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Electric Vehicle Parameters and Vehicle Range

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ABSTRACT

Wheel forces play a crucial role in electric vehicles as they enable the vehicle to overcome various resisting forces. The traction force (Ft) generated at the drive wheel is composed of these resistance forces, which include rolling resistance, aerodynamic drag, gradient resistance, and inertia resistance. This paper analyzes how wheel forces and wheel RPM are influenced by different vehicle speeds, and how wheel power changes with vehicle speed. Additionally, it examines the power requirements of the electric motor and the average energy consumption of the battery pack used in the electric vehicle.

KEYWORDS: *traction force, resistance forces, wheel rpm, wheel power, electric motor power, battery pack*

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I. INTRODUCTION

Global warming and environmental pollution have led to stricter regulations on CO2 and other pollutant emissions. Electric vehicles (EVs) have become an alternative to conventional vehicles as they offer a zero-emission solution. Additionally, they are cheaper to recharge since electricity is less expensive than petrol or diesel, and energy recovery is possible through regenerative braking in EVs.

However, the market penetration rate of EVs is not very rapid due to factors such as their limited range, long charging times, high battery replacement costs, and infrastructure-related limitations. This study specifically addresses one of these challenges: the limited range of EVs [1].

EVs generally have three times better fuel efficiency compared to internal combustion engine (ICE) vehicles. Electric motors naturally convert electrical energy into rotational motion, resulting in less noise and vibration, making them quiet and comfortable. Additionally, electric motors typically do not require fluids or filters, which simplifies maintenance schedules. They also provide a much flatter torque curve across the entire operating range, allowing for the elimination of transmissions or the use of only a few-speed transmissions. Furthermore, it is relatively simple to drive each wheel with a separate motor [2].

The EV market has been significantly impacted by the widespread use of lithium-ion cells. Lithium-ion cells offer several key advantages, such as fast charging, lightweight design, temperature tolerance, and long lifespan, which have solidified their role in electric vehicle design. However, compared to internal combustion engine (ICE) vehicles, the energy storage capacity of current cells is still relatively low. Among various battery types, lithium-ion batteries (LIBs) have dominated the EV market due to their high energy density and specific energy [3]. Energy consumption in EVs is a critical topic, as the adoption of these vehicles largely depends on the accurate and efficient estimation of their range.

II. VEHICLE TRACTIVE FORCE

To analytically calculate the energy consumption of an electric vehicle, it is crucial to determine the tractive force acting on the vehicle. The various forces acting on the vehicle are illustrated in Figure [1]. These forces include inertia force (FI), rolling resistance (FR), aerodynamic drag force (FA), and hill climbing force (FG). The sum of these forces is referred to as the total tractive force. The governing equations (Equations 1–5) are used to calculate these forces.

Inertia Force

$F_I = ma$ (1)

Where,
m = mass to be accelerated(kg)
a = the acceleration due to gravity(m/s²)

Aerodynamic Drag Force

$F_A = \frac{1}{2}\rho_a A_f C_d V^2$ (2)

Where,
ρ_a=the density of air (kg/m³)
C_d=drag coefficient
A_f=vehicle frontal area(m²)
V=speed of the vehicle

Rolling Resistance Force

$F_R = c_r mg \cos\alpha$ (3)

Where,
c_r=tire rolling resistance
m=mass of the vehicle(kg)
g=gravitational constant (9.81m/s²)
α=road inclination angle(degree)

Hill Climbing Force

$F_G = mg \sin\alpha$ (4)

Where,
m=mass of vehicle(kg)
α=the angle between level road and horizontal plane of the vehicle(degree)
g=gravitational constant (9.81m/s²)

Total Tractive Force

$F_T = F_I + F_A + F_R + F_G$ (5)

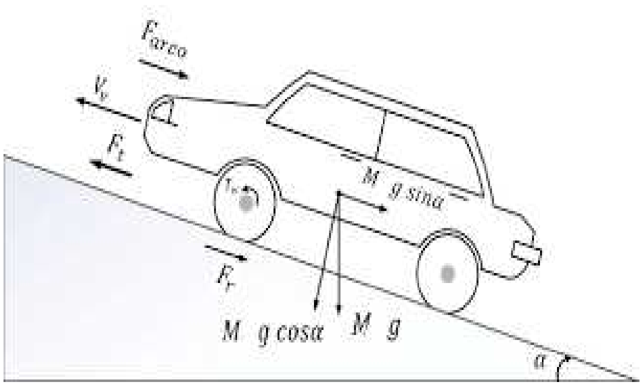

Fig 1. Various force acting on the Vehicle

Table 1. Specifications of vehicle

Parameters	Symbol	value	Unit
Gross mass	m	2070	kg
Acceleration gravity	g	9.81	m/s²
Rolling resistance	C_r	0.008	
Coefficient of drag	C_D	0.35	
Air density	ρ_a	1.2	Kg/m³
Frontal area	A	2.983	m²
Wheel radius	R	0.2159	m
Hill climbing angle	α	6	Degree

Table 2. The resisting forces of vehicle for different speed and road inclination 0% and 2%

Vehicle Speed	Gradient 0%			Gradient 2%		
	F_R (N)	F_A (N)	F_G (N)	F_R (N)	F_A (N)	F_G (N)
50	162.45	120.86	0	162.42	120.86	407.55
100	162.45	483.43	0	162.42	483.43	407.55
150	162.45	1087.67	0	162.42	1087.67	407.55
200	162.45	1933.74	0	162.42	1933.74	407.55

Table 3. The resisting forces of vehicle for different speed and road inclination 4% and 6%

Vehicle speed	Gradient 4%			Gradient 6%		
	F_R (N)	F_A (N)	F_G (N)	F_R (N)	F_A (N)	F_G (N)
50	162.32	120.86	811.4	162.16	120.86	1214.93
100	162.32	483.43	811.4	162.16	483.43	1214.93
150	162.32	1087.67	811.4	162.16	1087.67	1214.93
200	162.32	1933.74	811.4	162.16	1933.74	1214.93

Table 4. Total tractive forces of vehicle for different speed and road inclination 0%, 2%, 4%, and 6%

Vehicle speed (km/h)	Gradient 0%	Gradient 2%	Gradient 4%	Gradient 6%
	F_T	F_T	F_T	F_T
50	283.31	690.83	1094.58	1497.95
100	645.88	1053.4	1457.15	1860.52
150	1250.12	1657.64	2061.39	2464.78
200	2096.19	2503.71	2907.46	3310.83

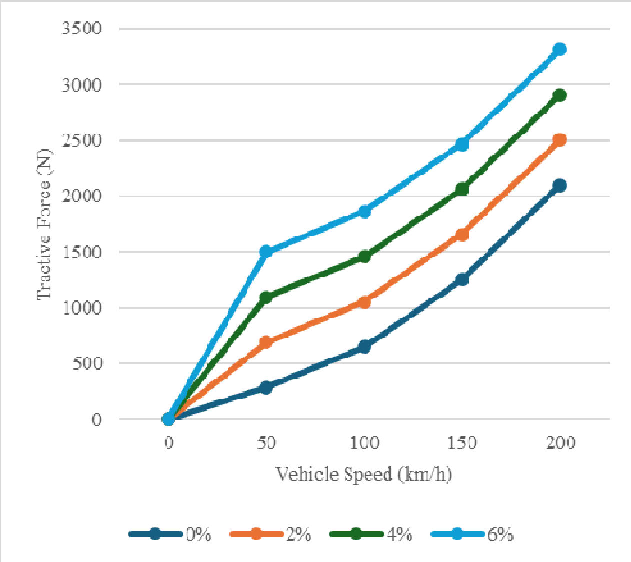

Fig 2. Graph of Tractive Force Versus Vehicle Speed

III. WHEEL TORQUE AND ANGULAR VELOCITY

The torque (T_w) required to drive the wheel is obtained by directly mounting a motor on the differential of by using a gear box or by using a chain drive to magnify the lesser torque to the torque that is needed to drive the wheel. The angular velocity of wheel helps determined how fast a wheel can rotate in a given period of time. The greater the rotation angle in given amount of time, the greater the angular velocity. Wheel torque and angular velocity are calculated using the total tractive forces represented in Equation (6) and (7), respectively.

Wheel Torque

$T_w = F_T \times r_w$ (6)

Where,
T_w=motor torque(N-m)
F_T =total tractive force(N)
r_w=wheel radius(m)

Angular velocity of wheel

$\omega_w = \frac{v}{r_w}$ (7)

Where,
ω_w=angular velocity of wheel(rad/s)
v=vehicle speed(m/s)
r_w =wheel radius(m)

where wheel torque (T_w) is measured in N-m. Angular velocity of the wheel (ω_w) is measured in rad/sec.

Table 5. Wheel torque of different speed and gradient 0%,2% for wheel diameter 17 inches (0.4318m)

Vehicle speed (km/h)	Gradient0%		Gradient2%	
	Tractive force (N)	Wheel torque (N-m)	Tractive force (N)	Wheel torque (N-m)
50	283.31	61.67	690.83	149.15
100	645.88	139.45	1053.4	227.43
150	1250.12	269.9	1657.64	357.88
200	2096.19	452.56	2503.71	540.55

Table 6. Wheel torque of different speed and gradient 4%,6% for wheel diameter 17 inches (0.4318m)

Vehicle speed (km/h)	Gradient4%		Gradient6%	
	Tractive force (N)	Wheel torque (N-m)	Tractive force (N)	Wheel torque (N-m)
50	1094.58	236.32	1497.95	323.41
100	1457.15	314.6	1860.52	401.69
150	2061.39	445.06	2464.78	532.15
200	2907.46	627.72	3310.83	714.81

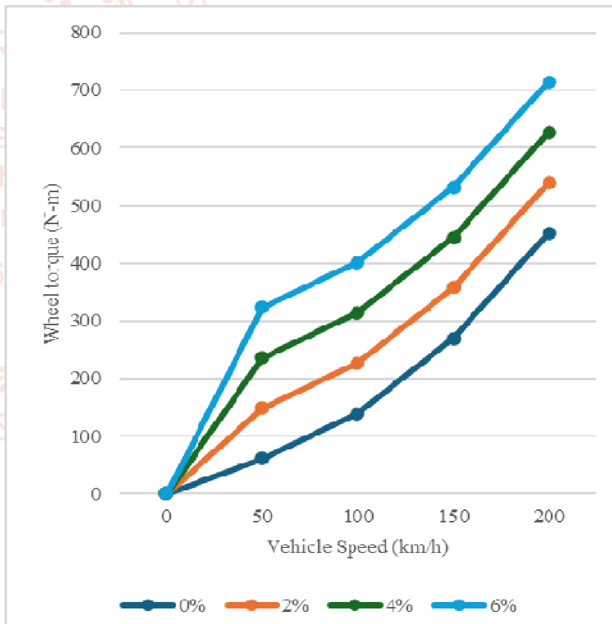

Fig 3. Graph of Wheel Torque Versus Vehicle Speed

Table 7. Wheel angular velocity for vehicle different speed

Vehicle speed (m/s)	Wheel radius (m)	Angular velocity of wheel (rad/s)	Speed of wheel (rpm)
13.9	0.2159	64.38	614.78
27.8	0.2159	128.76	1229.57
41.7	0.2159	193.14	1844.35
55.6	0.2159	257.53	2459.23

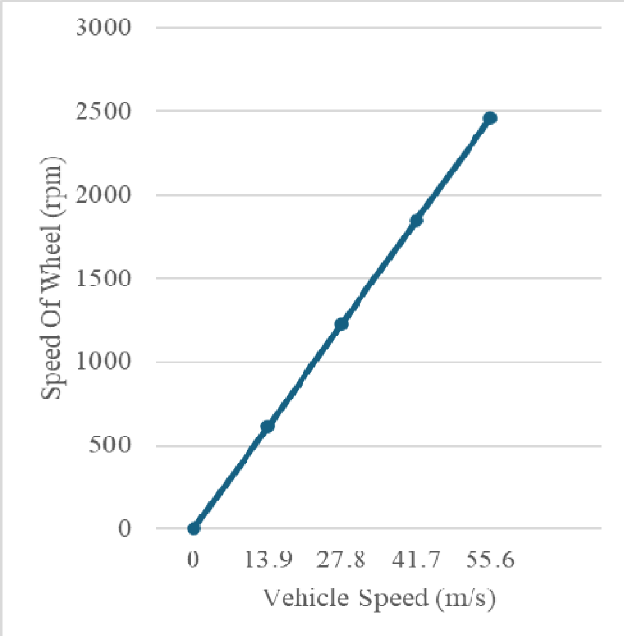

Fig 4. Graph of speed of wheel and vehicle speed

IV. MOTOR TORQUE AND ANGULAR VELOCITY

Motor torque is the rotational force a motor produce. For the torque in motors, however, it is irrelevant at first whether a movement actually takes place. It can also exist at standstill if it is counteracted by an equivalent counteracting force or combination of forces. It can therefore it only accelerate a rotation, but also brake it. The motor torque and angular velocity are calculated through the equations (Equation 8-13).

Angular Velocity of Motor (rpm)

$$\omega_M = \frac{\omega_W\left(\frac{rad}{s}\right)\times 60}{2\pi\times\eta_m} \quad (8)$$

Where,
ω_M = angular velocity of motor (rpm)
ω_w = angular velocity of wheel (rad/s)
η_m = mechanical efficiency (95%)

Motor speed(m/s)

$$V_M = \frac{\omega_w\,(rpm)\times 2\pi\times r_w(m)}{60} \quad (9)$$

$$T = \frac{Distance}{speed} = \frac{c_m}{v_m} = \frac{2\pi r_m}{v_m} \quad (10)$$

Where, r_m is the radius of the motor shaft.

Motor angular frequency

$$f = \frac{1}{T} \quad (11)$$

Angular velocity of motor

$$\omega_M = 2\pi f \quad (12)$$

Torque by the motor

$$T_W \times \omega_M = T_W \times \omega_W$$

$$T_M = \frac{T_W \times \omega_W}{\omega_M} \quad (13)$$

Where,
T_M= motor torque(N-m)
ω_M = angular velocity of motor (rad/s)
T_W = wheel torque(N-m)
ω_w = angular velocity of wheel (rad/s)

V. MOTOR POWER

Motors convert some portion of the input power into spinning the shaft, this portion is the output power. In an electric motor, the mechanical power is defined as the speed times the torque.

$$P_M = T_M \times \omega_M \quad (14)$$

Where,
P_M = motor power (w)
T_M = motor torque (N-m)
ω_M = angular velocity of motor (rad/s)

Table 8. Motor speed for different vehicle speed

Vehicle speed (km/h)	Wheel speed (rad/s)	Wheel speed (rpm)	Mechanical efficiency (%)	Motor speed (rpm)	Motor speed (rad/s)
50	64.38	614.78	95	647.14	67.77
100	128.76	1229.57	95	1294.28	135.54
150	193.14	1844.35	95	1941.42	203.31
200	275.53	2459.23	95	2588.66	290.03

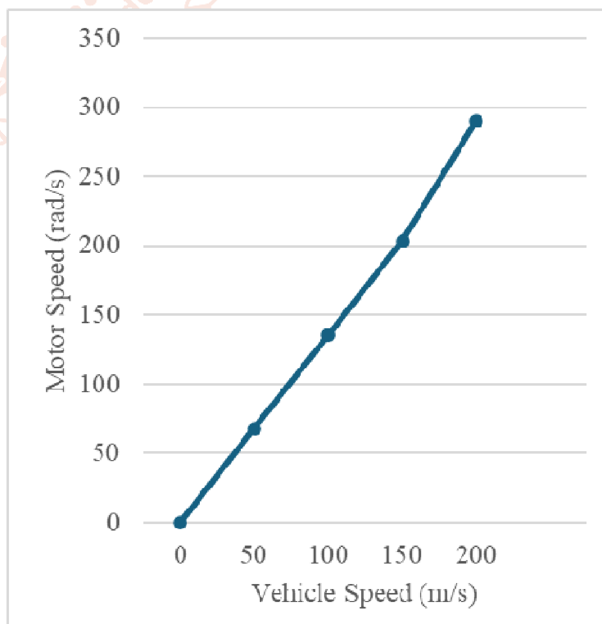

Fig 5. Graph of motor speed and vehicle speed

Table 9. Motor torque and power

Vehicle speed (km/h)	Wheel torque (N-m)	Angular velocity of wheel (rad/s)	Angular velocity of motor (rad/s)	Motor torque (N-m)	Motor power (w)	Motor (kw)
50	61.17	64.38	67.77	58.11	3938.12	3.94
100	139.45	128.76	135.54	132.47	17954.9	17.95
150	269.9	193.14	203.31	256.4	52128.7	52.13
200	452.56	257.53	290.03	401.85	116548.5	116.55

VI. BATTERY

In EVs, the high-voltage battery is a major component, and its parameters play a significant role in influencing other components of the vehicle. EV propulsion systems can use a variety of batteries; however, Lithium-ion batteries are used in the majority of electric vehicles due to their higher specific energy (w_h/kg) and specific power (w/kg). The maximum electrical power that can be supplied to EVs is determined by the battery's voltage level. To carry higher currents, the diameter of the wires must be larger, which results in greater thermal losses. To reduce these thermal losses, the current should be limited, and the nominal power can be achieved by using a higher voltage. In our calculations, a nominal battery voltage (V_{bat}) of 400V is considered. The battery is evaluated using the governing equations [Equations 15-19].

The volume of battery pack can be calculated as follows:

$$V_B = N_{TC} \times V_C \qquad (15)$$

where V_B is the volume of battery pack in m^3.

$N_{TC} = (N_S \times N_{BCS} \times N_B)$ is the total number of cells in battery pack.

N_S is the number of strings.

N_{BCS} is number of cells in each string and

N_B is the number of modulus.

$$V_C = \frac{\pi}{4} \times D_c^2 \times L_c \qquad (16)$$

where,
V_C is the volume of each cell and for cylindrical cell in m^3.

D_c is the diameter of each cell in meter.

L_c is the length of each in meter.

Number of battery cells need to be connected in series in each string.

$$N_{BCS} = \frac{V_{bat}}{V_{EC}} \qquad (17)$$

Where, V_{EC} is voltage of each cell.

The battery current be calculated as follows:

$$I_{bat} = \frac{P_{bat}}{V_{bat}} \qquad (18)$$

The mass of battery can be calculated as follow:

$$M_{BP} = M_{EC} \times N_{TC} \qquad (19)$$

Where, M_{EC} is mass of each cell.

VII. VEHICLE RANGE

To achieve a higher range while keeping battery voltage and Ampere-hour constant, increasing the speed will cause the current drawn from the battery to rise in order to supply more power to the motor. This demonstrates that the vehicle's range is dependent on the battery's capacity, the current drawn from the battery, and the speed. However, for a given battery pack specification and range, the vehicle's speed also depends on the motor speed and the wheel radius. The factors responsible for limiting the speed and range of the vehicle are calculated using the equations [Equation 20-21].

The maximum range of the vehicle is calculated using the equation.

$$R_V = \frac{\text{Battery pack volts} \times \text{Amperes-hour}}{\text{volts} \times \frac{\text{Amperes}}{\text{kMPH}}}$$

$$= \frac{\text{wh of battery pack}}{\text{wh/km}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (20)$$

Where, R_V is the vehicle range in km.

$$V_S = \frac{3.6 \times N_{rpm} \times r_w}{9.5493 \times G_r} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (21)$$

Where, V_S is the vehicle speed in kMPH.

N_{rpm} is speed of the motor in RPM

r_w is radius of the wheel in meter

G_r is gear ratio, it is the ratio of the number of the teeth on the wheel shaft to the number of teeth on the motor shaft and G_r = 1, if motor shaft is directly connected to wheel shaft.

VIII. CONCLUSION

This paper mainly focuses on evaluating the wheel forces, wheel speed, and wheel power of an electric vehicle based on vehicle performance. These wheel forces, speed, and power are directly proportional to the increase in vehicle speed. Thermal battery cooling and heating also help reduce energy consumption per kilometer and increase the range of electric vehicles.

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