CHAPTER 3

ENERGY MANAGEMENT & ITS ESTIMATION IN ELECTRIC VEHICLE

The power of a motor is calculated under city traffic conditions. Calculating power of a motor for electric vehicles under city traffic and dynamic conditions is quite complex and challenging. Most people assume steady state conditions and other linear and simple scenario to calculate power of a motor for electric vehicles. This chapter tries to dig deep on all possible scenarios while calculating power of a motor for electric vehicles under city traffic condition. All the mathematical calculations are done through MATLAB.

3.1FORCE MODEL :

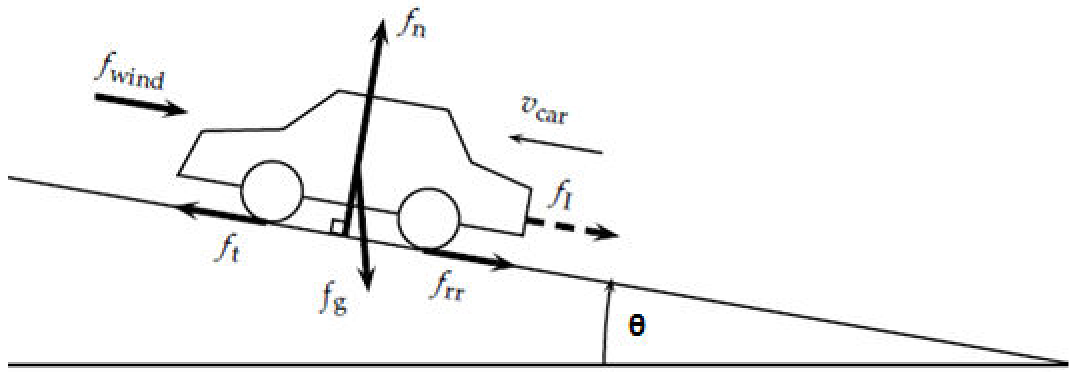

Fig. 3.1 Force Model for a Vehicle

The forces which the electric vehicle has to overcome are the forces due to gravity, wind, rolling resistance and inertial effect. These forces can also be seen in Fig. 3.1 where forces acting on the vehicle are shown:

$F_t = M_v.\alpha_v + M_v.g.\sin(\theta) + sign(V_v).M_v.g.\cos(\theta).C_{rr}$

$+sign(V_v + V_w).\frac{1}{2}.\rho_{air}.Area.C_d.(V_v + V_w)^2$..(3.1)

$C_{rr} = 0.01\ (1 + \frac{3.6}{100}.V_v)$...(3.2)

Where:

$M_v.\alpha_v = F_{initial}$ (Newton)

$M_v.g = F_{gravity}$ (Newton)

$M_v.g.\cos(\theta) = F_{normal}$ (Newton)

$\rho_{air}.Area.C_d.(V_v + V_w)^2 = F_{wind}$ (Newton)

Here,

M_v = Mass of Vehicle,

α_v = Acceleration of Vehicle,

g = Gravitational Acceleration,

θ= Angle of Driving Surface,

ρ_{air} = Air Density,

$Area$ = Frontal Area,

V_v = Velocity of Vehicle,

V_w= Velocity of Wind,

where f_t	[N]	Traction force of the vehicle
f_I	[N]	Inertial force of the vehicle
f_{rr}	[N]	Rolling resistance force of the wheels
f_g	[N]	Gravitational force of the vehicle
f_n	[N]	Normal force of the vehicle
f_{wind}	[N]	Force due to wind resistance
α	[rad]	Angle of the driving surface
M_{car}	[kg]	Mass of the vehicle
v_{car}	[m/s]	Velocity of the vehicle
$\dot{v}_{car}$	[m/s^2]	Acceleration of the vehicle
$g = 9.81$	[m/s^2]	Free fall acceleration
$\rho_{air} = 1.2041$	[kg/m^3]	Air density of dry air at 20 °C
c_{rr}	[−]	Tire rolling resistance coefficient
C_{drag}	[−]	Aerodynamic drag coefficient
A_{front}	[m^2]	Front area
v_{wind}	[m/s]	Headwind speed

3.1.1 Variable Acceleration

The acceleration of the vehicle can be calculated by equations 3.3, 3.4 and 3.5. where, X is the variable acceleration of the vehicle, Y is the constant Z is also a constant, β is the variable velocity of the vehicle, M is the mass of the vehicle and A is the frontal area of the vehicle, D_a is the density of the air and C_d is the air drag.[61, 62]

$$X(\beta) = \frac{Y}{\beta} - Z(\beta)^2 \qquad (3.3)$$

Here,

$$Y = \frac{746 * H.P.}{M} \qquad (3.4)$$

$$Z = \frac{D * A * Cd}{M} \qquad (3.5)$$

To calculate the variable acceleration from above equations first the variable velocity is calculated, for calculating variable velocity intelligent driver model is used. The intelligent driver model [3.1]-[3.7] is defined by equation 3.6 as shown below:

$$\frac{d\beta}{dt} = X * (1 - (\frac{\beta}{\beta_o})^4 - (\frac{\gamma}{\gamma 1})^2) \ldots\ldots (3.6)$$

$$\gamma = \gamma 0 + \beta S + \frac{\beta \Delta\beta}{2(XN)^{1/2}} \ldots\ldots (3.7)$$

In the above equation 3.6 and 3.7, γ_0 is the minimum distance kept between stand still in a traffic jam, β_0 is the velocity of the vehicle in free traffic, N is the braking deceleration and $\Delta\beta$ is the variation or fluctuation in the velocity.

All the values dependent on a particular city traffic condition. The acceleration in terms of velocity defined in equation 3.3 is put in equation 3.6 and the equation 3.6 is integrated, after calculating the net velocity, the variable acceleration is calculated. The value of both variable velocity and acceleration can be matched with standard value given in some urban cycles shown in Fig.3.3, Fig.3.4, and Fig.3.5. The velocity and acceleration is calculated for all 50 vehicles. [63, 64]

3.1.2 Drive Train

The Fig.3.2 shows a block diagram of variable gear drive train used in the propulsion system of electric vehicle. The Fig.3.1 shows the various forces considered in calculating the power of a motor

The various resistance forces as shown in Fig.3.1 are:

1. Rotational inertia
2. Gravity force
3. Aerodynamic drag
4. Rolling resistance

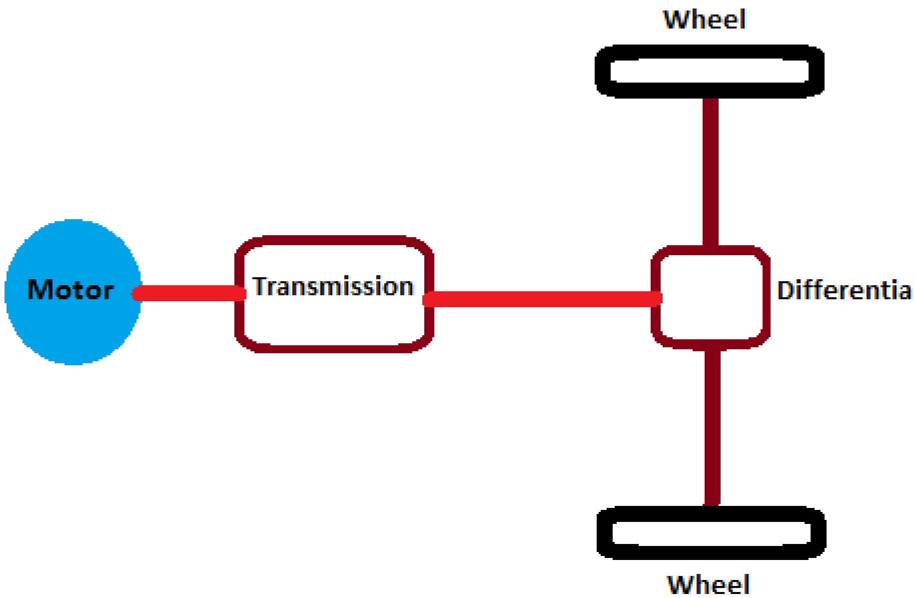

Fig. 3.2 Drive Train of an Electrical Vehicle

3.1.3 Rotational Inertia

The torque loss due to inertia [67] of rotating parts is calculated in equation 3.6.

$$C_{net} = C_{initial} - I\mu \quad \text{......(3.8)}$$

Where, $C_{initial}$ - initially torque given by the motor, I is the moment of inertia of motor and μ is the angular acceleration of the motor. Gear ratio amplifies the torque but again the torque is decreased by the inertia losses due to gear and shafts. So net torque delivered to drive shaft will be equal to as shown in equation 3.7.

$$C_{net1} = (C_{net} - I_1\mu_1).\alpha_1 \quad \text{......(3.9)}$$

Where, C_{net1} is the torque left after transmission losses and I_1 is the moment of inertia of transmission and α is the gear ratio. Torque delivered at axle is reduced by the inertia present at drive shaft but amplified by final drive ratio. Torque delivered at axle is shown in equation 3.8.

$$C_{net2} = (C_{net1} - I_2\mu_2).\alpha_2 \text{ ....} (3.10)$$

Where, I_2 and μ_2 are the moment of inertia of drive shaft and rotational inertia of the wheels.

The relation between rotational accelerations of the motor, transmission, and driveline and gear ratios is shown in equation 3.9.

$$I = I_1\alpha_1 = I_1 I_2 \alpha_2 \text{ ....} (3.11)$$

The above equations 3.6 to 3.9 can be combined to calculate the rotational inertia, which is also known as mass factor and its value, is taken as 1.1.

3.1.4 Gravity Force

Gravity force is given as

$$M.g.Sin(\theta) \text{ ....} (3.12)$$

3.1.5 Rolling Resistance

The rolling resistance is calculated by equation 11.

$$R_r = \frac{(D_r(D_2V + D_3) * M.g.Cos(\theta)}{1000} \text{ ....} (3.13)$$

Where D_r, D_2 and D_3 are rolling coefficient of resistance.

3.1.6 Aerodynamic Drag

The aerodynamic drag is given as shown in equation 3.14.

$$D_A = \frac{1}{2\rho V * C_d * A_{rea}} \text{ ....} (3.14)$$

Where, ρ is the air density, Area is the frontal area of vehicle and C_d is the aerodynamic drag coefficient. Some of the values used to calculate to calculate these values are shown in Table 1.

Table 3.1 Various Parameters Used for Calculations

M	**1000 kg**
C_D	**0.3**
R	**0.28 m**
D_r	**1 (Concrete Pavement)**
D_1	**0.0472**
D_2	**0.0328 (Radial Tyres)**
P	**1.19 kg / m^3**
H	**0.8 or 0.9**
Gear Ratio	**1.12, 1.67, 2.73, 4.6, 5.75**
Sin Ɵ	**0.0665**

3.1.7 Gear Losses

The Gear losses three types of components:

1. Oil churning losses,

2. Air windage losses and

3. Mechanical losses which mainly consists of sliding losses and rolling losses.

Oil churning losses

The churning loss [68] is defined by the equation 3.15.

$$P_{churing} = \frac{1}{2}.C_m * \rho * w * S_m * r^3 \quad \text{.....(3.15)}$$

Where, S_m is surface area in contact with the gear, C_m is $20/R_e$ where R_e is Reynolds number and its value is < 2000, r is the gear pitch radius and ρ is lubricant density.

Air Windage losses

The air windage [69] losses are defined by the equation 3.16.

$$P_{windage} = \frac{1}{2} * C_t * \rho * w^3 * r^5 \quad \text{...(3.16)}$$

With $C_t = C_f + C_l$

Here, $C_f = 2.3 * \frac{((3.1)^5)^{4.5}}{r^5} + 0.1011 * [\frac{1}{Re^{0.2}} - \frac{((3.1)^5)^{4.8}}{r^5}]$ ...(3.17)

$$C_1 = \varepsilon * \frac{Z}{4} * \frac{b}{r} * [\frac{1+2(1+x)}{z}]^4 * (1 - cos\theta) * (1 + cos\theta)^3 \quad \text{...(3.18)}$$

Where, ε is the coefficient for obstacles 0.5 for no obstacles, x is profile shift coefficient, θ is

$$\theta = \frac{\pi}{z-2} * (\frac{1}{\alpha P} - \frac{1}{\alpha A}) \quad \text{...(3.19)}$$

α_P and α_A are pressure angle at pitch point and at tooth tip.

Sliding losses

Sliding losses [70] is defined by the equation 3.20. (Rolling losses are quite small so they are neglected).

$$\Sigma\mu(k) * F(N, K) * V(N, K) \quad \text{...(3.20)}$$

With k: teeth whom come in contact.

$$\Sigma F(N,K) * V(N,K) = P_i * \pi * \frac{i+1}{Z_1 * i * cos\beta} * (1 - (\varepsilon A) + (\varepsilon 1)^2 + (\varepsilon 2)^2) \quad \text{...(3.21)}$$

With P_i is input power, ε_A profile contact ratio and ε_1, ε_2 are tip contact ratio.

$$\mu(k) = 0.0048 * (\frac{\frac{F_{bt}}{b}}{V_{\Sigma c}} * \rho_{redc}) * \eta oil * R_a * X_1 \quad \text{...(3.22)}$$

Where, F_{bt} is tangential force at the base circle, R_a is arithmetic mean roughness, X_l is lubricant factor, $V_{\Sigma c}$: sum speed at operating pitch circle and ρ_{redc} is reduced radius of curvature at pitch point.

Total gear loss is equal to sum of churning loss + windage loss+ sliding loss.

3.2 DRIVING CYCLES :

The Fig.3.3, Fig.3.4 and Fig.3.5 describe various urban drive cycle. These are the standard drive cycle and recorded in day to day normal traffic conditions.

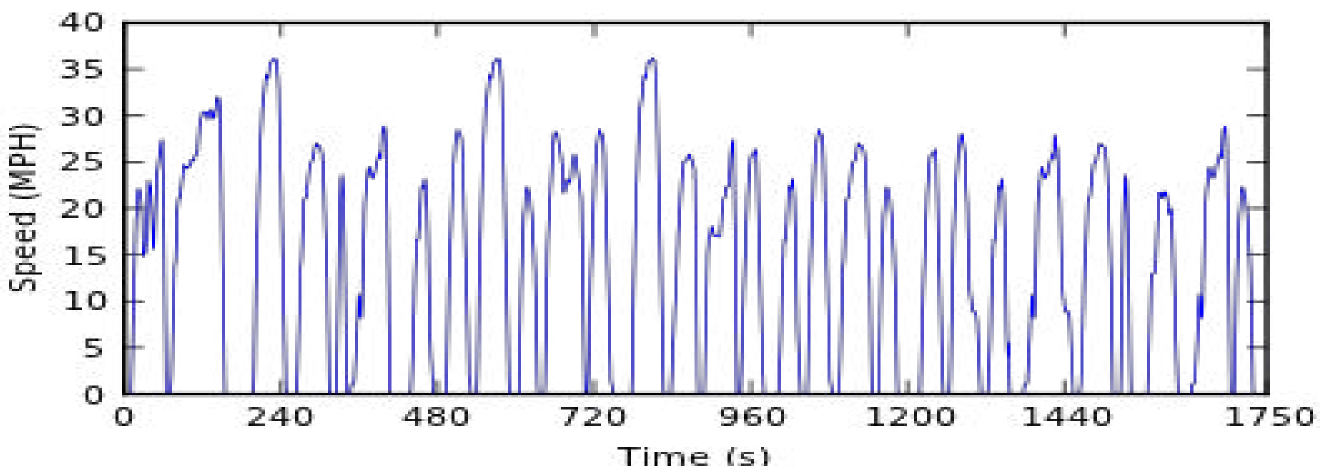

Fig. 3.3 Braunschweig City Driving Cycle

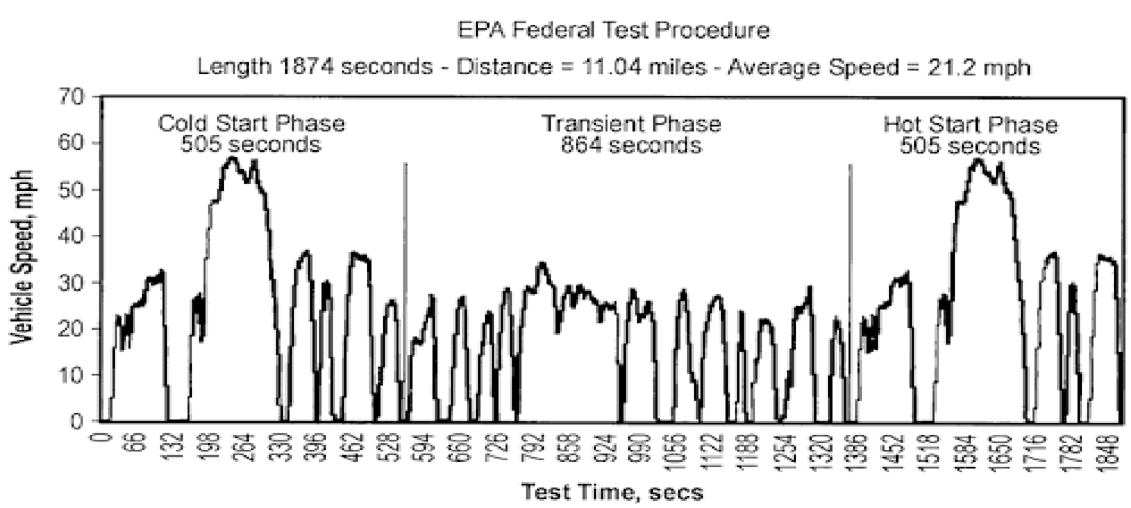

Fig. 3.4 FTP – 75 Test Driving Cycle established by EPA.

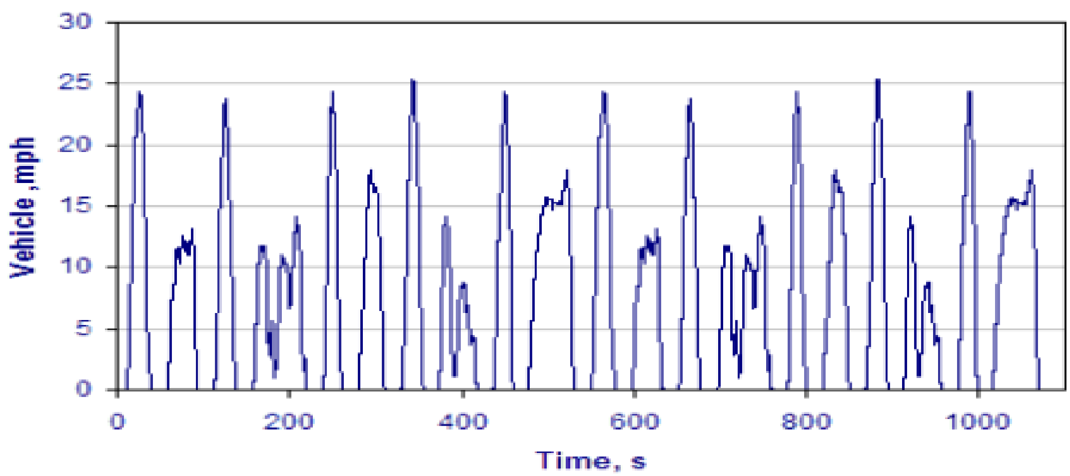

Fig. 3.5 Manhattan Bus Cycle

3.3 AUXILIARY LOAD:

The main purpose of the battery is to provide power for the wheels. However, a modern Electric Vehicle has also other electrical utilities which the battery should take the burden. These loads are due to necessary requirement for safety and comfort, etc. These loads are not constant, e.g. use of wiper, headlamps and air-conditioner depends on the surrounding environment. Even though some average values are suggested this can be seen in Table 3.2.

Table 3.2 Auxiliary Load Estimated.

Name of Utility	Power Consumption	Hours usage	Energy Requirement
Radio	80 W	4-6 hours	320-480 Wh
AC	470 W	4-6 hours	1880-2820 Wh
Lights + Wipers	316 W	N.P. *	N.P. *
Total	866 W	--	--

*N.P. = Not Possible to predict.

The average power load of the electric vehicle is 866 W, approximately 1 KW by taking electrical losses into consideration. For Two and three wheeler open body vehicle, this average value is 396 W, approximately 0.42 KW by considering electrical losses.

3.4 TRANSMISSION:

From the Fig.3.1, it can be understood that the torque, angular velocity and power of the transmission system are given by the following equations:

$$\tau_t = f_t r_w \quad \text{....(3.23)}$$

$$\tau_w = \frac{\tau_t}{2} \quad \text{....(3.24)}$$

$$p_t = f_t V_v \quad \text{....(3.25)}$$

$$w_w = \frac{V_v}{r_w} \quad \text{....(3.26)}$$

Here,

τ_t= Traction Torque [N.m]

τ_w= Torque at Driving Wheel [N.m]

r_w = Radius of Wheel [m]

w_w = Angular velocity of wheel [rad/sec]

P_t = Traction Power [Watt]

It is assumed that the power from the shaft of the electric machine to the two driving wheels has a constant efficiency of η_{TS} = 0.95. The shaft torque, angular velocity, and power of the electric machine are therefore;

$$\tau_s = \begin{cases} \eta_{TS} \cdot \frac{\tau_t}{G}, P_t < 0 \\ \frac{\tau_t}{\eta_{TS} G}, P_t \geq 0 \end{cases} \quad \text{....(3.27)}$$

$$w_s = G w_w \quad \text{....(3.28)}$$

$$P_s = \tau_s w_s \qquad (3.29)$$

Where,

T_s= Shaft Torque at Electrical Machine Side [N.m]

W_s= Shaft Angular velocity of Electrical Machine [rad/sec]

P_s = Shaft Power of Electrical Machine

G = Gear Ratio of Differential

3.5 POWER ESTIMATION :

3.5.1 SPECIFICATIONS :

Table 3.3 Parameter considered for Power Estimation

"Two Wheeler"								
α_v	**V_w**	**Area**	**C_d**	**D_a**	**C_{rr}**	**Mass**	**g**	**R_w**
m/s^2	**m/s**	**m^2**	**--**	**kg/m^3**	**--**	**kg**	**m/s^2**	**M**
2	2	2.58	1.4	1.3	0.012	118	9.81	0.28
"Three Wheeler"								
α_v	**V_w**	**Area**	**C_d**	**D_a**	**C_{rr}**	**Mass**	**g**	**R_w**
m/s^2	**m/s**	**m^2**	**--**	**kg/m^3**	**--**	**kg**	**m/s^2**	**M**
2	2	3.94	1.4	1.3	0.012	248	9.81	0.28
"Four Wheeler"								
α_v	**V_w**	**Area**	**C_d**	**D_a**	**C_{rr}**	**Mass**	**g**	**R_w**
m/s^2	**m/s**	**m^2**	**--**	**kg/m^3**	**--**	**kg**	**m/s^2**	**M**
2	2	4.63	1.4	1.3	0.012	326	9.81	0.28
"Heavy Vehicles"								
α_v	**V_w**	**Area**	**C_d**	**D_a**	**C_{rr}**	**Mass**	**g**	**R_w**
m/s^2	**m/s**	**m^2**	**--**	**kg/m^3**	**--**	**kg**	**m/s^2**	**M**
2	2	5.78	1.4	1.3	0.012	2185	9.81	0.28
**** Mass is considered without Battery, Supercapacitor & AC, but including passengers weight***								

Table 3.4 Parameter considered for Power Estimation - Addition

* Mass (kg) is considered with Battery, Supercapacitor & AC & passengers weight in above Table 3. 3	
“Two Wheeler”	**128**
"Three Wheeler"	**268**
“Four Wheeler”	**356**
“Heavy Vehicles”	**2385**

3.5.2 TWO WHEELER :

Table 3.5 Power Estimation for “2 – Wheeler”

θ	F_{wind}	F_{normal}	$F_{gravity}$	F_{intial}	F_{TOTAL}	Power	Aux. Load	Power
Deg.	Newton					Watt	Watt	Watt
5	-43.68	1211.82	1216.44	248.00	324.83	649.66	105.00	754.66
10	-98.28	1197.98	1216.44	248.00	375.22	1500.89	105.00	1605.89
15	-98.28	1175.03	1216.44	248.00	478.50	1914.01	105.00	2019.01
20	-174.72	1143.15	1216.44	248.00	502.84	3017.06	105.00	3122.06
25	-273.00	1102.58	1216.44	248.00	502.08	4016.61	105.00	4121.61
30	-393.12	1053.63	1216.44	248.00	475.46	4754.64	105.00	4859.64
35	-535.08	996.67	1216.44	248.00	422.29	5067.51	105.00	5172.51
40	-698.88	932.12	1216.44	248.00	341.89	4786.43	105.00	4891.43
45	-884.52	860.50	1216.44	248.00	233.62	3737.86	105.00	3842.86

3.5.3 THREE WHEELER :

Table 3.6 Power Estimation for "3 – Wheeler"

θ	F_{wind}	F_{normal}	$F_{gravity}$	F_{intial}	F_{TOTAL}	Power	Aux. Load	T. Power
Deg.	Newton					Watt	Watt	Watt
5	-58.24	2198.86	2207.25	450.00	610.42	1220.85	148.00	1368.85
10	-131.04	2173.75	2207.25	450.00	728.14	2912.55	148.00	3060.55
15	-131.04	2132.12	2207.25	450.00	915.54	3662.16	148.00	3810.16
20	-232.96	2074.27	2207.25	450.00	996.49	5978.93	148.00	6126.93
25	-364.00	2000.65	2207.25	450.00	1042.39	8339.12	148.00	8487.12
30	-524.16	1911.83	2207.25	450.00	1051.90	10518.99	148.00	10666.99
35	-713.44	1808.47	2207.25	450.00	1023.73	12284.74	148.00	12432.74
40	-931.84	1691.35	2207.25	450.00	956.65	13393.11	148.00	13541.11
45	-1179.36	1561.38	2207.25	450.00	849.52	13592.26	148.00	13740.26

3.5.4 FOUR WHEELER :

Table 3.7 Power Estimation for "4 – Wheeler"

θ	F_{wind}	F_{normal}	$F_{gravity}$	F_{intial}	F_{TOTAL}	Power	Aux. Load	Power
Deg.	Newton					Watt	Watt	Watt
5	-72.80	2931.81	2943.00	600.00	818.75	1637.50	872.00	2509.50
10	-163.80	2898.33	2943.00	600.00	981.77	3927.08	872.00	4799.08
15	-163.80	2842.82	2943.00	600.00	1231.64	4926.56	872.00	5798.56
20	-291.20	2765.69	2943.00	600.00	1348.06	8088.39	872.00	8960.39
25	-455.00	2667.54	2943.00	600.00	1420.19	11361.49	872.00	12233.49
30	-655.20	2549.10	2943.00	600.00	1446.21	14462.13	872.00	15334.13
35	-891.80	2411.29	2943.00	600.00	1424.42	17093.09	872.00	17965.09
40	-1164.80	2255.14	2943.00	600.00	1353.19	18944.63	872.00	19816.63
45	-1474.20	2081.84	2943.00	600.00	1230.97	19695.50	872.00	20567.50

3.5.5. HEAVY VEHICLES :

Table 3.8 Power Estimation for "Heavy Vehicles – Truck, Bus"

θ	F_{wind}	F_{normal}	$F_{gravity}$	F_{intial}	F_{TOTAL}	Power	Aux. Load	T. Power
Deg.	Newton					Watt	Watt	Watt
5	-72.80	5863.62	5886.00	1200.00	1710.30	3420.61	1200.00	4620.61
10	-163.80	5796.67	5886.00	1200.00	2127.34	8509.36	1200.00	9709.36
15	-163.80	5685.64	5886.00	1200.00	2627.08	10508.33	1200.00	11708.33
20	-291.20	5531.39	5886.00	1200.00	2987.33	17923.97	1200.00	19123.97
25	-455.00	5335.08	5886.00	1200.00	3295.37	26362.98	1200.00	27562.98
30	-655.20	5098.21	5886.00	1200.00	3547.63	35476.25	1200.00	36676.25
35	-891.80	4822.57	5886.00	1200.00	3740.65	44887.78	1200.00	46087.78
40	-1164.80	4510.28	5886.00	1200.00	3871.18	54196.45	1200.00	55396.45
45	-1474.20	4163.69	5886.00	1200.00	3936.14	62978.20	1200.00	64178.20