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Design and Development of a Prototype Vehicle for Shell Eco-Marathon

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***Abstract*—**Improvement in vehicle efficiency can reduce global fossil fuels consumptions. For that sole reason, Shell Global Corporation introduces Shell Eco-marathon where student teams require to design, build and test energy-efficient vehicles. Hence, this paper will focus on design processes and the development of a fuel economic vehicle which satisfying the requirements of the competition. In this project, three components are designed and analyzed, which are the body, chassis and powertrain of the vehicle. Optimum design for each component is produced through simulation analysis and theoretical calculation in which improvement is made as the project progresses.

***Keywords*—**Energy efficient vehicle, drag force, chassis, powertrain.

I. Introduction

A. Problem Statement

NOWADAYS, around 85% of energy consumptions are dependent on non-renewable energy which is mostly coming from fossil fuel such as natural gas, gasoline, diesel and coal [1]. On the other hand, renewable energy source such as solar and wind are dependent on availability of the source. So, it is appropriate to state that renewable energy source is unable to provide continuous energy supply for the system to operate [2]. Whereas, industries namely as automotive industries and power plant industries need continuous supply of energy source.

One of the solutions that can be implemented in automotive industries is to maximize the engine efficiency and the usage of energy content in every drop of the fossil fuel into usable power. In theory, the usage of fossil fuel can be reduced by roughly the same percentage of efficiency increase [3]. Vehicle efficiency can also be increased through advanced tribology technology and aerodynamics features such as streamlined design (see Fig. 1).

Fig. 1 Streamlined car design

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Currently, conventional internal combustion engines that use fossil fuels are capable of extracting only 42% of the energy content from the fuel to motive power where the other 58% are transformed into waste such as heat and greenhouse gas [4]. The idea of producing a better vehicle is embraced by Shell Global Corporation using Shell Eco-marathon competition. This event challenges university students from all over the world to produce the most energy efficient vehicle. Originated on the year of 1939 in USA, group of engineers compete each other for producing the vehicle with the highest mileage using the same amount of fuel [5].

The competition is divided into two vehicle categories which are urban concept and prototype. Plus, under the two categories, participants can further choose to produce vehicle which using any of these six energy types which are gasoline, alternative gasoline, diesel, alternative diesel, hydrogen and battery electric. Fig. 2 shows few prototype vehicles which competed in the Shell Eco-marathon Asia 2014 [5].

Fig. 2 Shell Eco-marathon prototype vehicle

B. Shell Eco-marathon Asia 2014 Final Results

TABLE I
Top 3 Teams in Prototype Battery Electric

Country	Institute	Best Attempt(km/kWh)
Thailand	Rattanakosin Technological College	263.4
China	Guangzhou College of South China University of Technology	247.9
Thailand	Nakhon Si Thammarat Rajabhat University	224.4

Table I shows the results for prototype battery electric categories in which this project will focus on particularly due to budget and other constraints. Accordingly, the aim of the project is to build a prototype battery electric vehicle with the performance of at least 263.4 km/kWh.

C. Background

1) Vehicle Chassis

Chassis provides support and structure to the vehicle as well as maintain shape when load is acting on the vehicle. When the chassis can withstand the design load and forces applied to the vehicle and all related parts in the vehicle are still functioning, it is called an acceptable strength of the chassis [6]. The performance and characteristic of a chassis can be accessed from the strength and stiffness of the chassis [7].

a) Stiffness

Chassis stiffness characteristic is usually referred to bending stiffness, K_B and torsion stiffness, K_T. Bending stiffness is a stiffness that relates to the vertical deflection of point near the center wheelbase to multiples of the total static loads on the vehicle symmetrically. Torsion stiffness is the stiffness that is related to the torsional deflection of the chassis structure [6].

b) Strength

Yield strength is the minimum strength that will cause plastic deformation which is also the maximum strength for the elastic behavior of a material. Elastic behavior is a region in a stress – strain curve where the deformation will return to its original shape and size when the loading is removed [8]. Any load exceeding the yield strength can cause permanent deformation or plastic deformation. List of ultimate strength and yield strength of common material is as in Table II.

TABLE II
MECHANICAL PROPERTY OF SEVERAL MATERIALS

Material	Density $\rho(g/cm^3)$	Tensile strength S_{ut} (MPa)	Yield strength S_y (MPa)
Steel ASTM A36	7.7	400	250
Aluminum alloy 6061 T6	2.7	300	241
Stainless steel AISI 302	8.2	860	520

c) Chassis Type

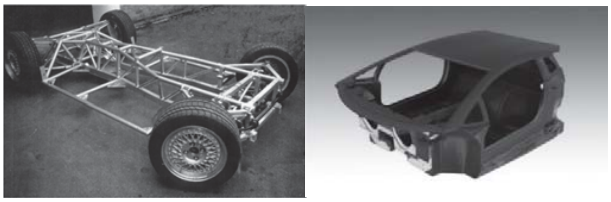

Fig. 3 Triangulated Chassis and Monocoque Chassis

Refer to [6], there are seven basic types of chassis as listed below;

i. Under floor chassis frame
ii. Backbone structure
iii. Triangulated tube structure (see Fig. 3)
iv. Pure monocoque (see Fig. 3)
v. Punt / platform structure
vi. Bird cage frame
vii. Integral body structure

2) Vehicle Body

For any object that moves through stationary fluid, there will be interaction between the body and the fluid which is represented in terms of stresses wall shear stress and normal stress [9]. Due to the presence of force that causes the stress, the body will experience drag force which act in the direction of flow [10]. Further researches show that total drag force consists of pressure drag and friction drag (see Fig. 4) which are caused by pressure difference and shear forces on the surface of the object respectively [11].

a) Viscous Drag

Drag is an undesirable effect that effects fuel consumption of automobile, ship and aircraft. Viscous drag is a function of wall shear stress and also known as skin friction drag [12]. As viscous drag is a function of wall shear force, thus it is highly affected by viscosity of the fluid and viscous drag will increase as viscosity of fluid increases. Friction drag is given by the equation as follows;

$$F_D = \frac{1}{2}\rho u^2 A C_{Df} \quad (1)$$

b) Pressure Drag

Pressure drag is due to the pressure difference and frontal area that facing the fluid flow [12]. Pressure drag occurs when there is flow separation in the boundary layer due to the adverse pressure gradient [9].

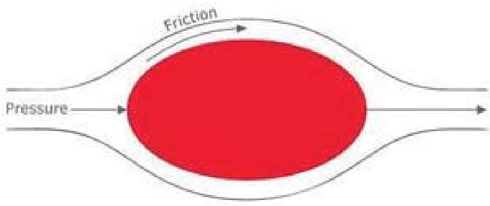

Fig. 4 Pressure acting on frontal surface

3) Gear and Powertrain

Gears can be used as speed manipulator as well as torque multiplier. Gears can be used to reduce and increase relative speed between input gear and output gear. This manipulation of speed is essential in certain machine design that requires higher speed at the output gear because the design motor can only run safely on certain speed on the input gear and so as the application that requires higher torque. In the gear analysis, velocity ratio is used to determine the ratio between the rotational speed of input gear to the rotational speed of the output gear [13].

The most important component for the vehicle's powertrain is the electric motor. Electric motor is classified into two categories; DC motor and AC motor where AC motor works with alternating current while DC motor works with direct current. Electric motor is one of the electric machines which convert electrical energy into mechanical energy of rotating shaft [14]. In general, DC motor is more reliable and has a simpler system compared to the AC motor. Plus, DC motor has more output power and torque density compared to AC motor [15].

Other component, battery, is an electrical device which converts chemical energy into electrical form of energy. Plus, battery works through two reactions; oxidation and reduction. Both of the chemical reaction will cause electron flows in between the positive and negative electrode [16]. Performance and rating on conventional battery usually refers to voltage, amp-hour and amps. Voltage is an electromagnetic force which represents the potential difference of the electric charge in a circuit. While amp – hour represent the energy capacity in terms current usage per hour. Higher Amp-hour rating indicates that the battery has higher energy storage [17].

II. Approach and Methods

This section covers the methodology of design criteria and design considerations of the body, chassis and powertrain. All the designs are strictly following the competition regulations and also the aim of this project which can be found in [18]. Theoretical calculation and simulation will be conducted to determine certain value related to this project such as coefficient of drag and stress under loading.

A. Vehicle Chassis

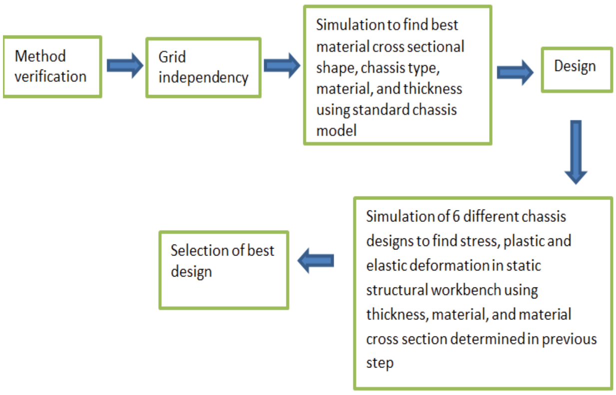

Fig. 5 Proper methodology

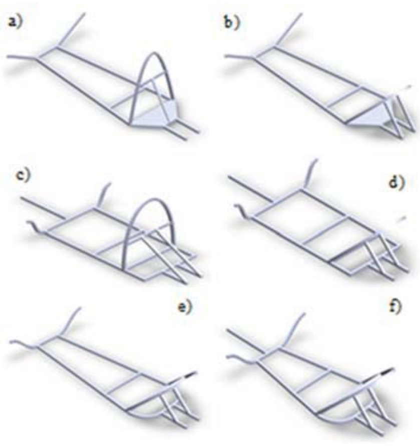

Fig. 6 Isometric view of chassis design; (a) Design 1; (b) Design 2; (c) Design 3; (d) Design 4; (e) Design 5; (f) Design 6

In the analysis of chassis, besides the selection of material that is based on the material strength, the other selection factors are the availability of material, its net price, and also the difficulty of machining the material. Thus, certain material albeit essential for the purpose of strength and lightweight such as carbon fiber, is not included in the analysis. Fig. 5 shows the steps implemented in this particular section. Much detailed data can be obtained in [18].

Six chassis are designed in 3D SolidWorks model and each design will undergo the analysis of static structural to determine the effect of different material type, beam cross-section shape and beam thickness on mechanical property of each chassis design. The static structural analysis uses stress and deflection as the standard mechanical property to fulfill the strength requirement of a chassis. The selection of chassis is discussed in later section which depends on the design performance based on the design matrix.

Fig. 6 shows the proposed designs for vehicle chassis. There are two types of material that will be used in the analysis; aluminum alloy and steel because both materials are available locally with variety of shape and sizes. Moreover, both materials are relatively easy to work with besides inexpensive.

B. Vehicle Body

For standard and simple body shape, coefficient of drag can be found in graphs and table of drag coefficient as a function of Reynolds number for two and three dimensional object. Due to the technology nowadays, the coefficient of drag is determined through CFD software such as Star CCM and ANSYS Fluent as used for this project. Coefficient of drag value for standard shape is shown in Fig. 7.

No	Body	Status	Shape	C_D
1	Square rod	Sharp corner		2.2
		Round corner		1.2
2	Circular rod	Laminar flow		1.2
		Turbulent flow		0.3
3	Equilateral triangular rod	Sharp edge face		1.5
		Flat face		2
4	Rectangular rod	Sharp corner	L/D = 0.1	1.9
			L/D = 0.5	2.5
			L/D = 3	1.3
		Round front edge	L/D = 0.5	1.2
			L/D = 1	0.9
			L/D = 4	0.7
5	Elliptical rod	Laminar flow	L/D = 2	0.6
			L/D = 8	0.25
		Turbulent flow	L/D = 2	0.2
			L/D = 8	0.1
6	Symmetrical shell	Concave face		2.3
		Convex face		1.2
7	Semicircular rod	Concave face		1.2
		Flat face		1.7

Fig. 7 Drag coefficient of 2D object

In vehicle body design, SolidWorks surface modeling is used to create 3D surfaces, refer [18] for all six designs. Each design is based on the streamline shape which is known to have low drag force and essential for this project. Each body design will be compatible to be integrated with any chassis design as the basic layout of the body design is slightly larger than the dimension of each chassis design so that to allow the chassis to be placed inside each body design. For chassis with inclined roll bar and shorter vertical height, simple modification will be made.

For each body design, two front wheels are located outside the body and thus the body shape can have much more freedom in design process. Steering system, driver, control system, powertrain system and rear wheel is located inside the body. Besides, each body design is fully closed to further reduce drag force. In this part, the opening for rear wheel is negligible as the opening will be very small compare to the overall size of the body designs.

C. Gear and Powertrain

As discussed in Section I, the aim of this project is to produce battery electric vehicle with energy consumption performance of 263.4 km / kWh. Thus, calculation of energy used in the competition for 12 km of distance travel is:

$$performance = 263.4\frac{km}{kWh} = 263.4\ m/Wh$$

$$\frac{1}{263.4} = 0.00379650\ Wh/m$$

For 12 000 m of distance travel, the energy is:

$$0.00379650\frac{Wh}{m} \times 12\ 000\ m = 45.55\ Wh$$

In terms of amps- hour, for 45.55 Wh of energy, let say the motor uses 18 V:

$$18 \times x = 45.55\ \gg x = \frac{45.55}{18} = 2.53\ Ah$$

where, 2.53 Ah indicates the energy used for one hour with total of 45.55 Wh.

Theoretical power train design for maximum design load:

Rolling resistance:

$$F_R = c\ w_T \qquad (2)$$

where, w_T is the total weight.

Acceleration force:

$$F_a = GW\ \times V_{max} \times \frac{1}{at} \qquad (3)$$

Grade force:

$$F_G = w_T \times \sin(\theta) \qquad (4)$$

Drag force:

$$F_D = \frac{1}{2}C_D\rho v^2 A \qquad (5)$$

Total tractive force:

$$F_T = F_R + F_a + F_G + F_D \qquad (6)$$

Wheel torque is:

$$T = F_T \times r \times RF \qquad (7)$$

Gear calculation:

At maximum vehicle speed and motor speed, the maximum gear ratio which determines maximum gear ratio to achieved design maximum vehicle speed is:

$$VR = \frac{n_{motor\ max}}{n_{wheel}} \qquad (8)$$

Minimum gear ratio to achieved minimum torque required:

$$VR = \frac{T}{T_m} \qquad (9)$$

III. Result and Discussion

A. Vehicle Chassis

As mentioned earlier, for each test, there will be several simulations to match the stress and deflection values which the independent variable will be manipulated for each simulation attempt. Only non-failure simulation result will be discussed in this section. The condition to ensure safe design is safety factor of at least 2.5 for yield strength, 1 mm for plastic deformation and 15 mm for elastic deformation. As aluminum alloy is a ductile material, von-Mises equivalent stress theory is used to measure failure design. Fig. 8 shows the loading condition with its direction.

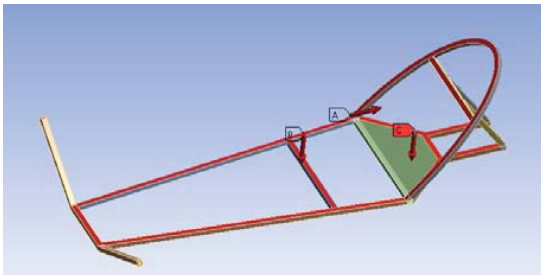

Fig. 8 Example of load condition

In the simulation process, the meshing or element size used is 2.03 mm as determined in [18]. Moreover, the loading was divided into three sources: driver & equipment weight, roll bar strength and powertrain system weight. Figs. 9, 10 and 11 shows the results for chassis design 6 which is the design with the best result in terms of its deflection analysis. In order to fully analyze the chassis, a design matrix is developed as in Table III with selected parameters. The given mark for each criterion is from the range of 1 to 5.

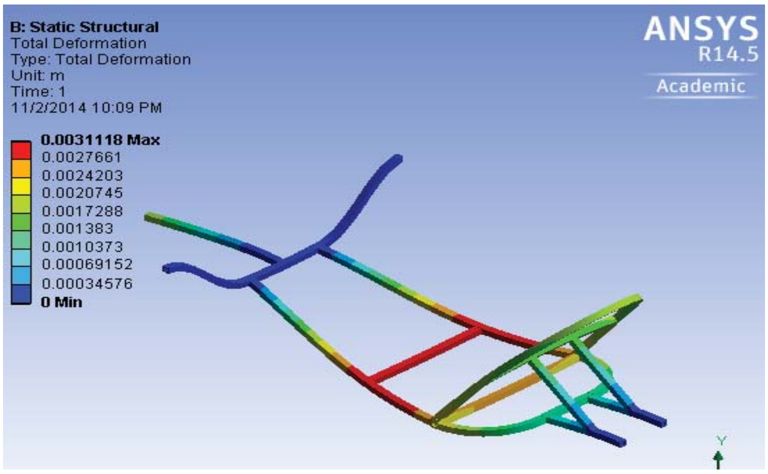

Fig. 9 Total deformation result for Design 6

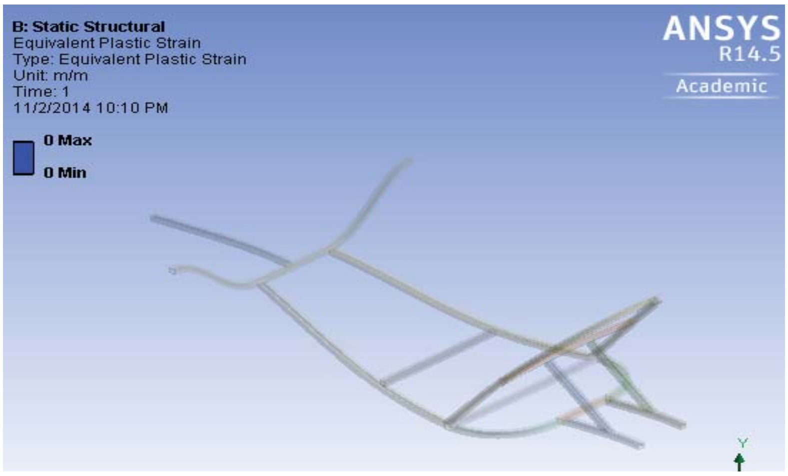

Fig. 10 Plastic deformation result for Design 6

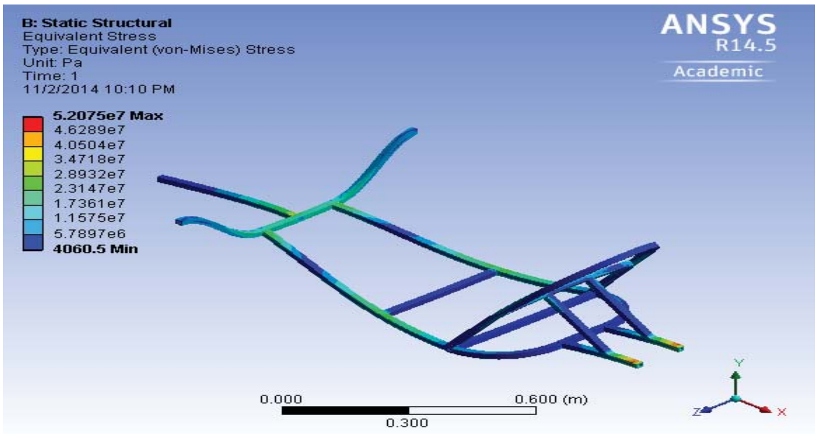

Fig. 11 Von-Mises equivalent stress result for Design 6

TABLE III
DESIGN MATRIX FOR VEHICLE CHASSIS

Parameter	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
Mass (kg)	2	2	2	2	2	3
Deflection (mm)	2	2	3	3	1	4
Height	1	2	1	2	2	2
SF	2	4	5	5	3	5
Total	7	10	11	12	10	14

TABLE IV
RESULT COMPARISON BETWEEN BODY DESIGNS

Parameter	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
Total drag coefficient	0.1487	0.2241	0.1995	0.1494	0.1266	0.1293
Weight (kg)	0.1667	0.2651	0.1807	0.1523	0.1704	0.1448
Total surface area (mm^2)	37043	58902	40146	33847	37856	32170

Based on the design matrix, it can be seen that chassis design 6 has the highest mark and thus the best design in terms of total weight, deflection, safety factor and height. Thus, specification of design 6 such as weight will be used for further analysis in the energy consumption calculation.

B. Vehicle Body

In this particular section simulation process, a scaled down body of 1:10 is used to shorten the computing time. The flow characteristics for all designs are listed below and calculated using (1);

i. Medium = Air
ii. Air density = 1.225 kg/m^3
iii. Air viscosity = 1.7894× 10^{-5} $\frac{kg}{m-s}$
iv. Flow speed = 14 m/s or 50 km/h

1) Result for Vehicle Body Design 1

From simulation, the result is listed as below;

i. Frontal area = 0.0023471 m^2
ii. Reynolds number = 4457.168
iii. Viscous coefficient = 0.04189
iv. Pressure coefficient = 0.09433
v. Total drag coefficient = 0.18425

CFD simulations are used to analyze designs with minimum drag. In addition to the analysis, Table IV is used to find design which is lightweight, has good manufacturability and also cost wise. Parameter that has been used in the design process to determine drag performance of the design is coefficient of drag, C_d. Basically, the least total drag represented by the least coefficient of drag. For comparison purpose, material of each body design is assumed to be a standard epoxy glass fiber with density of 1500 kg/m^3.

Based on Table IV, it can be seen that body design 6 has the best performance in terms of total drag, weight and total surface area. As the simulation is based on 1/10 of the actual design scale, the actual body weight for each design should be multiplied by 10. However, it can be stated that all body design still has relatively high coefficient of drag. Hence, improvement will be made to further fine the streamline feature of design 6.

The result from the original body design 6 shows that there are still some parts on the rear part of the body that cause pressure drag as that location has low pressure situation (see Figs. 12 and 13). In the improved design, the area that contributes to the pressure is lengthened and thus provides less steep body to prevent separation and results in smoother fluid flow.

Besides that, there are flow separations indicated by low pressure at the bottom of the body which is flat surface. This is due to the blunt area connected to the horizontal surface and vertical surface. To improve the problem, underside body is made non-flat surface with little help of less steep surface that will allow fluid to flow much smoother and thus prevent flow separation.

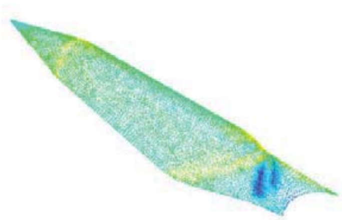

Fig. 12 Side view of original body design 6

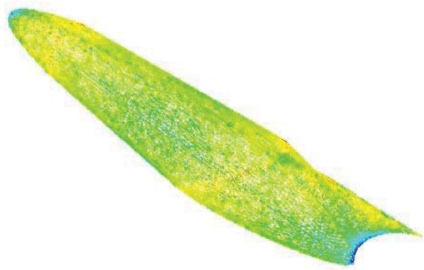

Fig. 13 Side view of modified body design 6

C. Gear and Powertrain

For powertrain system, it is actually designed simultaneously with the design process of the chassis and body to allow proper integration with the other two vehicle parts. The gear system used is from the multiple speed gear of a normal mountain bike which practices sprocket as gear and chain to connect and lock two sprockets gear together and allowing rotation torque to be transferred from motor shaft to its rear wheel. Fig. 14 shows the final design of the powertrain system. Complete calculation for the gear and powertrain system can be obtained from [18].

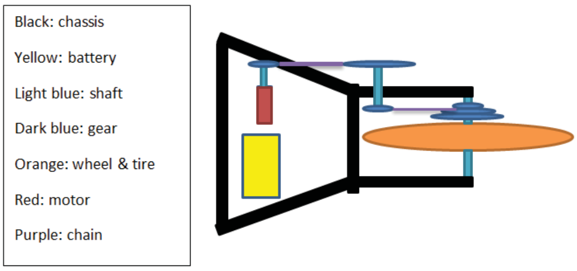

Fig. 14 Simple illustration of powertrain system

IV. Conclusion

The virtual design environment selection such as SolidWorks and ANSYS software application is a viable solution to any new design and development project. First and foremost, it reduces production time and cost. Accordingly, this project achieved the initial target to produce a fuel-efficient vehicle.

Chassis design 6 passes the minimum target for safety factor of 2.5, maximum 15 mm deflection, 1 mm plastic deformation and weight just only 5.95 kg. The modified body design 6 has lower coefficient of drag (from 0.155 to 0.0697) with a reduction of 55%. At this rate, the drag force is only 1.633 N at 50 km/h. As for the powertrain, the maximum torque required for the motor to move the vehicle with acceleration of 10 m/s^2 is 192 Nm with assumed wheel rims and wheel diameter of 0.6 m. The motor has 185 Nm of torque at 18 V of voltage with maximum speed of 2800 rpm. Subsequently, for the gear design, the gear system is a compound gear system with two stages of gear and 3 shafts. With 6 speed gear system, more efficient use of torque at lowest possible current rating is achievable.

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