ANALYSIS OF ELECTROSTATIC AND MAGNETOSTATIC BEHAVIOR OF ELECTRIC VEHICLE EXTERNAL PARTS WITH DIFFERENT CASES OF LIGHTNING EFFECTS

Prepared By

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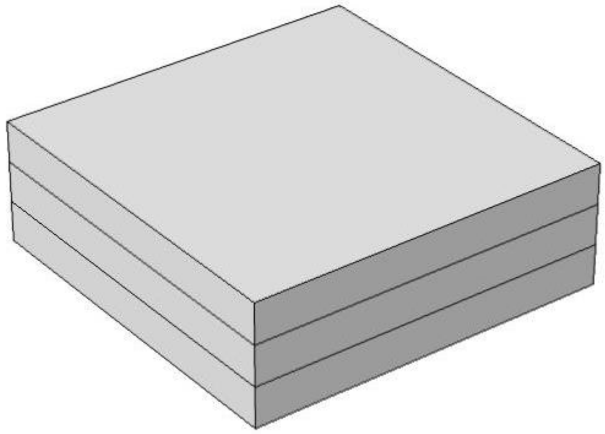
Title	A study on transient magnetic field in an Electric Vehicle due to Lightning
Field of Work	High Voltage Engineering
Simulation Package	COMSOL Multiphysics
Analysis	Finite Element Method (FEM)
Solver	Electrostatic | Magnetostatic
Project Contents	1. Vehicle design 2. Field distribution inside the vehicle 3. Filed distribution on external parts of vehicle 4. Motor design 5. Battery Design 6. Field distribution on Motor 7. Filed distribution on battery 8. Current distribution on battery 9. Calculation of “C” rate and Potential

Electrostatic Analysis in Parallel Plate Capacitor with Single Dielectric

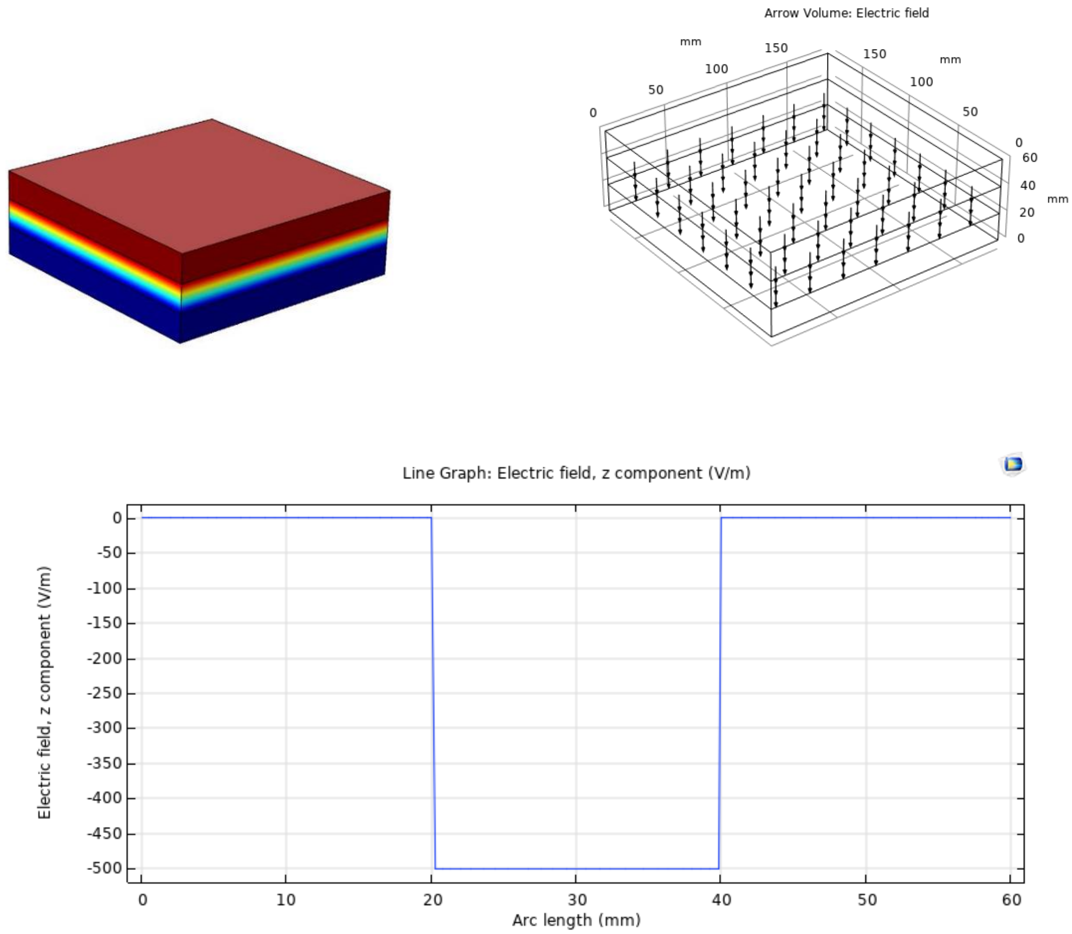
Configuration:



Configuration Details:

1.	**Problem**	Electrostatic field analysis in Parallel Plate Capacitor with Single Dielectric
2.	**Solver**	Electrostatic
3.	**Study**	Stationary
4.	**Governing Equation**	$\varepsilon \nabla^2 V = 0$
5.	**Dimension**	3D | Conductor's height = 20 mm | Width = 180 mm | Depth = 180 mm
6.	**Material Properties**	Silver and Polycrystalline | Relative Permittivity of silver | Relative Permittivity of Polycrystalline
7.	**Source**	Higher Potential = 10 V | Lower Electric Potential = 0 V
8.	**Analytical Solution**	$Electric\ Filed\ Intensity, E = \left(\frac{V}{d}\right)$ | $Capacitance, C = \left(\frac{\varepsilon_0 \varepsilon_r A}{d}\right)$ $Energy, W = 0.5CV^2$
9.	**Software**	COMSOL Multiphysics 5.2 – AC/DC Module

Plot Details:



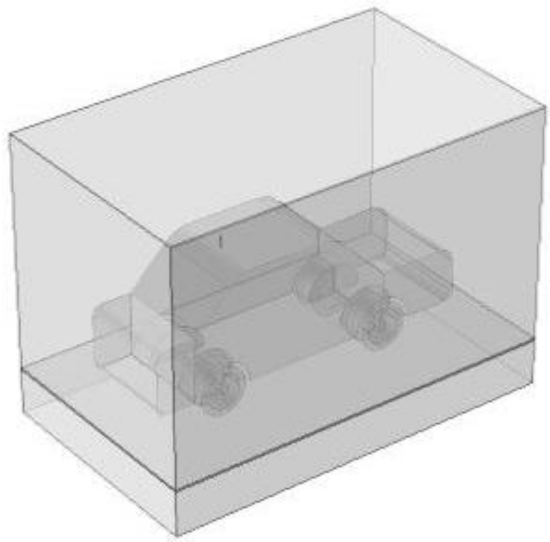
[Parallel Plate Capacitor Surface Plot and Electric potential graph]

Inference:

The voltage distribution linearly decreases with respect to distance. Due to fringing effect non-uniform field is produced near the edges of parallel plate capacitor. When the dielectric medium changed, then voltage and electric field distribution decreases or increases with respect to material used as a dielectric medium.

Electrostatic Analysis in Electric Vehicle Solid Structure with Air Medium

Configuration:

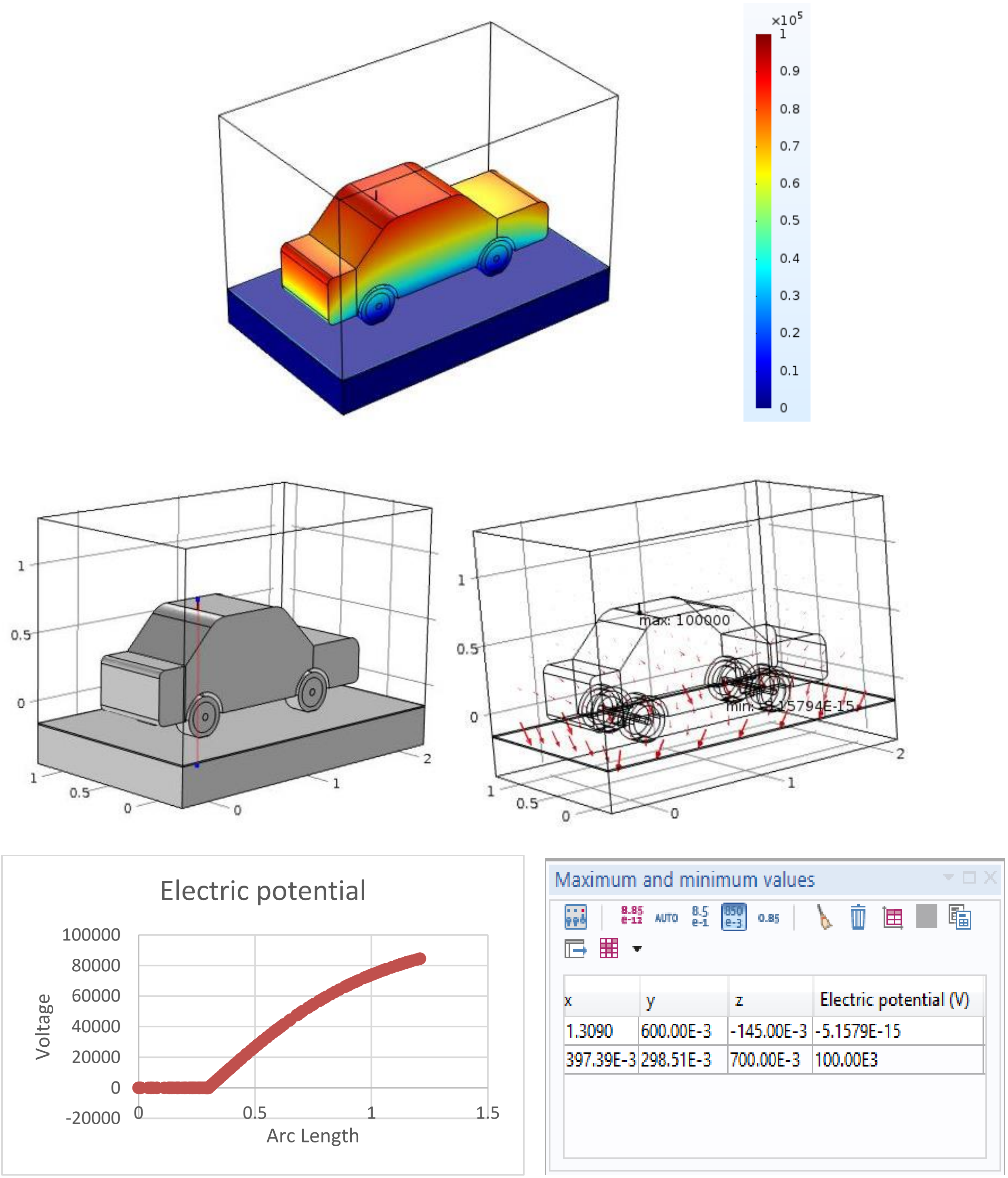


Configuration Details:

1.	**Problem**	Electrostatic field analysis in Electric Vehicle dimensionless Solid Structure with Air medium.
2.	**Solver**	Electrostatic
3.	**Study**	Stationary
4.	**Governing Equation**	$\varepsilon\nabla^2 V = 0$
5.	**Dimension**	3D | Car dimensionless solid structure
6.	**Material Properties**	Air | Copper | Sand | Steel | Epoxy Resin Relative Permittivity of Air | Relative Permittivity of Copper | Relative Permittivity of Sand | Relative Permittivity of Steel | Relative Permittivity of Steel .
7.	**Source**	Terminal Potential = 100 kV | Ground Potential = 0 V
8.	**Software**	COMSOL Multiphysics 5.2 – AC/DC Module

Plot Details:

Surface: Electric Potential



x	y	z	Electric potential (V)
1.3090	600.00E-3	-145.00E-3	-5.1579E-15
397.39E-3	298.51E-3	700.00E-3	100.00E3

[Fig – Electric Vehicle Surface Plot and Electric potential graph]

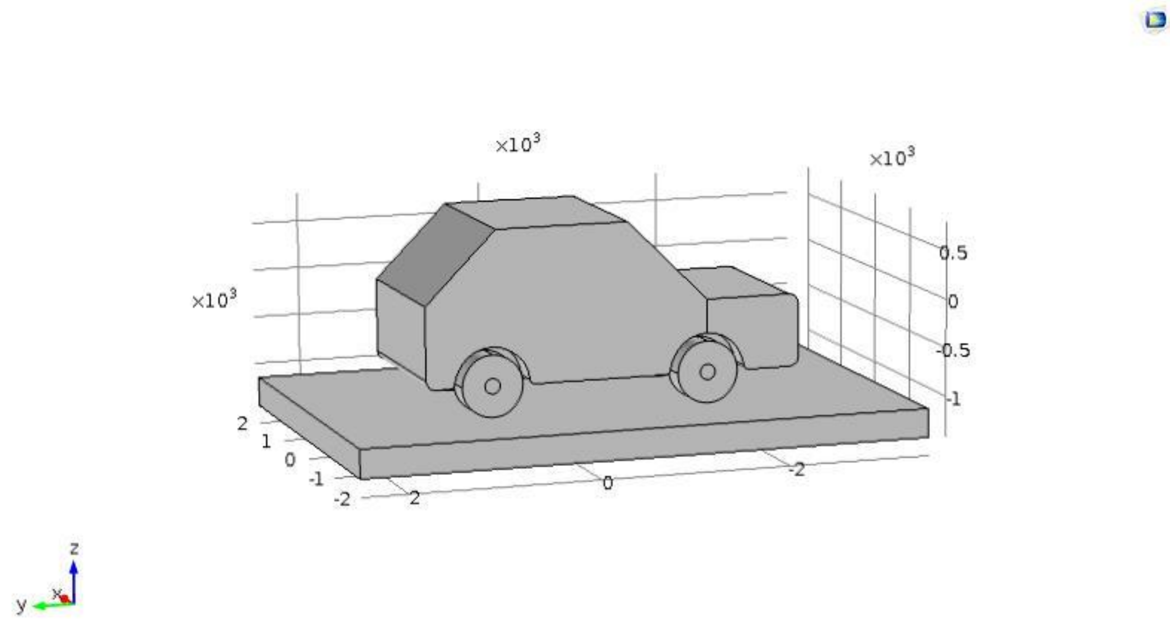
Range of Electrostatic Field distribution		
Source Point	**Discharging Points**	**Maximum Values (Volts)**
Vehicle Antenna and Air ionisation mediym	Antenna and Top roof	$1\ X10^{5}$
	Vehicle Front Body	$0.6\ X10^{5}$
	Vehicle back Body near mirror	$0.6\ X10^{5}$
	Vehicle shaft area	$0.4\ X10^{5}$
	Vehicle Rim area	$0.2\ X10^{5}$
	Vehicle wheel area	$-5.15\ X10^{-15}$

Inference:

Surface of the solid electric vehicle body carries more electric field than inside the vehicle body conductor. The voltage distribution is decreases linearly and it carries different values in different parts of electric vehicle. Maximum amount of electric potential placed current injecting point (Vehicle Antenna) and minimum amount of electric potential in discharging point (Vehicle wheel). Air medium get energized due to lightning and it produce maximum amount of temperature (Five times more than Sun temperature). This air medium also acts as a current source and it affect the vehicle body. The effects of Air due to lightning also a major parts of high voltage lightning analysis in Electric vehicle.

Electrostatic Analysis in Electric Vehicle Solid Structure with Air Medium

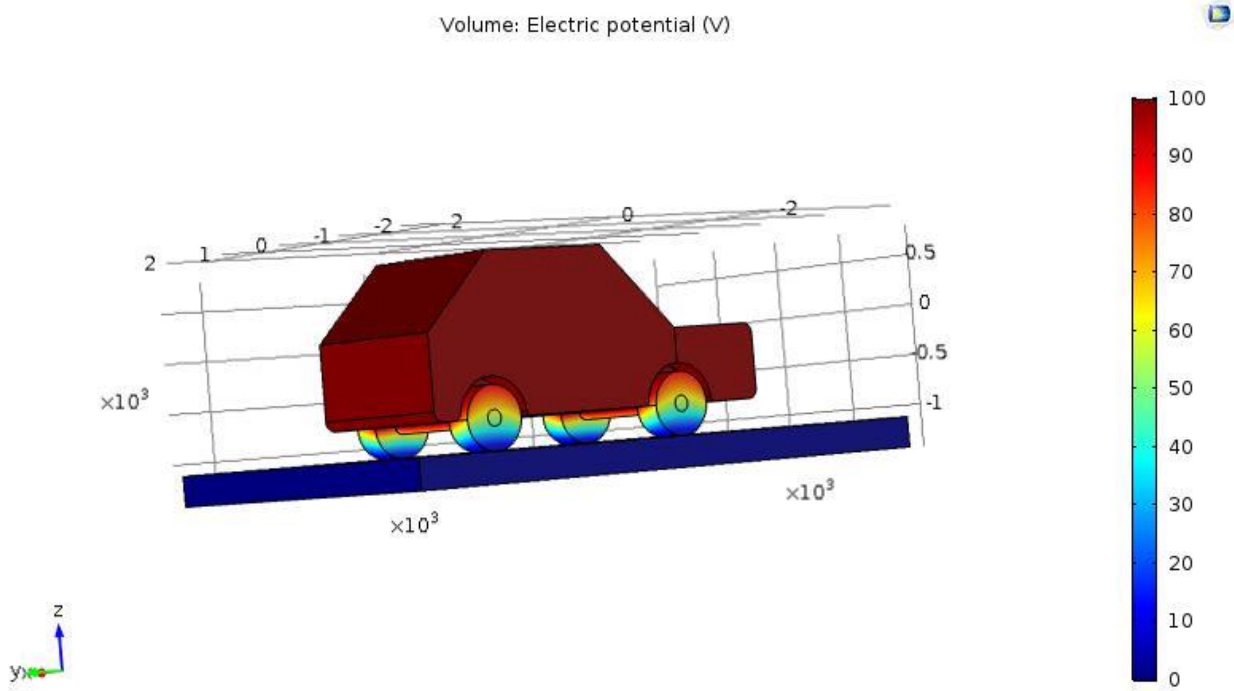
Configuration:

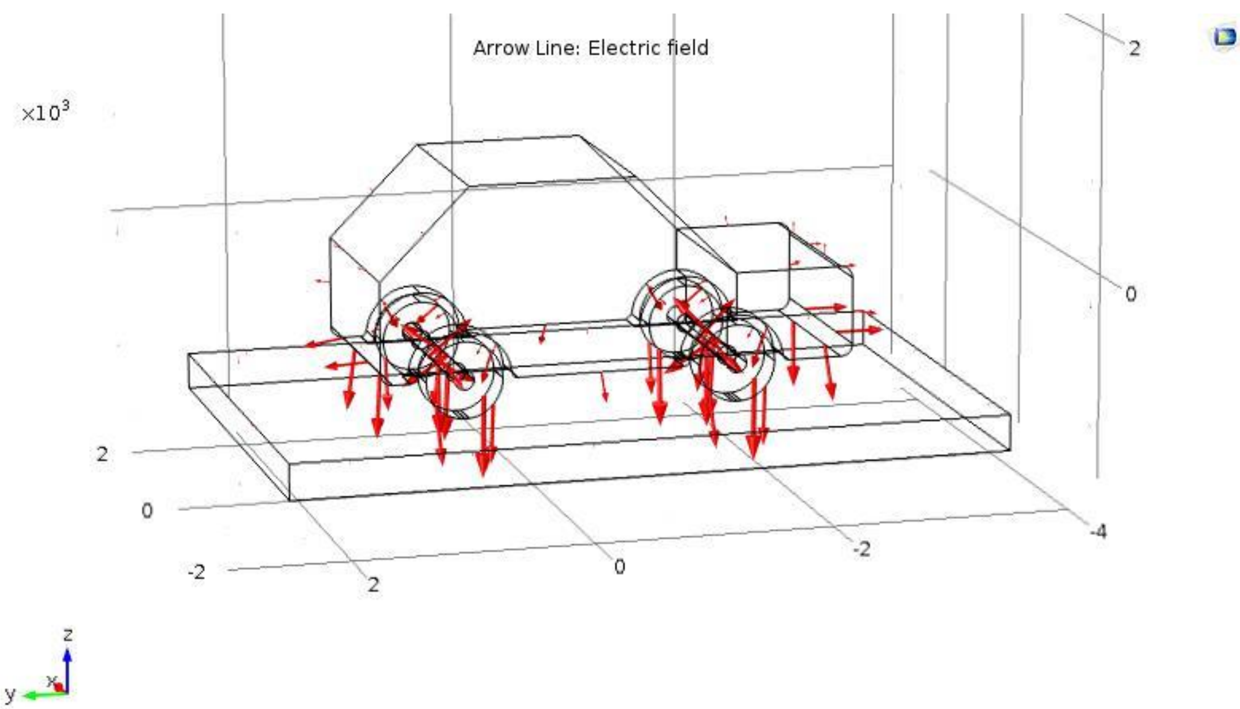


Configuration Details:

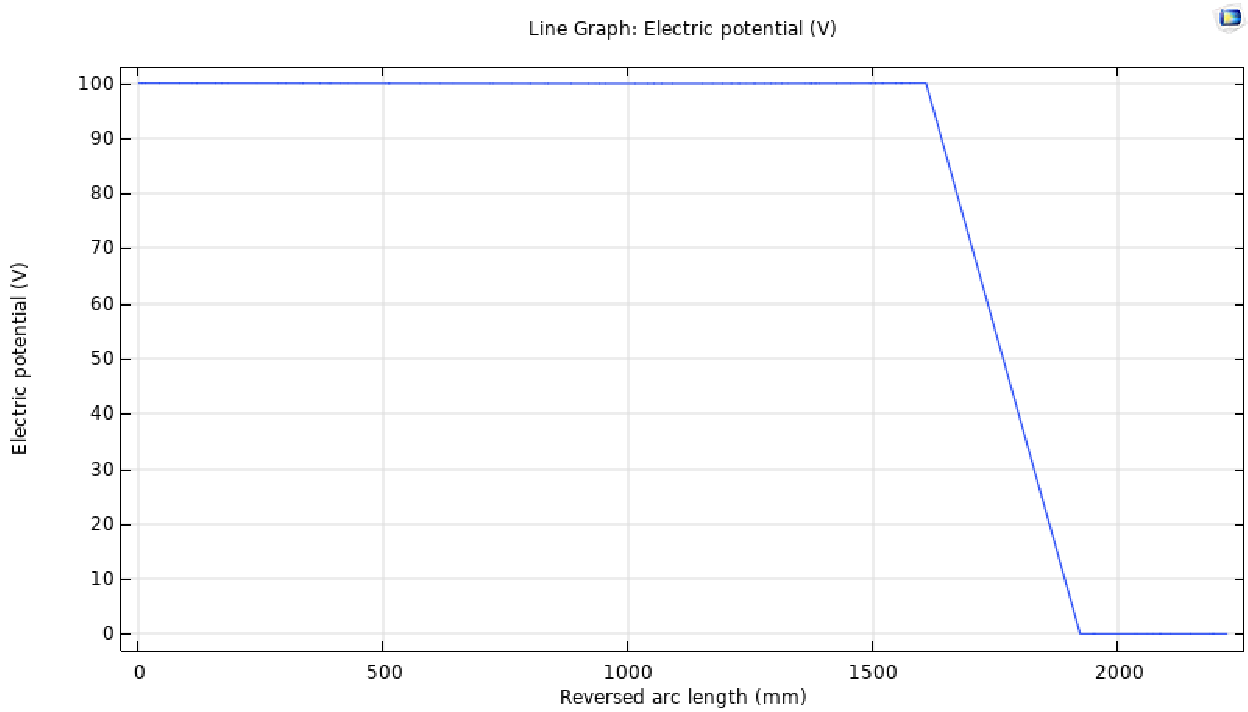
1.	**Problem**	Electrostatic field analysis in Electric Vehicle Solid Structure with Air medium.
2.	**Solver**	Electrostatic
3.	**Study**	Stationary
4.	**Governing Equation**	$\varepsilon \nabla^2 V = 0$
5.	**Vehicle Dimension**	3D | Length – 3994mm | Width – 1811mm | Height – 1607mm
6.	**Material Properties**	Air | Copper | Sand | Steel | Epoxy Resin Relative Permittivity of Air | Relative Permittivity of Copper | Relative Permittivity of Sand | Relative Permittivity of Steel | Relative Permittivity of Steel .
7.	**Source**	Terminal Potential = 100 V | Ground Potential = 0 V
8.	**Software**	COMSOL Multiphysics 5.2 – AC/DC Module

Plot Details:

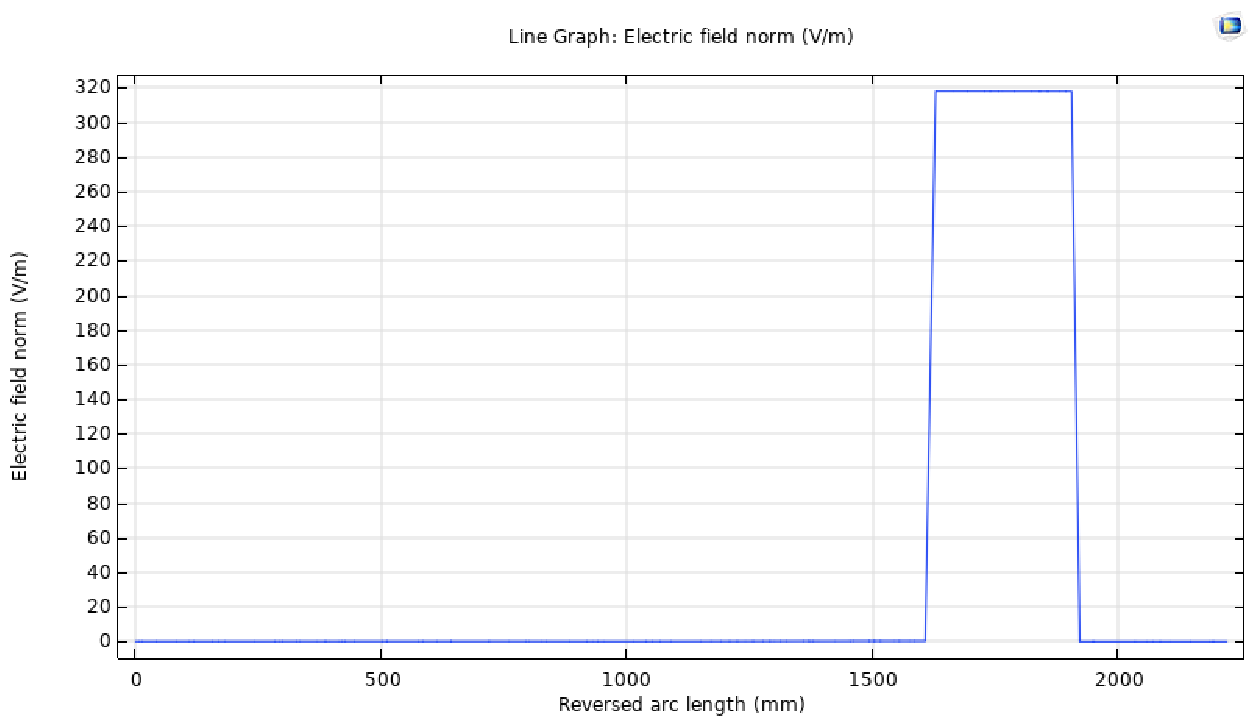




[Fig – Electric Vehicle Potential and Electric Field graph]



[Fig – Electric Potential graph]

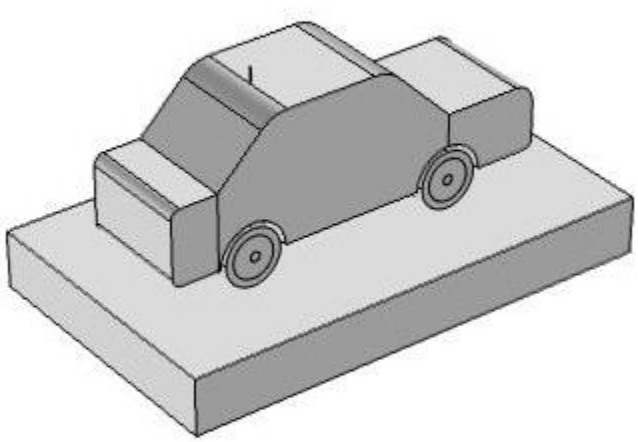


[Fig –Electric Field graph]

Range of Electrostatic Field distribution		
Source Point	**Discharging Points**	**Maximum Values (Volts)**
Vehicle Antenna and Air ionisation mediym	Top roof	100
	Vehicle Front Body	100
	Vehicle back Body near mirror	100
	Vehicle shaft area	60
	Vehicle Rim area	50
	Vehicle wheel area	40

Electrostatic Analysis in Electric Vehicle Solid Structure without Air Medium

Configuration:

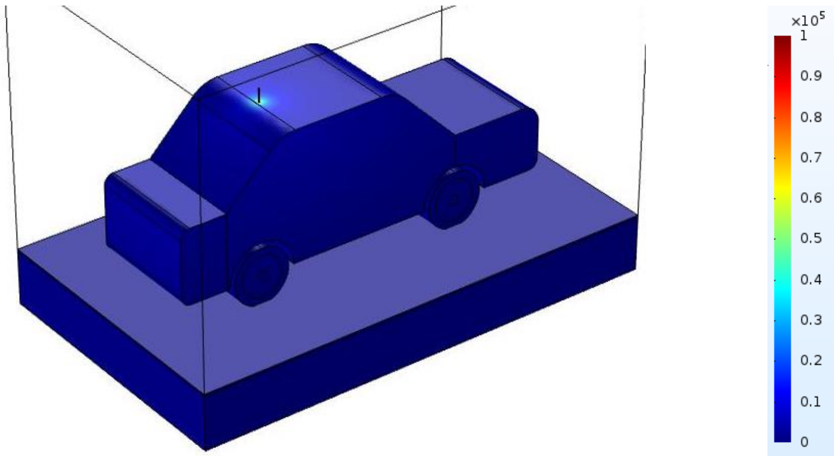


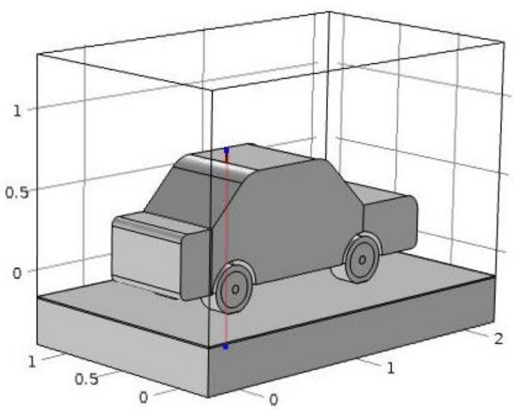
Configuration Details:

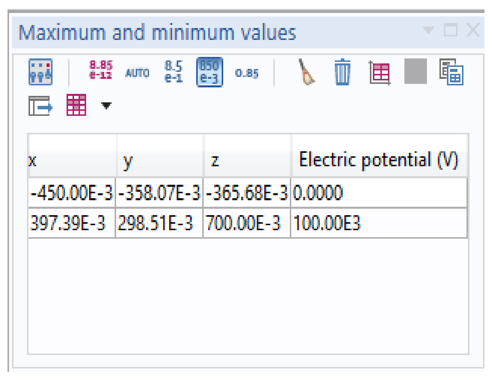
1.	**Problem**	Electrostatic field analysis in Electric Vehicle dimensionless Solid Structure without Air medium.
2.	**Solver**	Electrostatic
3.	**Study**	Stationary
4.	**Governing Equation**	$\varepsilon \nabla^2 V = 0$
5.	**Dimension**	3D | Car dimensionless solid structure
6.	**Material Properties**	Air | Copper | Sand | Steel | Epoxy Resin Relative Permittivity of Air | Relative Permittivity of Copper | Relative Permittivity of Sand | Relative Permittivity of Steel | Relative Permittivity of Steel .
7.	**Source**	Terminal Potential = 100 kV | Ground Potential = 0 V
8.	**Software**	COMSOL Multiphysics 5.2 – AC/DC Module

Plot Details:

Surface: Electric Potential

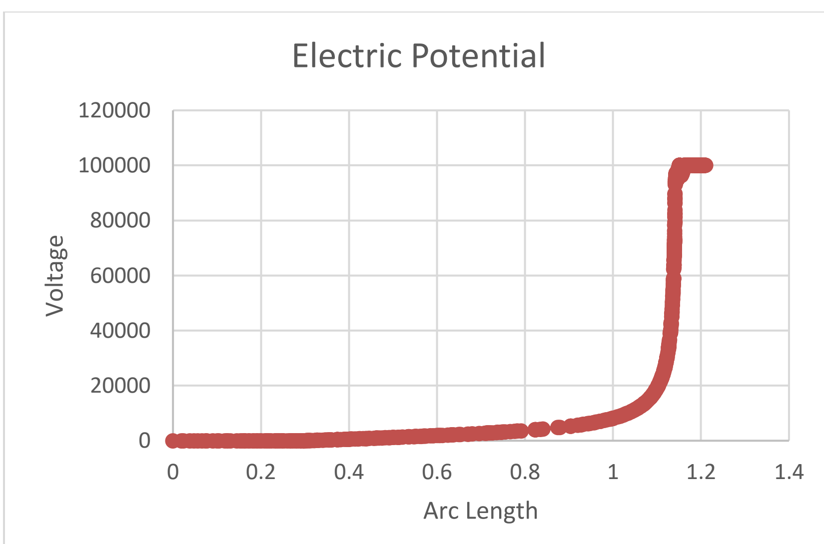






Maximum and minimum values

x	y	z	Electric potential (V)
-450.00E-3	-358.07E-3	-365.68E-3	0.0000
397.39E-3	298.51E-3	700.00E-3	100.00E3



[Fig – Electric Vehicle Surface Plot and Electric potential graph]

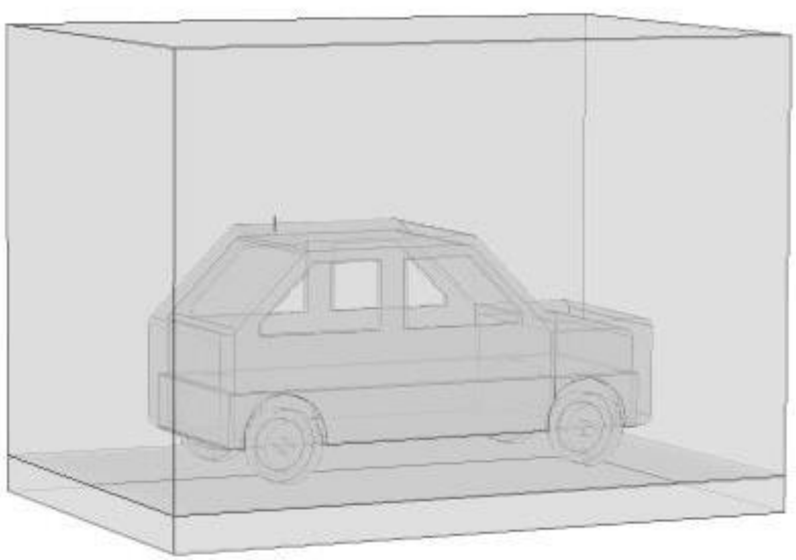
Range of Electrostatic Field distribution		
Source Point	**Discharging Points**	**Maximum Values (Volts)**
Vehicle Antenna	Antenna and Top roof	$1\ X 10^5$
	Vehicle Front Body	$0.7\ X 10^5$
	Vehicle back Body near mirror	$0.2\ X 10^5$
	Vehicle shaft area	0
	Vehicle Rim area	0
	Vehicle wheel area	0

Inference:

Surface of the solid electric vehicle body carries more electric field than inside the vehicle body conductor. The voltage distribution is decreases linearly and it carries different values in different parts of electric vehicle. Maximum amount of electric potential placed current injecting point (Vehicle Antenna) and very minimum amount of electric potential is in discharging point (Vehicle wheel). Without air medium, the potential distribution is entirely decreasing compared to with Air medium analysis. But practically without Air medium is not possible. So Maximum potential appearing in vehicle body. So, we need to protect the vehicle body as well as internal parts of electric vehicle.

Electrostatic Analysis in Electric Vehicle Hollow Structure with Air Medium

Configuration:

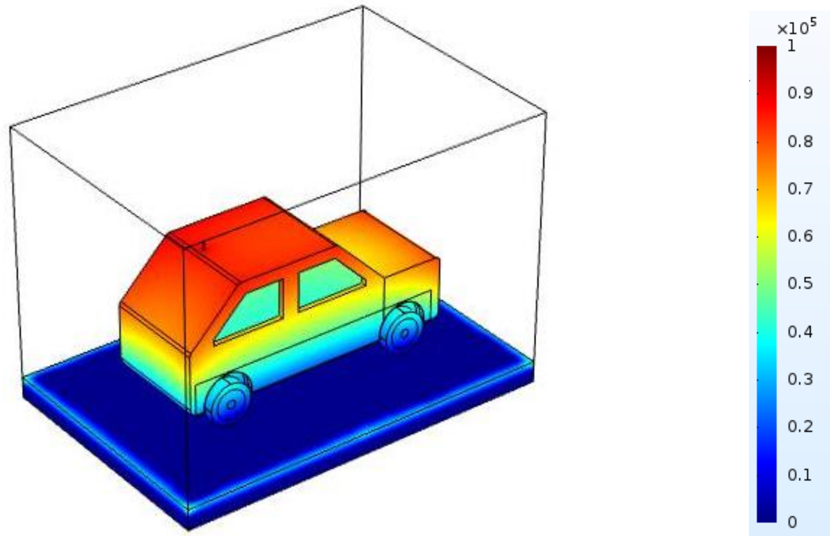


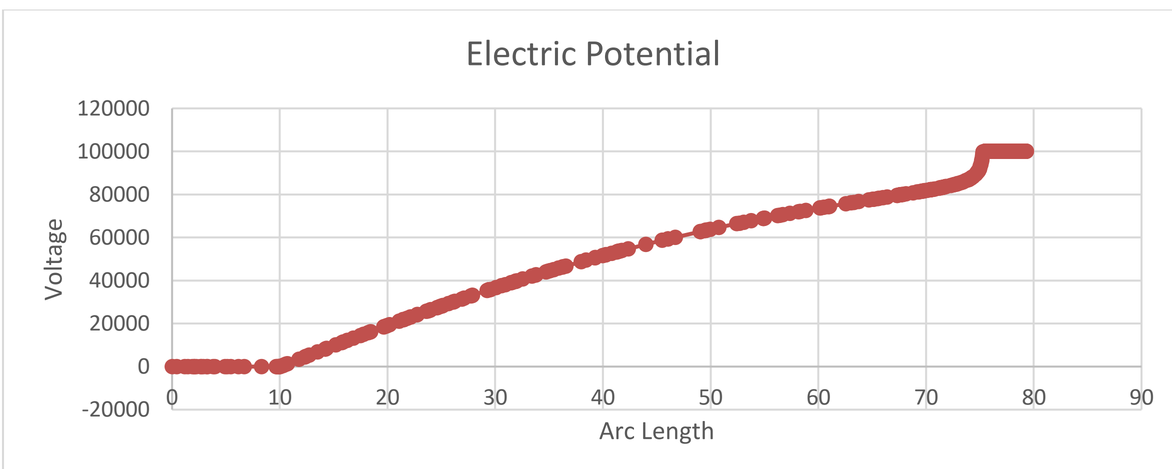
Configuration Details:

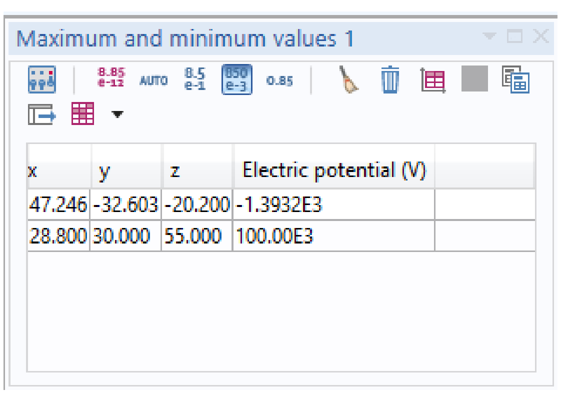
1.	**Problem**	Electrostatic field analysis in Electric Vehicle dimensionless Hollow Structure with Air medium.
2.	**Solver**	Electrostatic
3.	**Study**	Stationary
4.	**Governing Equation**	$\varepsilon\nabla^2 V = 0$
5.	**Dimension**	3D | Car dimensionless hollow structure
6.	**Material Properties**	Air | Copper | Sand | Steel | Epoxy Resin Relative Permittivity of Air | Relative Permittivity of Copper | Relative Permittivity of Sand | Relative Permittivity of Steel | Relative Permittivity of Steel .
7.	**Source**	Terminal Potential = 100000 V | Ground Potential = 0 V
8.	**Software**	COMSOL Multiphysics 5.2 – AC/DC Module

Plot Details:

Surface: Electric Potential

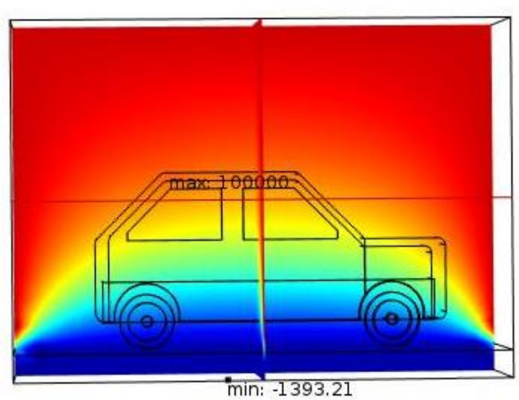






Maximum and minimum values 1

x	y	z	Electric potential (V)
47.246	-32.603	-20.200	-1.3932E3
28.800	30.000	55.000	100.00E3



[Fig – Electric Vehicle Surface Plot and Electric potential graph]

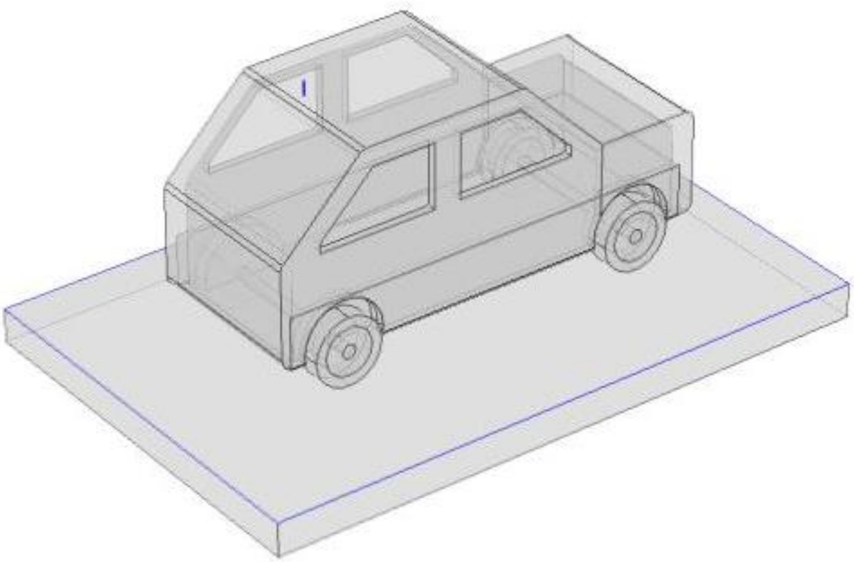
Range of Electrostatic Field distribution		
Current Injecting Point	**Discharging Points**	**Maximum Values (Volts)**
Vehicle Antenna and Air ionisation mediym	Antenna and Top roof	$1\ X10^{5}$
	Vehicle Front Body	$0.9\ X10^{5}$
	Vehicle back Body near mirror	$0.6\ X10^{5}$
	Vehicle shaft area	$0.4\ X10^{5}$
	Vehicle Rim area	$0.3\ X10^{5}$
	Vehicle wheel area	$0.1\ X10^{5}$

Inference:

Surface of the solid electric vehicle body carries more electric field than inside the vehicle body conductor. The voltage distribution is decreases linearly and it carries different values in different parts of electric vehicle. Maximum amount of electric potential placed current injecting point (Vehicle Antenna) and very minimum amount of electric potential is in discharging point (Vehicle wheel). Air medium get energized due to lightning and it produce maximum amount of temperature (Five times more than Sun temperature). This air medium also acts as a current source and it affect the vehicle body. The effects of Air due to lightning also a major parts of high voltage lightning analysis in Electric vehicle.

Electrostatic Analysis in Electric Vehicle Hollow Structure without Air Medium

Configuration:

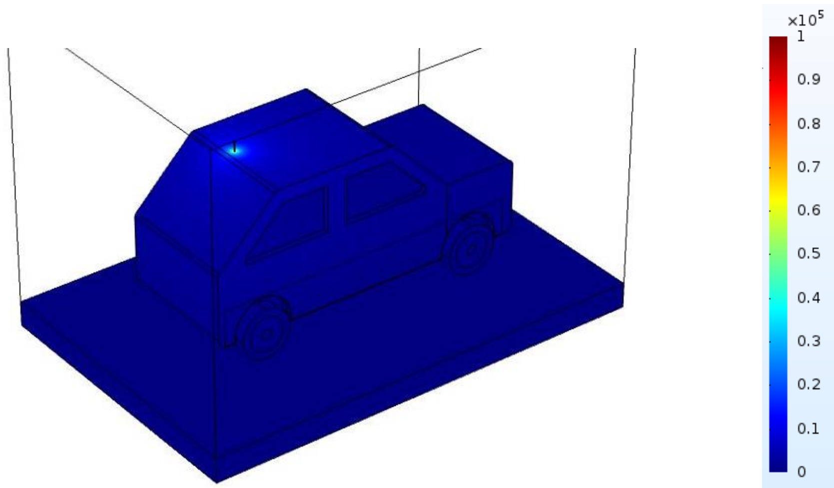


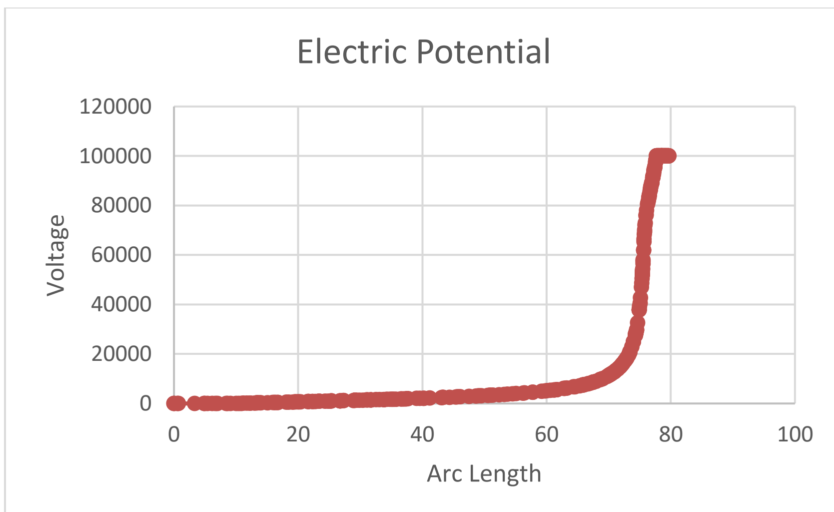
Configuration Details:

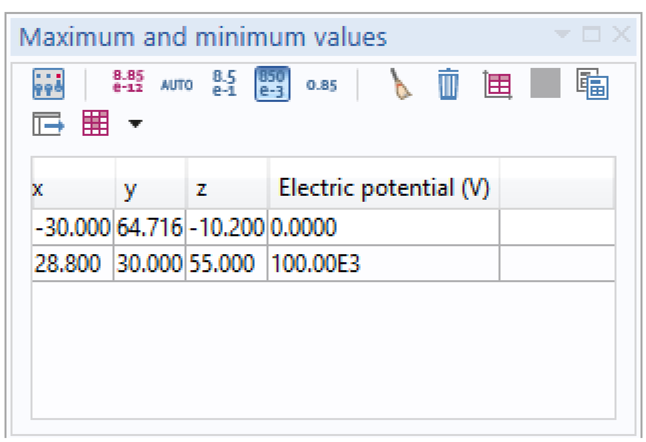
1.	**Problem**	Electrostatic field analysis in Electric Vehicle Hollow Structure without Air medium.
2.	**Solver**	Electrostatic
3.	**Study**	Stationary
4.	**Governing Equation**	$\varepsilon \nabla^2 V = 0$
5.	**Dimension**	3D | Car dimensionless hollow structure
6.	**Material Properties**	Air | Copper | Sand | Steel | Epoxy Resin Relative Permittivity of Air | Relative Permittivity of Copper | Relative Permittivity of Sand | Relative Permittivity of Steel | Relative Permittivity of Steel .
7.	**Source**	Terminal Potential = 100000 V | Ground Potential = 0 V
8.	**Software**	COMSOL Multiphysics 5.2 – AC/DC Module

Plot Details:

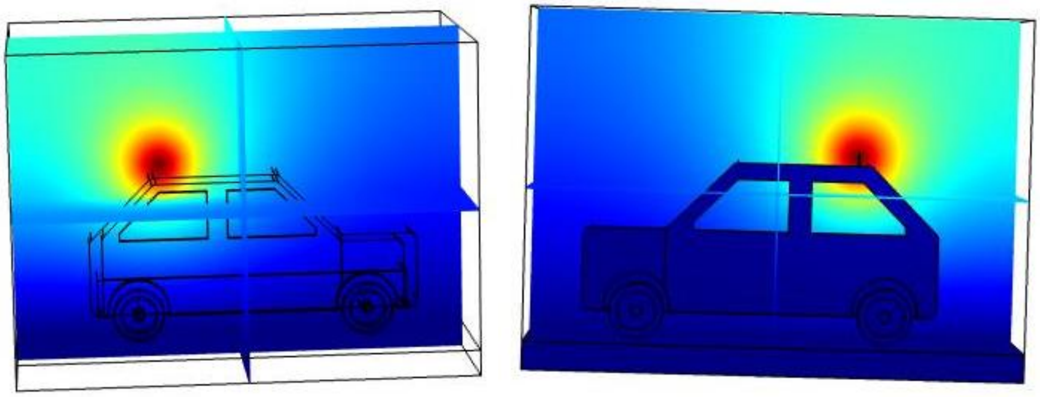
Surface: Electric Potential






Maximum and minimum values

x	y	z	Electric potential (V)
-30.000	64.716	-10.200	0.0000
28.800	30.000	55.000	100.00E3



[Fig – Electric Vehicle Surface Plot and Electric potential graph]

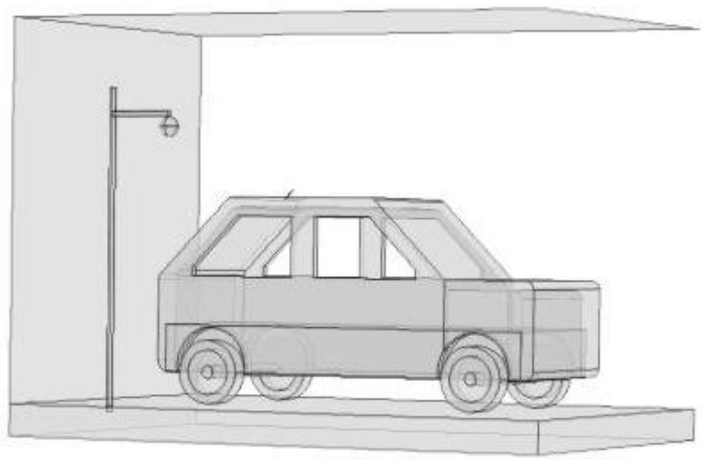
Range of Electrostatic Field distribution		
Current Injecting Point	**Discharging Points**	**Maximum Values (Volts)**
Vehicle Antenna	Antenna and Top roof	$1\ X10^5$
	Vehicle Front Body	$0.5\ X10^5$
	Vehicle back Body near mirror	$0.3\ X10^5$
	Vehicle shaft area	$0.2\ X10^5$
	Vehicle Rim area	$0.1\ X10^5$
	Vehicle wheel area	0

Inference:

Surface of the solid electric vehicle body carries more electric field than inside the vehicle body conductor. The voltage distribution is decreases linearly and it carries different values in different parts of electric vehicle. Maximum amount of electric potential placed current injecting point (Vehicle Antenna) and very minimum amount of electric potential is in discharging point (Vehicle wheel). Without air medium, the potential distribution is entirely decreasing compared to with Air medium analysis. But practically without Air medium is not possible. So Maximum potential appearing in vehicle body. So, we need to protect the vehicle body as well as internal parts of electric vehicle.

Electrostatic Field Analysis in Electric Vehicle with Nearest Object

Configuration:

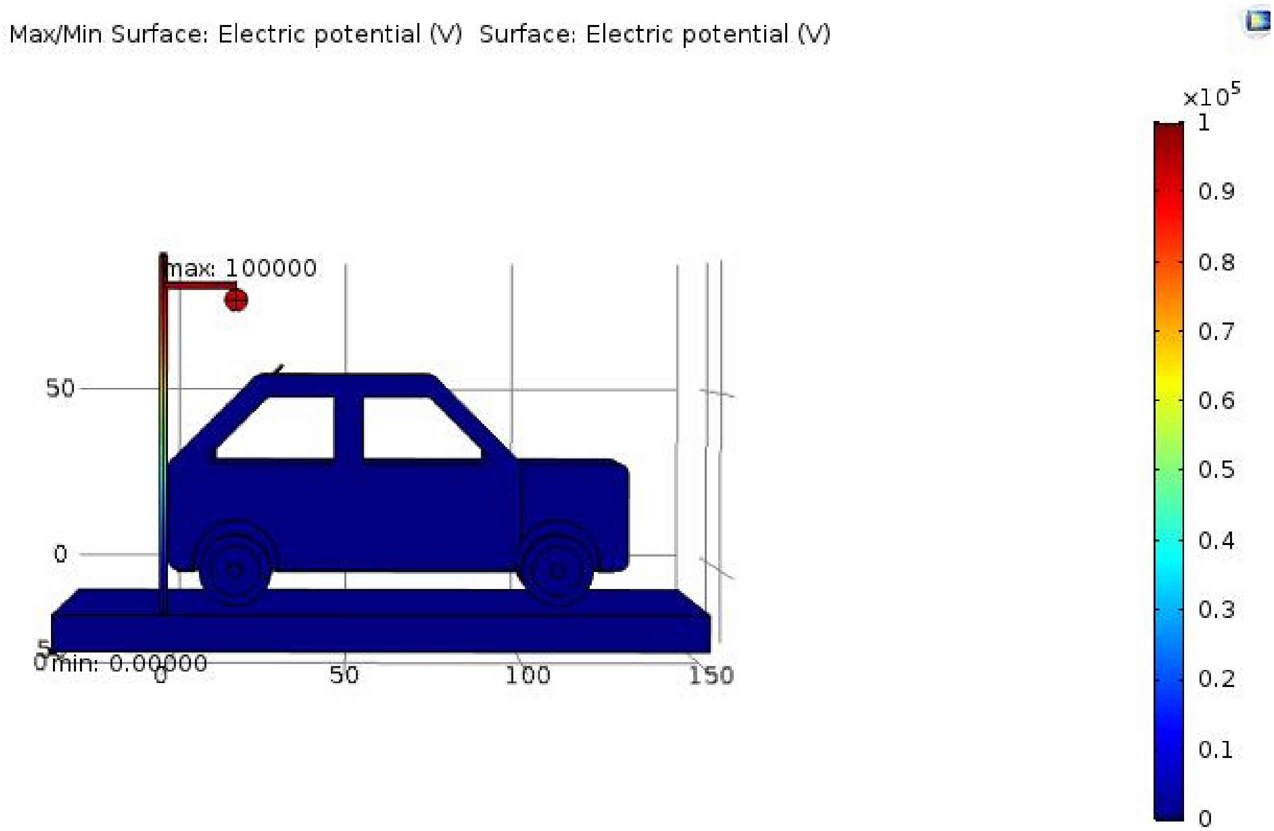


Configuration Details:

1.	**Problem**	Electrostatic field analysis in Electric Vehicle solid Structure with nearest object
2.	**Solver**	Electrostatic
3.	**Study**	Stationary
4.	**Governing Equation**	$\varepsilon \nabla^2 V = 0$
5.	**Dimension**	3D | Car dimensionless solid structure
6.	**Material Properties**	Air | Copper | Sand | Steel | Epoxy Resin Relative Permittivity of Air | Relative Permittivity of Copper | Relative Permittivity of Sand | Relative Permittivity of Steel | Relative Permittivity of Steel .
7.	**Source**	Terminal Potential = 100 kV | Ground Potential = 0 V
8.	**Software**	COMSOL Multiphysics 5.2 – AC/DC Module

Plot Details:

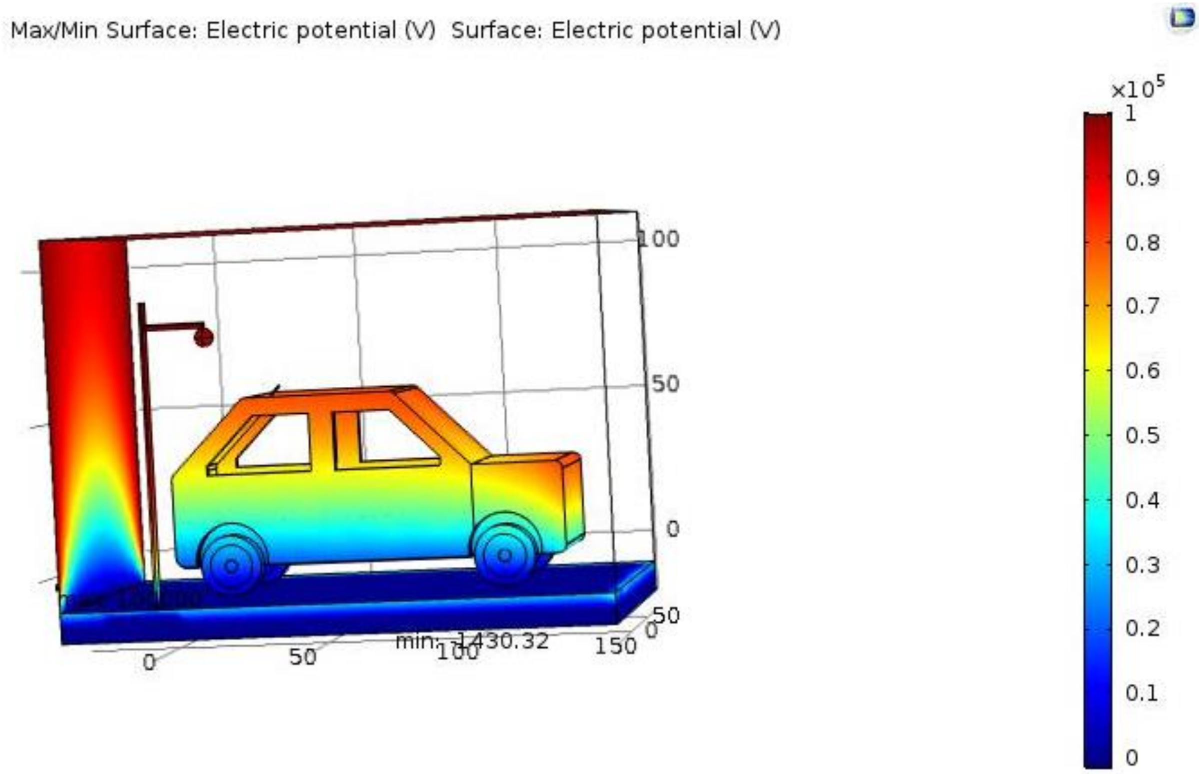
Case – I (Source Point is top of the tower)



[Fig – Surface Plot without Air medium: Electric Potential]

Range of Electrostatic Field distribution		
Source Point	**Discharging Points**	**Maximum Values (Volts)**
Tower Top Edge	Antenna and Top roof	0
	Tower Top Edge	$1\ X10^5$
	Tower Bottom edge	$0.1\ X10^5$
	Vehicle Front Body	0
	Vehicle back Body near mirror	0
	Vehicle shaft area	0
	Vehicle Rim area	0
	Vehicle wheel area	0

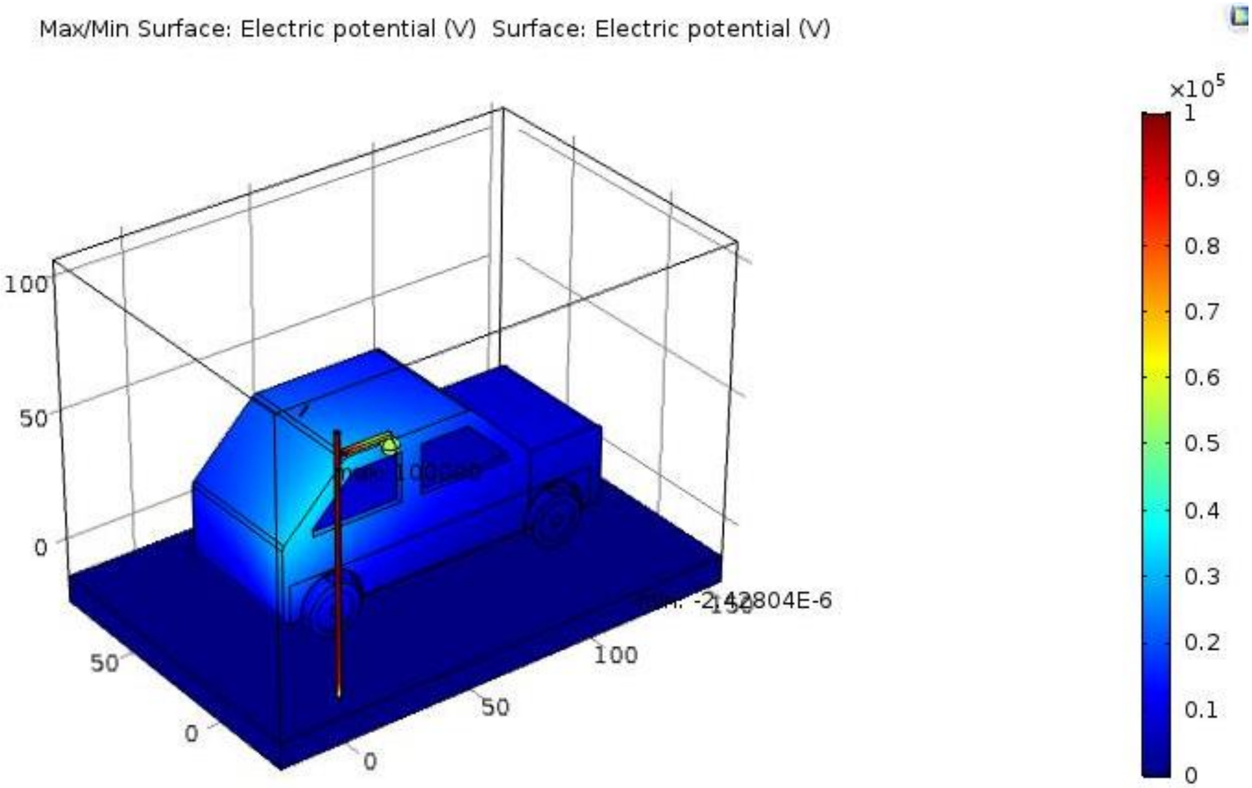
Case – II (Source Point is top of the tower and Air medium)



[Fig – Surface Plot with Air medium: Electric Potential]

Range of Electrostatic Field distribution (Including Air Medium)		
Source Point	**Discharging Points**	**Maximum Values (Volts)**
Tower and Air	Antenna and Top roof	$1\ X10^5$
	Tower Top Edge	$1\ X10^5$
	Vehicle Front Body	$0.5\ X10^5$
	Vehicle back Body near mirror	$0.1\ X10^5$
	Vehicle shaft area	$0.1\ X10^5$
	Vehicle Rim area	$0.1\ X10^5$
	Vehicle wheel area	$0.1\ X10^5$

Case – III (Source Point is side portion of tower near to vehicle)



[Fig – Surface Plot without Air medium: Electric Potential]

Range of Electrostatic Field distribution		
Source Point	**Discharging Points**	**Maximum Values**
Tower side part	Antenna and Top roof	$0.1\ X 10^5$
	Tower Top Edge	$1\ X 10^5$
	Vehicle Front Body	0
	Vehicle back Body near mirror	$0.1\ X 10^5$
	Vehicle shaft area	0
	Vehicle Rim area	0
	Vehicle wheel area	0

Inference:

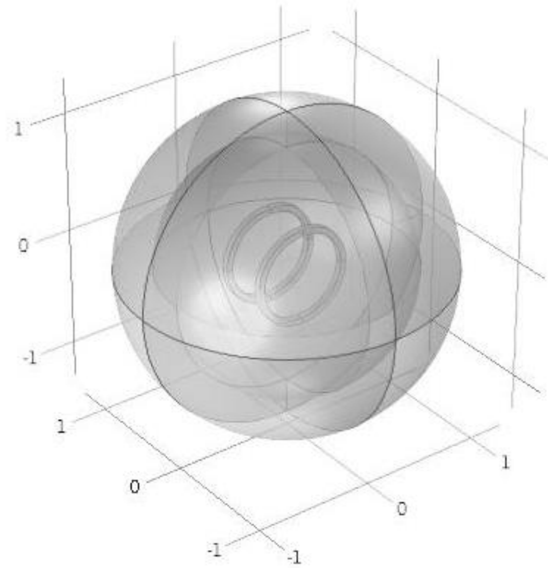
In case I, the electric potential applied top edge of tower, so that the total electric potential discharged through the ground. There is no field distribution near to the object. But this process done without air medium.

In case II, the electric potential applied top edge of tower and consider the air medium ionizing due to lightning. Here the electric potential distributing through the air medium as well as tower potential sent through ground. Therefore, maximum amount of field is distributing through vehicle body as well as tower body.

In case III, the electric potential applied side portion of tower without air medium. Therefore, minimum amount of field is distributing through vehicle body and maximum amount of field distributing through tower body. Therefore, electric vehicle is affected due to lightning strikes nearest object also.

Magnetostatic Analysis in Helmholtz Coil

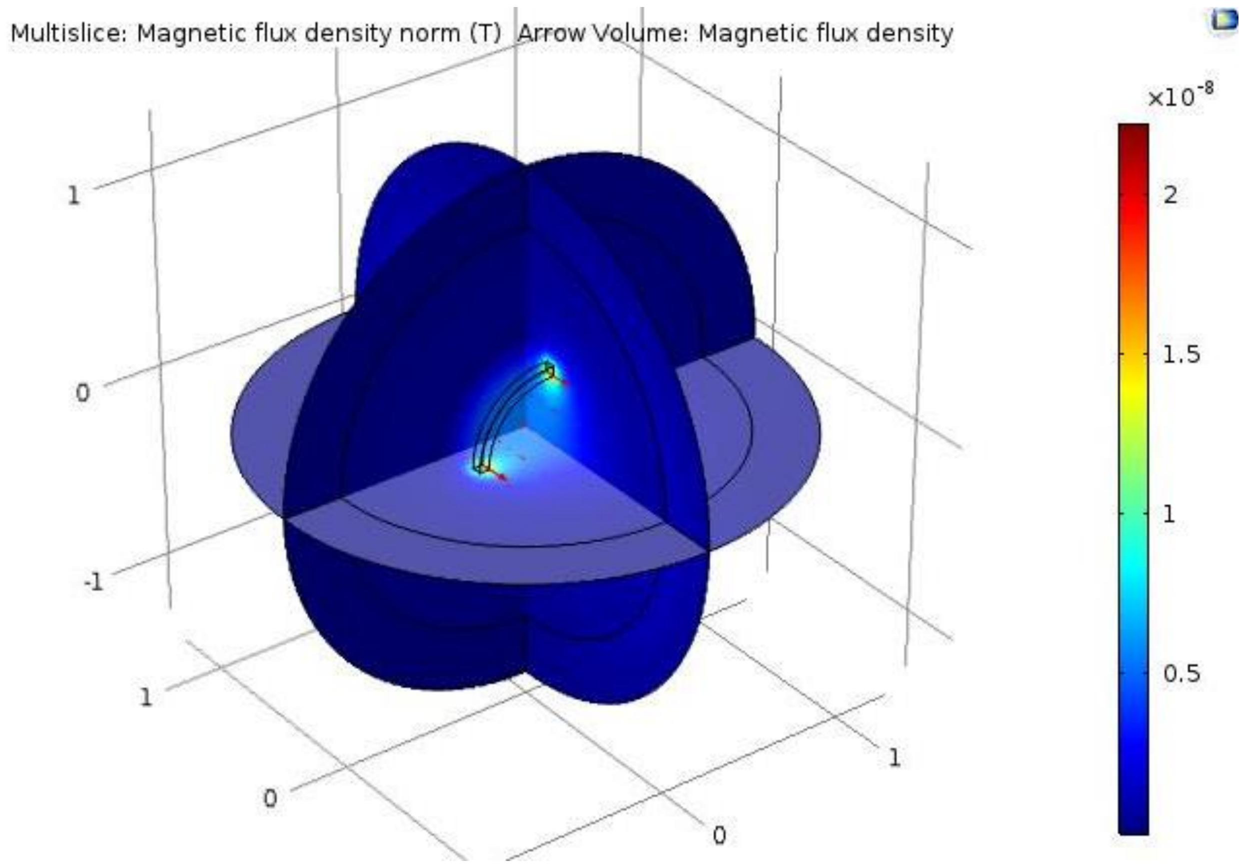
Configuration:



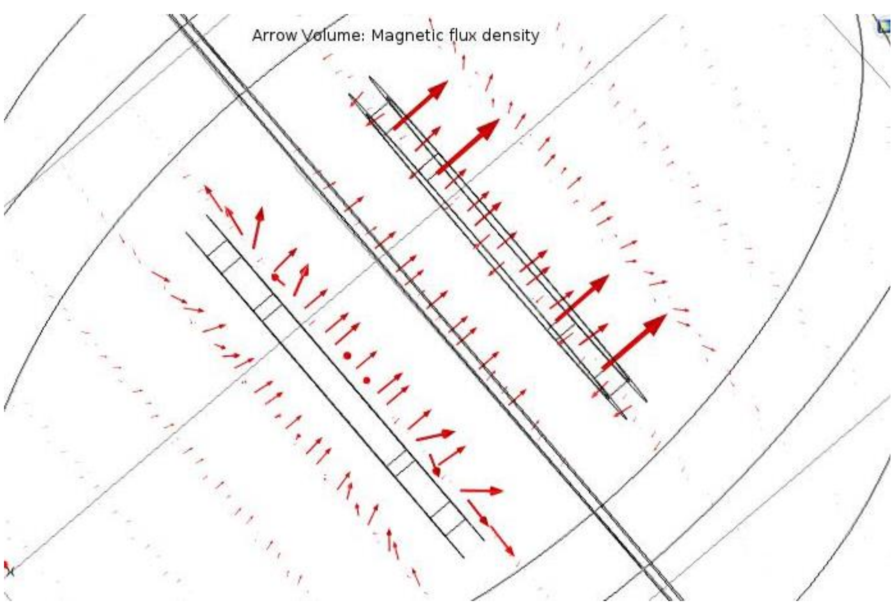
Configuration Details:

1.	**Problem**	Magnetostatic field analysis in Helmholtz Coil
2.	**Solver**	Magnetostatic
3.	**Study**	Stationary
4.	**Governing Equation**	$\varepsilon\nabla^2 V = 0$ | $\nabla . D = \rho_v$ | $E = -\nabla V$
5.	**Dimension**	3D | Car solid structure
6.	**Material Properties**	Air | Coil Relative Permittivity of Air | Relative Permittivity of Iron | Electrical Conductivity of Coil
7.	**Source**	Coil Current = 0.25 mA
8.	**Software**	COMSOL Multiphysics 5.6 – AC/DC Module

Plot Details:



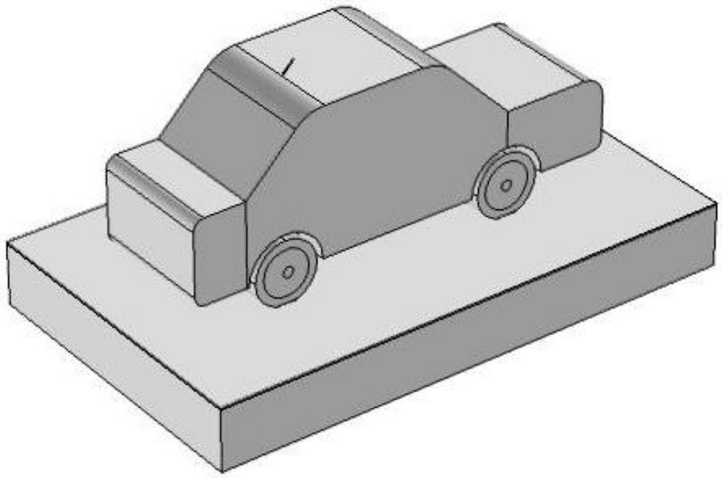
[Fig – The slice plot shows the magnetic flux density norm. The arrows indicate the magnetic field (H) strength and direction]



[Fig – Arrow Volume Magnetic Flux Density]

Magnetostatic Analysis in Electric Vehicle Solid Structure

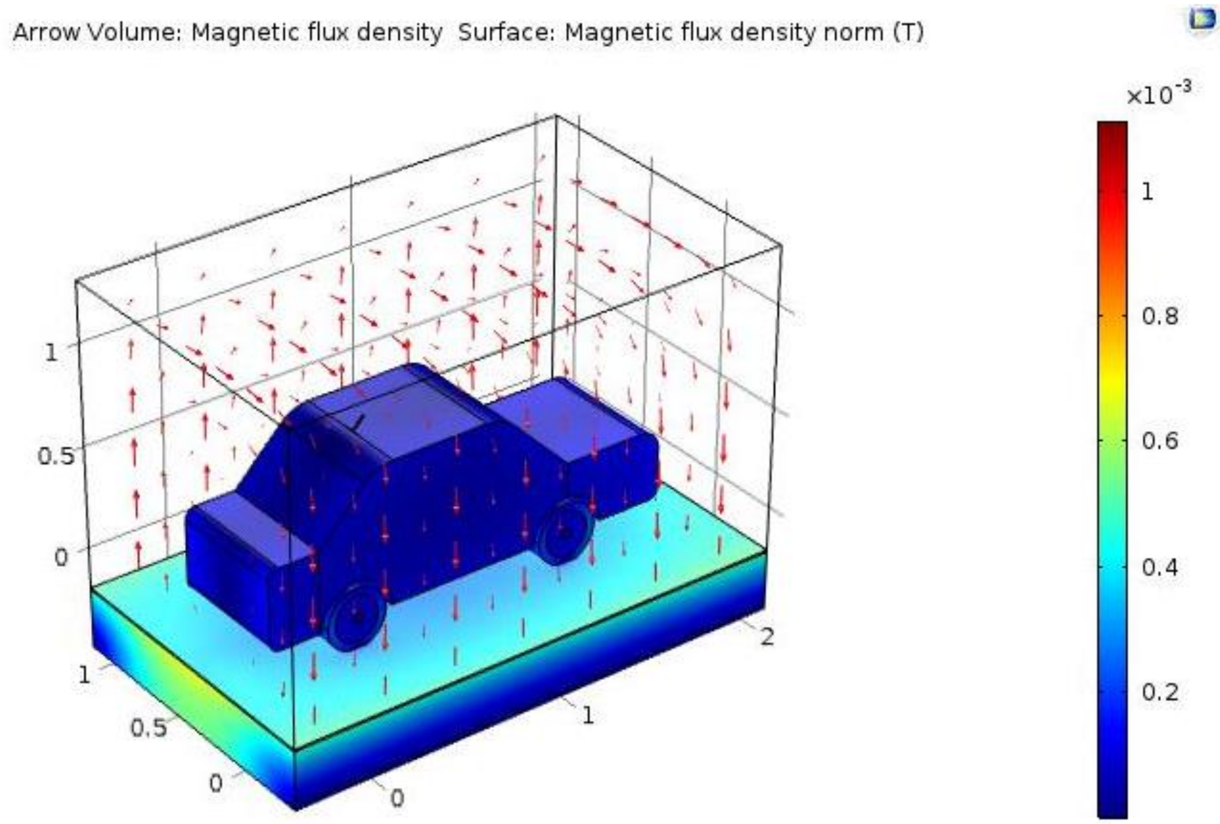
Configuration:



Configuration Details:

1.	**Problem**	Magnetostatic field analysis in Electric Vehicle Solid Structure without Air medium.
2.	**Solver**	Magnetostatic
3.	**Study**	Stationary
4.	**Governing Equation**	$\varepsilon\nabla^2 V = 0$ | $\nabla . D = \rho_v$ | $E = -\nabla V$
5.	**Dimension**	3D | Car solid structure
6.	**Material Properties**	Air | Copper | Sand | Steel | Epoxy Resin Relative Permittivity of Air | Relative Permittivity of Copper | Relative Permittivity of Sand | Relative Permittivity of Steel | Relative Permittivity of Steel .
7.	**Source**	Surface current Density = 750kA/m | External Current density = $1A/m^2$
8.	**Software**	COMSOL Multiphysics 5.6 – AC/DC Module

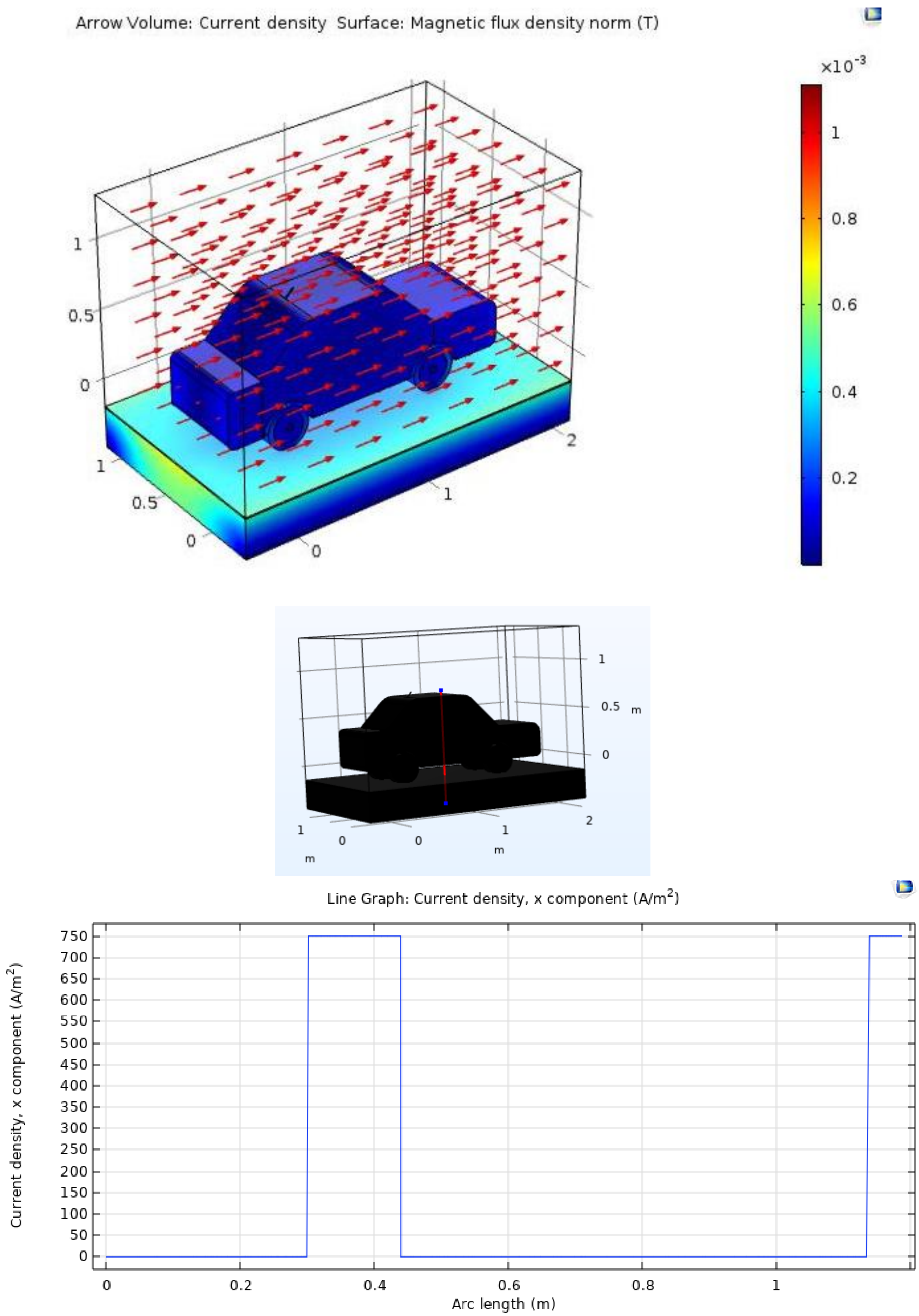
Plot Details:



Maximum and Minimum Values

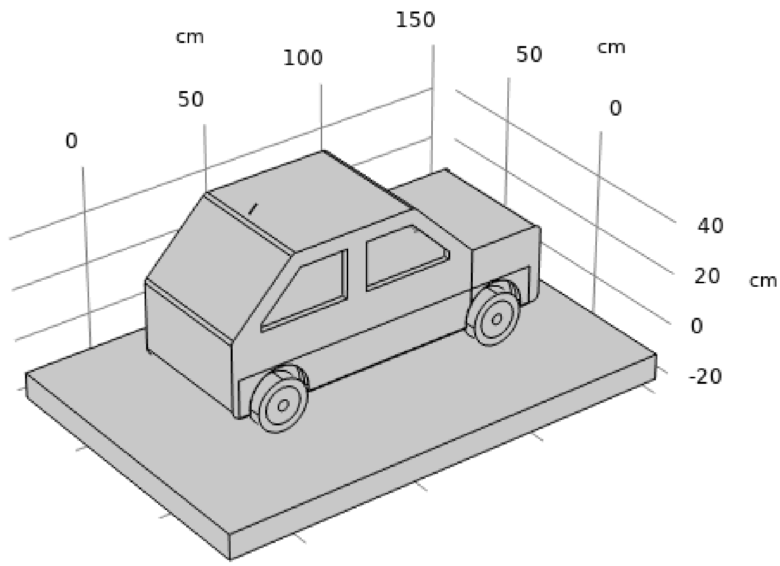
x	y	z	Magnetic flux density norm (T)
-450.00E-3	1.0500	-440.00E-3	250.29E-12
429.75E-3	303.00E-3	726.75E-3	1.1891E-3

[Fig – Maximum Flux Density]



[Fig – Current Density]

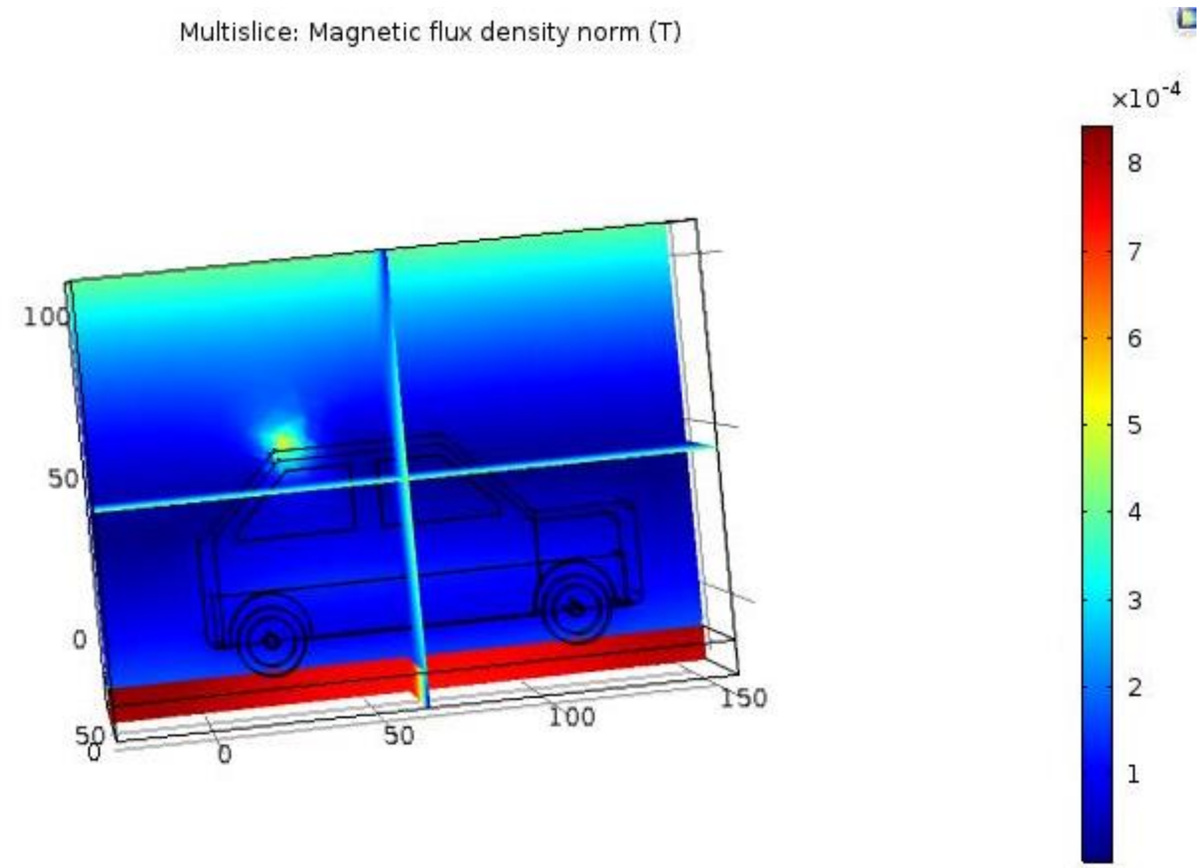
Configuration:

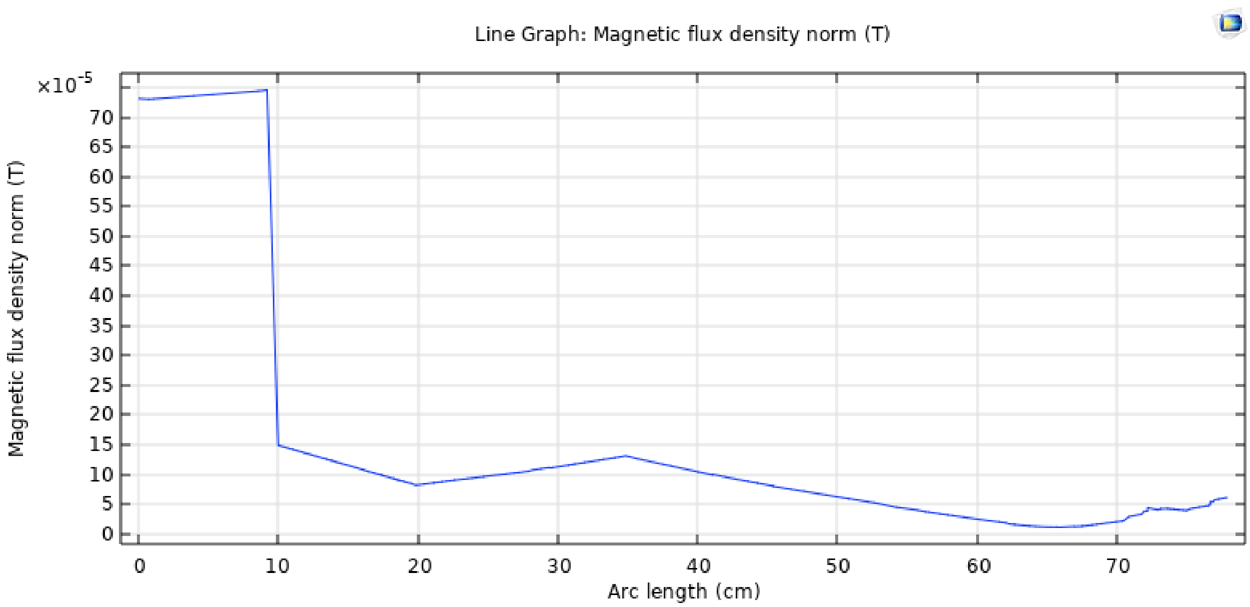


Configuration Details:

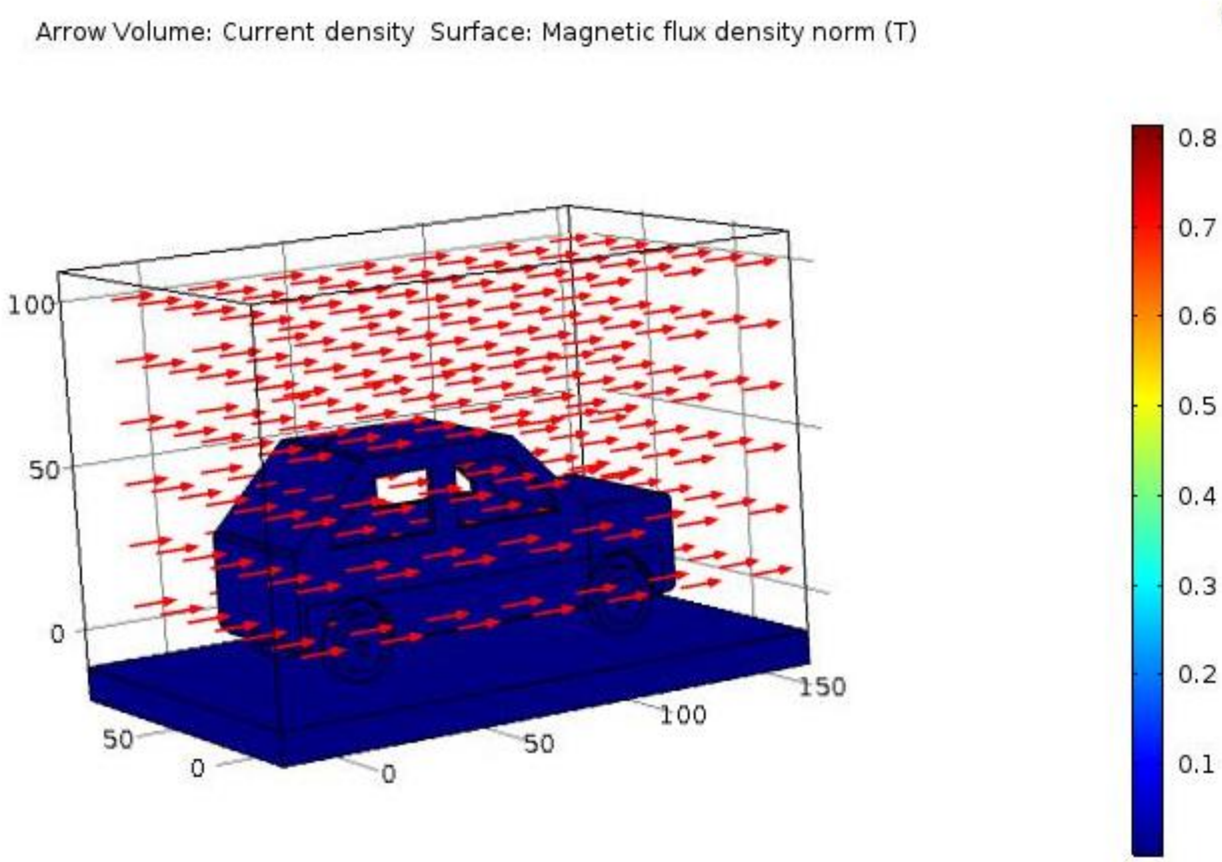
1.	**Problem**	Magnetostatic field analysis in Electric Vehicle hollow Structure
2.	**Solver**	Magnetostatic
3.	**Study**	Stationary
4.	**Governing Equation**	$\varepsilon\nabla^2 V = 0$ | $\nabla . D = \rho_v$ | $E = -\nabla V$
5.	**Dimension**	3D | Car Hollow structure
6.	**Material Properties**	Air | Copper | Sand | Steel | Epoxy Resin Relative Permittivity of Air | Relative Permittivity of Copper | Relative Permittivity of Sand | Relative Permittivity of Steel | Relative Permittivity of Steel .
7.	**Source**	Surface current Density = 750kA/m | External Current density =$1A/m^2$
8.	**Software**	COMSOL Multiphysics 5.6 – AC/DC Module

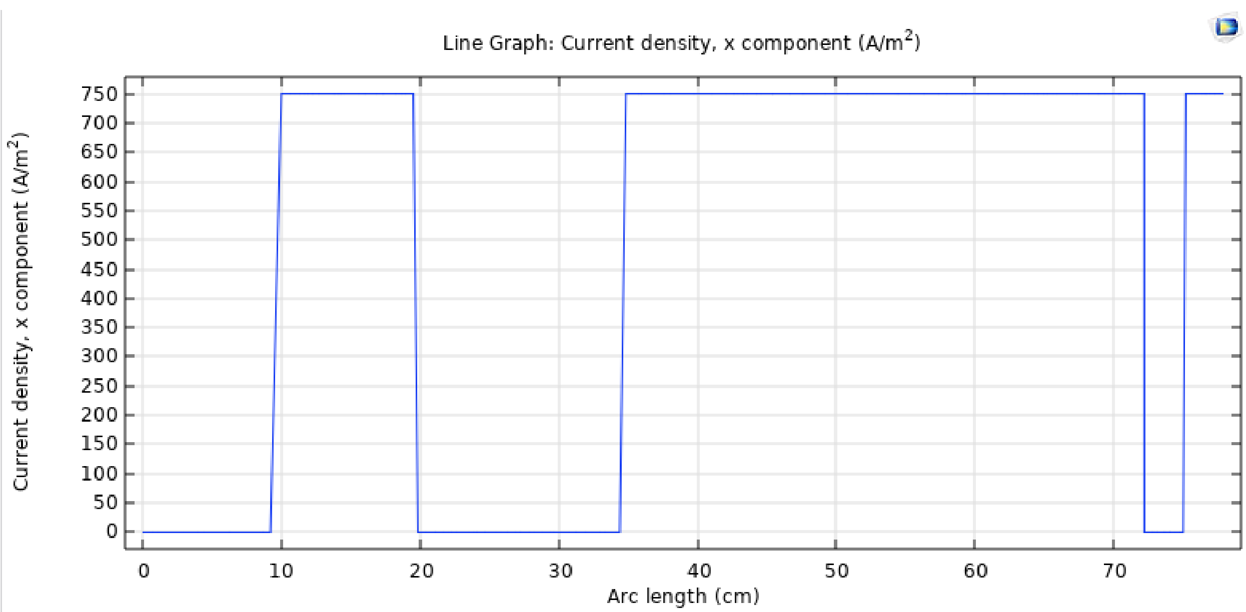
Plot Details:





[Fig – Magnetic flux density]

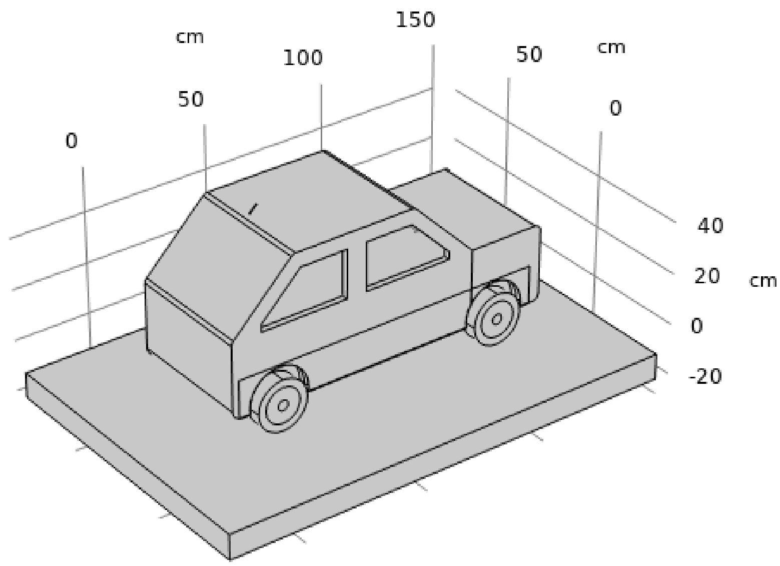




[Fig – Current Density]

Magnetostatic Analysis in Electric Vehicle with direct and Indirect Lightning

Configuration:

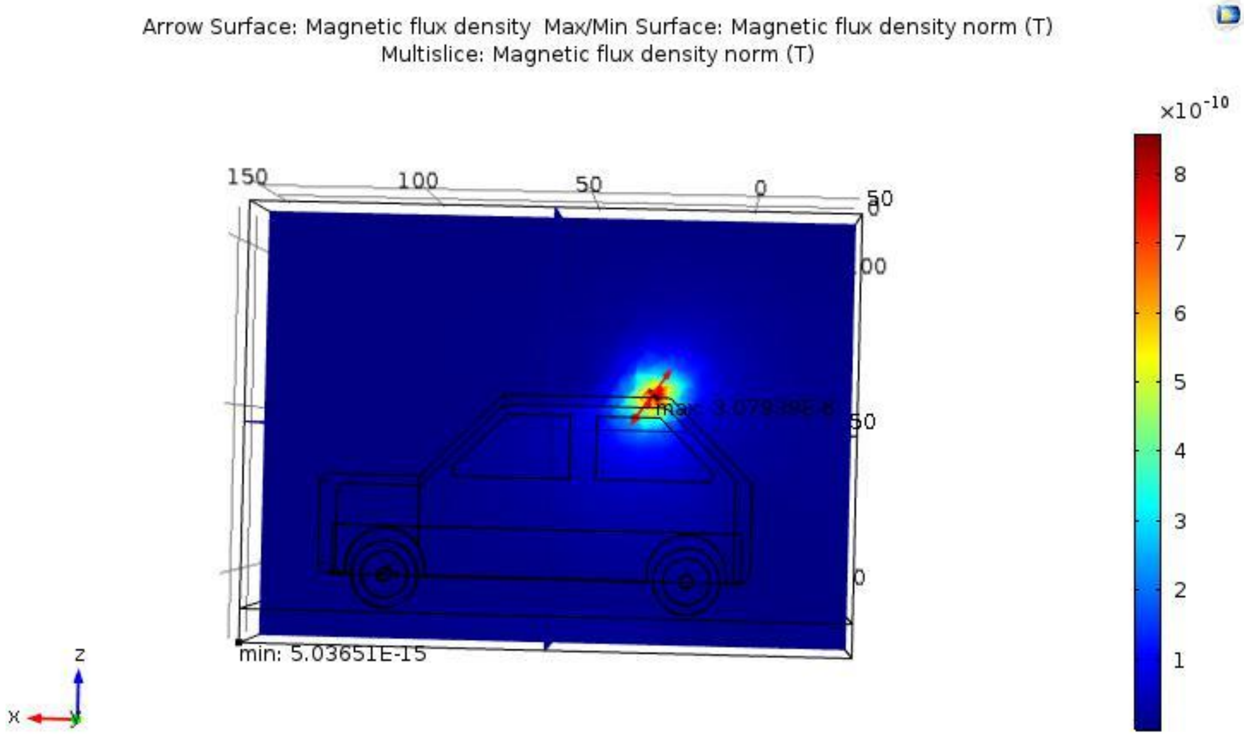


Configuration Details:

1.	**Problem**	Magnetostatic field analysis in Electric Vehicle hollow Structure with direct and indirect lightning effects
2.	**Solver**	Magnetostatic
3.	**Study**	Time Dependent
4.	**Governing Equation**	$\varepsilon\nabla^2 V = 0$ | $\nabla.D = \rho_v$ | $E = -\nabla V$
5.	**Dimension**	3D | Car Hollow structure
6.	**Material Properties**	Air | Copper | Sand | Steel | Epoxy Resin Relative Permittivity of Air | Relative Permittivity of Copper | Relative Permittivity of Sand | Relative Permittivity of Steel | Relative Permittivity of Steel .
7.	**Source**	Surface current Density = 1 A/m | External Current density = $1A/m^2$
8.	**Software**	COMSOL Multiphysics 5.6 – AC/DC Module

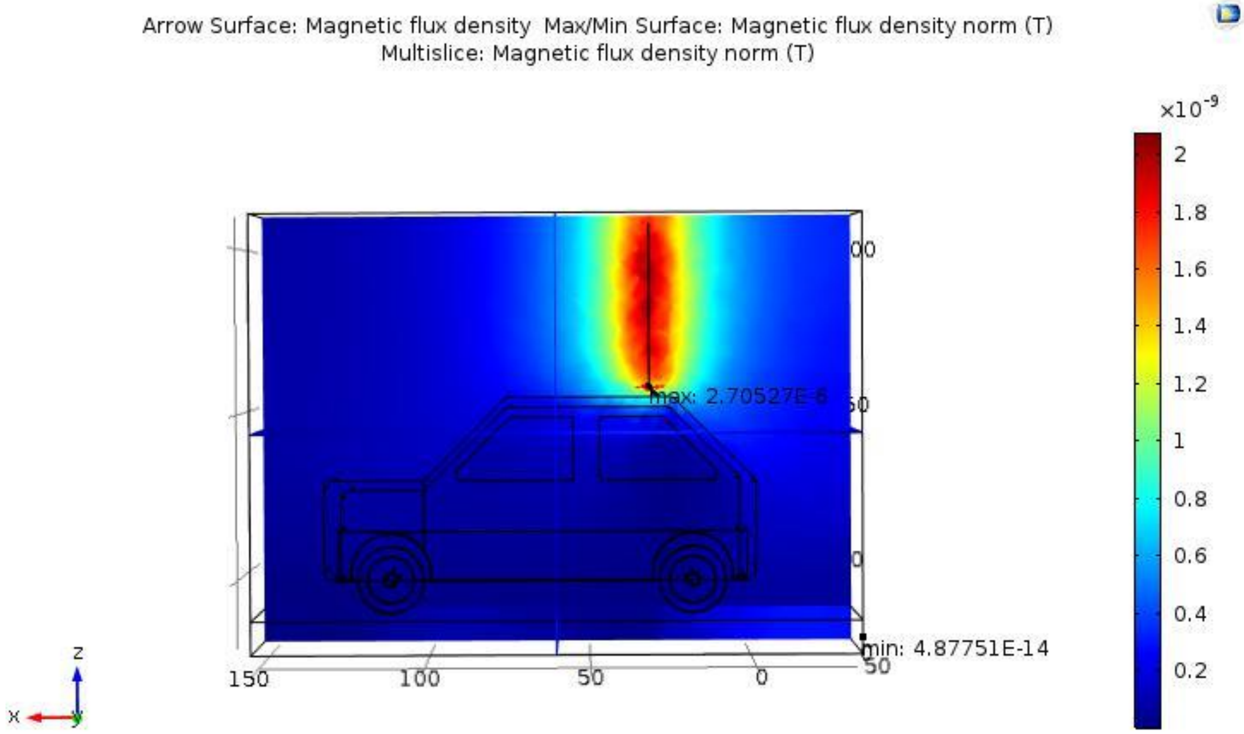
Plot Details:

Case (1): Simulation Setup in the case of direct lightning stroke:



Range of Magnetic Field distribution		
Source Point	**Discharging Points**	**Maximum Values ($Tesla$)**
Antenna (1 A and 1 ns)	Antenna Terminals	$3.079X\ 10^{-6}$
	Back Area	$2X\ 10^{-10}$
	Front area	$1X\ 10^{-10}$
	Front Wheel Shaft	0
	Front Wheel	5.036 X10^{-15}
	Back Wheel	5.036 X10^{-15}

Case (2): Simulation Setup in the case of direct lightning stroke from long distance:



Range of Magnetic Field distribution		
Source Point	**Discharging Points**	**Maximum Values ($Tesla$)**
Current Lead Wire (1A and 1 ns)	Antenna Terminals	$2.705X\ 10^{-6}$
	Top surface of the vehicle	$0.8X\ 10^{-9}$
	Front area	$0.4X\ 10^{-9}$
	Front Wheel Shaft	0
	Front Wheel	$4.877\ \mathrm{X}10^{-14}$
	Back Wheel	$4.877\ \mathrm{X}10^{-14}$

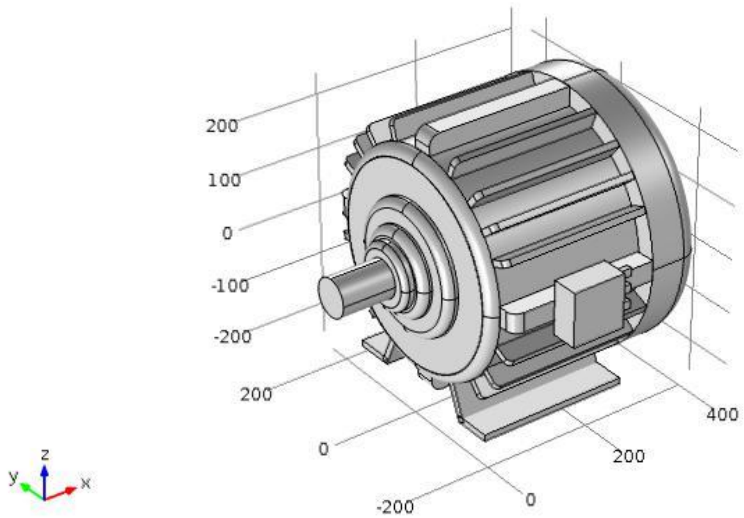
CONCLUSIONS

Based on the study of transient magnetic field, current distribution and electric field distribution in an electric vehicle, electric field distribution mainly occurs in the back wheel area as a heavily damaging part.

More amount of electric field intensity, magnetic flux density and current density occurs in back wheel part. From that when, the lightning effects affects the internal parts of electric vehicle through the transmission medium and shaft present in EV. So, care should be taken for internal parts of electric vehicle and human beings from lightning strokes.

The field distribution and current distribution on electric vehicle and internal parts is based on structure of vehicle, Material properties, Electrical design and Thermal design.

Configuration:



Configuration Details:

1.	**Problem**	Electrostatic field analysis in Permanent Magnet Motor
2.	**Solver**	Electrostatics
3.	**Study**	Stationary
4.	**Governing Equation**	$\varepsilon\nabla^2 V = 0$ | $\nabla . D = \rho_v$ | $E = -\nabla V$
5.	**Vehicle Dimension**	Length – 3994mm | Width – 1811mm | Height – 1607mm | Front track – 1540mm | Rear track – 1530mm | Rear interior width – 1350mm | Ground clearance – 205mm | Length between wheel midpoint – 2498mm | Front sheet to top height – 920mm | Back sheet to top height – 880mm | Front to sheet distance – 810 max to 630 min | Front sheet to back sheet distance – 880 max to 680 min
6.	**Motor Details**	Tata Nexon – Permanent magnet Synchronous Motor | Type - Surface magnets and pole shows
7.	**Material Properties**	Rotor Magnet – Ferrite |

8.	**Battery Rating**	30.2kWh | Nominal Voltage – 220 V
9.	**Temperature Range**	-5 to 45^0 Celsius
10.	**Source**	Higher Potential = 10000 V | Lower Potential = 0 V
11.	**Software**	COMSOL Multiphysics 5.2 – AC/DC Module

Design Calculation:

Consider the TATA Nexon Electric Vehicle specification as a reference for motor design. Permanent Magnet Synchronous motor with Surface magnets and pole shoe motor used.

Motor Specifications given data:

- $Power, P = 96{,}000(129HP)$
- $Torque, T = 245Nm$
- $Frequency, f = 50Hz$
- $Number\ of\ pole\ pairs, p' = 1$
- $Phase\ voltage, V_{ph} = 220V$

Calculation:

- $Line\ voltage, V_L = \sqrt{3}V_{ph} = 400V \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$
- $Angular\ Speed, \omega = \left(\frac{P}{T}\right) = \left(\frac{96000}{245}\right) = 391 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$
- $Number\ of\ Poles, p = \left(\frac{120f}{N_s}\right) = \left(\frac{120\ X\ 50}{3740}\right) = 2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$

The diameter and length of electrical machine obtained from the following equation,

- $Power, P = 4.44NK_\omega ABD_r{}^2 l' f \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (4)$

  Where,

  $A - RMS\ value\ of\ linear\ current\ density$

  $P - Machine\ power$

  $K_\omega - Winding\ factor$

$Dl - Main\ dimension\ of\ machine$

$T = tangential\ force\ X\ r_r$

- $tangential\ force, \delta_{\tan\,(ave)} = \left(\frac{AB\ cos\theta}{\sqrt{2}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(5)$

For PMSM;

- $Current\ Density, A = 30 - 80kA/m$
- $Yoke\ flux\ density, B = 1 - 1.6T$

We choose: $A = 40kA/m$ and $B = 1.3T$

- $\delta_{\tan\,(ave)} = \left(\frac{AB\ cos\theta}{\sqrt{2}}\right) = \left(\frac{40000\ X\ 1.3\ X\ 1}{\sqrt{2}}\right) = \frac{36{,}769.55A}{m} \ldots\ldots..(6)$

We know that,

- $Torque, T = \left(\frac{P}{\omega}\right) = 245Nm$

  $245 = 2\ X\ 36{,}769.55V_r$

- $V_r = \left(\frac{245}{73539.1}\right) = 0.003331561m^3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(7)$

  $\frac{\pi D_r{}^2 l'}{4} = 0.00333156 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$

- $D_r{}^2 l' = \left(\frac{4\ X\ 0.00333156}{\pi}\right) = 0.0042440268m^3$

Let assume, $x = \left({l'}/{D_r}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$

Where;

$l' - Machine\ stalk\ length$

$D_r - Rotor\ external\ diameter$

$x - Constant$

$x = \frac{\pi}{4p}\sqrt{p} = 0.785 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(10)$

Let assume, $D_r = 0.2$ and $l' = x\ X\ D_r = 0.8\ X\ 0.2 = 0.16$

$$D_r{}^2 l' = 0.0042440268m^3$$

$D_r = \left(\frac{0.0042440268m^3}{l'}\right)$

$$= \left(\frac{0.0042440268m^3}{0.16}\right)$$

- $D_r = 0.162865489$

From the above calculation we found diameter and length of the machine.

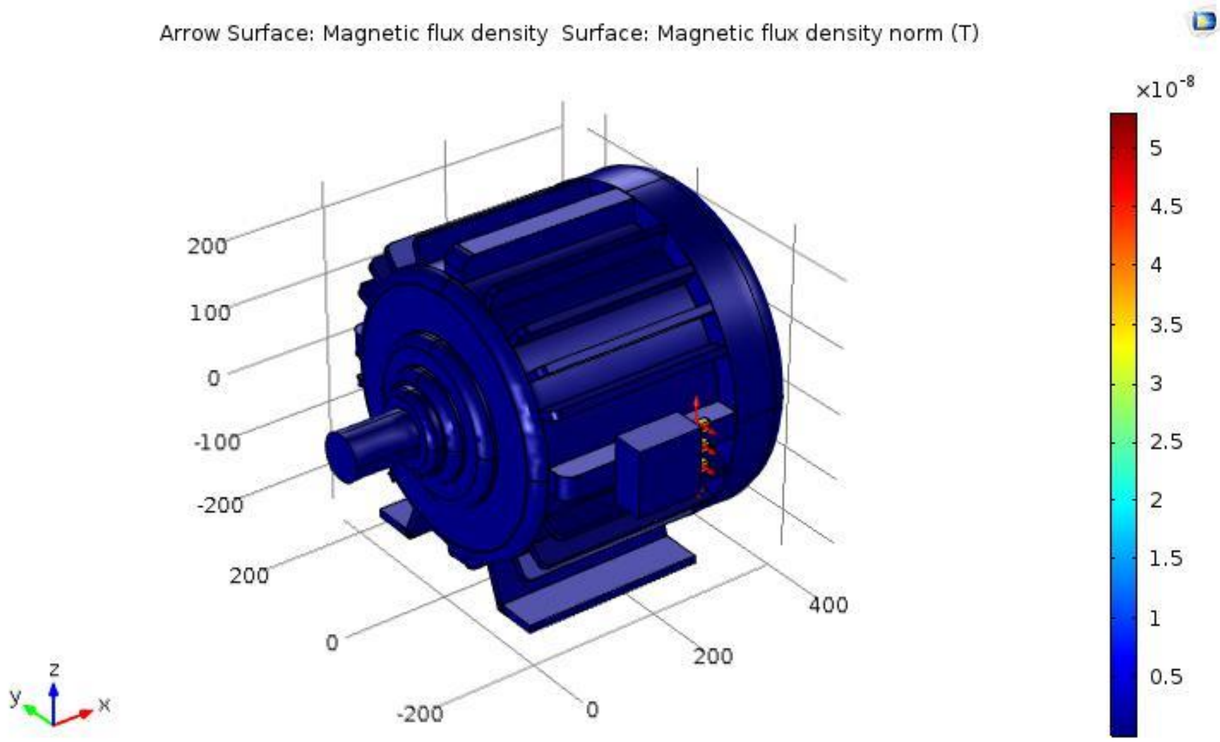
- $D_r = 0.163m = 163mm$
- $l' = 0.16m = 160mm$

Summary of Design Calculation:

Description	Values
Power (P_{Max})	96,000W, 129HP (96kW)
Frequency (f)	50Hz
Number of poles (P)	2
Number of pole pair (p)	1
Number of phases (m)	3
Phase voltage V_{Ph}	220V
Line voltage V_L	400V
Number of slots (Q)	4
Speed (ω)	$3740\ rpm = 62\ rps = 391\ rad$
Power factor ($cos\varphi$)	1
Linear current density (A)	$40kA/m$
Stator yoke flux density (B)	$1.3T$
Average tangential stress (δ_{Tan})	$36769.55A/m$
Torque (T)	$245Nm$
Rotor Volume (V_r)	$0.003331561m^3$
Rotor Diameter (D_r)	$0.163m\ or\ 163mm$
Machine stalk length (l')	$0.160m\ or\ 160mm$
Stator external diameter $\left(D_{s,Ext}\right)$	$0.204m\ or\ 204mm$
Pole pitch $\left(\tau_{pp}\right)$	$256mm$
Pole pitch angel	180^0
Number of slots per pole	2
Circumference of the machine	$512mm$
Rotor shaft diameter	55mm

Shaft extension dimension	100mm
Height of PM	22mm Approx.

Plot Details:

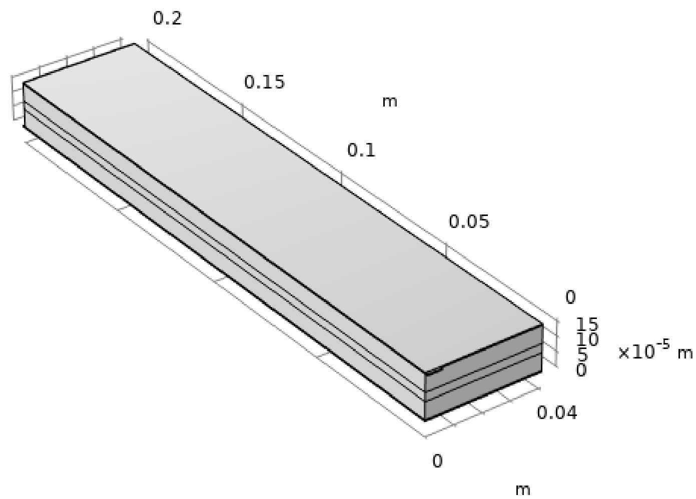


[Magnetic Flux Density in Permanent Magnet Motor]

Range of Magnetostatic Field distribution		
Source Point	**Discharging Points**	**Maximum Values**
Motor Terminals	Terminals	$4X10^{-8}Tesla$

Design of Battery Cell for EV application

Configuration:



Configuration Details:

1.	**Problem**	Battery Cell design
2.	**Solver**	Lithium Ion Battery
3.	**Study**	Current Distribution | Time Dependent
4.	**Governing Equation**	$\varepsilon\nabla^2 V = 0$ | $\nabla . D = \rho_v$ | $E = -\nabla V$
5.	**Vehicle Dimension**	Length – 3994mm | Width – 1811mm | Height – 1607mm | Front track – 1540mm | Rear track – 1530mm | Rear interior width – 1350mm | Ground clearance – 205mm | Length between wheel midpoint – 2498mm | Front sheet to top height – 920mm | Back sheet to top height – 880mm | Front to sheet distance – 810 max to 630 min | Front sheet to back sheet distance – 880 max to 680 min
6.	**Battery Cell Details**	Cell Width – 0.082m | Cell height – 0.2m | Tab height – 0.001m | Tab width – 0.01m | Initial cell state of charge – 0.2 | C rate – 1 and 4 | Positive electrode thickness - 60µm | Negative electrode

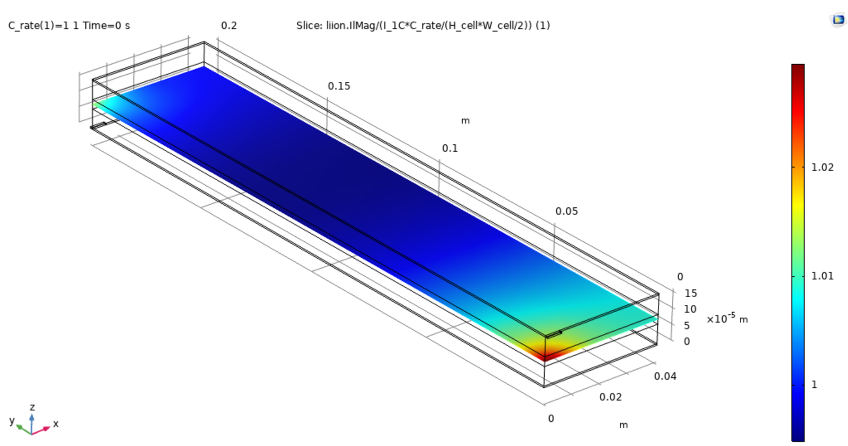
		thickness - 60µm | Positive current collector thickness - 10µm | Negative current collector thickness - 10µm.
7.	**Material Properties**	Aluminium | Copper | Graphite Electrode | LMO Electrode | Liquid Electrolyte | Positive Current Collector – Aluminium | Negative Current Collector – Copper | Negative Electrode – Graphite Electrode | Positive Electrode – LMO Electrode | Separator – LIPF 6 ECEMC Liquid Electrolyte
8.	**Battery Rating**	30.2kWh | Nominal Voltage – 320 V
9.	**Temperature Range**	-5 to 45^0 Celsius
10.	**Source**	Higher Potential = 10000 V | Lower Potential = 0 V
11.	**Software**	COMSOL Multiphysics 5.2 – AC/DC Module

Summary of Design Calculation:

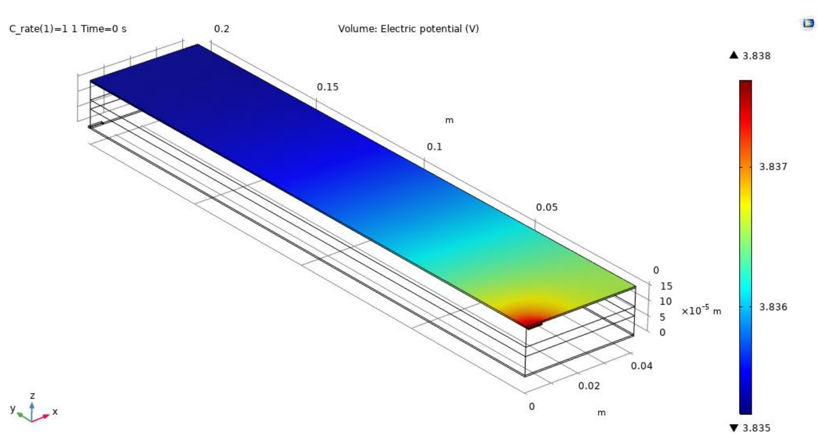
Description	**Values**
Power (P_{Max})	96,000W, 129HP (96kW)
Nominal Voltage (V)	320 V
Battery Rating	30.2kWh
Type of battery	Pouch and cylinder
Cell voltage	3.6 V
Capacity of single cell	3.2Ah
Height of cell	0.2m
Width of cell	0.08m
Thickness of cell	0.007m
Weight of cell	0.032kg
Specific energy density	9.13Wh
Volume of pouch cell	$0.00017m^3$
Energy of single cell	11.52Wh
Torque (T)	$245Nm$
Energy density of single cell	360Wh/kg
No of battery cell connected in series	88
Energy content of string	1024Wh

Average energy consumption	188.045Wh/kg
Battery pack total energy	47Kwh
No of string of battery pack	45
Battery pack capacity	144Ah
No of cells in the battery pack	3960
Peak Current for 1C	3.2A
Battery pack peak current for 1C	45A
Battery material for TATA Nexon	Steel

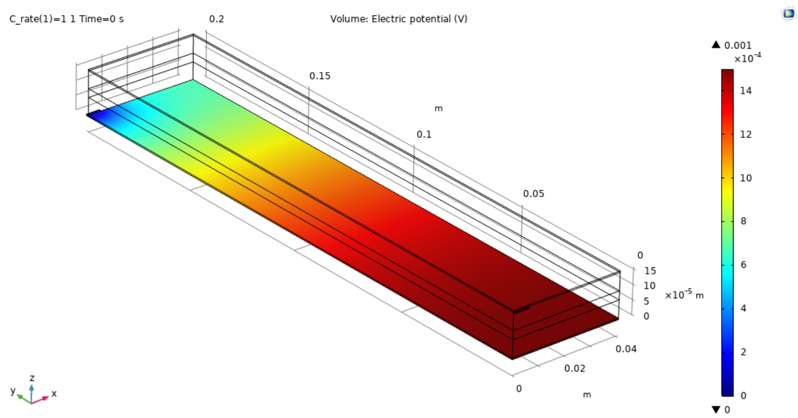
Plot Details:



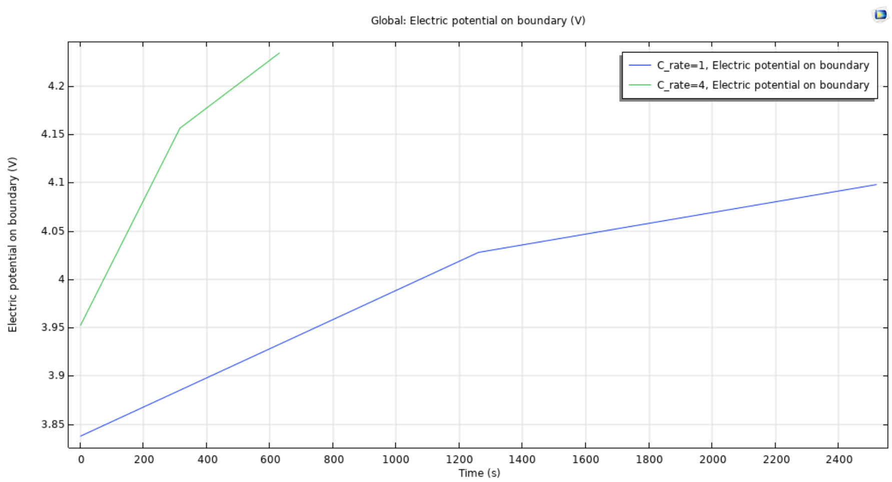
[Current distribution in the middle of the separator]



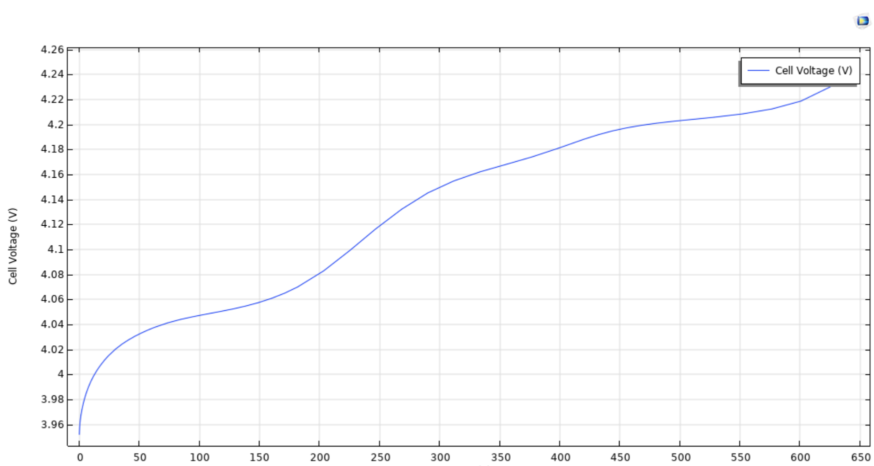
[Potential distribution in the positive metal foil]



[Potential Distribution in Negative Metal foil]



[Electric Potential on Boundary at 1 and 4 C rate]

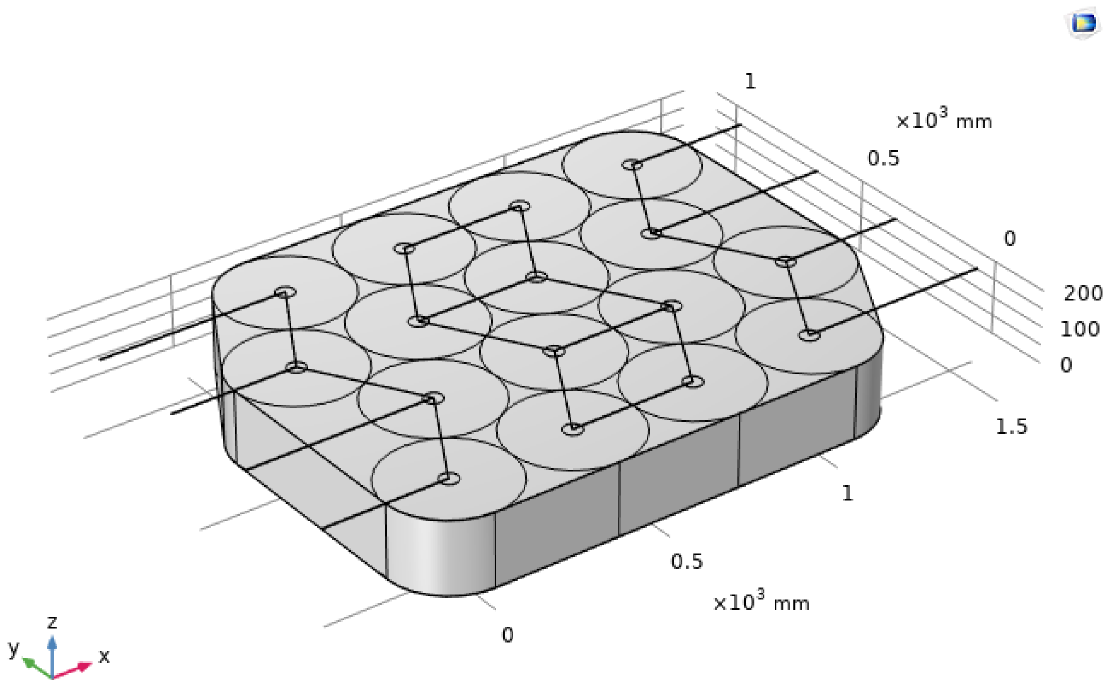


[Cell Voltage]

C Rate	Discharge Rate	C Rate Ratio	Battery Current (A)
0.2 C	5 $Hours$	${}^{144AH}/{}_{5H}$	28 A
0.5 C	2 $Hours$	${}^{144AH}/{}_{2H}$	72 A
1 C	1 $Hours$	${}^{144AH}/{}_{1H}$	144 A
2 C	0.5 $Hours$	${}^{144AH}/{}_{0.5H}$	288 A
4 C	0.25 $Hours$	${}^{144AH}/{}_{0.25H}$	576 A
Inferences			
High C Rate | High Potential Stress | Fast charging and discharging | High Temperature | Low battery life | High Power.			

Design of Battery Pack for EV application

Configuration:



Configuration Details:

1.	**Problem**	Battery Pack design
2.	**Solver**	Lithium Ion Battery
3.	**Study**	Current Distribution | Time Dependent
4.	**Governing Equation**	$\varepsilon\nabla^2 V = 0$ | $\nabla . D = \rho_v$ | $E = -\nabla V$
5.	**Vehicle Dimension**	Length – 3994mm | Width – 1811mm | Height – 1607mm | Front track – 1540mm | Rear track – 1530mm | Rear interior width – 1350mm | Ground clearance – 205mm | Length between wheel midpoint – 2498mm | Front sheet to top height – 920mm | Back sheet to top height – 880mm | Front to sheet distance – 810 max to 630 min | Front sheet to back sheet distance – 880 max to 680 min

6.	**Battery Cell Details**	Cell Width – 0.082m | Cell height – 0.2m | Tab height – 0.001m | Tab width – 0.01m | Initial cell state of charge – 0.2 | C rate – 1 and 4 | Positive electrode thickness - 60µm | Negative electrode thickness - 60µm | Positive current collector thickness - 10µm | Negative current collector thickness - 10µm.
7.	**Material Properties**	Aluminium | Copper | Graphite Electrode | LMO Electrode | Liquid Electrolyte | Positive Current Collector – Aluminium | Negative Current Collector – Copper | Negative Electrode – Graphite Electrode | Positive Electrode – LMO Electrode | Separator – LIPF 6 ECEMC Liquid Electrolyte
8.	**Battery Rating**	30.2kWh | Nominal Voltage – 320 V
9.	**Temperature Range**	-5 to 45^0 Celsius
10.	**Source**	Higher Potential = 10000 V | Lower Potential = 0 V
11.	**Software**	COMSOL Multiphysics 5.2 – AC/DC Module

Design Calculation:

Consider the TATA Nexon Electric Vehicle specification as a reference for Lithium-ion battery design. Here we used pouch and cylinder type of battery and battery pack.

Battery Specifications given data:

- $Kerb\ Weight = 1400kg$
- $Nominal\ voltage = 320V$
- $Battery\ rating = 30.2kWh$
- $Type\ of\ battery\ cell = Pouch\ and\ cylinder$
- $Cell\ voltage = 3.6V$
- $Capacity\ of\ single\ cell = 3.2Ah$
- $Height\ of\ the\ cell = 0.272m$
- $Width\ of\ the\ cell = 0.082m$
- $Thickness\ of\ the\ cell = 0.0072m$
- $Weight\ of\ the\ cell = 0.032m$

- $Specific\ energy\ density = 9.13Wh$

Calculation:

- $Volume\ of\ the\ pouch\ cell:$

$$V_{pc} = H_{pc}\ X\ W_{pc}\ X\ T_{pc} = 0.00017m^3 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(1)$$

- $Energy\ of\ the\ cell:$

$$Cell\ voltage\ X\ capacity\ of\ single\ cell = 3.6\ X\ 3.2 = 11.52Wh \dots\dots\dots..(2)$$

- $Energy\ density\ of\ the\ cell:$

$$= \left(\frac{11.52}{0.032}\right) = \frac{360Wh}{kg} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(3)$$

- $Number\ of\ cell\ connected\ series = \left({}^{320}/_{3.6}\right) = 88 \dots\dots\dots\dots\dots\dots\dots\dots\dots(4)$

- $Battery\ pack\ total\ energy = E_{Ave}\ X\ Vehicle\ range = 188.45\ X\ 250 = 47kWh \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(5)$

- $No\ of\ strings\ of\ battery\ pack =$

$$\left({}^{Battery\ pack\ total\ energy}/_{Energy\ content\ of\ string}\right)$$

$$= \left({}^{47000}/_{1024}\right) = 45 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(6)$$

- $Battery\ pack\ capacity = No\ of\ stringof\ battery\ pack\ X\ Capacity\ of\ single\ cell$

$$= 45\ X\ 3.2 = 144Ah \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(7)$$

- $No\ of\ cells\ of\ the\ battery\ pack =$

$$No\ of\ string\ of\ battery\ pack\ X\ no\ of\ battery\ connected\ in\ series$$

$$= 45\ X\ 88 = 3960 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(8)$$

- $Peak\ current = C\ rate\ X\ capacity\ of\ single\ cell \dots\dots\dots\dots\dots\dots\dots\dots.(9)$

$$For\ 1\ C: 1\ X\ 3.2 = 3.2A$$

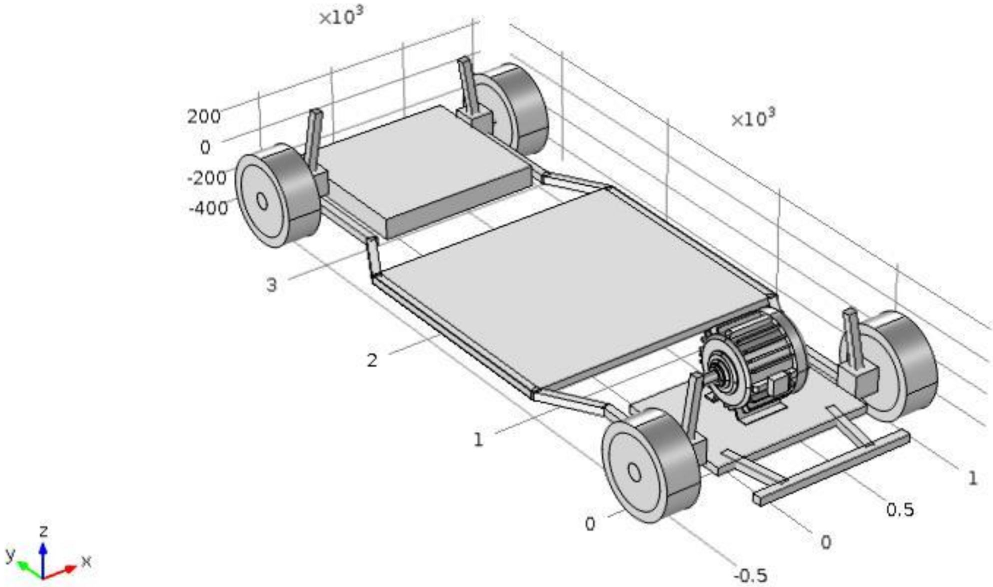
$$For\ 2\ C: 2\ X\ 3.2 = 6.4A$$

$$For\ 4\ C: 4\ X\ 3.2 = 12.8A$$

Summary of Design Calculation:

Description	Values
Power (P_{Max})	96,000W, 129HP (96kW)
Nominal Voltage (V)	320 V
Battery Rating	30.2kWh
Type of battery	Pouch and cylinder
Cell voltage	3.6 V
Capacity of single cell	3.2Ah
Height of cell	0.2m
Width of cell	0.08m
Thickness of cell	0.007m
Weight of cell	0.032kg
Specific energy density	9.13Wh
Volume of pouch cell	$0.00017m^3$
Energy of single cell	11.52Wh
Torque (T)	$245Nm$
Energy density of single cell	360Wh/kg
No of battery cell connected in series	88
Energy content of string	1024Wh
Average energy consumption	188.045Wh/kg
Battery pack total energy	47Kwh
No of string of battery pack	45
Battery pack capacity	144Ah
No of cells in the battery pack	3960
Peak Current for 1C	3.2A
Battery pack peak current for 1C	45A
Battery material for TATA Nexon	Steel

Configuration:

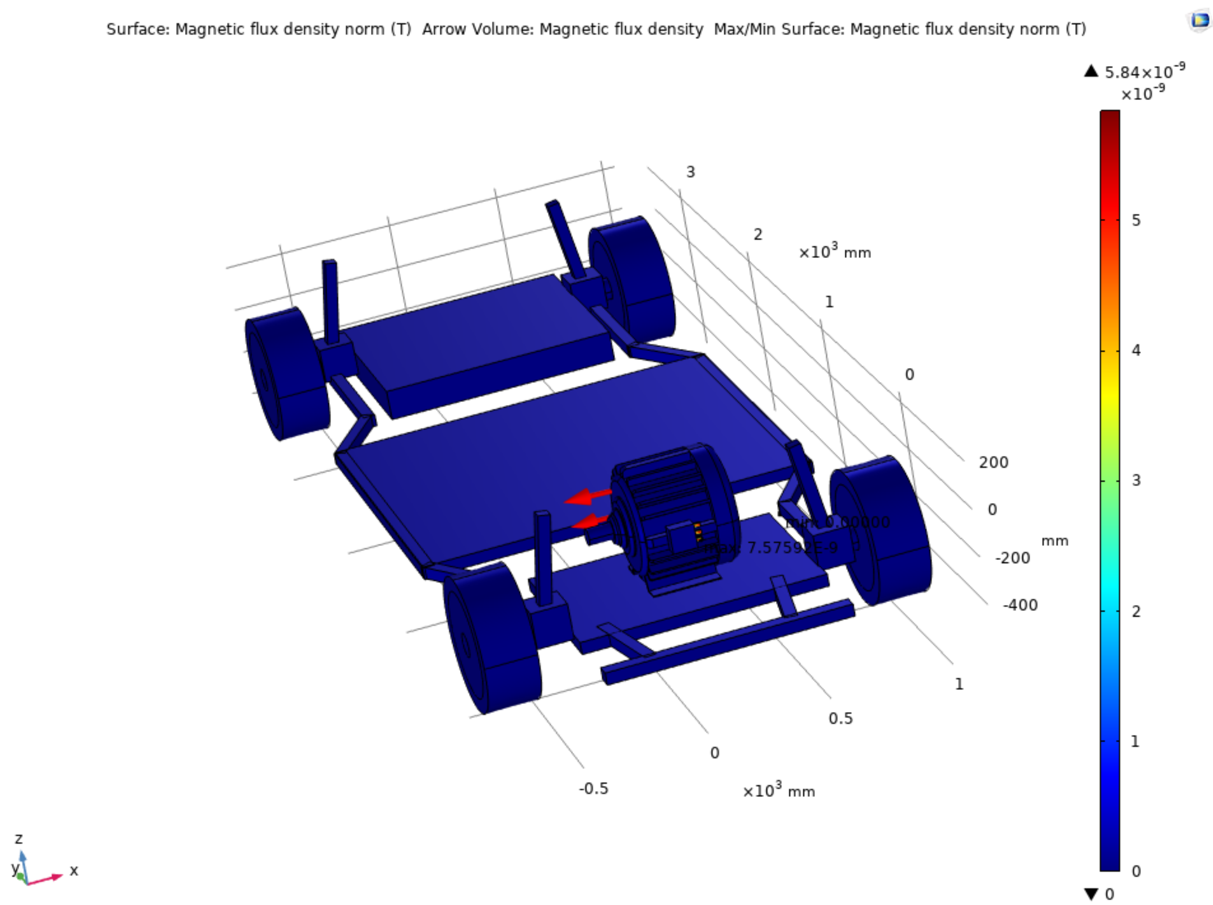


Configuration Details:

1.	**Problem**	Internal Field Distribution – Motor Mode
2.	**Solver**	Magnetostatic
3.	**Study**	Stationary
4.	**Governing Equation**	$\varepsilon\nabla^2 V = 0$ | $\nabla . D = \rho_v$ | $E = -\nabla V$
5.	**Vehicle Dimension**	Length – 3994mm | Width – 1811mm | Height – 1607mm | Front track – 1540mm | Rear track – 1530mm | Rear interior width – 1350mm | Ground clearance – 205mm | Length between wheel midpoint – 2498mm | Front sheet to top height – 920mm | Back sheet to top height – 880mm | Front to sheet distance – 810 max to 630 min | Front sheet to back sheet distance – 880 max to 680 min
6.	**Motor Details**	Tata Nexon – Permanent magnet Synchronous Motor | Type - Surface magnets and pole shows

7.	**Material Properties**	Rotor Magnet – Ferrite |
8.	**Battery Rating**	30.2kWh | Nominal Voltage – 220 V
9.	**Temperature Range**	-5 to 45^0 Celsius
10.	**Source**	Higher Potential = 10000 V | Lower Potential = 0 V
11.	**Software**	COMSOL Multiphysics 5.2 – AC/DC Module

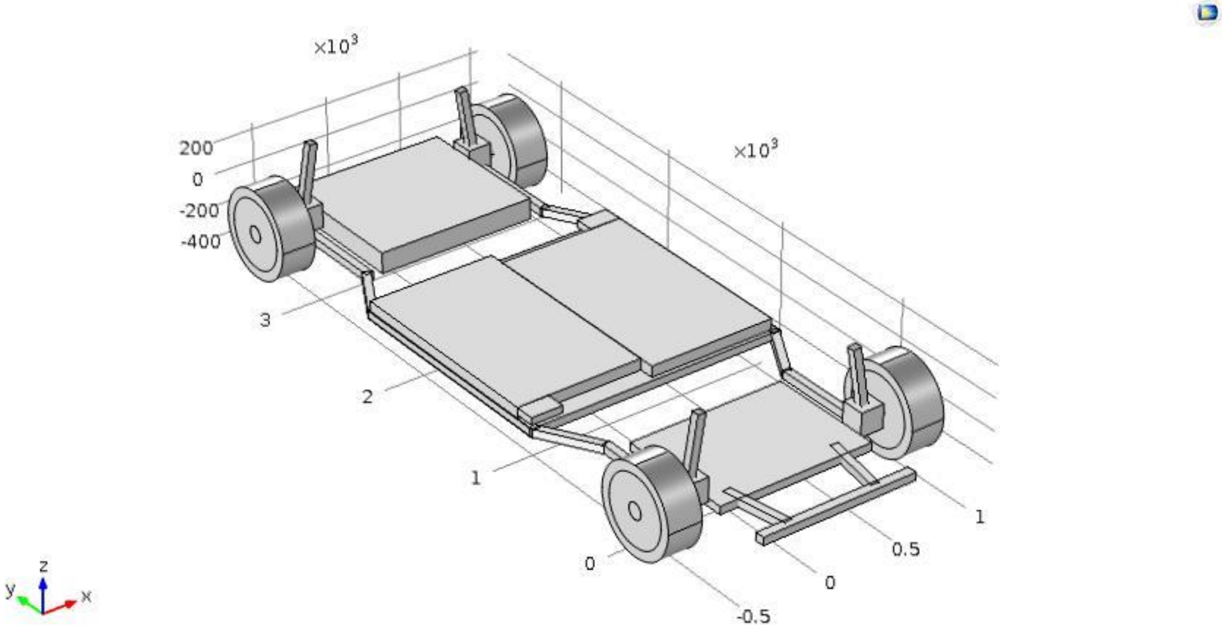
Plot Details:



[Internal Field Distribution – Motor Mode]

Range of Magnetic Field distribution		
Source Point	**Discharging Points**	**Maximum Values (Tesla)**
Motor Terminals	Motor Terminals	$5.84\ X\ 10^{-9}$
	Surface	$7.575\ X\ 10^{-9}$
	Motor Frame	$7.575\ X\ 10^{-9}$
	Front Wheel Shaft	0
	Front Wheel	0
	Back Wheel	0

Configuration:

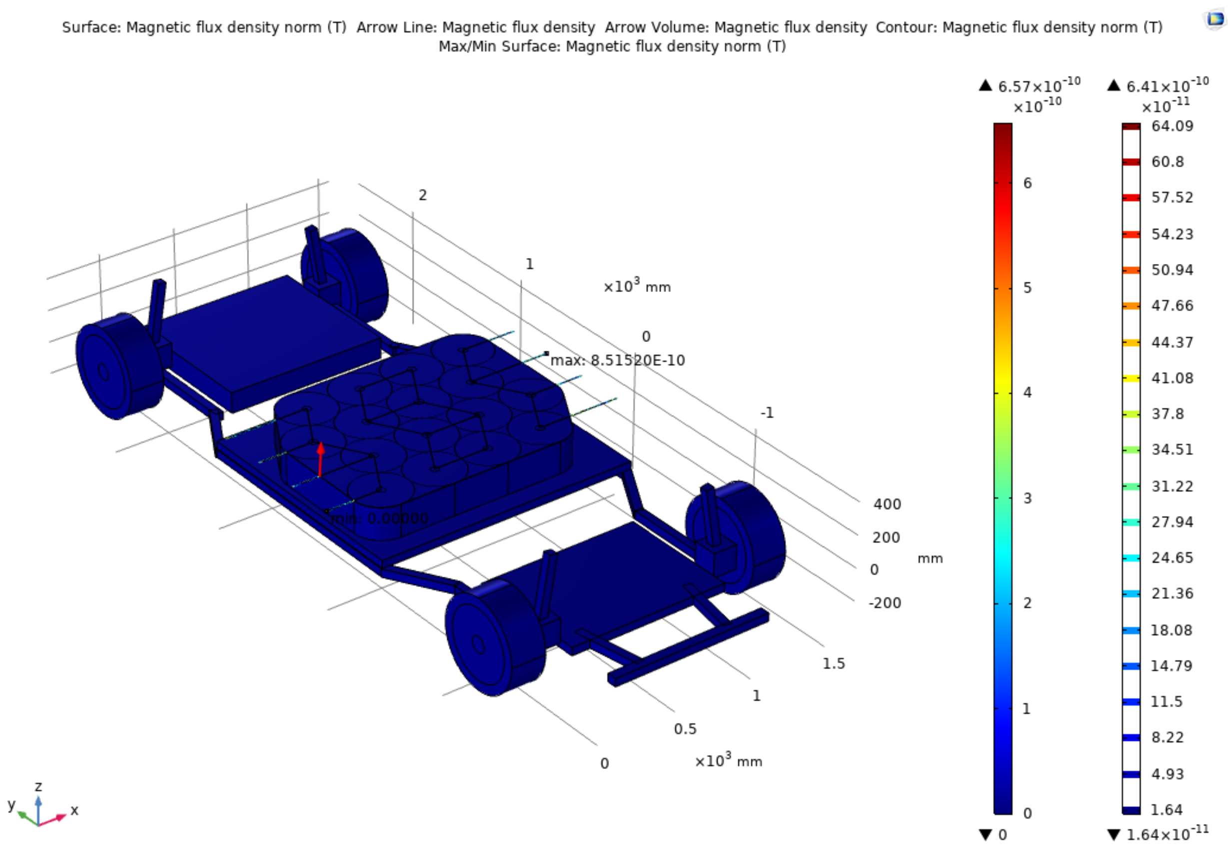


Configuration Details:

1.	**Problem**	Internal Field Distribution – Battery Pack Mode
2.	**Solver**	Magnetostatic
3.	**Study**	Stationary
4.	**Governing Equation**	$\varepsilon\nabla^2 V = 0$ | $\nabla . D = \rho_v$ | $E = -\nabla V$
5.	**Vehicle Dimension**	Length – 3994mm | Width – 1811mm | Height – 1607mm | Front track – 1540mm | Rear track – 1530mm | Rear interior width – 1350mm | Ground clearance – 205mm | Length between wheel midpoint – 2498mm | Front sheet to top height – 920mm | Back sheet to top height – 880mm | Front to sheet distance – 810 max to 630 min | Front sheet to back sheet distance – 880 max to 680 min
6.	**Motor Details**	Tata Nexon – Permanent magnet Synchronous Motor | Type - Surface magnets and pole shows

7.	**Material Properties**	Rotor Magnet – Ferrite |
8.	**Battery Rating**	30.2kWh | Nominal Voltage – 220 V
9.	**Temperature Range**	-5 to 45^0 Celsius
10.	**Source**	Higher Potential = 10000 V | Lower Potential = 0 V
11.	**Software**	COMSOL Multiphysics 5.2 – AC/DC Module

Plot Details:



[Internal Field Distribution – Battery Pack Mode]

Range of Magnetic Field distribution		
Source Point	**Discharging Points**	**Maximum Values (Tesla)**
Battery Pack Terminals	Battery Terminals	$6.57\ X\ 10^{-10}$
	Surface	$8.51\ X\ 10^{-10}$
	Battery Frame	$8.51\ X\ 10^{-10}$
	Front Wheel Shaft	0
	Front Wheel	0
	Back Wheel	0

CONCLUSIONS:

The field distribution and current distribution on electric vehicle and internal parts is based on structure of vehicle, Material properties, Electrical design and Thermal design. Also, Electric Vehicle battery pack life is based on C rate, Potential stress, Fast charging and discharging rate, Temperature and power.