STUDY AND DESIGN OF A SPECIAL RELUCTANT MOTOR FOR DIRECT ELECTRICAL DRIVE OF A BICYCLE

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Abstract – **The paper deals with an overview regarding the implementation of individual urban transportation using reluctant motor driven electric bicycles. A particular case of Cluj-Napoca city is taken as reference. Study of opportunity, state of the art in the field of electrical driven bikes and a proposed solution in the field are presented. Preliminary design is described with the study of magnetic field in order to provide the optimal geometry of the motor and adequate windings**
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Keywords: electric bike market, motor design, finite element method for field analysis.

1. INTRODUCTION

Individual urban transportation in Cluj-Napoca has blown up since 1990, due to the expansion of car number [1]. This fact has produced a crisis in urban transportation, for which local authorities cannot face satisfactorily. Electric two-wheel vehicles could be the best means for urban individual transportation, provided other conditions be accomplished, as people mentality related to such a transportation mode will change and, not finally, the budget problems.

Following actual trends of the bike market and taking into account specific traffic conditions in Cluj-Napoca, there is a good opportunity to approach the research of in-wheel direct drive motorizing with various types of motors. Among them, electric reluctance motors seem to open a good perspective for in-wheel direct drive of the bicycle, special designed for low speed, high torque, self-commutated, at an output power below 500W.

2. ELECTRIC BIKE MARKET

2.1. Electric bikes

Electric bike is a 2-wheel electric motor based autonomous vehicle designated for short and medium distance urban individual displacements. It belongs to larger family of 2-wheel vehicles, which includes city bugs (no-seat cycles), electric bikes and electric scooters.

Electric bike market is one of the most dynamic today, involving a large number of producers and various types of units, concerning technical data and prices [2]. For example, in figure 1 is presented the evolution of the electric bike market in China, comparatively with personal car production [3].

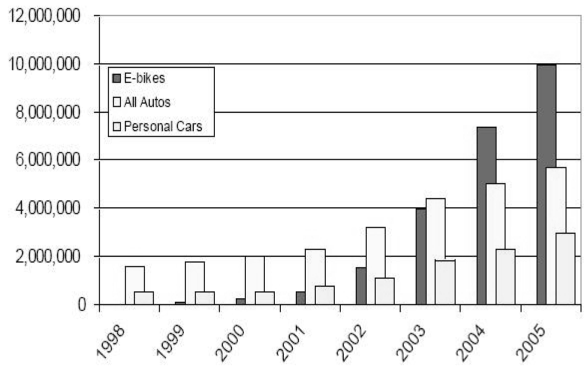

Figure 1: Production of e-bikes and cars in China.

Table 1 shows some representative units of this market, taking into account the main characteristics of electric bikes.

Model & Producer	EB01-RD WJ Power Sports, USA	ES-501 Yongkang Sport El. Vehicle Manf., China	Helio Cycle M20, eGO Cycles, USA	NyceWheels, USA
Max load [kg]	125	150	110	NS
Weight [kg]	55	40	59	27
Max speed [km/h]	30	20	20	20
Range [km]	50	40	35	10
Electric motor	Brushless dc, 250W	NS 250W	PM brush dc, 480W	Brushless dc, 240W
Battery	3x12V, 12Ah	36V, 12Ah	24V, 34Ah	24V, 20Ah
Price,USD	549	240	NS	600

Table 1: Some representative electric bikes.

This study has been made using info documentation from the Internet. At first sight, one can remark some construction strategies, as:

- most producers use conventional electrical motors of DC types, that are cheaper and suitable for electric traction within powers of hundred Watts;
- no special batteries are used, only conventional lead-acid type;
- conventional 1-quadrant electrical drive, with mechanical braking is adopted, from economical reasons, so that no special electronic part is involved;
- No version of upgrading a classical bike towards an electric one has been found.

Technical information from this Table, as most information provided by other producers, shows the ride speed up to 30 km/h, motor output power under 500W, ride range under 50km and prices of hundred US dollars. The prices are also dependent on looking characteristics.

2.2. Electric motors

Electric motors involved in bike driving consist in the most important problem of designing and manufacturing of an electric bike, thus this study is focused towards motorizing and driving the electric bike. An overview of main solutions for electrical drives as given in Table 2, taking into account some specifications that could make difference between them.

Electric motor type (within hundred Watts)	Max efficiency [%] *Over* Specific power [kW/kg]	Inverter type	Control strategy	Specific cost [$/kW]
3-phase Induction motor	72 0.04	3 Full bridges, PWM	Vector control, DTC	700
PM Brush DC motor	75 0.028	1 Full bridge, PWM	PI torque control	1000
Brushless DC motor	82 0.2	2-3 Full bridges, PWM	Self-commutated	2000
3-phase PM-synchronous motor	90 0.3	3 Full bridges, PWM	Vector control, DTC	3000
3,4-phase Switched reluctance motor	85 0.15	3,4 Half bridges, PWM or dual voltage	Self-commutated	2500

Table 2: Electric motors for driving bikes.

Some conclusions provided by this study will be very useful to approach a new solution for motorizing electric bike, as follows:

- induction motors are not suitable for driving electric bikes, in spite of their costs, due to low energy efficiency;
- brush or brushless DC motors, of conventional construction, even most popular, are of limited prospect for enhancing bikes' technical performances;
- other solutions, as 3-phase PM-synchronous motor and 3- or 4-phase switched reluctance motor are still in research, but only special motor constructions will have successful future.

Beyond market information, recent studies of Chinese and European scientists [3-6] show certain tendency referring to electric bikes improvements. Constant efforts are being made to develop alternative types of motor drive systems with equally or almost as good characteristics, but without commutator and brushes (involving maintenance requirements and gear, thus increasing cost and weight of the bike). In this purpose, new driving methods have been approached, such as:

- adopting special construction of electric motors, using non-conventional configurations and materials;
- placing the motor directly on front wheel (in-wheel solution) and, therefore, a direct drive is proposed, at low speed and high torque;
- accounting for a 2-quadrant drive, to save more energy from battery.

Of course, ideal electric bike will be obtained when significant improvements are also made in battery construction.

At the end of this study, we consider to approach the research of in-wheel direct-drive motorizing with electric reluctance motor of radial construction, at 24 or 36V, properly designed for low speed, high torque, self-commutated, at an output power below 500W.

2.2. Inverters and controller

PWM inverters for motor electronic supply are dependent on the motor type. Usually, in case of PM synchronous motors and Brushless DC motors, bipolar current inverters are needed, so full-bridge inverters have to be used. In case of switched reluctance motors, unipolar inverters lead to cheaper half-bridge inverters. As expected, low-power inverters have to be taken into account, at voltages of 24-36V and power up to 500W, accordingly to motor output power. This fact corresponds to a max bridge current of 20A. PWM inverter market is also very large, with a great variety of voltages and currents, number of phases etc. From this point of view, there is no difficulty in choosing suitable inverters for supplying the electric bike motor.

3. ELECTRICAL DRIVE OF THE BIKE

Electric bikes are conventional bicycles with an added battery-powered electric motor. All of the bicycles use rider pedaling in varying degrees of power sharing. The more powerful electric motors and larger battery packs require the least rider power, primarily on hills. An electric bike can maintain a higher average speed than a conventional bicycle, but takes advantage of the same un-congested network of cycle facilities, giving access to routes that cars and motorcycles cannot reach. The result is often a faster door-to-door journey time than any other transport mean.

As electric vehicle, the electric bike is an electromechanical device, which converts electric energy provided by battery into mechanical energy for moving its wheels. Away from battery, rider and mechanic structure of the bike, this device consists of an electrical drive system, which is the object of this study. Block diagram of this system is given in figure 2, emphasizing its main parts: electric motor, inverter and controller.

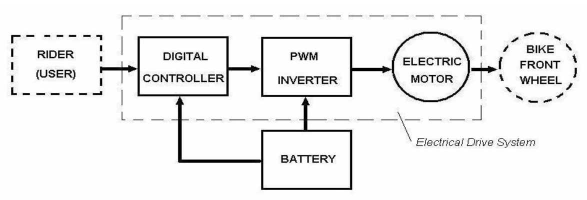

Figure 2: Electrical drive system into the bike configuration.

The main problem encountered with this vehicle refers to the power of electric motor. The power of the motor may be estimated as:

$$P = 1200*(x+0.05)*y \qquad [W], \qquad (1)$$

where x is the road gradient, and y is the running speed in m/s. This expression is written for a total weight of 120 kg (80kg of the rider and 40kg of the bike itself) for a usual friction coefficient of 0.05. For road gradients between 0 (horizontal road) and 0.12 (12%) and running speed from 0 to 10 m/s (36 km/h), the motor output power is represented in Figure 3.

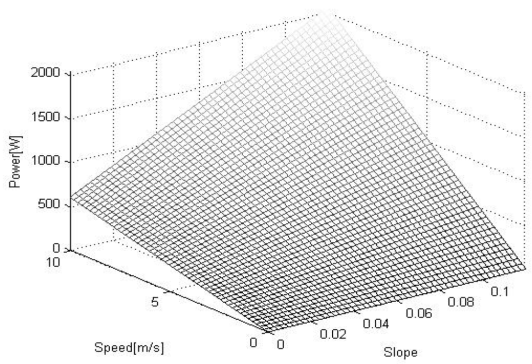

Figure 3: Graphic representation of power/speed/slope relationship.

Expression (1) shows that for the ranges given above, needed power is in the range 500-2000W (max power for max speed and max slope). Also, for a given power of 500W, one can reach maximum speeds between 2.5-8 m/s, depending on the road gradient – at a load of 80kg, and 20-30% higher speeds – at a load of 60kg, as shown in figure 4.

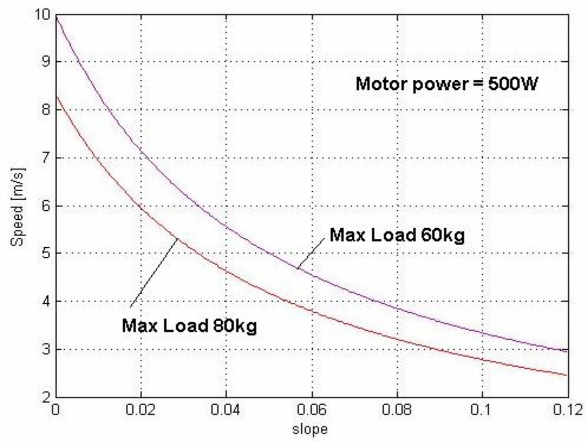

Figure 4: Variation of maximal speed with road gradient.

Preliminary calculus indicates satisfactorily results below 500W, in accordance with existing performances on present market.

4. DESIGNING THE RELUCTANCE MOTOR

In wheel drive of the bike involves the placement of the electric motor inside the front wheel, that is a direct drive. Accordingly, a high torque- low speed motor is to be designed for this application. Electric reluctant motor of reverse construction (inner stator – fixed on the wheel shaft, and outer rotor) have been taken for study. A 16 pole, 4 phase motor (4 poles/phase) is proposed, as shown in figure 5.

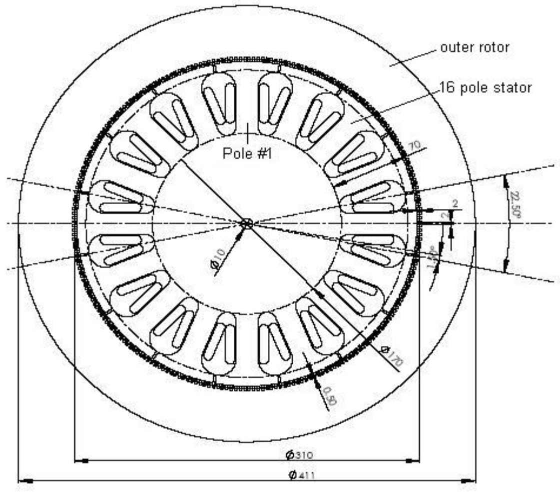

Figure 5: Cross section of the proposed motor.

The 4 phases are respectively placed on poles 1-5-9-13, 2-6-10-14, 3-7-11-15, and 4-8-12-16. Accordingly, the motor phase #1 is schematic represented in figure 6.

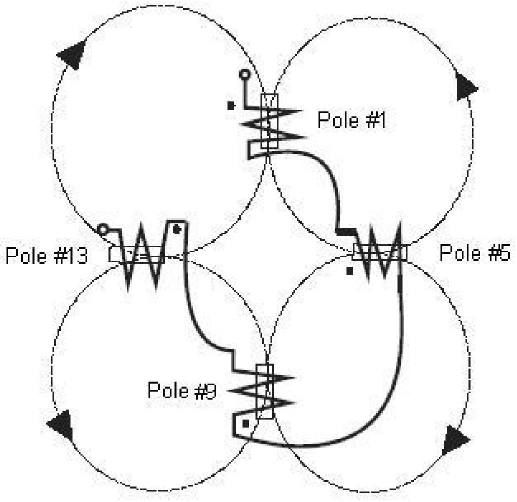

Figure 6: The winding placement of phase #1.

Each phase is built by 4 series mounted windings, with alternating magnetic orientation.

4.1. Toothed structure of the motor

As a reluctant motor, the structure of the air-gap is similar to the variable reluctance stepping motors. This structure offers the reduction of the rotor movement, to acquire the requirement of a direct drive. Figure 7 shows a detailed picture of the toothed structure.

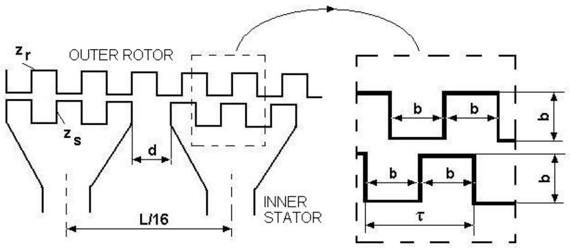

Figure 7: Stator/rotor toothed arrangement.

The rotor has z_r = 244 teeth, identical as dimensions with each of z_s = 14 teeth/stator pole. The key dimension is the amount of the tooth b = 2 mm, as taken for study. With these starting magnitudes and using some additional calculations, the following main characteristics of the motor are obtained:
Number of phases m = 4;
Number of steps/revolution N_p = 976 steps/rev;
Number of rotor teeth z_r = 244;
Number of stator teeth per pole z_s = 14;
Tooth dimension b = 2 mm;
Distance between stator poles d = 3 mm;
Air-gap length L = 97.6 cm;
Air-gap diameter Φ = 31.1 cm.
Number of wire turns per pole N = 260.
These preliminary data lead to general sized motor arrangement, as given in figure 8.

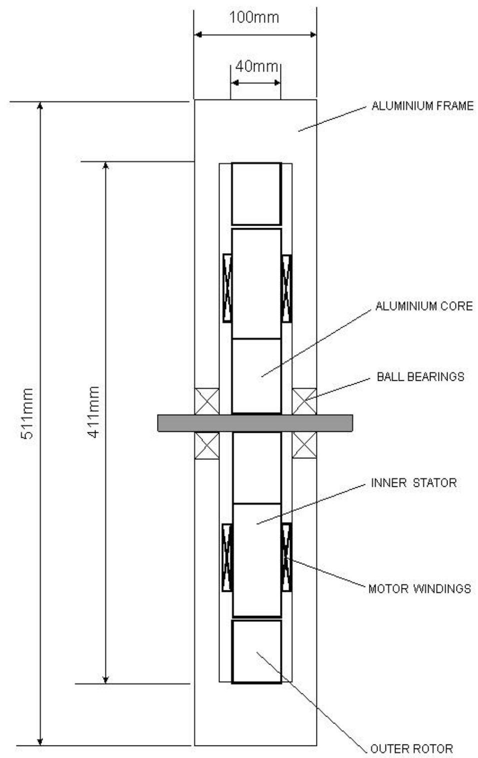

Figure 8: Stator/rotor toothed arrangement

As shown earlier, the inner stator is fixed on front wheel shaft, while the outer rotor is mounted on the wheel rim. The dimensions given in figure 8 are of first try in our study. Figure 9 depict a 3D representation of the proposed motor. The final arrangement of the motor is still in progress.

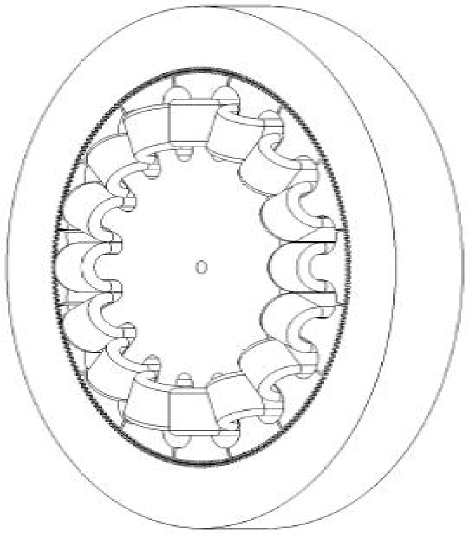

Figure 9: 3D representation of the proposed motor.

4.2. Speed and torque of the motor

Preliminary study indicates for a usual angular speed of 1 rot/sec = 60 rot/min, a motor pulse frequency of 976 pulses/sec. With this value one can calculate the linear speed of the bike with:

$$v = \Omega R = \frac{\pi n}{30} R = 1.88\, m/s = 6.78\, km/h \quad (2)$$

that is an acceptable value for practical purpose.
For this amount, the needed torque, in case of motor power of 500W:

$$M = \frac{P \cdot R}{v} = 75\, Nm \quad (3)$$

To obtain such a torque, one must use the simplified torque formulae [7]:

$$M_{max} = z_r L_1 I^2 \quad (4)$$

For an active inductivity L_1 = 0.02H, with a phase current I = 5A, one obtains M_{max} = *122 Nm.* This value is higher than the needed torque as calculated with expression (3), and that is a good option for designing the power unit.

5. FIELD ANALYSIS

The motor as it has been designed was studied using FEMM environment in order to examine magnetic field in the VRSM and to observe the flux density inside critical regions of the magnetic circuit.
FEMM is a software for bi-dimensional analysis of magneto-static frequency configurations [8]. It allows importing geometric data such as stator/rotor lamination contours, from a file provided by a CAD environment, for instance AUTOCAD with *dxf* files.
FEMM processor uses Maxwell equations to solve the magnetic field and a post processor provide graphical results. Figure 10 presents a triangular mesh for the proposed model of the motor.

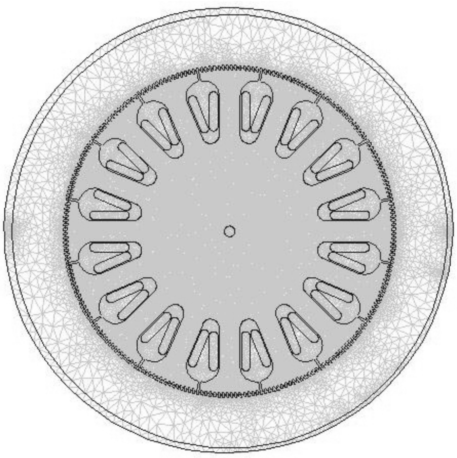

Figure 10: Mesh of finite elements.

Figure 11 shows the picture of the flux linkage provided by the post processor in case of tooth per tooth position or the rotor (aligned position), and figure 12 depicts the results in case of unaligned position.

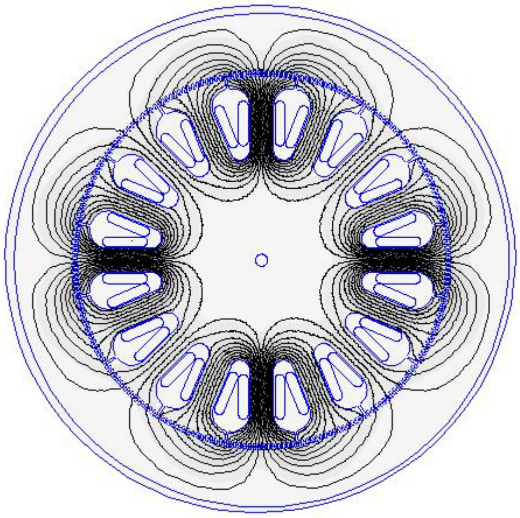

Figure 11: Flux linkage for aligned position.

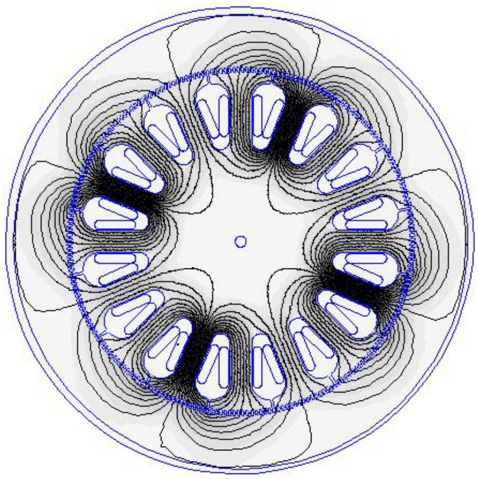

Figure 12: Flux linkage for unaligned position.

Analyzing the results of the field study, we can see that the diameter of the motor can be reduced. After a set of analyses for different dimension, the proper dimension of the motor diameter was chosen. In figure 13 and 14 one can see the results of field analysis made for new motor diameter, in case of aligned respectively unaligned position of the rotor. Figure 15, and figure 16, shows the picture of the flux density provided by the post processor for one pole in case of half aligned position, respectively aligned position.

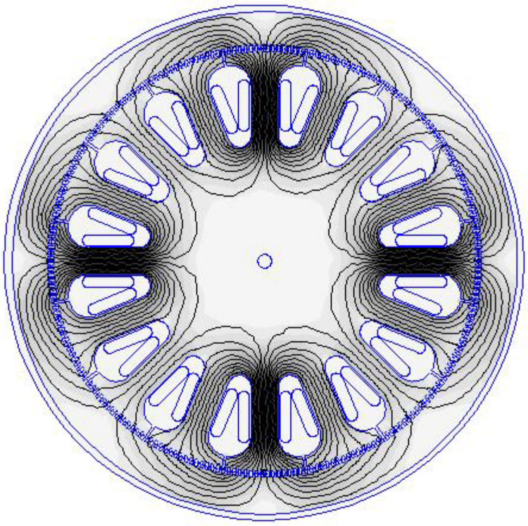

Figure 13: Flux linkage for aligned position at new motor diameter.

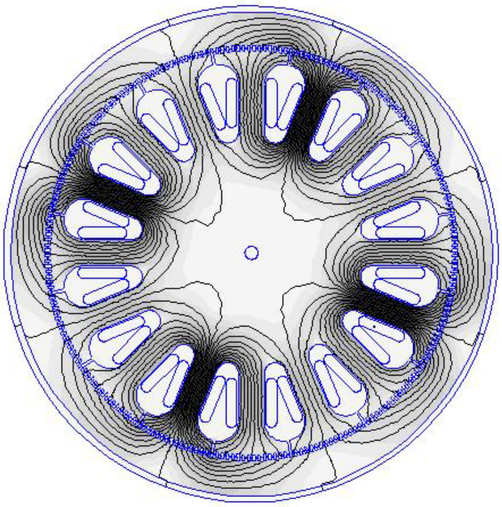

Figure 14: Flux linkage for unaligned position at new motor diameter.

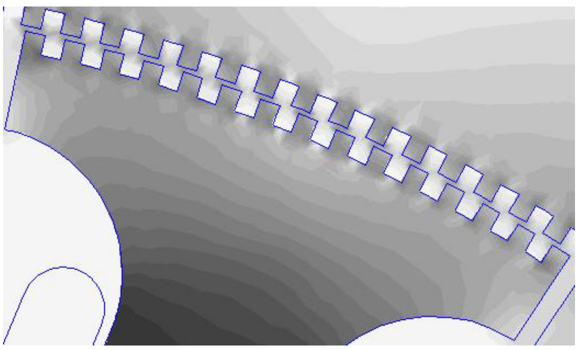

Figure 15: Flux density per one pole for half aligned position.

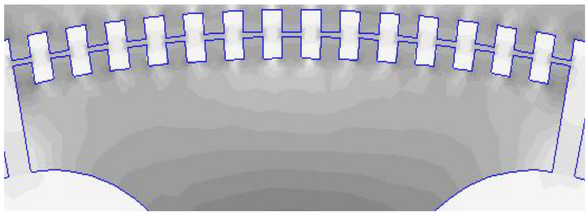

Figure 16: Flux density per one pole for aligned position.

4. CONCLUSIONS

A robust electric motor, as reluctant motor, is proposed for direct driving the front wheel of the bike. Preliminary calculus indicates good performances for this new type of motor and field analysis shows correct flux density, which confirms a good preliminary design of the motor.

The project will continue with a comparative study of various external dimensions of the motor, such as motor diameter and axial length in order to find the most economical and efficient solution for electrical bike's driving.

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