Architectural Study of Hybrid Electric Propulsion Systems for Indian Cities

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Abstract—*The three-wheeled vehicle, commonly called an "auto-rickshaw", with a two- or, more recently, four-stroke petrol, LPG or CNG engine is one of the most common and affordable means of transportation (for hire) in Indian cities. It is a small, highly maneuverable vehicle and ideally suited for the narrow and traffic-clogged streets of cities in India. One of its main disadvantages is that it emits a large amount of white smoke and other pollutants which are easily visible near the tail pipe This paper presents in detail a survey of relevant literature, establishes the need for a low-cost hybrid propulsion system for Indian cities, presents simulation studies based on the modified Indian Driving Cycle, uses the results obtained from these simulations for detailed design of some of the key components. Extensive study and simulations have been done to arrive at a candidate, low-cost hybrid electric propulsion system configuration which can alleviate the pollution problem to a very large extent, in addition to significantly increasing the fuel efficiency of the vehicles*

Keywords: Hybrid Electric Vehicle, Urban Mobility, Indian Driving Cycle, Urban Vehicle, Fuel Economy

I. Introduction

It is almost universally accepted that the urban human population will continue to increase monotonically and significantly for the foreseeable future [1]. The population growth is expected to be more in less developed countries, as opposed to developed countries, and it is expected go up from 2.5 billion to more than 4 billion by 2025 in less developed regions. In particular, according to an UN study done in 2002, most of the new and rapid urbanization will take place in India, China, South-East Asia, Latin America, Africa and South America which are the less developed regions of the world. This increased urbanization and economic growth and the accompanying need for personal transportation is expected to lead to increased demand for energy, increased emission of CO_2 and other Greenhouse gases(GHGs), increased environmental impact and pollution[2]. One of the key questions is how we can address these challenges and develop sustainable personal mobility solutions. Some of the key requirements (in addition to many other issues) for the next generation urban vehicle must be a) high fuel efficiency, b) low or zero emissions and c) compact design to negotiate crowded roads. It is becoming increasingly clear that the future is biased towards "small, beautiful, drivable and affordable'' vehicles. It is becoming increasingly clear that hybrid electric vehicles are the most promising propulsion systems [3] – [5].

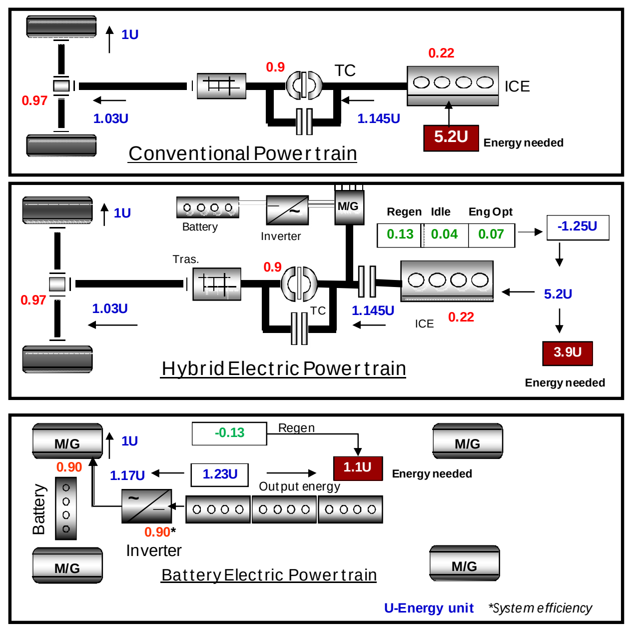

Figure 1: Schematic comparison between three powertrains

Figure 1 shows a schematic comparison between an Internal Combustion Engine (ICE) powered conventional vehicle, a Hybrid Electric Vehicle (HEV) and a Battery Electric Vehicle (BEV). For one unit of energy (**1 U**) to be delivered at the wheel and using reasonably accepted efficiency assumptions for conversion of fuel to mechanical power, losses in transmission and savings due to regenerative braking, the amount of energy required are **5.20 U, 3.90 U** and **1.23 U** for typical conventional, hybrid and electric propulsion systems, respectively. The figures are a bit misleading since the efficiency of producing and transmission of electricity are not taken into account for the electric and hybrid case.

Nevertheless, it is clear (and accepted by almost all researchers) that a purely electric vehicle would be the most efficient in terms of energy use and emissions. The use and commercialization of purely electric vehicles are, however, severely constrained by the current energy storage capabilities of batteries. The currently affordable lead-acid batteries are heavy and most electric vehicles are restricted to a maximum range of about 80 km (the effective distance is 40 Km, in the absence of recharging stations, since the vehicle must come back to its home base for recharging). The alternatives such as Nickel-Metal Hydride or Lithium-ion batteries are currently too expensive for less developed countries and they too do not give significantly larger range. In the absence of advanced and affordable batteries, the most promising configuration appears to be a hybrid electric vehicle with a combination of an IC engine and electric propulsion.

In India, studies show that 80% of the growth in the personal transport segment is expected for small cars, in particular in the so-called A& B segments as shown in **Figure 2**.

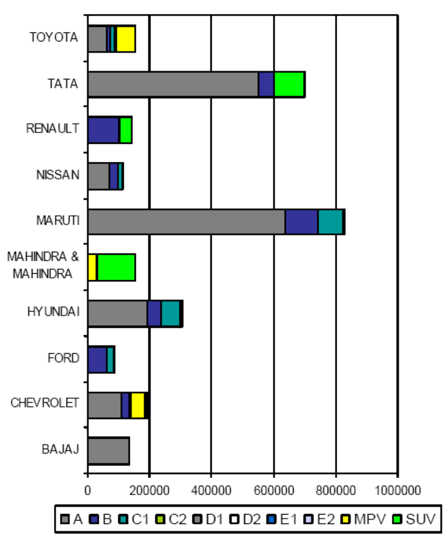

Figure 2: Distribution of cars by size in India

This trend is also seen in many other markets. In India and a few other Asian countries, a three-wheeled vehicle called an "auto rickshaw'' is one of the most affordable and convenient form of public (for hire) transportation. The popularity is primarily due to the low-cost with minimal features, reasonable fuel efficiency and the small size and narrow body making them perfectly suited for navigating the narrow and heavily congested roads of Indian cities and urban environment. These vehicles are usually powered by a two- or four-stroke gasoline engine. Due to the design and other factors, auto-rickshaws are typically highly polluting as has been mentioned by researchers [2]. In recent years, alternative models using compressed natural gas (CNG) and liquefied petroleum gas (LPG) models have been introduced to deal somewhat with the pollution problem. It is clear that there is widespread and growing need for a fuel efficient and low emission small vehicle. It is also accepted that a low-cost hybrid propulsion system is very promising at the present moment. These were the main motivations for this project dealing with study and development of lost-cost hybrid propulsion systems. The three-wheeled auto-rickshaw, primarily due its usage pattern, is an ideal candidate for redesign as a hybrid vehicle. We start with a brief review of the various types of hybrid architectures that are available in literature. We restrict ourselves to hybrid architectures which use batteries, motors and IC engines. It may be kept in mind that there are several other concepts, with or without batteries, such as the use of super capacitors, flywheels, pneumatic and other kinds of electro-chemical techniques to store energy and fulfill power needs in hybrid systems (see, for example, [6]-[13], and the references contained therein). There are various kinds of hybrid architectures which can be used in vehicles. At the top most level we can classify hybrids into **series** and **parallel** (see [3] **-** [5], [14] – [16] and the references contained therein). **Figures 3** and **4** show, schematically, the series and parallel hybrid configuration respectively.

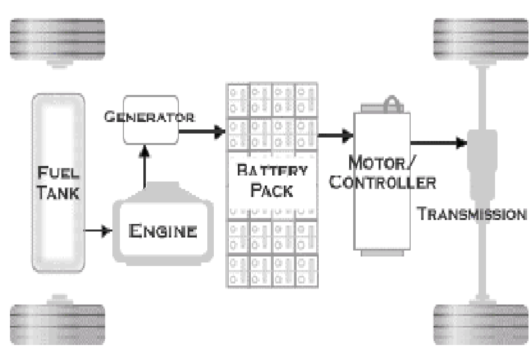

Figure 3: A schematic of a series hybrid propulsion system

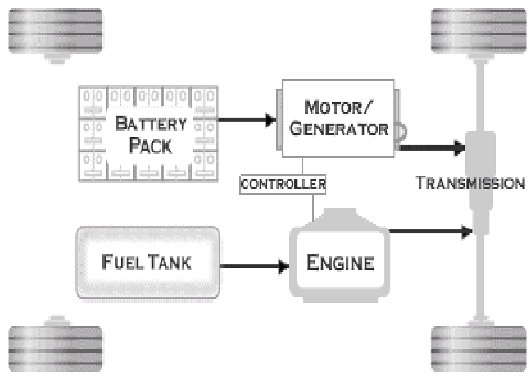

Figure 4: A schematic of a parallel hybrid propulsion system

In a series hybrid the IC engine runs an electric generator which produces electricity to charge batteries. The batteries drive the electric motor to propel the vehicle – the arrangement is similar in principle to well known diesel-electric locomotives. Since the engine does not `see' the wheel, it can be made to run at an optimized operating condition (best in terms of fuel efficiency and emissions) [17]. The DC motor driving the wheel can take care of all vehicle speed changes. It is also possible to charge the batteries by connecting to external grid power, and depending on the storage (range) capability of the batteries the vehicle can run in a purely electric mode for certain distances with the IC engine started only when the batteries are almost discharged. In a series hybrid, for a desired power of say **X** HP from the vehicle, the IC engine must be able to produce **X** HP, the generator and batteries must be capable of giving the equivalent of **X** HP and the electric motor must also be capable of delivering **X** HP. One can clearly see that all the equipments in the power train must be designed to meet the desired peak load. This could potentially make the entire system expensive. In a parallel hybrid, the power can flow in parallel to the wheels from either the batteries or the IC engine. An electronic controller can sense the load and speed of the wheel/vehicle and using built-in algorithms, the power can be made to flow either from the batteries or the IC engine or from both. In most urban driving (especially in crowded and narrow streets in less developed countries), the peak speed or power is rarely required. In such situations, the parallel hybrid can be configured in a way such that most of the time, the vehicle runs on batteries resulting in low emissions and high fuel efficiency. Only when required, power can be added to the wheels from the IC engine. In this framework, the IC engine, the batteries and generator, and the electric motor individually need not be designed to meet peak requirements. This makes a parallel hybrid configuration potentially cheaper. There is the added complication of designing power trains where power can be added and use of an electronic controller. The basic parallel hybrid architecture of figure 4 is often implemented in several ways. Figure 5 shows four ways a parallel hybrid propulsion system can be implemented. A good example of **P1** is the GM BAS/BAS+ system and the proposed architecture in this work, i.e., the hub mounted wheel motor plus an IC engine, is an example of **P4**.

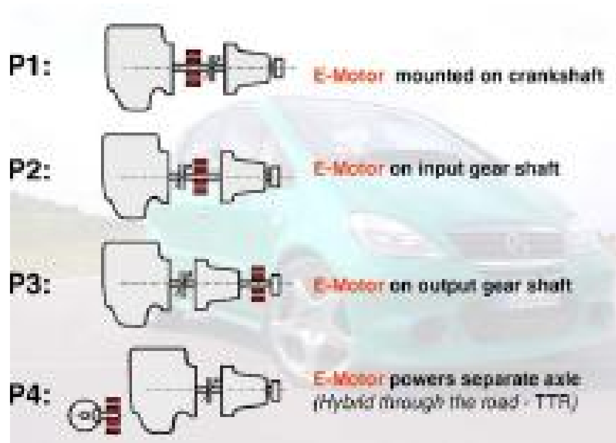

Figure 5: Various parallel hybrids architectures (from [3])

II. Baseline Specifications

The proposed three wheeled parallel hybrid electric vehicle (HEV) is based on the very commonly seen "auto-rickshaw'' seen in the **Figure 6**. The detailed specifications and usage pattern of this vehicle are available in reference [18]; we present them here for completeness. The auto-rickshaw comes with a 2/4 stroke IC engine. The 2 stroke version is shown below.

Figure 6: A three-wheeled "auto-rickshaw''

The geometry of the above vehicle is given below [18].

PHYSICAL DIMENSIONS OF THE AUTO RICKSHAW

Length	2675 mm
Width	1240mm
Height	1690mm
Clearance	200mm
Frontal Area	2.09 m2
Coeff of drag	0.5
Center of veh mass	0.4 m
Wheel Base	1.075m

The specifications related to weight of the main components are

WEIGH SPECIFICATIONS OF THE AUTO RICKSHAW

Components	**Weight**
Kerb weight	290 kg
Engine	35kg
Transmission	15kg
Battery	10kg
Tank	10kg

The engine specifications are as follows:

PHYSICAL SPECIFICATIONS OF THE ENGINE

Parameter	**Value**
Type	Four Stroke, SI, Forced air Cooled
Weight	45kg
No. of Cylinders	One
Displacement	173.52cc
Max. Power	6kW @ 5000 rpm
Max. Torque	12.7Nm @ 4000 rpm
Max payload	310kg
Average payload	100kg

The study reported in [18] also gives the typical usage of the three-wheeled vehicle in an urban environment. The survey details are presented in F**igures 7 and 8.**

Results of the survey

Three-wheelers	Units
No. of vehicles	1084
Distance covered/day	97.45 km/day
On road duration	4.69 h/day
Fuel consumption	4.73 l/100 km
Maintenance cost/month	~ Rs 600/month
Fuel cost/month	~ Rs 550/month
Cost/km	~ Rs 5.70/km

Figure 7: Results of survey on usage of auto-rickshaw [18]

The typical range of speeds is shown in figure 8. It can be see that more than 83% of the time the speed is less than 10 mph (or 16 Km/h) and more than 95% of the time the speeds are less than 15 mph (25 Km/h). This indicates that performance requirement as derived from the modified Indian Driving Cycle (see Section III) and the computations on power and storage (battery) requirement will be a gross overestimate.

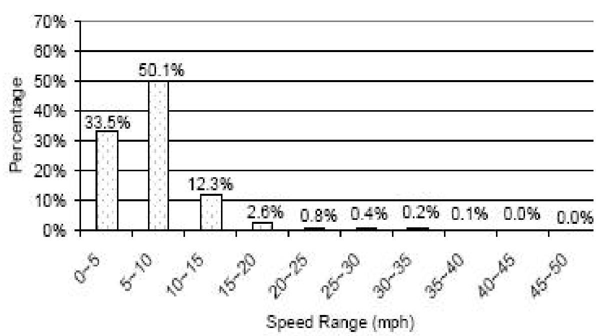

Figure 8: Typical usage pattern of an auto-rickshaw [18]

III. Modeling, Simulation and Design

Based on the survey results, it is clear that a range of about 120 km will be sufficient for most Indian urban driving conditions. Rarely high speeds or large ranges are required. A hybrid vehicle, configured in a way such that it runs most of the time (about 90%) on electric power and on demand (or requirement) an IC engine adds power at the wheels, has the potential of very low emissions and high fuel efficiency. In order to avoid the complicated power trains present in a parallel hybrid, we propose to use hub mounted motors and extensive electronic control, to take advantage of sub-system modularity and to study the control challenges resulting from such an arrangement.

A schematic **layout** of the main components of the chosen hybrid propulsion system is shown in the **Figure 9**.

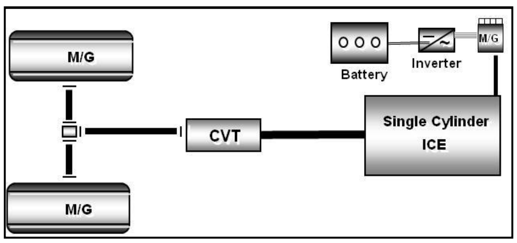

Figure 9: Schematic of the chosen low-cost parallel hybrid propulsion system

In order to arrive at the sizing of the electric motors, IC engine and batteries, we conducted extensive numerical simulations based on the Indian Driving Cycle (IDC). The IDC is a standardized pattern of speeds, accelerations, gear change, idling and detailed timings used to determine, among other things, the fuel efficiency and emission characteristics of vehicles in India [19, 20]. We have used the modified Indian Driving Cycle [20] to arrive at the sizing of the key components of the proposed hybrid architecture. The main and relevant features of the modified IDC are

a) The modified IDC is composed of 15 phases

b) The duration of one cycle is 195 seconds

c) The peak acceleration is 1.04 m/sec and the cruising speed is 50 Km/h.

The plot of velocity versus time is shown in blue color in **Figure 10**.

The power requirement for the proposed hybrid is based on the following assumptions (drawn from the baseline model).

Assumptions:

1. Rolling friction $\mu = 0.015$
2. Total mass M = 700 kg – 330 kg on each rear wheel and 40 kg on front wheel.
3. Radius of wheel = 0.226 m
4. Drag coefficient $C_d = 0.35$
5. Frontal area = 2.09 m^2
6. Inclination of road = 1 in 20
7. Maximum speed 50 Km/h.

The energy method was applied to calculate the power required during acceleration of the vehicle based on the modified IDC. The power required during acceleration at each wheel is

$$P = 0.5\,(M\,(v_2^2 - v_1^2)\,/2t + \mu\, Mg\,(v_2 - v_1) + Mg \tan\theta\,(v_2 - v_1) + \rho\, A\, C_d\,(v_2^3 - v_1^3))$$

Using assumed values of M, A, μ and C_d, we get for an inclined road

$$P = 172.5\,(v_2^2 - v_1^2)\,/t + 220\,(v_2 - v_1) + 0.027\,(v_2^3 - v_1^3)$$

For a straight level road, we get

$$P = 172.5\,(v_2^2 - v_1^2)\,/t + 50.77\,(v_2 - v_1) + 0.027\,(v_2^3 - v_1^3)$$

where v_2 and v_1 are final and initial velocities obtained from the modified IDC (see blue plot in Figure 10) and t is the time. Using the above formulas the power requirement for each wheel was computed for one cycle of 195 seconds. This is shown in **Figure 10**.

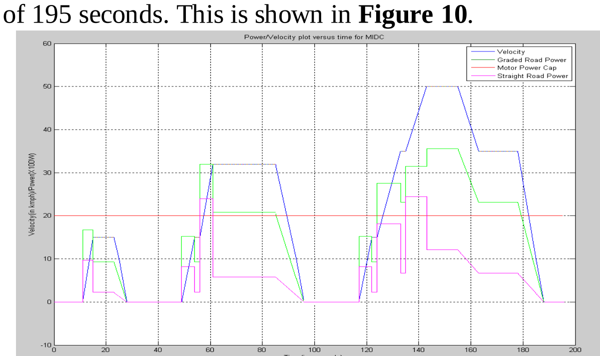

Figure 10: Simulations results for the modified Indian Driving Cycle

The cyan colored plot shows the power requirement on level road and the green colored plot shows the power requirement on inclined road. The 2 KW red line is shown in the figure and one can see that a 2-3 KW DC motor will meet *almost all* the requirements. It maybe noted that the power requirement is for a speed of 50 Km/h and since typical urban speeds are much lower, the estimates above are significant overestimates**.** Based on the above computation, the choice of a brushless and gearless DC motor capable of supplying power from 2 to 3 KW was chosen for each of the two rear wheels.

As mentioned earlier, an Internal Combustion Engine (ICE) is present to supply additional power as and when required. From simulations, it is estimated that a small IC engine of around 100- 150 cc will be enough to meet the occasional power needs. The ICE can also be configured to charge batteries in situations when electric power is not available.

To choose the battery, a range of 120 km is assumed. The vehicle is assumed to follow the modified IDC on a flat road – the power required on inclines can be provided by the IC engine. The energy required is to provide kinetic energy, to overcome rolling friction and to overcome drag. The formula for the energy required is

$$E = 0.5M (v_2^2 - v_1^2) + \int[(\mu + \tan \theta) Mg + 0.5 \rho A C_d v_2^2]dx$$

Using the data from the modified IDC and assumptions, and assuming that the motor will operate on the average at 70% of rated power, we obtain that the total energy required to be about 10 KWh. This number is consistent with the number obtained from the amount of energy from 4.73 l or fuel consumed on the average for 100 Km (see survey results). For a chosen operating voltage of 48 V and assuming that batteries are discharged up to a maximum of 70%, about 300 Ah is required for the energy requirement of 10 KWh. For a daily use of about 6.5 hours (120 driving cycles), the batteries must provide power at a discharge rate of about 46.15A and the average power would be 2.2 KW at each wheel. This can be achieved by 4 batteries, each of 12 V and 100 Ah. In this combination one can obtain continuous operation of 2 hours and 10 minutes. Typical lead acid batteries available in India with the above capabilities weigh about 35 Kg and hence the total battery weight is about 140 Kg. Cheaper lithium-ion batteries as and when they are a available will weigh much less – existing lithium-ion batteries with the same capabilities as the lead-acid batteries weigh about 30 kg. More details about batteries are available at references [21]-[23].

The computations to arrive at the choice of batteries and the number of batteries are again based on modified IDC. As seen from the survey these are significant overestimates and in actual practice the continuous operating time of 2 hours 10 minutes will be significantly larger. The computations also do not assume regenerative braking which is typically used in all electric and hybrid vehicles. With the use of regenerative braking the continuous operating time will again increase. In summary, we expect that the combination of two 2.5 KW hub motors, a 100 cc IC engine and 4 lead acid batteries (48 V, 300 Ah) will be sufficient to power the proposed hybrid architecture.

The IC engine can be coupled to the inner stator and add power as and when required [24]. This leads to simpler transmission. However, a manual transmission cannot be used since the speed and driving condition at which the IC engine will add power will not be known a priori. To overcome this difficulty a simple continuously variable transmission (CVT) is planned to be used. A CVT in its simplest description contains two cone shaped pulleys – one end is attached to the output of the engine and the other end is attached to the wheel shaft (in our case the stator of the hub motor) often with a fixed gear ratio. A fixed length belt transmits power from one pulley to the other. A mechanism, operating on centrifugal forces, changes the location of belt on the pulley and thus the ratio of the input to output speed is changed [25, 26]. It is known in literature that CVT are efficient at low power transmission and one easily achieve an efficiency of over 70%. Following the CVT design guidelines available in [27, 28] the following preliminary CVT specifications was obtained.

CVT specifications:

- Maximum diameter of pulleys=160mm
- Minimum diameter of pulleys=30mm
- Speed ratio range=0.1873 to 5.867
- Belt length=701mm
- Center to center distance=190mm

One can also calculate the maximum power and torque handling capacity and the maximum loads acting on the shafts and belts which make up the CVT.

In addition to the choice of DC motors, IC engine, batteries and CVT, there are several other key sub-systems which also need to be designed and modeled. Some of the other key additional sub-systems are a clutch to engage and disengage the engine, an electronic control unit (ECU), a start-stop system and other accessories and sensors for measuring the state of the batteries and other systems. Additional work is required to arrive at a final choice for these and details about these additional sub-systems are not presented here.

IV. Vehicle Components Arrangement & Layout

Based on the choice of the components, a possible arrangement of the main components on the chassis was obtained. This is shown in the **Figures 11a - b**. It can be seen that the overall dimensions of the vehicle is similar to the existing three-wheeled vehicle (see Baseline Specifications in Section II) and hence no compromise on the navigability in crowded urban roads is expected. It can be seen that an attempt is made to distribute the weight coming from batteries, engines and other components.

V. Conclusions

This paper presents an architectural study of a low-cost hybrid electric vehicle for Indian urban environments. It is expected that inevitable large scale urbanization in developing world will lead to increasing congestion, pollution and use of fossil fuel. The need and justification of a hybrid electric vehicle providing significant increase in fuel efficiency and lowered pollution has been argued and presented. Starting from an existing baseline ``auto-rickshaw'', an attempt has been made to arrive at a suitable architecture for a hybrid ``auto-rickshaw''. Simulations and literature show that such a hybrid vehicle can lead to 35 % increase in fuel efficiency and a similar reduction in pollution. For future work, we are planning to perform more refined and elaborate simulations and then fabricate hardware/test-bed to validate the modeling and simulation results.

Acknowledgements

The contributions of Sadiq Mohamed who performed some of the simulations are gratefully acknowledged. The research was conducted under a grant from General Motors, Warren, USA, and the first author gratefully acknowledges this and the continued funding from General Motors towards fabrication of the low-cost hybrid propulsion system architecture.

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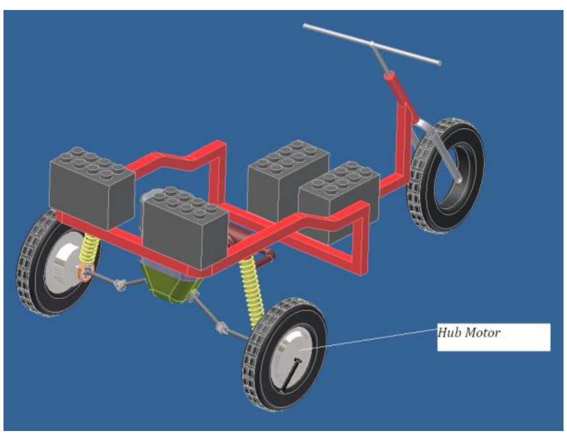
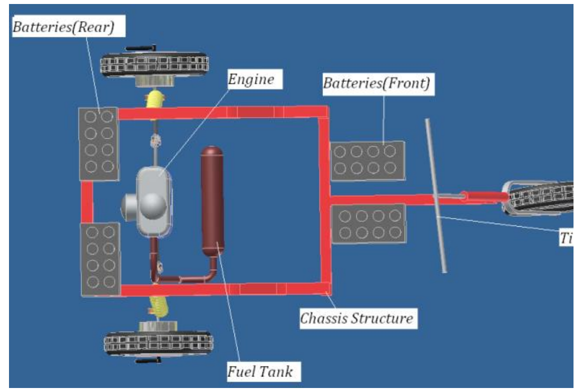
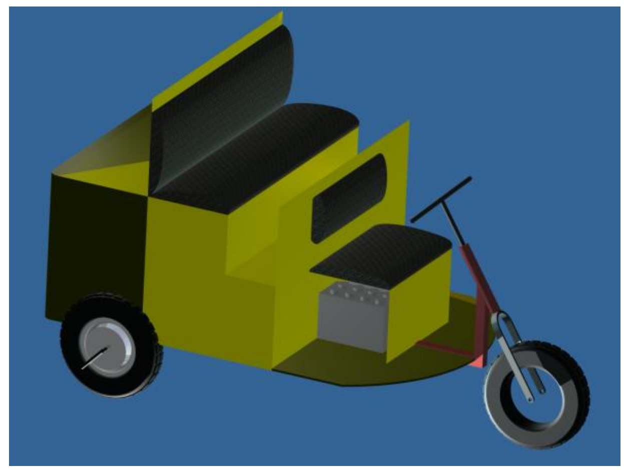


(a) Isometric view of three wheeled vehicle



(b) Top view of the three wheeled vehicle



(c) Vehicle without cover

Figure 11: Arrangement of components in hybrid electric vehicle.