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Flexible Matching Design Analysis of the Battery and Power Module for Electric Vehicles

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Abstract

As the power resource of an electric vehicle (EV) is different from the traditional internal combustion engine vehicle, the overall design thinking on the chassis for EV must transcend the design mode for traditional internal combustion engine vehicles. The main power source of the EV is the battery module attached to the drive motor; hence, this study proposed a new kind of thinking that assumed the chassis for EV as the motherboard of a computer, the battery module as the DRAM, and the driver motor as the CPU. Then, on the basis of the common chassis, consumers can choose to flexibly equip different quantities of battery packs and/or different motor power according to their needs for travel distance and/or vehicle performance, thus achieving the performance of car models ranging from City Car to Sedan or even SUV. This study is carried out based on the chassis with the wheel base being 2600mm, curb weight 1400kg and battery pack space of 220 liter. The planned battery module volume of the battery space is 18kWh – 36kWh (aggregated by standard battery modules of 6kWh each); while the planned dynamic module power of the engine bay is 50kW-150kW, as shown in Figure 4, by means of which the flexible matching of the batteries and the power modules were investigated to examine the feasibility of achieving car types with different performance demands.

Keywords: Electrical Vehicles, Battery, Power Module, Running Chassis, MIRDC

1 Introduction

Electrical Vehicles (EV) are undergoing extensive research and development because of their potential for high efficiency and low pollution of the environment. How an electric car generates power is very different from a traditional car that depends on the internal combustion engine. The chassis of an electric car is significant, and it has to be innovatively designed. An electric car mainly depends on the battery module and the drive motor for its power generation sources. This paper proposed a new idea while regarding the chassis of an electric car as a computer's motherboard, the battery module as the DRAM, and the drive motor as the CPU. The idea was based on using the same chassis while elastically matching different numbers of battery modules with different power motors according to the driving distance and the vehicle performance.

In the paper [1], the application of batteries and ultracapacitors in electric energy storage units for battery powered (EV) and charge sustaining and plug-in hybrid-electric (HEV and PHEV) vehicles have been studied in detail. The use of IC engines and hydrogen fuel cells as the primary energy converters for the hybrid vehicles was considered. The study focused on the use of lithium-ion batteries and carbon/carbon ultracapacitors as the energy storage technologies most likely to be used in future vehicles. According to the same study the paper [2] this paper investigated the relationships between vehicle cost, mass total range, and battery pack mass. The mass compounding effect for battery electric vehicles was investigated and found to be of significant importance to understand the system integration of battery electric technology. In the paper [3], global methodology together with a detailed analysis of the impact of different types of powertrains EMs, namely, PMSM drive and IM drive, in different drive cycles for typical daily EV use (ECE-15, NEDC and 50-km/h fixed speed), is presented. In the paper [4], the plug-in vehicle has a modular topology where different solutions for the battery-power converter electric machine chain of a plug-in electric vehicle are possible to be simulated. In the simulation results of a solution for this electric chain allowing bi-directional power flow and using different types of batteries is presented and analyzed.

This paper addresses the design considerations involved in the conversion of a gasoline powered vehicle to electric. Discussion of the various design elements in an electric vehicle conversion will include: Vehicle Dynamic Modelling, Motor Selection, Gear Ratio Selection, Power Battery Selection and integration of electric vehicle accessory systems. For practical purposes the electric vehicle is achieved based on MIRDC running chassis first generation at the end of this paper.

2 Vehicle Dynamic Modelling

Issues relating to performance and range in electric vehicle is very important. The first step in vehicle performance modelling is to produce an equation for the tractive effort. This is the force propelling the vehicle forward, transmitted to the ground through drive wheels. Equation 1 [5]-[7] shows that the tractive effort can be reduce into four main categories, the rolling resistance force $F_{rolling}$ due to friction of the vehicle tires on the road, the aerodynamic drag force F_{areo} caused by the friction of the body moving through the air, overcoming the current vehicle state of motion $F_{inertia}$, and finally the grade or inclination that the vehicle is travelling on F_{grade}. Figure 1 shows a physical representation of the forces as they affect the vehicle during motion. The total tractive effort is equal to F_{tr} and the sum of the resistive forces in the x-direction accounted for in equation 1.

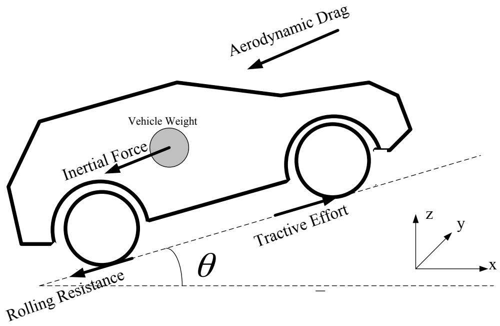

Figure1: Vehicle Dynamic.

$$F_{tr} = F_{rolling} + F_{aero} + F_{grade} + F_{inertia} \quad (1)$$

Equations 2 through 5 express the different terms making up the tractive effort equation. The parameter C_{rr0} is the coefficient of rolling resistance, C_{rr1} coefficient of rolling resistance affected by Velocity, m is vehicle mass, g is the acceleration due to gravity, ρ is the density of air, C_D is aero-dynamic drag coefficient, A_f is the frontal area of the vehicle, V is vehicle velocity, M_i is an inertial mass factor term to account for the rotating inertia of the wheels, tires, and other rotating components, dV/dt is the acceleration from one time step to the next for the drive cycle, and θ (related to grade) is the angle of incline. For normal inclines, the sin(θ) term that could be included in Equation 2 is approximated as 1. The variables are summarized in Table 1.

$$F_{rolling} = C_{rr0}mg + C_{rr1}mgV \quad (2)$$

$$F_{inertia} = mM_i \frac{dV}{dt} \quad (3)$$

$$F_{grade} = mg\sin(\theta) \quad (4)$$

$$F_{aero} = \frac{1}{2}\rho C_D A_f V^2 \quad (5)$$

Table1: Vehicle Parameter

c_{rro}	Static Coefficient of rolling resistance	[-]
c_{rr1}	Moving coefficient of rolling resistance	[-]
m	Vehicle mass	kg
g	Gravity	m/s^2
V	Velocity	m/s
ρ	Density of air	kg/m^3
C_D	Coefficient of Drag	[-]
A_f	Frontal Area	m^2
M_i	Inertia mass factor	[-]
dV/dt	Drive cycle acceleration	m/s^2
θ	Degree of inclination	[-]

The rolling resistance term is always present when the vehicle is in motion. Aerodynamic drag force increases with the square of velocity, so with higher speeds comes more drag on the vehicle. The inertia term is dependent on vehicle acceleration rate, and will sum to zero for a drive cycle that starts and ends at zero speed. Grade, while not always present, does have an impact on the energy required to complete a drive cycle, and if present, should be accounted for.

3 Motor Selection

Choosing normal rated power of motor correctly is very important, because too low the motor would be overloaded all the time and too high the motor would run under low load. If the motor always runs under low load, its efficiency and power factor would decrease leading to a waste of electricity and an increase of the capacity of power battery; thus, the total economic benefit would decrease. The design skill of motor parameters is shown as follows according to the above-mentioned requirements. Select the motor with a working power range rating equal to or greater than the power range calculated for the vehicle dynamic form equation 1. The factors involved in computing the power are: the tire torque, the vehicle speed, tire's rotations per mile, and overall drive-train-efficiency. If the customer specifies the final drive ratio, select the motor based on the torque necessary to give the desired tractive effort. If the maximum vehicle weight and maximum vehicle speed in the working range are specified, the vehicle Power Range can be computed from the following formula.

1. Based on maximum vehicle velocity (MAX_V), the motor power is estimated from

$$Motor\_Power = (2 \times \pi \times (c_{rr0} mg + c_{rr1} mg MAX\_V + \frac{1}{2}\rho C_D A_f (MAX\_V)^2)$$
$$\times r \times Motor\_Speed) / 60 / 1000 / GearRatio \qquad (6)$$

2. Based on inclination θ (related to grade) and vehicle velocity (*Need_V*), the motor power is estimated as follow

$$Motor\_Power = (2 \times \pi \times (mg \sin(\theta) + c_{rr0} mg + c_{rr1} mg Need\_V + \frac{1}{2}\rho C_D A_f (Need\_V)^2)$$
$$\times r \times Motor\_Speed) / 60 / 1000 / GearRatio \qquad (7)$$

Generally, the motor's efficiency is about 90%, assuming a middle motor.

4 Gear Ratio Selection

To satisfy the highest speed, greatest grad ability, and accelerating time as planned, the selection of gear ratio of drive line system is crucial. The selection of gear ratio would be based on two alternatives, single gear or multiple gears, according to the existing design concept. This design requirement is mainly based on the chosen motor performance and car performance. For instance, if the chosen motor could meet the performance requirement and its governing range is sufficient, then a gear box with constant speed ratio could be used directly. The use of gear box with single gear ratio could not only decrease the weight and size of electric car, but also promote drive efficiency and lower the cost. Its specifications are as follows:

(1) Upper limit of gear ratio of drive line system:

The upper limit of drive line system ratio is mainly decided by the highest rotational speed of the motor (n_m) and the required highest vehicle velocity (v_m), so it can be illustrated as

$$G_H \le \frac{0.377 n_m r}{v_m} \qquad (8)$$

$$G_H = i_0 \times i_g \qquad (9)$$

where

r is wheel radius

i_0 is differential ratio

i_g is transmission ratio

From the above formula, one can know that if the wheel size is fixed, the relationship of motor speed and car speed with different gear ratio is shown in the following Figure 2. The diagram shows that if the motor speed is consistent, lower gear ratio would result in higher corresponding car speed; if driving resistance has to be overcome, then motor output torque must be increased if the gear ratio is lower.

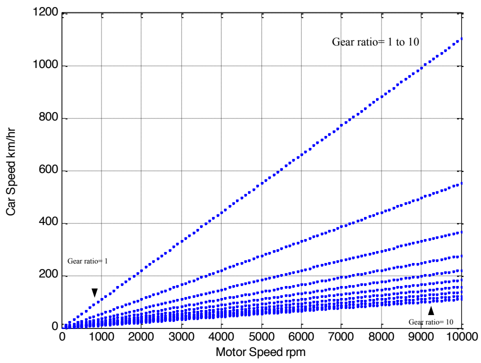

Figure2: Motor speed and Car speed.

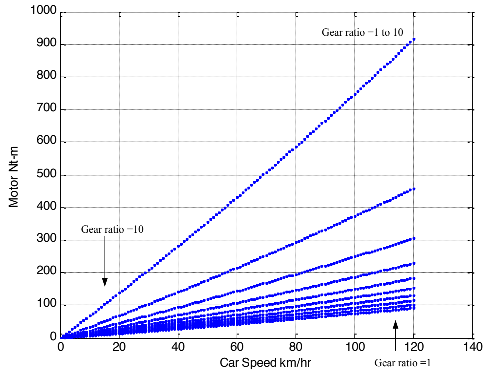

Figure3: Motor output torque and different gear ratio

(2) Lower limit of gear ratio of drive line system:

For lower limit of gear ratio of drive line system, the maximum value of gear ratio of drive line system could be calculated using the following two formulas. Drive ration should always be selected based on attaining the vehicle tractive effort and vehicle speed specifications.

The lower limit of drive ratio of drive line system is decided according to the corresponding output torque (T_{nm}) of the highest motor speed and corresponding driving resistance (F_{nm}) of the highest car speed (v_m)

$$G_L \geq \frac{F_{nm} r}{\eta_t T_{nm}} \quad (10)$$

Where

r is wheel radius

η_t is drive efficiency

$$F_{nm} = c_{rr0} mg + c_{rr1} mg v_m + \frac{1}{2} \rho C_D A_f v_m^2 \quad (11)$$

$$T_{nm} = 9549 \frac{P_e}{n_m} \quad (12)$$

Figure 3 shows the corresponding motor output torque demand relationship under fixed wheel size, different gear ratio, and same driving resistance. It shows that under consistent driving resistance, the corresponding output torque (T_{nm}) is higher if the corresponding highest motor speed of gear ratio is smaller.

(B) The lower limit of gear ratio of drive line system is decided according to the highest motor output torque (T_{am}) and corresponding driving resistance (F_{nm}) of highest climbing angle (θ)

$$G_{La} \geq \frac{F_{am} r}{\eta_t T_{nm}} \quad (13)$$

where

$$F_{am} = mg \sin(\theta) + \frac{1}{2} \rho C_D A_f v_\alpha^2 + c_{rr0} mg + c_{rr1} mg v_\alpha \quad (14)$$

v_α is the corresponding car speed km/hr of highest climbing angle.

5 Power Battery Selection

Because EVs do not have an alternator, many auxiliary systems must depend on EV batteries to supply the necessary power. Air-conditioning, power steering, lamps and radios are just some of the accessories of an EV which have to rely on power converters to provide power from batteries. The number of batteries in an electric vehicle conversion will depend on the voltage of the battery type to be used, the desired nominal system voltage, and the size of vehicle in which the batteries will be installed. In general, a greater system voltage will result in increased performance, whereas a greater watt-hour capacity will result in increased vehicle driving range. Thus, the development of battery technology has been accelerated, in which a set of criteria including the specific energy, specific power, energy efficiency, charging rate, cycle life, operating environment, cost, safety and recycling must be needed. The total capacity of power battery is decided by the continuous driving mileage of the electric car, so the total capacity limit of power battery could be obtained from designed continuous driving mileage of electric car.

$$P_b = L \times e \quad (15)$$

P_b : Total capacity of power battery, kWh;

L : Continuous driving mileage, km;

e : Consumed capacity of unit distance, kWh/km;

A good approximation of the grid consumption of a battery-electric vehicle with current technology in mixed city traffic can be given by the empirical formula [8]

$$E_s = 80 + 80 / m \quad (16)$$

where

E_s is the specific energy consumption in Wh/km

m is the mass of the vehicle in tons

In order to achieve the desired nominal system voltage, the vehicle must be large enough to carry the required number of batteries. For example, assume that a subcompact car is to be converted to electric, and that performance is the chief design objective. A typical medium-sized vehicle weighing 1500 kg would have an energy consumption of

$E = 1.5 \times (80 + 80/1.5) = 200 Wh / km$

To drive this vehicle over a distance of 50 km, a typical urban range for battery-electrics or plug-in hybrids, the following amount of energy would be needed from the grid:

$E = 50km \times 200Wh / km = 10kWh$

First of all, the requirement of normal rated voltage must be decided; thus, the power e value consumed by unit distance is obtained according to the electric cars with the same rated power. And then, the required total capacity of the battery P_b is obtained according to the continuous driving mileage L. If the discharge current of the battery is I_b, the normal voltage of the battery after connection is

$$V_b \geq P_b / I_b \quad (17)$$

Next, from the perspective of rated power, if motor normal rated power output is P_e, then its normal rated power input is

$$P_{e,in} = P_e / \eta_t \quad (18)$$

Thus, the voltage of battery after connection is

$$V_b \geq P_{e,in} / I_b \quad (19)$$

According to the requirement of driving mileage, the balance of normal rated power must be $V_b > E_b / I_b$ and $V_b \geq P_{e,in} / I_b$.

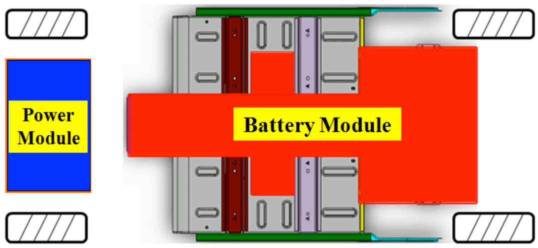

Figure4: Batteries and Power Modules

Within the fixed configuration space of the chassis, the rationality of the flexible match between the batteries and power modules must take the following factors into account: endurance, batter power rate (C-Rate), battery weight, battery volume and vehicle payload.

A. When considering endurance: if the energy consumption of the EV is assumed to be 150Wh/km, and the reference setting of endurance is > 100km, then endurance is calculated as: Endurance = Battery Energy / Energy Consumption, as shown in Table 2.

Table2: Endurance Computation

Energy Consumption / Battery Energy (kWh)		Endurance >100km
		150 Wh/km
Module	18	120
	24	160
	30	200
	36	240

B. When considering battery power rate (C-Rate): the reference setting of battery power rate (C-Rate) is < 6C, thus: Battery Power Rate (C-Rate) = Electric Power / Battery Energy, as shown in Table 3.

Table3: Battery Power Loading Analysis

Motor Power (kW) / Machine-Power / Electric-Power / Battery Energy (kWh)		Battery Power Rate (C-Rate) < 6C			
Machine-Power		50	80	120	150
Electric-Power		60	96	144	180
Module	18	3.3	5.3	8.0	10.0
	24	2.5	4.0	6.0	7.5
	30	2.0	3.2	4.8	6.0
	36	1.7	2.7	4.0	5.0

C. When considering battery weight: the reference setting of battery weight is that it must be less than 30% of the curb weight. As the curb weight is 1400kg, the battery weight shall be less than 420kg. The battery weight is calculated as: Battery Weight = Battery Energy (kWh) / Pack Energy Density (Wh/kg), as shown in Table 4, of which 4 types of Energy Density were assumed: 60Wh/kg, 75Wh/kg, 90Wh/kg, and 112.5Wh/kg.

Table4: Battery Weight Computation

Battery Energy (kWh) \ Pack Energy Density (Wh/kg)		Battery Weight (kg) < 420kg			
		60	75	90	112.5
Module	18	300	240	200	160
	24	400	320	267	213
	30	500	400	333	267
	36	600	480	400	320

D. When considering battery volume: the batteries must be capable of fitting into the space of the battery pack (< 220 liter). The battery volume is calculated as: Battery Volume = Battery Energy (kWh) / Pack Energy Density (Wh/liter), as shown in Table 5, of which 4 types of energy density were assumed: 96Wh/liter, 120Wh/liter, 144Wh/liter and 168Wh/liter.

Table5: Battery Volume Computation

Battery Energy (kWh) \ Pack Energy Density (Wh/kg)		Battery Volume (liter) < 220liter			
		96	120	144	168
Module	18	188	150	125	107
	24	250	200	167	143
	30	313	250	208	179
	36	375	300	250	214

E. With the evaluation of vehicle payload, the reference design was computed by deducting the battery weight from 40% curb weight, namely: Vehicle Payload = Curb Weight * 40% - Battery Weight. Based on the specification of the chassis mentioned in the study, with estimated passenger number of four adults (about 75kg each) plus 20kg cargo weight, the vehicle payload shall be more than 320kg. The vehicle payload calculated with different batteries is shown in Table 6.

Table6: Vehicle Payload Computation

Battery Energy (kWh) \ Pack Energy Density (Wh/kg)		Vehicle Payload (kg) < 320kg			
		60	75	90	112.5
Module	18	260	320	360	400
	24	160	240	293	347
	30	60	160	227	293
	36	-40	80	160	240

6 EV's Powertrains Matched Designed Case

For practical purposes the electric vehicle is achieved based on **MIRDC running chassis first generation,** 24kWh batteries is scaled. The volume for the energy system is 179,453,980 mm^3, the structure of the battery system are show as Figure 5. The volumes include housings, connections, cells and battery management systems.

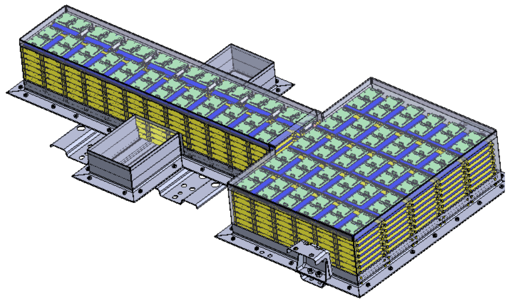

Figure5: Structure of the battery system

Base on the power system models built above, pre-transmission electric vehicle is built in the MATLAB/Simulink software environment. The speed of simulation tracks the aimed speed of the ECE15 [3] driving cycle. In this simulation, use the MIRDC running chassis first generation vehicle parameter. The vehicle performance are define as follow

(A) Max. Speed > 120 km/h;

(B) Grade-ability > 30%;

(C) An acceleration performance of *0–100 km/h* in *10.4 sec* for short time intervals.

The gear ratio select as follow

(1) Upper limit of drive ratio of drive line system:

$$Gear\_H \le \frac{0.377 n_m r}{v_m} = 9.1909$$

(2) Lower limit of drive ratio of drive line system:

$$Gear\_L \ge \frac{F_{nm} r}{\eta_t T_{nm}} = 2.6155$$

(3) The lower limit of drive ratio of drive line system is decided according to the highest climbing angle ($\theta = 21.98$) as follow

$$Gear\_A \ge \frac{F_{am} r}{\eta_t T_{nm}} = 6.9281$$

$v_\alpha = 30\, km/hr$ is the corresponding car speed for highest climbing angle.

The motor select as follow

(4) Based on the car speed 120km/hr, the motor continuous power is 100kW. The tractive motor can provide power at peak of 150kW.

(5) Based on the car speed 30 km/hr and highest climbing angle ($\theta = 21.98$,Gear = 8.28) the motor output power is 48.6699(kW)

Table7: System Parameter

C_{rro}	0.001	[-]	ρ	1.2	kg/m^3
C_{rr1}	0.006	[-]	C_D	0.25	[-]
m	1549	kg	A_f	2.2	m^2
g	9.81	m/s^2	dV/dt	[-]	m/s^2
$V_{\max}$	120	km/hr	θ	21.98	degree

Battery voltage is 320V. Simulation results show in Figure. 6 (a) is the vehicle required power in the ECE15 driving cycle, Figure. 6 (b) is the output torque of the motor in the driving cycle. The ECE15 driving cycle is a good representation of the urban circuit in a typical European city on 200 s. It was analysis the dynamical response of the proposed **MIRDC running chassis first generation** for this circuit test from Figure 7 (a), it appears that car speed follow the ECE-15 reference speed, but when it is required a greater speed, case of the acceleration to the maximum speed, the motor drive responds more slowly and does not track the ECE-15 reference very well. This drive has a greater capacity for rapid acceleration and to start causing the current highest values present, but for shorter time this result are show in Figure 7 (b).

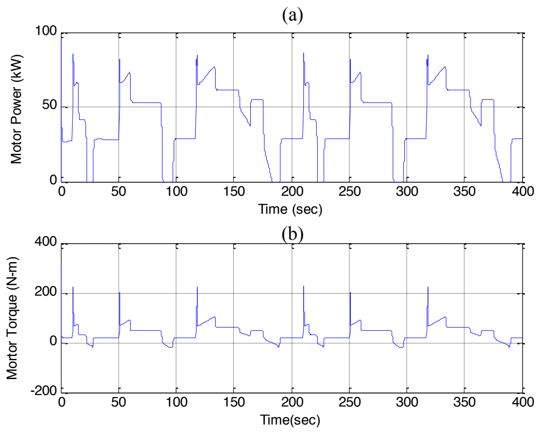

Figure6: (a) Motor Power (b) Motor Torque

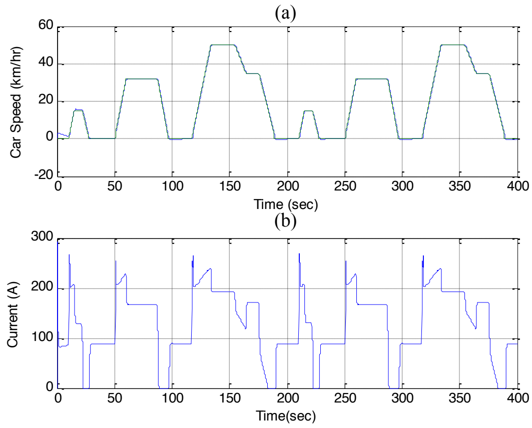

Figure7: (a) Car Speed (b) Current

7 Conclusion

In this paper, developed with MATLAB/Simulink, is a vehicle-modelling package used to simulate performance and battery economy. It allows one to realistically estimate the wheel torque needed to achieve a desired speed by sending commands to different components, such as throttle position for the motor, gear number for the transmission, or mechanical braking for the wheels. The presented study can be used in the EV powertrains selection and motor selection, taking into account the vehicle utilization or duty cycle.

From the analysis results, the study produced car types of different performances, as shown in Table 8, from the matching of different batteries with different power modules within the fixed space planned for the battery module and power module on the same chassis. From the analysis, the problem existing with current EVs can be observed, which is the battery weight being too heavy, as shown by the computational results in Table 3 and 5. If car manufacturers do not wish to sacrifice the vehicle payload, then the possible resolution is to request battery manufacturers to produce batteries of even higher density.

Table8: Different Car Types Produced from Matching Different Battery Modules with Different Power Modules

Motor Power / Battery Energy	50kW	80kW	120kW	150kW
18kWh	City	City	--	--
24kWh	City	City/Sedan	Sedan	--
30kWh	--	Sedan	Sedan/SUV	SUV
36kWh	--	--	SUV	SUV

It is important to note that the simulation results predict well the behaviour of the motor and vehicle available, being in accordance with the data provided by MIRDC [9].

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