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An electro-driven system design on Formula Student Racing Car

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Abstract

Formula student racing has been carried out over more than 30 years in the world. With the environmental protection and energy crisis the electric drive system is applied on the formula student car recently. An electric formula car has been successfully designed and manufactured. The overall design is based on tournament rules during the design process. Required for the power performance and economic performance of the car, the power matching is designed, and the appropriate motor, controller, gearbox, batteries are selected. We analyze and calculate the power parameters on this basis of the optimizing design. The test results prove the design requirements are obtained. On general layout and design, with the use of advantages of pure electric car batteries that can be flexibly furnished and ergonomic principles, we make the general arrangement for the batteries, motors, steering system, transmission, suspension systems, brake systems and get a reasonable distribution of axle load. At the same time, the problem of huge axle load of fuel FSC racing car is eased. Subsequently, we launch a specific design to the steering system, frame, suspension, brakes systems, suspension systems, and establish a three-dimensional model for simulation and checking calculations. The electric formula car is tested which shows that he parameters are similar as the simulation.

Keywords: Electronic Formula student car , electric drive, vehicle performance, modelling, simulation

FSC is initiated by the U.S. After 20 years' development, it has become an annual periodic grand event for global top young university engineers. Because of the rising oil price and people's growing awareness of energy conservation and environmental protection, countries all over the world have started a competition on technology and market in the field of electrical vehicle. At the same time, electrical vehicle has become a huge issue which revitalized Chinese automobile industry and achieved prominent development [1]. It has great significance to study electrical racing vehicle through FSC entries in China. This paper discussed the power matching and suspension design of electrical FSC racing vehicle through the experience of postgraduates from Beijing Institute of Technology.

1 Identify the motor

Electric FSC racing car uses motor and batteries as power. The choice of motor and gear box directly impacts the vehicle's dynamic property. Small motor will often run in overload conditions which can cause poor heat dissipation and reduce lifetime. Conversely, large motor will often operate in under-load state which can cause low efficiency, low power and poor economy. According to FSC competition rules[2] and electric car's performance requirements, motor selection should meet the following five main requirements: firstly, to meet the car's acceleration and maximum speed requirements, the motor should have great peak power, large peak torque and strong overload capability. Secondly, the motor should be small and light to adapt the car's lightweight design. Thirdly, the voltage of motor system should fit the battery pack. Fourthly, the motor should be efficient and reliable. Finally, the motor should have a great speed adjustable rang to meet a wide range of vehicle speed changes.

1.1 Determine motor's rated power

There is not clear maximum speed limit in FSC competition rules, but the maximum speed indirectly affects five dynamic test program results. Based on the first Chinese FSC racing competition experience, the maximum speed is satisfactory as long as it exceeds 120 km/h. Acceleration is the key to influence the dynamic test results. The motor's rated power is:

$$P_N = \frac{1}{\eta_T}\left[\frac{mgf}{3600}u_{a,\max} + \frac{C_D A}{76140}u^3{}_{a,\max}\right] \qquad (1)$$

Peak Power

The motor's peak power is often determined by the maximum speed, the maximum acceleration and maximum grade ability. FSC racing car has the highest requirement on acceleration performance. However, it needs smaller grade ability. And its highest speed is more easily to meet. Therefore, the motor's peak power should be primarily determined by the power corresponding to the maximum acceleration. The motor power:

$$P_m = \frac{1}{\eta_T}\left[\frac{mgf}{3600}u + \frac{\text{mg}i}{3600}\frac{C_D A u^3}{76140} + \frac{\delta mu}{3600}\frac{du}{dt}\right] \qquad (2)$$

Use a maximum speed to determine the motor's peak power: $P_{m1} = \frac{1}{\eta_T}\left[\frac{mgf}{3600}u + \frac{C_D A}{76140}u^3 + \frac{\delta mu}{3600}\frac{du}{dt}\right]$ (3)

And take the power corresponding to maximum speed and the power corresponding to grade ability into account.

$$P_{m2} = \frac{1}{\eta_T}\left[\frac{mgf}{3600}u_{a,\max} + \frac{C_D A}{76140}u^3{}_{a,\max}\right],$$

$$P_{m3} = \frac{1}{\eta_T}\left[\frac{mgf}{3600}u + \frac{C_D A}{76140}u^3 + \frac{mgiu}{3600}\right]$$

The motor's peak power is:

$$P_m = \max\{P_{m1}, P_{m2}, P_{m3}\} \qquad (4)$$

1.2 Rated torque and maximum torque

Based on the characteristics of the motor, the stage of the constant torque is from the starting to the achieving of the rated speed. Then the motor reaches the constant power. That means the motor reaches its maximum torque and rated torque when at rated speed. Then we can get the maximum torque $T_M = \frac{9554 P_m}{n_N}$, the rated torque $T_N = \frac{9554 P_N}{n_N}$.

Select motor type

The basic parameters of the motor are initially set through the above analysis and calculation. Next we will discuss the motor type.

Generally speaking, the current motors used in Electric vehicles include DC motors, induction motors, switched reluctance motors, permanent magnet brushless motors and permanent magnet synchronous motor. The permanent magnet synchronous motor is the most competitive electric car drive system and has been highly valued by domestic and international Electric car industry and widely used in Japan [3]. Compared with other motors, permanent magnet synchronous motors has advantages of high efficiency, simple structure, high torque density, small size, light weight, fast response ability, high power factor, etc. Especially, the built-in permanent magnet synchronous motor has great power density and strong overload. It is very suitable to be the electric car drive motor [4]. Given its prominent advantages, we chose the magnet synchronous motor.

2 Transmission ratio

Transmission ratio has great impact on power performance and economy of the Electric FSC racing car. In general, greater transmission ratio means better acceleration and worse power economy. However, if the transmission ratio is too large, the power of the motor can not be fully played. It also goes against the chain drive layout. Smaller gear ratio means higher maximum speed and better economy. But it will cause poor acceleration and grade ability. Therefore, in the specific design progress, it is possible to comprehensively consider the simulation analysis of the selected motor and choose the best value. Besides, the transmission ratio needs to meet three conditions: maximum speed, maximum acceleration, slope stop starting. They are $u_m \le \frac{0.377 r \cdot n_m}{i_g \cdot i_0}$, $a_m \le \frac{T_m i_g \cdot i_0 \eta_T}{r \cdot m}$, and $mg\left(f+i\right) \le \frac{T_m i_g \cdot i_0 \eta_T}{r}$. And conventional speed should be close to the motor rated speed in order to improve the economy: $i_g \cdot i_0 \approx \frac{0.377 r \cdot n_N}{u_c}$.

3 Design example

3.1 Design goals and basic parameters

Take the "Black Shark", the first generation of Electric FSC racing car of Beijing Institute of Technology, as an example to make the matching calculation and simulation. The dynamic design goals of the car are 75m straight line acceleration time <4.5s, 0-100km/h acceleration time<4.5s, top speed>120km/h, normal speed is 48-57km/h, endurance mileage>50km. Parameters of the car is shown in Table 1.

Table 1: Parameters of pure electric FSC race car

Full quality/kg	300	Windage coefficient	0.3
Frontal area/m^2	0.8	Wheel radius/mm	228.6
Wheel resistance	0.000056u +0.076 [5]	Transmission efficiency	0.92
Conversion factor	1.04	Reference vehicle's reduction ratio	5

3.2 Select the motor

According to the above calculation formulas for choosing the motor, gear ratio of the reference model and transmission ratio, we can get the basic parameters of the needed motor.

Table 2: Parameters of the needed motor

Rated speed/ Maximum speed/r min^{-1}	Rated torque/ Maximum torque/Nm	Rated power/ Peak power /kW
3000/6300	25/140	7/44

Select the permanent magnet synchronous motor with rated power 21kw. Its main parameters are: system voltage is 288V, rated power is 21kw, peak power is 45kw, the maximum torque is 145Nm, the rated speed is 3000r/min and the maximum speed is 9000 r/min.

3.3 Determine the transmission ratio

After the motor is selected, we can further determine the transmission ratio value. According to the formula for initially determining transmission ratio, we can get the economic power transmission ratio that can meet dynamic conditions: $4.540 \le i_g \cdot i_0 \le 5.386$. According to the traditional FSC racing design experience and compact layout of the space, the car does not use gear box and its main reducer use a chain drive. In this case, the vehicle has simple structure, high transmission efficiency and reliability. Taking the force of small sprocket in the chain drive into account, the wrap angle of small sprocket is preferably not less than 120 degrees. At the same time, simultaneously meshing teeth of the small sprocket and chain is not less than 3, and the small sprocket teeth should be greater than 9. When the sprocket modulus is determined, more teeth means larger diameter sprocket. The number of large sprocket teeth should be less than 60 considering the teeth are set in limited space of the FSC racing car and can not cause interference with space truss-frame and double wishbone suspension. According to the roller chain drive parameter selection principle in the literature [6], when the selected number of sprocket teeth and the number of chain is odd prime number, chain drive wears more evenly in use. Therefore, choose an odd number as the teeth number of two sprockets whenever possible.

3.4 Dynamic analysis

After the motor type, transmission and main reducer transmission ratio are determined, the specific racing car's power can be analyzed, and the motor and transmission options can be verified and optimized according to the results of analysis. If the racing dynamic analysis does not correspond with the design goals, you can adjust the value of the transmission ratio, choose a variety of situations to make a comparative analysis and then choose the best solution. Another situation is power performance of the racing car can not meet the design goals no matter how you choose the transmission ratio. Then the motor selected is inappropriate. You should rematch the motor and calculate again until you obtain the satisfactory result. The derivation formula of vehicle power performance can lead to:

Driving force $F_t = \dfrac{T_m i_g \cdot i_0 \eta_T}{r} = 4.024 T_m i_g \cdot i_0$

Driving resistance $F_f + F_w = mgf + \dfrac{C_D A}{21.15} v^2$

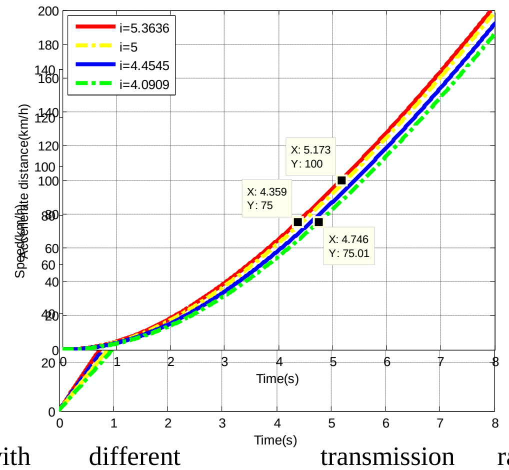
$$= 22.344 + 0.16464v + 0.011348v^2$$

Power factor:

$$D = \frac{F_t - F_w}{G} = 6.84 \times 10^{-3} T_m - 3.860 \times 10^{-6} v^2$$

Acceleration $a = \dfrac{du}{dt} = \dfrac{g}{\delta}(D - f) = 9.423(D - f)$

Select different transmission ratio to make quantitative analysis of power performance of the racing car. Figure 2 shows different power performance parameters of the car corresponding



with different transmission ratios drawn with the software MATLAB.

Fig 2: Force and acceleration distance under different transmission ratio

Analyze the simulation results of different transmission ratios and comprehensively consider factors such as power performance and space arrangement to select total transmission ratio. The maximum speed of the vehicle depends on the maximum speed of the motor. At the same time, the motor should have some back-up power when the vehicle is at the maximum speed.

The transmission ratio of this example racing car is 5, and we can get theoretical power performance parameters as shown in Table 3.

Tab 3: The theoretical dynamic parameters

Maximum speed	Maximum acceleration	75m acceleration	0-100km/h acceleration
155km h^{-1}	9.21m s^{-2}	4.315s	3.818s

4 Battery and driving range

When electric FSC racing car is driving uniformly at a regular speed on a level road, the output power of the motor is: $P_C = \frac{1}{\eta_T}\left[\frac{mgf}{3600}u_c + \frac{C_D A}{76140}u^3{}_c\right]$

The loss efficiency of motor and battery η_d is 0.85, and the allowed battery discharge depth η_{dis} is 0.85.

The output power of power battery

is: $P_b = \frac{1}{\eta_T}\left[\frac{mgf}{3600}u_c + \frac{C_D A}{76140}u^3{}_c\right] / \eta_{dis} / \eta_d$

The battery energy is: $E = C \cdot U \geq P_b \cdot \frac{S}{u_c}$, while calculating the conventional speed, take the maximum of the average travel speed of the endurance race, 57km/h. Substitute the value and get $C \geq 5.56$ Ah.

In order to meet the requirements of the motor system voltage, there is $C = \frac{P_N}{U} \cdot \frac{1}{\lambda}$. U is the system voltage of motor, and λ is battery discharge rate. Select a high-power iron-phosphate-based lithium-iron battery of 20Ah, 3.2V voltage will need 90 cells. At this point, the rated discharge current is 3.6c, and the actual driving range is 180km.

According to FSC competition rules, FSC racing car can complete the game as long as its endurance mileage is greater than 22km (total mileage in Endurance race). Endurance race includes straight, continuous curve, hairpin bends, obstacles and complex tracks. The average speed of racing car measured by standard instructions is 48km/h~57km/h. Cars traveling with an approximate constant medium-low speed on the curves, obstacles and complex tracks. That will consume less power. On the straights, cars will accelerate firstly and then slow down. That will increase power consumption greatly. Since the racing car's endurance mileage 180km is eight times of total mileage of endurance race and is far greater than the total mileage of travel acceleration, the battery selected in the design example is fully capable of completing FSC race.

5 Suspension design

5.1 Suspension orientation organization

The model uses double wishbone suspension. After knowing the influence of double-wishbone suspension's upper and lower control arms to the roll center, the wheelbase and the wheel camber change [7], racing suspension model is established by using Adams/View [8]. Then use the model to optimize the value of upper and lower arms. It can save a lot of computing time. The car model is as follows:

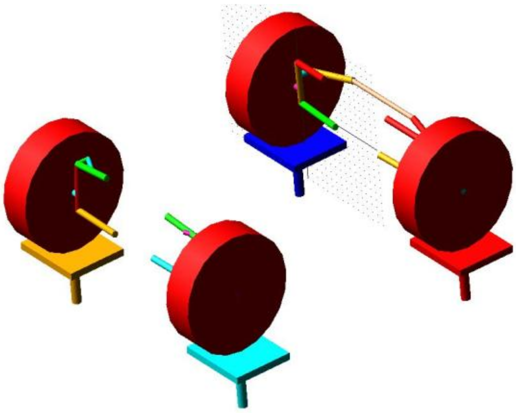


Fig 3: car model

The model shown in the drawing can separately modify various parameters of the front and rear suspensions. It is very conducive to optimize the design of suspension. In the design process, only optimize the length of the upper and lower arms and do not optimize angles of other space. Identify each suspension parameters firstly, and then analyze by five cases: the length ratio of upper and lower arms is 0.6, the length ratio of upper and lower arms is 0.7, the length ratio of upper and lower arms is 0.8, the length ratio of upper and lower arms is 0.9, the length of upper and lower arms are equal [9]. There are five simulation results of the upper and lower arms length as shown below:

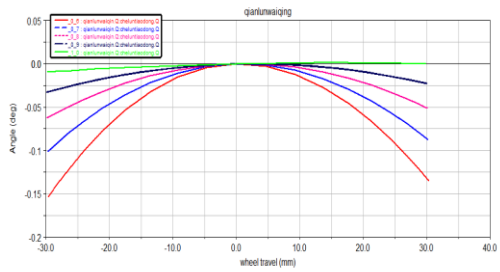


Fig 4: Wheel camber-jumping wheels

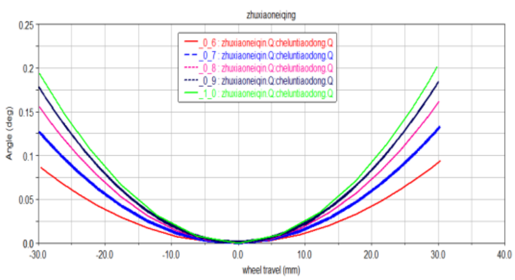


Fig 5: Caster- jumping wheels

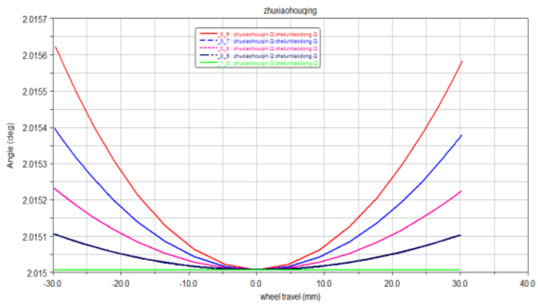


Fig 6: Kingpin inclination-jumping wheels

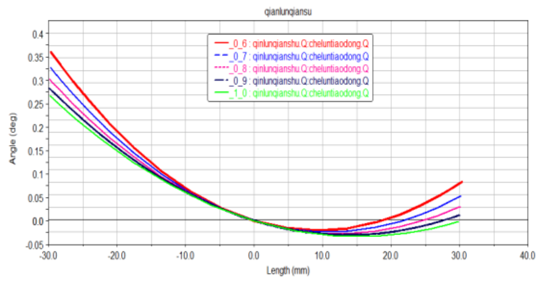


Fig 7: Front wheel toe- jumping wheels

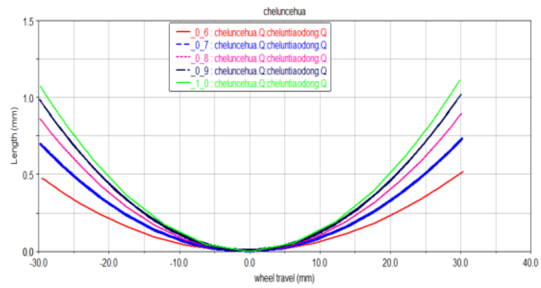


Fig 8: Wheel base- jumping wheels

Analyzing those figures, it is very obvious that when the length ratio of upper and lower arms is 0.6, the change of alignment parameters is the best but the upper control arm is too short. It can cause the frame at the upper control arm is too broad and then increase the car’s quality. Therefore, choose the length ratio of upper and lower arms as 0.8.

At last, combining frame space requirements, choose 320mm as the upper control arm length and 400mm as the lower control arm length. The curve of front wheel alignment parameters is shown with the pink curve in middle of those above charts:

Wheel camber change rate: 0.15 °/ 30mm,

Wheel base change rate: 1.1mm / 30mm,

Caster angle change rate: 0.2 °/ 30mm,

Kingpin inclination change rate: 2 °/ 30mm,

Front wheel toe angle change rate: 0.35 °/ 30mm.

5.2 Spring design of front and rear suspensions

The match of the spring and the racing car is a continuous project. Even after the spring and the shock absorber assembly designs is completed, stiffness of the car's roll angle and suspension lines can change by replacing the spring as long as the performance of the racing car can be improved when turning the suspension. Therefore, designed spring stiffness has 4 options: 150lbs/in, 175 lbs/in, 200 lbs/in, 225lbs/in. They also can be 26229N/m, 30600N/m,34972N/m,39343.5N/m. The relationship between the spring stiffness K_S and suspension lines stiffness K_W is:

$$K_W = K_S \times MR^{-2} \qquad (5)$$

In the formula: MR is the suspension leverage ratio.

Because the stiffness of spring used in FSC racing car is relatively higher, tire stiffness is a factor that can not be ignored in 1/4 car model.

Apparently, take suitable stiffness is the equivalent stiffness of suspension stiffness and tire stiffness in series.

Left and right sides of the racing car is symmetrical. All types of the spring can be calculated by formula and get the correspondence of below, front and rear suspension stiffness, take suitable stiffness and roll angle stiffness [10]. As shown in the table below:

Tab.5 Stiffness corresponding to different springs

Spring	Suspension position	K_S (N/m)	K_R (N/m)	$K_{\phi s}$ ($N\frac{m}{\circ}$)
150lbs /in	Front	40983	34054	251
	Rear	40983	34054	214
175lbs /in	Front	47813	38641	285
	Rear	47813	38641	243
200lbs /in	Front	54644	42984	317
	Rear	54644	42984	270
225lbs /in	Front	61474	47100	347
	Rear	61474	47100	296

As already calculated the suitable stiffness of front and rear suspensions respectively are 57.2N/mm and 46N/mm. According to the above tables, the spring of 225lbs/in is the right choice for both front and rear suspensions.

5.3 Stabilizer bar layout

5.3.1 Do not install stabilizer bar

When the car rolls, do not consider the roll of the wheel, then the car's front tire load transfer value ΔW_F is:

$$\Delta W_F = \frac{K_{\Phi F}\Phi}{t_F} = \frac{K_{\Phi F}}{t_F}\frac{\Phi}{A_Y}A_Y = \frac{K_{\Phi SF}}{t_F}\frac{\Phi}{A_Y}A_Y = 294A_Y N \qquad (6)$$

The transfer value of the rear tire ΔW_R is:

$$\Delta W_R = \frac{K_{\Phi R}\Phi}{t_R} = \frac{K_{\Phi R}}{t_R}\frac{\Phi}{A_Y}A_Y = \frac{K_{\Phi SR}}{t_F}\frac{\Phi}{A_Y}A_Y = 271A_Y N \qquad (7)$$

Compare ΔW_F with ΔW_R . When the car's lateral acceleration is 1g, the transfer value of front tire is bigger than rear tire for 23N. That can cause some under-steer effect [11].

5.3.2 Stabilizer bar on the front suspension

Stiffness of the front suspension roll angle:

$$K_{\phi F} = K_{\phi SF} + K_{\phi RB} = 398Nm/(\circ) \qquad (8)$$

Stiffness of the rear suspension roll angle:

$$K_{\Phi R} = K_{\Phi SR} = 296Nm/(\circ) \qquad (9)$$

The lateral acceleration of 1g is $\Delta W_F = 337Nm/(\circ)$, $\Delta W_R = 271Nm/(\circ)$. It can be seen that the difference between the front and rare tire load transfer value is greater and achieves 66N.m. Therefore, installing a separate stabilizer bar on the front suspension is not desirable.

5.3.3 Stabilizer bar on the rare suspension

Stiffness of the front suspension roll angle:

$$K_{\Phi F} = K_{\Phi SF} = 347Nm/(\circ) \qquad (10)$$

Stiffness of the rare suspension roll angle:

$$K_{\Phi R} = K_{\Phi SR} + K_{\Phi RB} = 347Nm/(\circ) \qquad (11)$$

The lateral acceleration of 1g is $\Delta W_F = 294Nm/(\circ)$, $\Delta W_R = 305Nm/(\circ)$. Obviously, the transfer value of the front and rare tire load is basically the same amount. And the racing car tends to neutral steering. Therefore, install the stabilizer bar on the rare suspension, and the roll stiffness of stabilizer bar is adjustable. Then adjust the car's steering by adjusting the roll stiffness of the stabilizer bar.

6 Conclusion

This paper firstly chooses the motor and its drive system, and then makes a match calculation. Secondly, it makes simulation analysis and optimization design to the racing car's motor system. Thirdly, it calculates various performance indicators of the lithium-ion battery and the permanent magnet synchronous motor. Lastly, its simulation and optimization to the double wishbone suspension determines the lengths of the upper and lower arms. It also analyzes the influence of various spring stiffness and stabilizer bar layout to suspension performance. And it determines parameters of suspension ultimately.

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