 PHEV
- BMW i8



Direct Expansion Cooling
No glycol Liquid – Only Refrigerant

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Battery Pack Cooling system Comparison

Cooling Methods Comparison

	Air Cooling	Liquid Cooling	Refrigerant Cooling
Cooling/heating performance	☹ low, not for heavy duty or extreme performance	high	☺ Very high
System complexity	☺ simple	☹ Complicated	Compact structure
Cost	☺ Low cost	☹ High cost	☺ Potential lower cost
Weight	☺ Light weighted	☹ Relative heavy	
Safety	☺ Better in sealing and waterproof	☹ Leakage concern	☺ Safety advantage
Temperature spread	☹ Difficult to maintain even temp.	☺ Easy to maintain.	☺ Better temperature uniform distribution
Control	☹ Limited control	☺ Precise to control	

Battery Pack – Electrical Connections Design

Important Considerations of Electrical Design

- ❑ Least resistance to current flow
- ❑ Control of temperature rise due to current flow
- ❑ Short circuit current stresses and protection
- ❑ EMI noise Suppression
- ❑ Joining Methods and performance

Important Considerations of Busbar Design

An Improperly designed busbar can leads to;

- ❑ Inefficient system operation
- ❑ Result in poor efficiency
- ❑ Overheat self & nearby Components
- ❑ Safety & Reliability Issues

Battery Pack – Electrical Connections Design

For any conductors, Ohm's Law states that

$$Conductor\ Potential\ Drop\ (V) = Current\ Flow\ (I)\ x\ Resistance\ (R)$$

Resistance of the conductor is based on the Material Property and Conductor Geometry

$$Conductor\ Resistance\ (R) = Resistivity\ (\rho) x \frac{Conductor\ Length}{Conductor\ Area}$$

Resistivity of the conductor material is function of heat

$$\rho_t = \ \rho_{t0}\, x\ [1 + (\alpha)(T - T_0)]$$

Material	ρ (Ω•m) at 20 °C Resistivity	σ (S/m) at 20 °C Conductivity
Silver	1.59×10^{-8}	6.30×10^{7}
Copper	1.68×10^{-8}	5.96×10^{7}
Annealed copper	1.72×10^{-8}	5.80×10^{7}
Gold	2.44×10^{-8}	4.10×10^{7}
Aluminum	2.82×10^{-8}	3.5×10^{7}
Calcium	3.36×10^{-8}	2.98×10^{7}
Tungsten	5.60×10^{-8}	1.79×10^{7}
Zinc	5.90×10^{-8}	1.69×10^{7}
Nickel	6.99×10^{-8}	1.43×10^{7}
Lithium	9.28×10^{-8}	1.08×10^{7}

For calculating current carrying capacity of the busbar limited by its maximum acceptable temperature,

So the equation can be

Heat generated by Joule heating < Heat dissipated to the ambient

$$I^2R\ x\ S \leq hA\ (Tbusbar - TA_{mbient})$$

For all Materials resistivity: https://sciencenotes.org/table-of-electrical-resistivity-and-conductivity/

Example Calculation-1 – Busbar sizing

A busbar should be designed for a maximum resistance of $10^{-4}\Omega$. The length of the busbar is constrained to 6cm. Assuming the busbar can go up to 50°C, Find the cross section of the busbar. Material properties copper: $\alpha = 0.00393°C^{-1}, \rho_{20°C} = 1.72x10^{-8}\Omega.m$

$we\ know\ that,$

$Resistivity\ of\ the\ copper\ busbar\ \rho_t = \ \rho_{t0}\,x\,[1 + (\alpha)(T - T_0)]$

$\rho 50°C = \ \rho 20°C\ (1 + \alpha(T - Tamb) = (1.72x10^{-8})\big(1 + (0.00393)(50 - 20)\big) = 1.922\ x\ 10^{-8}\Omega.m$

Resistance of the busbar in the assembly R = $10^{-4}\Omega$

$$Conductor\ Resistance\ (R) = Resistivity\ (\rho)x\frac{Conductor\ Length}{Conductor\ Area}$$

$$10^{-4} = 1.922x10^{-8}\ x\ \left(\frac{l}{A}\right) \Rightarrow A = \frac{1.922x10^{-8}x0.06}{10^{-4}} = 1.1x10^{-5}m^2$$

Assume the busbar to be 8mm wide

$$t = \frac{1.1\ x\ 10^{-5}}{0.008} = 1.3x\ 10^{-3} = 1.3mm$$

Example Calculation-2 – Busbar sizing

Consider 2P16S battery pack, for 1C discharging current of 15Ah in each cell. Design a busbar considering the given dimensions. Assume busbar to be made of copper & Ambient temperature is 30°C. Surface temperature of busbar is 50°C. the convective heat transfer coefficient of busbar is 0.038W. Also evaluate the net voltage drop of the battery pack due to busbar connection

Heat generated by Joule heating < Heat dissipated to the ambient

$$I^2R\ x\ S \leq hA\ (Tbusbar - TAmbient)$$

$$Qjoule = Qconv\ \rightarrow I^2R = 0.038W\ or\ R = \frac{0.038}{900} = 4.23x\ 10^{-5}\Omega$$

Hence the busbar thickness

$$t = \frac{(1.855x10^{-8})x\ 0.059}{0.0065\ x\ 4.23x10^{-5}} = 3.98x10^{-3}m = 4mm$$

$$for\ Busbar\ welding\ 4mm\ is\ very\ high, Need\ to\ do\ the\ tradeoff\ between\ Width\ and\ thickness$$

$$Feasible\ thickness\ of\ the\ busbar\ for\ welding\ - 1mm$$

$$Resulting\ width = \frac{26mm^2}{1mm} = 26mm \rightarrow Busbar\ dimensions = 59mm\ x\ 26mm\ x\ 1mm$$

$$\underline{Resitance\ of\ copper\ busbar}$$

$$R = \frac{\rho 30°C\ * l}{A} = \frac{(1.855x10^{-8}) * 0.059}{0.0065\ x\ 0.004} = 4.2x10^{-5}\Omega$$

$$\underline{Voltage\ drop\ across\ busbar}$$

$$V = IR = 30\ x\ 4.2x10^{-5} = 0.0012V$$

No of busbar for 2P battery pack = 15Nos

$$V = 0.0012\ x\ 15 = 0.018V$$

Chapter – 4
Introduction to Electric Motor

Design of Electric Motor

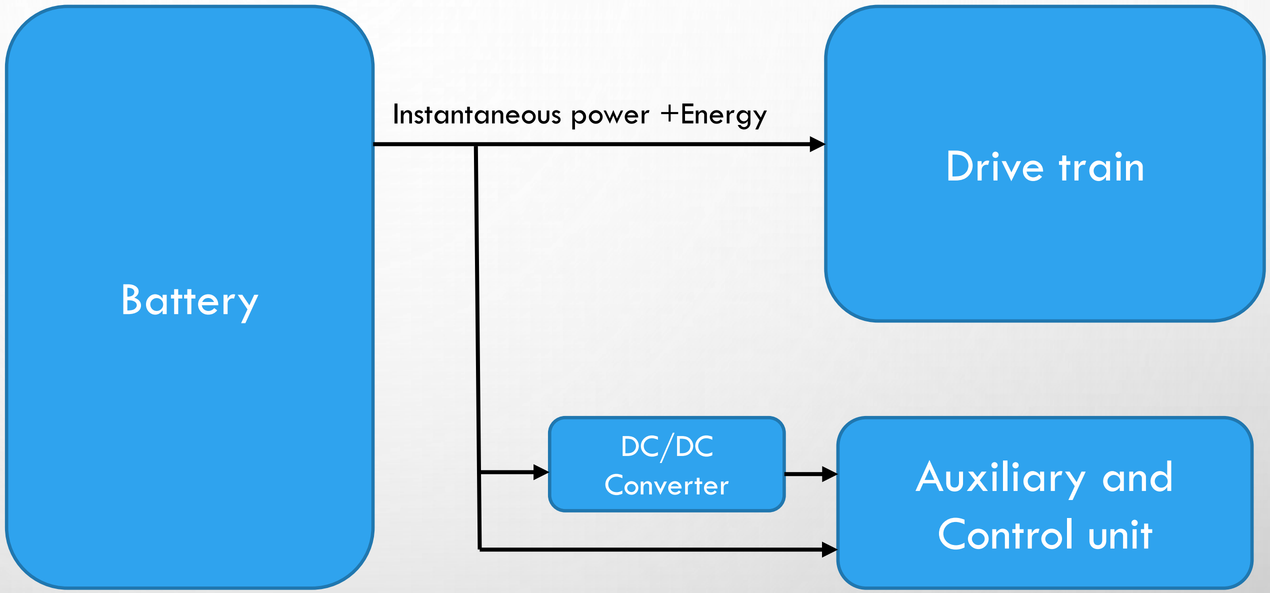
Drivetrain – EV Sub system

EV Drivetrain

EV Battery

DC-DC Converters

Auxiliary and control unit



Auxiliary and control units includes, Lights, head-Lights, Power-Brakes, Power steering, air conditioners & Heaters, other motors (Wiper, Windows) and sensors

Selection of Motors and Controllers

Selection of Motors and controllers derived from the

1. Vehicle drive Requirements
2. Gear ratio Used

Motor Specification can be derived by
Torque and Speed Curve : Nominal Torque and Speed as well as Peak torque and speed.

The important difference between Nominal and Peak Condition will be heat dissipation
Generally motors are designed to attain Max torque, Power and speed for significantly less duration, because in peak condition heat dissipation will be vey high and it may reach the threshold temperature of the components, in other hand efficiency will drop compare to the nominal operation condition but due to less duration this will not taken into the account generally.
Motors designed to dissipate the heat which generates at the nominal operating condition.

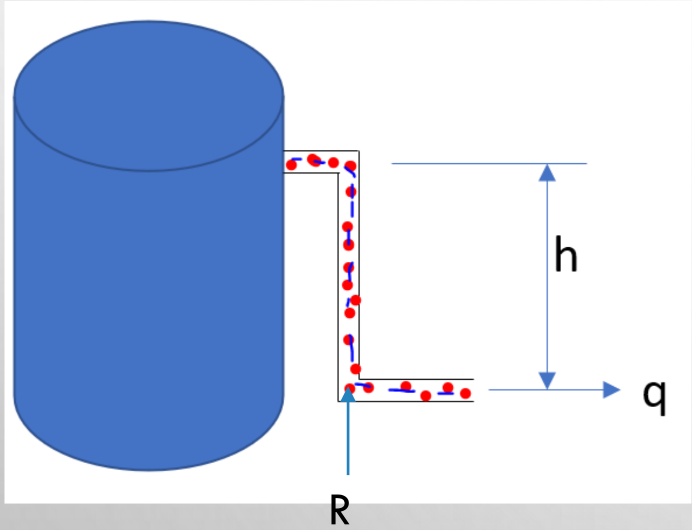
Thermal : Some components included permanent magnet impact by the heat
Mechanical : Vibrations, size and weight.

Flow of Electricity

Basic Physics behind the flow in the motors and controllers

Ohm's Law Compared with Fluid Mechanics

The current through a conductor between two points are directly proportional to the voltage across the points with consideration of resistance



Q = the Flow in Lit/Min → Referred as Current "I"

h = Potential Head in M → Referred as Voltage "V"

R = Resistance to the flow

More Length = More resistance

More Area = Less Resistance

$Ohm's\ Law\ h = R\ x\ q$

Where, $R = \rho\ x\ \left(\frac{l}{A}\right)$ l=Length of the conductor, A = Area of the conductor

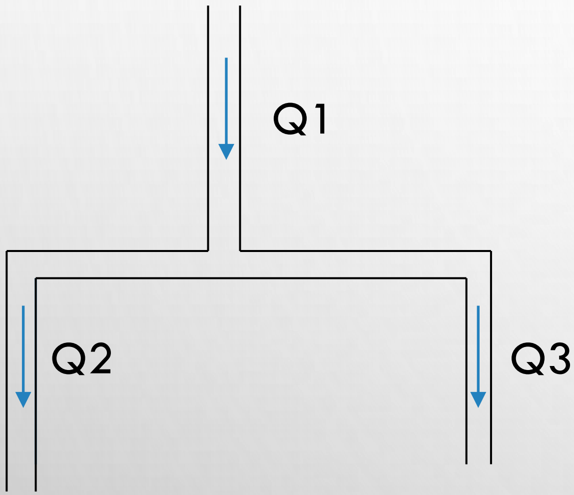
$Ohm's\ Law\ V = IR$

Flow of Electricity

Basic Physics behind the flow in the motors and controllers

Kirchhoff's First law

Sum of all current at any point at any electrical network is zero.



$$Q1 = 3\frac{M^3}{s}$$

$$Q3 = 5\frac{M^3}{s}$$

$$Q2 = -2\frac{M^3}{s}$$

Q2 is actually flowing towards inside, if we change the sign according to the flow sign
3+2-5 = 0

Hence, Sum flow at any point is Zero, which is same as "continuity Equation" in Fluid dynamics

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Flow of Electricity

Basic Physics behind the flow in the motors and controllers

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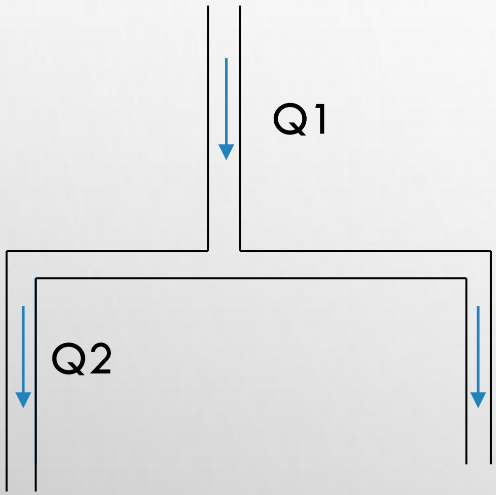

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3+2-5 = 0

Hence, Sum flow at any point is Zero, which is same as "continuity Equation" in Fluid dynamics

As per Kirchhoff's Second law

Series Connection

R = R1+R2+R3

Parallel Connection

$$\frac{1}{R} = \frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3}$$

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Flow of Electricity

Basic Physics behind the flow in the motors and controllers

Flow of Electricity

$Electricity$

$$I = \frac{V}{R}\,;R = \rho\left(\frac{l}{A}\right)$$

Where,

$$\rho = Resistivity;\frac{1}{\rho} = \sigma = Conductivity$$

$l = Length\ of\ the\ conductor$

$A = area\ of\ the\ conductor$

$$I = \frac{V}{\rho.\left(\frac{l}{A}\right)}$$

By Rearranging the equation

$$\frac{I}{A} = \frac{V}{l}x\frac{1}{\rho}$$

Segregating the terms in to three parts

$$\frac{I}{A} = J$$

$$\frac{V}{l} = E$$

$$\frac{1}{\rho} = \sigma$$

$On\ Re\ arranging,$

$J = E.\sigma$

$$E = Electric\ Field = \frac{V}{l}$$

$$J = Current\ Density = \frac{I}{A}$$

$$\sigma = Conductivity = \frac{1}{\rho}$$

Electrical and magnetic Flow Summary

FLOW		Field	Ohm's Law
Fluid	q	h	h = q * R
Electric Current	I	V	V = I * R
Magnetic Flux	Φ	F	F = $\Phi * R$
Heat	Q	Δt	$\Delta t = q * R$
Current Density	J	E	$j = \sigma * E$
Flux Density	B	H	$B = \mu * H$
Flux Linkage	Ψ	I	$\Psi = I * L$

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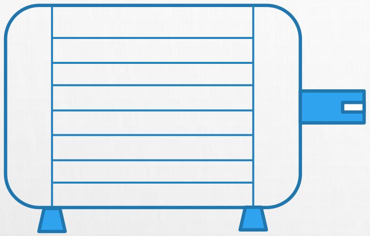
Electric Motor to Wheel

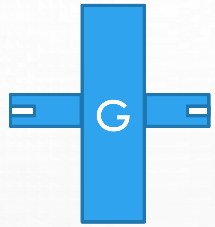
Electrical to Mechanical Conversion

Motor



Gear Box

$\tau * \omega$



$\tau' * \omega'$

Wheel

Electrical Power Input $P = V * I$

Electrical Motor Output $P = \tau * \omega$

Gear train Output $P = \tau' * \omega'$

$Vehicle\ Power\ P = F * V$

$Tractive\ Force\ F = \frac{\tau'}{Wheel\ Radius}$

$Vehicle\ Speed\ v = \omega' * Wheel\ Radius$

Losses in Motor

$$Copper\ Loss = I^2R$$

Steel Losses

1. Depends on Material Grade
2. Proportional to $\omega^2 approx.$

Motor Efficiency = Pout/Pin

$$Gear\ ratio = G$$

$$G = \frac{\omega}{\omega'}$$

$$\omega' = \frac{\omega}{G}$$

Gear efficiency is 80% considering FOS

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Electric Motor - Thermal Design

Ohm's $Law\ \Delta t = q\ * R$

Conduction

$$R = \frac{l}{\lambda DH} = \frac{l}{\lambda A}$$

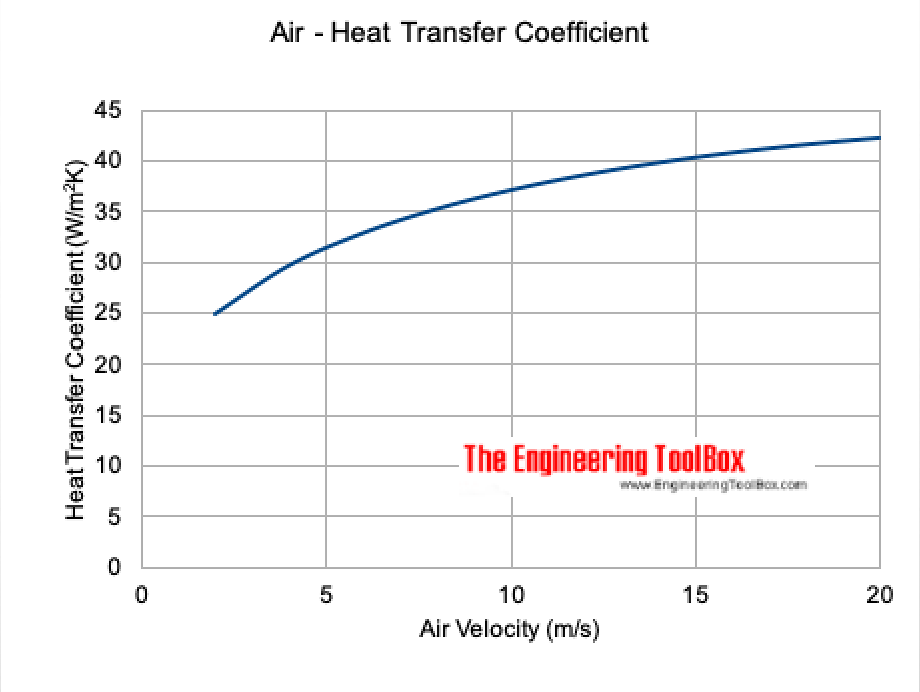
R in K/W, λ in W/(mK)

Convection

$R = 1/(hA)$

h=Heat transfer coefficient

Estimating Heat transfer Coefficient



Heat transfer coefficient vary with respect to air velocity, above graph plotted for 2m/s to 20m/s

Empirical Formula to compute Heat transfer Coefficient

$$h = 12.12 - 1.16v + 11.6\sqrt{v}\ - Applicable\ from\ 2\ to\ 20\frac{m}{s}$$

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THANK YOU