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Realization of Hybrid-Electric Powertrain System for a Three Wheeler Auto Taxi

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Abstract

In this paper, the mechanical powertrain of a conventional three wheeler auto taxi was first analyzed and converted into a hybrid electric power train for similar vehicle requirements. Packaging design strategy of key power train components have been calculated and proposed. The preliminary design is simulated as a series hybrid fuel cell Ni-MH battery vehicle model in PSAT software for a typical city driving cycle. Further, an environmental and economic study has been prepared for the proposed vehicle by calculating the emission levels and payback period. This design can be implemented in the longer run on wide range of vehicles; thus creating independence from fossil fuels.

***Keywords**: Fuel cell, Ni-MH battery, Hybrid electric vehicle, three wheeler*

1. Introduction

In today's automotive industry, the research and development is focused on the development of fuel efficient and alternative fuel vehicle [1]. One of the most pressing needs of this century is an alternative, clean, efficient, intelligent and environmental friendly urban transport system. The recent progress in Electric and Hybrid Electric Vehicles can be visualized as a new era of the automobile technology [2]. The figure below shows the comparison of Alternative Fuel Vehicles and HEV developed and commercialized by prominent automotive company from the year 1991-2011[3].

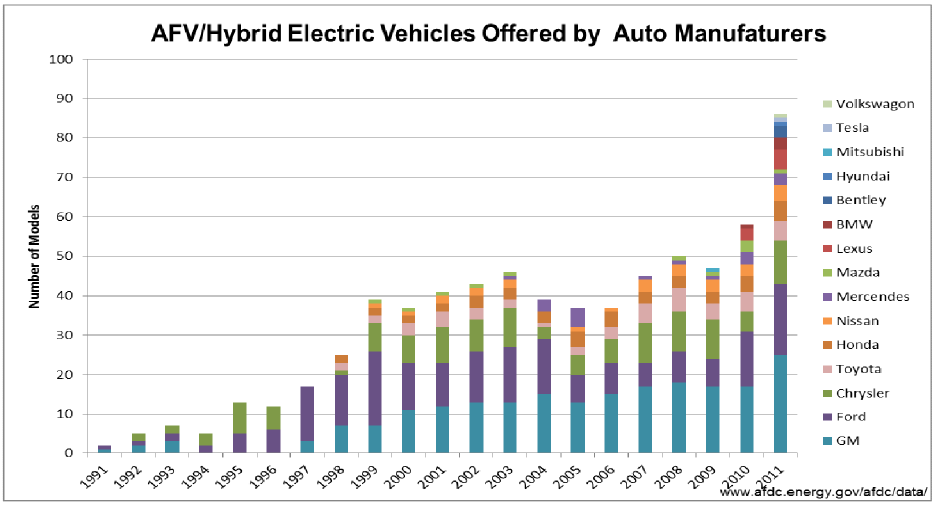

Figure 1. Hybrid Electric Vehicles offered by Auto Manufacturers.

It is expected in the next 20 years that hybrid electric and fuel cell vehicles will capture the market as they deliver the same functionality at a higher fuel economy subject to the mass

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production [1-2]. Some studies and experiments have been done involving hybrid fuel cell vehicles [4 - 8]. In [5], the requirements on energy storage devices in a fuel cell vehicle are analyzed. A midsize SUV and a midsize car are designed and simulated using ADVISOR in order to help the Freedom Car technical teams. In [6], a fuel cell system with nominal power of 48 kW is hybridized with super capacitors with a storage capacity of 0.360 kWh. The hybrid system is implemented on a road vehicle and tested. In [7], optimization tools are linked to ADVISOR for the optimal design of a battery fuel cell SUV. In particular, ratings of fuel cell, battery and energy management strategy are optimized to maximize fuel economy while meeting the pre-specified vehicle performance constraints.

The purpose of this research work is to test the feasibility of substituting a four-stroke, internal combustion engine found on a 3-wheel motor scooter with a hydrogen powered fuel cell or hybrid combination. A Bajaj three wheeler scooter (also known as auto rickshaw) was first analyzed and designed with similar vehicle requirements without compromising the vehicle current performance. The conventional gasoline engine is completely removed and replaced with an electric motor powered by a fuel cell and Ni-MH battery bank. Analysis showed that an 8 HP continuous electric motor could supplant the physical aspects of the current vehicle. In order to power such a motor, a 6 kW prototype PEM fuel cell was suggested and designed to provide the necessary power. The fuel cell would draw its fuel from a hydrogen cylinder located onboard. In order to assist the fuel cell with the transient loading, a battery pack would optimize the design. The batteries chosen were Ni-MH batteries. A total of 40 cells in series are required with a cell voltage of 1.2 V and 6.0 A – hr., which are capable of discharging large amount of currents rapidly and far lighter in weight compared to the conventional lead acid batteries [9]. Thus the vehicle would use the fuel cell as its primary source of power, and the batteries as backup for transient power requirements, such as starting the fuel cell, accelerating the vehicle and driving uphill. During normal driving, the fuel cell will provide the power to the vehicle and excess energy from the fuel cell will charge the batteries. Two battery packs would be installed onboard so as to ensure continuous and smooth driving of the vehicle. The battery packs will assist the electrical power train for the starting of the fuel cell, during the over load conditions and uphill drive cycles. For all driving conditions, only one battery pack will be in the power train loop. The second battery pack is considered as a backup for worst case conditions, when the first battery pack is completely discharged. During such conditions, the backup battery pack will be considered in the electrical power train loop to avoid any compromise on the vehicle performance. The simulation of hybrid vehicle performance was carried out by using the Power train System Analysis Toolkit (PSAT). The original idea was developed and purposed in [10] by the author.The basic research shows that there is much promise in the innovation of a hybrid hydrogen fuel cell and Ni-MH batteries based on three wheeler scooters, in respect to both the environment and the cost subject to mass production.

2. Background and Motivation

In fact, 3-wheeler auto taxis play significant importance in developing countries like India. To understand why they are a major part of public transportation, it will help to analyze India's situation in congested cities like Delhi, Mumbai, and Calcutta etc. First, the tariffs to ride in 3-wheelers are cheaper than regular taxis, and the majority of India's societies are relative poor. As a result, auto taxi, are more popular and in high demand. Also, the small percentages of population that can afford taxis are often prosperous enough to possess their own modes of transportation. The Specifications for Bajaj RE 4S three wheeler scooter are outlined in Table 1.

Besides being cheaper than car taxis, these auto rickshaws are smaller and more maneuverable in congested cities than cars. They can also be used for small scale material distribution. These delivery vans are optimal mainly due to their size and the fact that there are so many undersized businesses that cannot afford better transport.

The most critical problem is the pollution created by these vehicles. The capital city of New Delhi is one of the most polluted cities in the world although majority of the public transport is currently based on the Compressed Natural Gas (CNG) technology. Moreover, as the oil prices are getting high, it is necessary to start some researchs which is sustainable, environmentally clean as well as suits to economic situation of India.

Table 1. Specification RE 4S three wheeler Scooter [16]

Engine	
Type	4 Stroke
Displacement	173 cc
Max. Power	8.17 bhp (6.01 kW) @ 500 rpm
Max. Torque	11.5 Nm @ 4000 rpm
Weights &	**Measures**
Max. Pay load	325 Kg
GVW	305 Kg
Chassis type	Monocoque
Dimensions	
Overall length	2625 mm
Over all width	1300 mm
Over all height	1710 mm
Wheelbase	2000 mm
Ground clearance	2000 mm
Turning Radius	2.88 m
Electrical System	
Battery Pack	12Velectrolyte deep-cycle batteries

3. Outline of PEM Fuel Cell

PEMFC was invented at *General Electric* (*GE*) in 1955 through the work of Thomas Grubb and Leonard Niedrach [11]. There is an increasing interest in the use of Proton Exchange Membrane (PEM) fuel cells for both mobile and stationary applications as an environmental friendly power source [12]. The emphasis is placed on high power density with adequate energy conversion efficiency for mobile applications and on high-energy efficiency with adequate power density for stationary applications. Two key issues limiting the widespread commercialization of fuel cell technology are durability and cost. The Major operating parameters include cell temperature, pressure, and reactant stoichiometry and gas stream composition.

A PEM fuel cell is capable of using both oxygen directly from the air and purified oxygen. In most situations, the simplest solution is to use air, collected and delivered from the surrounding atmosphere. At the anode, hydrogen is electrochemically oxidized to form protons and electrons. At the cathode, oxygen is electrochemically-reduced and combined with the protons transported through the membrane and the electrons that pass through an external circuit. The overall reaction in the cell is the electrochemical oxidation of hydrogen to form water. The electrons flowing through the external circuit are capable of performing useful work due to the energy released by reaction [7, 13]. PEM fuel cells also operate at low temperature, less than 100 degrees Celsius, allowing faster start-ups and immediate responses to change in the power demand.

3.1. PEM Fuel Cell Design for an Auto Taxi Chassis

For the proposed hybrid vehicle, the dimensions of the fuel cell were calculated to be 12 x 14 x 40 cm. These estimates were made with the help of Dr. Kumar Romesh from Argonne National Lab, an expert on fuel cells. The current density of the actual membrane was estimated to be 0.4 A/cm^2. This value is also evident from the following graph, and can be seen in figure 2 followed by the detailed calculations.The necessary power determined as 6kW i.e. P = I*V = 6kW and a charge density of 0.4 A / cm^2 was determined as i = 0.4 A / cm^2. Choosing a suitable size of 7 x 9 cm leads to a current, I = 0.4 * 63 = 25 A. Now, it is possible to determine the necessary voltage, V = P/I = 6000/25 = 240 V. Assuming one hundred cells in series at 2.4 V each, output power P = I*V = I *Σ V = 25 * 240 = 6 kW. The width of the cells is assumed as 0.4 cm .With an additional 5 cm space in length and height added for the flow channels leads to a total size of 12 x 14 x 0.4 cm. So, for a 100 cell stack, a volume of 12 x 14 x 40 cm^3 has been obtained.

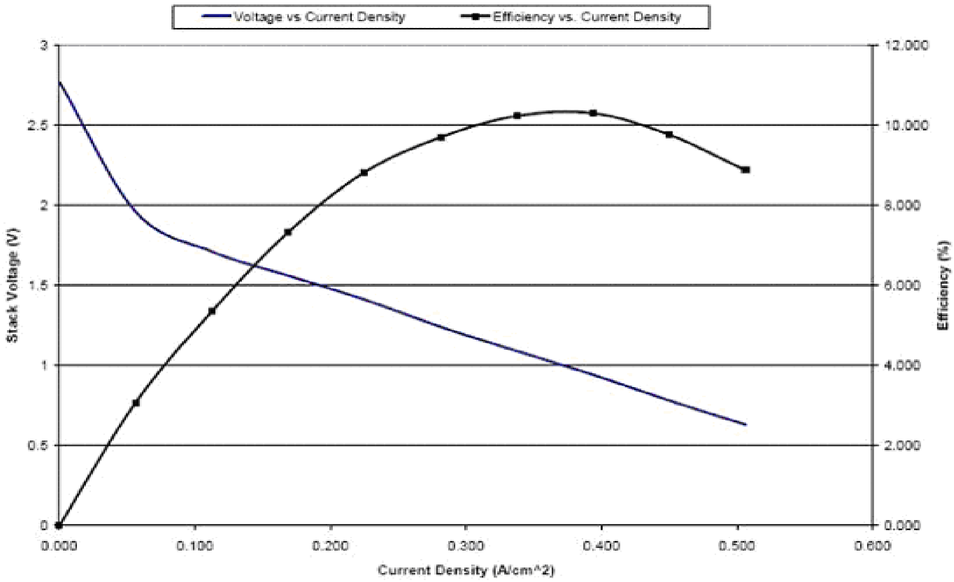

Figure 2. PEM Efficiency vs Current Density

4. Overview of Ni-MH Batteries

Currently, available nickel metal hydride batteries with specific energy and power levels intermediate to those required for power-assist hybrid electric vehicles (HEVs) and pure battery electric vehicles (BEVs), respectively, come close to meet the performance of conventional vehicles [14-15]. The life cycle capabilities of existing intermediate-power NiMH batteries appears sufficient for HEVs of a 50-80 Kilometers (km) electric range to attain about 130k-150k total vehicle km (corresponding to 7-10 years of HEV driving) over the life of these batteries. Based on this brief research, the optimal batteries for this design seem to be Ni-MH. Ni-MH batteries are capable of discharging rapidly and often, which is needed for congested city traffic. The maximum voltage variation of a typical Ni-MH battery with varying ambient temperature conditions is plotted in Figure 3.

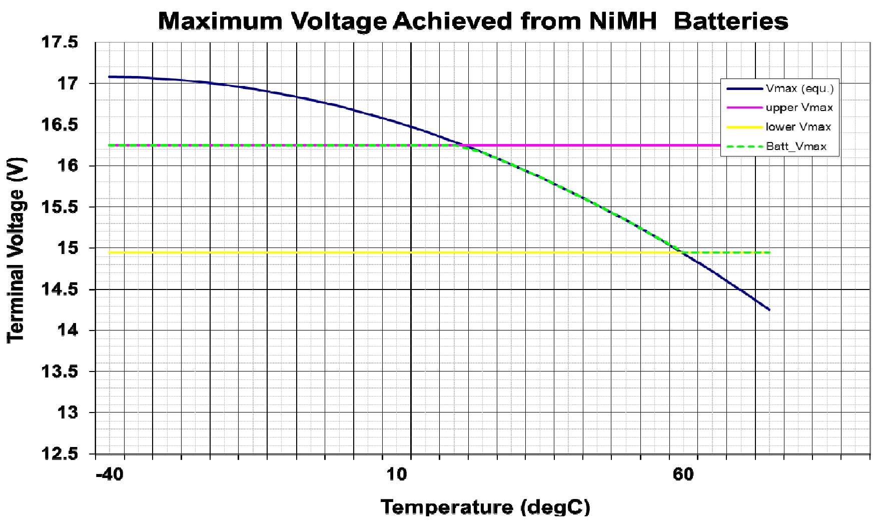

Figure 3: Voltage profile of a Ni-MH battery during different ambient temperatures [14]

4.1. Ni-MH battery packaging for an Auto Taxi Chassis

As obvious from the following plot that a typical Ni-MH battery performs optimally at moderate temperatures. For an average weather condition, it was determined that forty 1.2 V cells connected in series is necessary to produce 48 volts. 48 V was determined as the necessary voltage from the motor. The maximum current is calculated as Imax = P/V = 6000 / 48 ~ 120 A. An average power value of 4 kW was estimated and determined to be necessary for 5 hrs. operations, this was based off a driving radius of 100 km and a fuel capacity of 1 kg of hydrogen, or 20 kW-hrs. In order to achieve these specifications, Ni-MH batteries were chosen with a cell voltage of 1.2 V and 6.0 A – hr. So the number of cells required is equal to volts necessary / cell voltage = 48 / 1.2 = 40 cells in series. Also, Ni-MH batteries can generate a max I = 20 C – rate, which will satisfy the peak power requirements of 6 kW. For worst case and over load conditions, the second battery pack will be available as back up auxiliary battery power to assist fuel cell to meet the necessary power demand of the hybrid electric power train of the three wheeler auto taxi. As mentioned earlier, the first battery pack will be charged from the extra power available from the fuel cell, once the vehicle is in constant load conditions.

5. System Integration Strategy

We decided to place the fuel cell under the passenger seat and the hydrogen tank on the free space behind the passenger seat. Batteries and hybrid controller unit would be incorporated underneath the driver's seat and electric motor in the front portion. The proposed format is drawn below in Figure 4.

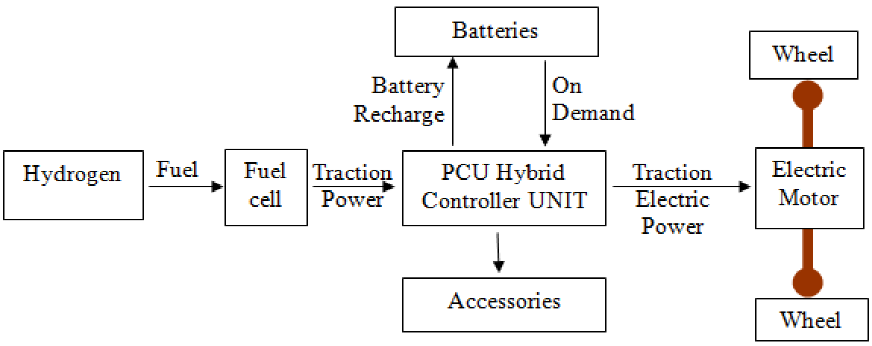

Figure 4. Proposed placement of the power train equipment on the vehicle

The volume of each component behind the passenger seat was calculated from the given dimensions and it has been found out that fuel cell, battery and hydrogen cylinder would acquire approximately 915.36 in^3, 397.61 in^3, 3,468.71 in^3 respectively. So, the total space required is 4,781.68 in^3.The space available behind the passenger seat was then determined by taking into a packaging account factor. This allows, for a more realistic approximation, to the possibility of the design fitting in the allotted space. The space under passenger seat is 15,819.51 in^3.Thus available room after placing the power train components would be 15,819.51 – 4,781.68 (*3) = 1,474.47 in^3. Hence, the calculations show that there is room for the specified design components along with ample space for passenger's luggage.

6. Simulation & Result

Developing fuel cell and hybrid electric vehicles (HEVs) requires accurate and flexible simulation tools. Argonne National Lab undertook a collaborative effort to further develop the Power train System Analysis Toolkit © (PSAT) under the direction of and with contributions from Ford, General Motors, and DaimlerChrysler [17]. PSAT is simulation software that allows users to simulate predetermined configurations of different vehicle types or design new hybrid vehicles. It predicts fuel economy, emissions and the performance of the vehicle taking into account transient behavior and control system characteristics [17].The hybrid auto taxi has been preliminarily designed in PSAT. It is simulated as a hybrid fuel cell series vehicle with the power train as shown in Figure 5.

The designed vehicle model is simulated for a typical city cycle of an auto taxi. The vehicle speed trace demand is given in Figure 6. The three wheeler power demand under city cycle is given in Figure 7.

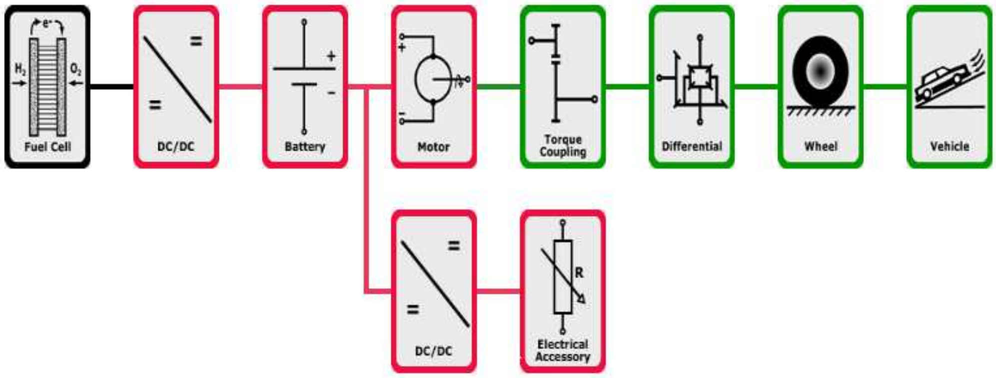

Figure 5. Power train diagram of the hybrid fuel cell electric power train system in PSAT

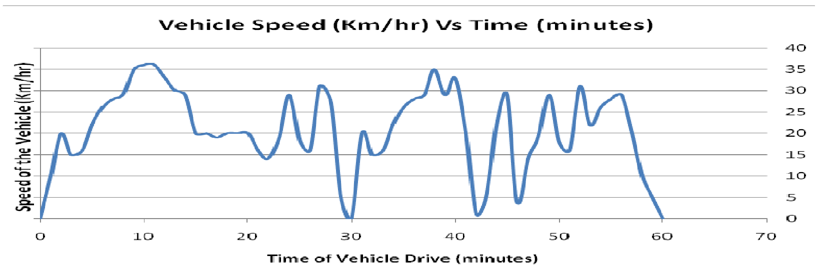

Figure 6. The three wheeler speed demand from a typical city cycle

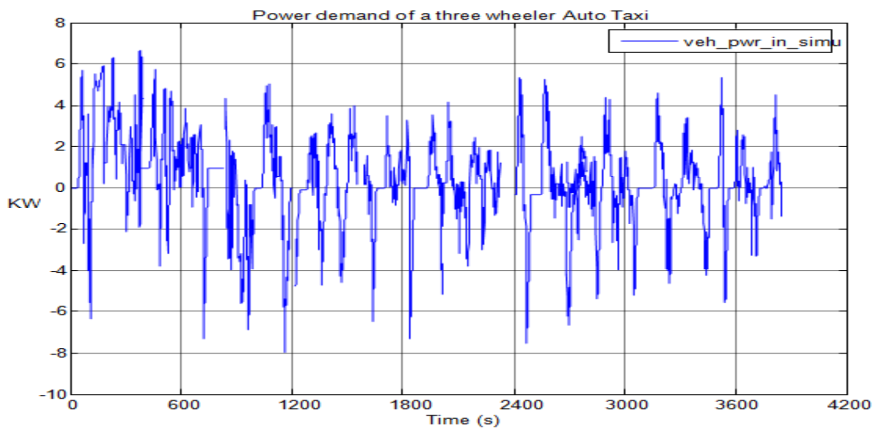

Figure 7. Hybrid electric three wheelerauto taxi power demand for a typical city cycle drive

8. Economic Viability of a hybrid-Electric Auto Taxi

The cost and time implications of traditional automotive design approaches are significant. However, a hybrid FCV drive system is compatible with all vehicle models and does not sacrifice vehicle performance and driver amenities for the sake of clean air and reduced consumption of petroleum. Ultimately, the business benefits that result from this approach include improved quality and reliability in the end product, as well as faster time-to-market and significantly reduced prototyping costs.

8.1. Parameters taken in to Account

The current price for Internal combustion engine based three wheelers is estimated around 82,600 Indian rupees(INR) and for the electric three wheeler is estimated around INR 1,00,000, and for annual running cost is estimated around INR 28,880. The maintenance cost is assumed to be approxiamately INR 5,500. Thus the operating cost is around INR 34,300 plus the net fixed cost around INR 8597 which will give the total operating cost to be INR 42,897.

For the Hybrid vehicles the annual running cost is estimated around INR 15,303Rs +2750. Maintenance cost net fixed cost per year gives total operating cost around INR 30,740. Here, the data is based on the assumptions that the total distance traveled by these vehicles is around 24,000 km annually and price of gasoline is INR 40 per liter and electricity is INR 3/KWh with the requirement of the battery change every two and a half years, when the vehicle is used 300 days per year. The energy consumption for gasoline three wheelers is calculated as 1.39 KWh/km and the energy consumption for an HFCV is estimated as 0.065 KWh/km.

Based on the assumptions above, the simple payback as calculated for the current and proposed hybrid fuel cell three wheelers are 5.2 and 14.67 months respectively.

Such a huge difference in the payback period of the two vehicles is due to the high capital cost of fuel cell, but it should be considered that the life of the fuel cell three wheeler is nearly three years more than the Internal combustion (IC) engine based three wheeler because of the minimum maintenance requirements. This will ultimately increase the net profit earned throughout the life of three wheeler. Also, the refueling in the HEV is less compared to the IC engine based three wheelers result due to higher fuel efficiency by the Fuel Cell Prototype. The pay back period in terms of monthly savings for conventional three wheeler auto taxi and the pay back period for hybrid electric fuel cell three wheeler auto taxi is plotted in figure 9 and 10 respectively.

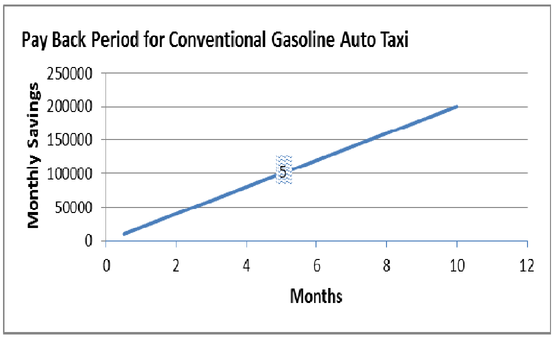

Figure 9. Simple pay back for Internal Combustion Engine 3 wheelers

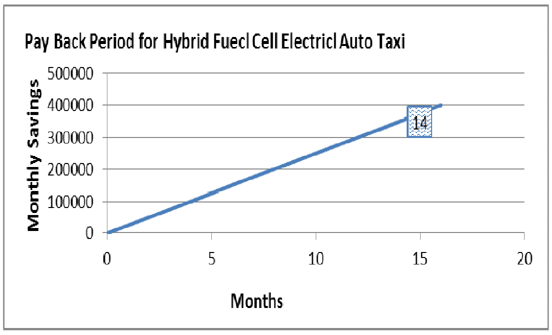

Figure 10. Estimated pay back for the proposed Hybrid Electric Vehicles

Table 2. Estimated emissions from the proposed hybrid-electric vehicle.

KmPL and Emission Ratios for Hybrid Electric Auto Taxi	
Gasoline Equivalent Imply	105%
Exhaust VOC	0.00%
Evaporative VOC	0.00%
Carbon Monoxide (CO)	0.00%
Knox	0.00%
Exhaust PM10	0.00%
CH4	0.00%
N2O	0.00%

9. Environmental Benefits

Combustion of petroleum fuels in IC engines is considered to be one of the dominant anthropogenic sources of the polluting gases. The design and condition of engine, operating conditions, and ambient air characteristics have considerable influence on the nature and type of emissions. The growing awareness of the role of hydrogen as a future fuel is primarily due to its limited polluting emissions during combustion. As hydrogen obviously contains no carbon, all emissions of greenhouse gases are essentially eliminated. A brief emission analysis has been estimated with the GREET software based on the default values for a hybrid vehicle [18-19] and outlined in Table 2.

10. Conclusion and Further Mile Stone

The elementary investigation confirms that there is considerable potential in producing a hybrid electric fuel cell vehicle, in terms of both the environmental and price subject to market manufactured. From initial proposed design, packaging scheme and simulation, the alteration of the current Bajaj three wheeler to a hybridelectric fuel cellvehicle is achievable. This novel idea can be brought to commercialization subject to corpus manufacture. Challenges consist of on-board hydrogen storage, refueling infrastructure, and high initial cost. This plan has covered many of the preliminary research, design aspects and has made progress towards the objective. However, there is still many work to be done; both in the validation of the hybrid system and the component selection. After estimate the emissions with software analysis, the next step would be to build such a prototype for real world testing and development.

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