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A Study of Fuel Cell Hybrid Auto Rickshaws Using Realistic Urban Drive Cycles

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Abstract

The popular three-wheeled vehicles known as auto rickshaws are common in Asian cities where due to their older two-stroke engines they have been significant contributors to the current air quality issues that plague the urban areas. Recent changes to four-stroke engines as well as those powered by diesel, compressed natural gas (CNG) or liquefied petroleum gas (LPG) reduce the pollution and greenhouse gas emissions. However, because of the large number of vehicles emission of such vehicles is still an important issue.

Some studies about converting an internal combustion engine (ICE) rickshaw to an electrical or fuel cell rickshaw have been done recently. Most of the rickshaw conversion studies used one of the standard urban drive cycles. Such drive cycles do not accurately portray the demands on a rickshaw. Thus, results with unrealistic drive cycles may be misleading.

In this study a comparison between ICE and hybrid fuel cell rickshaw configuration was done using a realistic drive cycle. An ICE and two candidate fuel cell rickshaw models were created and assessed using the Powertrain System Analysis Toolkit (PSAT) software. Two drive cycles that would closely emulate the true demands on a rickshaw operated in an urban environment were developed in order to more accurately simulate the performance of conventional and fuel cell hybrid rickshaws as a means of determining the current feasibility of fuel cells for use in rickshaws.

Keywords: Rickshaw; Fuel Cell, PSAT; Hybrid Vehicle; Drive Cycle.

Nomenclature

CNG	compressed natural gas
LPG	liquefied petroleum gas
ICE	internal combustion engine
Ni-MH	nickel metal hydride
Li-ion	lithium-ion
FC	fuel cell
PEM	proton exchange membrane
SOC	state of charge

1. Introduction

Alternative energy solutions received a great deal of attention in the last decade due to the need of sustainable and environmental friendly energy sources. The main pollutant source in urban areas is the emission of vehicles with ICE 0. Increased concerns over global and local pollution, depletion of fossil fuels, and higher gas prices have motivated ambitious plans for new vehicle types with alternative energy sources. Hybrid electrical vehicles that combine the advantages of two power sources, ICE and electrical motors, have been the focus of attention recently. Nowadays, such vehicles are available in the auto market and are becoming more popular due to high fuel prices and the increasing concerns about he environment. Fuel cell and electric hybrid driven vehicles is another promising alternative technology. These vehicles have been proposed as the next generation of vehicles since they promise clean performance and show higher energy efficiency than conventional vehicles 0[2].

Auto rickshaws are one of the most popular vehicles in developing Asian countries where they are used as taxis and to transport goods. In India alone there are about 2.5 millions rickshaws currently on the road and 250,000 new vehicles are sold each year 0[3]. Figure 1 shows a typical three-wheel auto rickshaw. Due to their small size and maneuverability they are popular method of transportation in large urban centers.

A two or four stroke gasoline engine usually powers these vehicles. Thus, rickshaws are typically highly polluting. In recent years, alternatives such as CNG and LPG models have been introduced to deal with the pollution problem. While these vehicles reduce the amount of particulate matter and other harmful pollutants they do not eliminate them and cities where rickshaws are numerous will continue to have poor air quality. The capital city of New Delhi is one of the most polluted cities in the world although the majority of the public transport is currently

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based on the CNG technology [4]. Some studies about converting an ICE rickshaw to an electrical or fuel cell vehicle have been done recently. In [5] a photovoltaic battery powered rickshaw was investigated. Results showed the proposed hybrid battery/photovoltaic configuration was more efficient and resulted in fewer emissions than the ICE rickshaw.

A hybrid fuel cell/battery rickshaw was studied in [4]. Using the Highway Fuel Economy Test as the drive cycle the results showed promise in creating a hydrogen fuel cell vehicle, with respect to both the environment and cost. It is known that the high costs and fuel storage requirements for the fuel cell vehicle have hindered their use in four-

Figure 1: Standard three-wheel auto rickshaw

wheel light duty vehicles. However, these drawbacks are partially mitigated in a rickshaw since the lower power demand results in a reduced cost for the fuel cell compared to a four-wheel vehicle. Daily rickshaw ranges are between 70 and 150 km with a maximum speed of 60km/hr at most which does not necessitate as much hydrogen to be stored on board for a full run 0[1].

Most of the rickshaw conversion studies used one of the standard urban drive cycles. Such drive cycles do not accurately portray the demands on a rickshaw since they are primarily located in urban centers where they are subjected to mostly stop-and-go traffic and a large amount of braking and acceleration. In 0[6] a driving cycle that represents the driving pattern of the auto rickshaw in India was proposed and compared to the India urban drive cycle that is commonly used for rickshaws analysis.

In this study a comparison between ICE and hybrid fuel cell rickshaw configurations was done based on running cost using a realistic drive cycle. Two drive cycles based on 0[6] were developed in order to more accurately simulate the performance of conventional and fuel cell hybrid rickshaws as a means of determining the current feasibility of fuel cells for use in rickshaws.

2.System Main Components

2.1 Fuel Cell

Fuel cells (FC) are electrochemical devices that convert chemical energy of a reaction directly into electrical energy. Among the various types of fuel cells, Proton

Table 1 provides the primary auto rickshaw specifications used in the vehicle model from manufacturer specifications and experimental results.

Exchange Membrane (PEM) fuel cell has drawn the most attention due to its simplicity, viability, quick start up, higher power density and lower temperature operation 0[2]. Inputs to a PEM fuel cell are oxygen and hydrogen while the outputs are electricity and water. A PEM fuel cell is capable of using both oxygen directly from air, or purified oxygen. 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 0[4].

A standalone FC system may not be sufficient to satisfy the load demands, especially during start-up and transient events. Moreover, the FC system would have to supply all of the power demand thus increasing the size and cost of the FC system. As a result, downsizing the FC system and hybridizing it with an energy storage system decreases system cost and improves performance.

2.2 Battery

The two primary battery competitors for use in both electric vehicles and hybrid-electrics are nickel metal hydride (Ni-MH) and lithium-ion (Li-ion). While Ni-MH currently has an edge over Li-ion in terms of production readiness, Li-ion has twice the energy density of Ni-MH 0[7]. One great advantage of Li-ion batteries is their low self-discharge rate of only approximately 5% per month approx compared to over 30% per month and 20% per month in nickel metal hydride batteries and nickel cadmium batteries respectively 0[7].

3.Auto Rickshaw Configuration Models

Conventional ICE Rickshaw

A Mahindra Alfa is a three-wheel rickshaw that is powered by a diesel engine. Figure 2 shows the PSAT generated configuration of the conventional vehicle and its components.

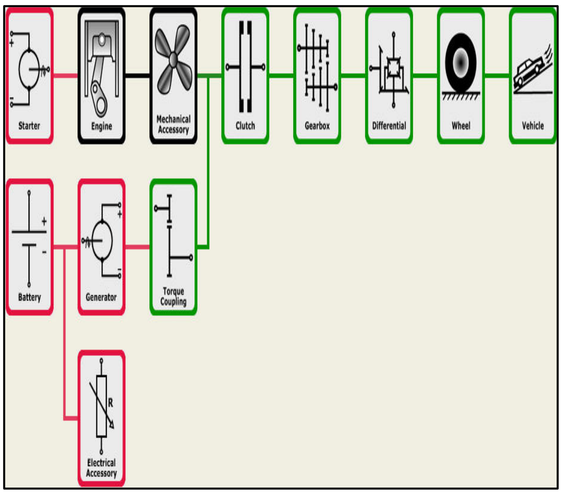

Figure 2: PSAT component configuration for conventional rickshaw

Table 1: Auto rickshaw parameters used in the model as taken from 0[6] and (www.mahindrasmallcv.com).

Engine Type	4-stroke, Single Cylinder, diesel
Max. Power (kW)	5.51 KW±5% @ 3600 rpm
Max. Torque (Nm)	16.7 Nm±5% @ 2200-2800 rpm
Transmission	Constant Mesh, 4 Forward
Tire Size	4.50" x 10", 8PR
Maximum Speed	53 km/h
Battery	12 V, 50 Ah
Headlights	2 x 35 W
Fuel Capacity	10.5 L
Max GVW	800 kg
Curb Weight	480 kg
Frontal Area	2.09 m^2
Coefficient of Drag	0.5
Max Acceleration	2.1 m/s^2
Average Payload	100 kg

3.2 Fuel Cell Hybrid Rickshaw

A hybrid configuration was selected in order to utilize a lower power PEM FC. The FC provides power to the vehicle's motor and battery. PSAT can only create a series fuel cell hybrid vehicle configuration therefore no parallel configurations have been tested. Figure 3 shows the configuration for the fuel cell hybrid rickshaw.

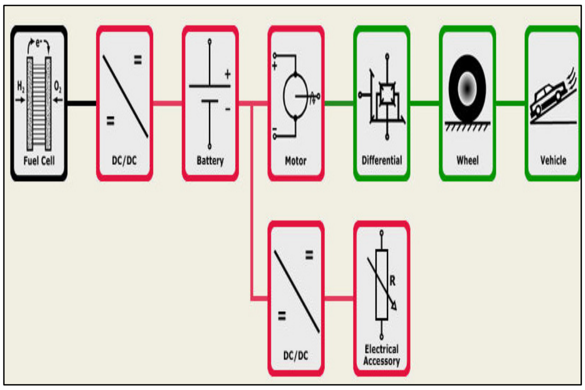

Figure 3: PSAT component configuration for series fuel cell hybrid rickshaw

It is expected that the fuel cell will be the most critical component in the hybrid configuration. In order to match the performance of the conventional diesel rickshaw the power supply of the hybrid must be appropriate. The effect of the FC power was investigated by considering two sizes of the PEM FC. An 8.8 kW high power rickshaw configuration where the bulk of the vehicle power is provided by the FC and a 4.4 kW FC low power version that would only be able to provide part of the power when the maximum is demanded. FCs with both specifications are commercially available.

Onboard hydrogen fuel is in the form of pressurized gas with a mass of 1.79 kg in a 38 kg cylinder. Li-ion batteries were integrated into the models with a capacity of approximately 8.4 kWh. With the batteries there is a concern when it comes to deep discharging and its effect on capacity over time. Therefore a maximum discharge has been considered to be a drop in the state of charge (SOC) by 40% in order to maintain their lifespan.

An AC electric induction motor with an 8 kW maximum power output was selected based upon the specifications of the conventional rickshaw. Additionally the DC/DC converters operate at an efficiency of 95%. A single final drive differential was selected as opposed to a full transmission, which reduces the overall weight of the vehicle. The rickshaw, however, was not entirely changed from the specifications of the conventional model. Passenger and driver masses were also kept the same to maintain a direct comparison between the conventional and FC hybrid models.

4.Drive Cycles

A drive cycle is the series of conditions a vehicle will experience in a set amount of time that can be used a reflection of the conditions over a longer period of time. The drive cycle defines when the vehicle is at rest, accelerating, decelerating or at a constant speed. Most existing drive cycles were designed for four-wheel light duty vehicles. The maximum acceleration, deceleration and top speed in such drive cycles are above the capabilities of rickshaws. Thus such drive cycles do not accurately portray the demands on a rickshaw. In 0 new drive cycles for rickshaws in India were designed. The new drive cycles were developed using GPS data that was collected from rickshaws in operation. The study looked at rickshaws driving in New Delhi at different times and developed daytime and evening drive cycles.

In this study two drive cycles were designed based upon the results presented in 0. The daytime drive cycle was based upon the periods of peak traffic when speeds were limited. By comparison the evening cycle allows for higher speeds when there is less traffic on the roads and shorter stop durations. The statistics of both drive cycles and the India urban drive cycle that is usually used in rickshaw analysis are shown in Table 2.

Table 2: Drive cycles statistics

Parameter	India Urban cycle	Day cycle	Evening cycle
Time (s)	2689	5650	4849
Distance (km)	17.4	8.7	17.40
Maximum Speed (km/h)	62.2	44.0	49.96
Average Speed (km/h)	23.3	5.5	12.92
Maximum Acceleration (m/s^2)	1.7	7.0	7.0
Maximum Deceleration (m/s^2)	-2.1	-7.0	-7.0
Average Acceleration (m/s^2)	0.3	0.8	1.02
Average Deceleration (m/s^2)	-0.4	-0.9	-1.0449
Idle Time (s)	267	405	222
Number of Stops	52	31	31

5.Simulation Results

The ICE conventional rickshaw model was designed to replicate the baseline for comparison to all the alternative powered vehicles. The main results for comparison based upon the rickshaw drive cycles are displayed in Table 3. The "LP FC" and "HP FC" columns represent the low and high power FC hybrid configurations. "Conv" represents the conventional model.

5.1 Comparison of Drive Cycles

The three drive cycles described in Section 4 were simulated using the conventional vehicle model. Results are shown in Table 3. There was a distinctive difference between the two developed realistic drive cycles and the mainstream cycle. The fuel economy for the India Urban cycle was significantly less than that of the two other cycles. Based upon a typical rickshaw routine the conventional rickshaw needs additional fuel every day. This conflicts with the India Urban cycle results thatindicate that a rickshaw could travel for almost three days without refueling. It is unrealistic to expect that in heavy traffic with a great deal of acceleration and braking that a conventional rickshaw would achieve a remarkable 2.43 L/100 km diesel fuel economy when loaded with passengers. The intensity of the two developed cycles is made clear from the high demands for fuel and significant amounts of exhaust shown in the simulation results. Based upon the results from the developed cycles the need for refueling is greater, which more accurately portrays the usage of auto rickshaws in urban Indian streets. The intensive drive cycle shows a marked increase in rate of carbon dioxide released which are higher than that reported in [8], which indicated that a typical four-stroke gasoline auto rickshaw would release 78.5 g/km.

5.2 LP FC versus HP FC

As shown in Table 3 the LP FC configuration has better fuel economy, cost/km, and range than the HP FC configuration for both daytime and evening drive cycles. While both configurations utilized the braking energy almost at equal percentage, the electrical consumption in the case of the HP FC configuration was negative. This negative value indicates that the HP FC configuration inevitably wastes fuel by charging the battery when it is already sufficiently charged. On the other hand while the LP FC configuration provided just enough power to keep the SOC constant it was still greater than was required. The first 80 seconds of the daytime drive cycle is plotted in Figure 4, in it the speeds and accelerations are relatively low and the intensity of the drive cycle is at a minimum.

Figures 5 and 6 show the plot of the power outputs with respect to the same eighty seconds of the daytime drive cycle. The fuel cell output approaches its peak power and is used in greater proportion than the batteries are despite the low power requirements. The emphasis on the fuel cell in both the LP and HP FC models results in greater fuel consumption than may have been required if the control strategy were optimized for greater hybridization. The LP FC configuration was found to be better than the HP FC configuration in almost every aspect, thus it will be used for comparison with the conventional configuration.

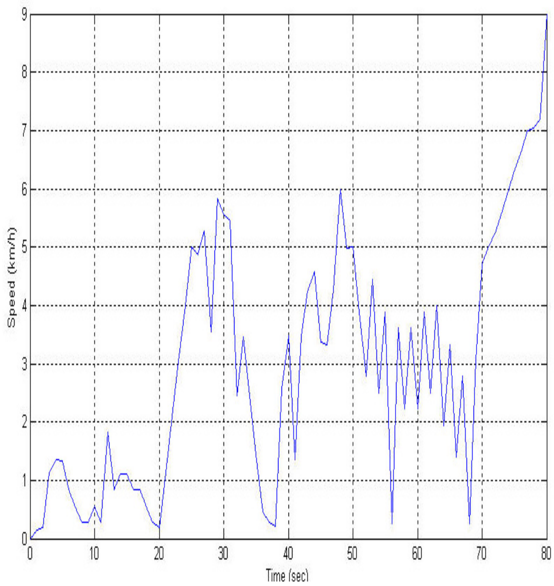

Figure 4: Speed versus Time for the Daytime Drive Cycle Simulation

Table 3: Summary of Simulation Results

Result	Conventional			LP FC		HP FC	
	India Urban Cycle	Day Cycle	Evening Cycle	Day Cycle	Evening Cycle	Day Cycle	Evening Cycle
Fuel Economy (L/100km)	2.4	6.2	4.3	44.9	36.2	50.7	42.1
Fuel Economy Gasoline Equivalent (L/100km)	2.7	6.9	4.8	3.0	2.5	3.4	2.9
Range based on fuel capacity (km)	432.1	170.2	244.8	268.6	332.5	237.7	286.5
CO_2 Emissions (g/km)	64.8	164.7	114.5	0	0	0	0
Final SOC (%)	NA	NA	NA	69.18	68.99	70.07	71.69
Distance Traveled (km)	16.1	7.6	15.0	8.1	16.1	8.1	16.1
Percentage of Braking Energy Recovered at Battery (%)	0	0	0	4.9	11.3	5.6	11.5
Fuel Mass Consumed (kg)	0.3281	0.3894	0.5384	0.0655	0.1050	0.0739	0.1218
Electrical Consumption (Wh/km)	NA	NA	NA	8.4	4.8	-1.4	-9.9

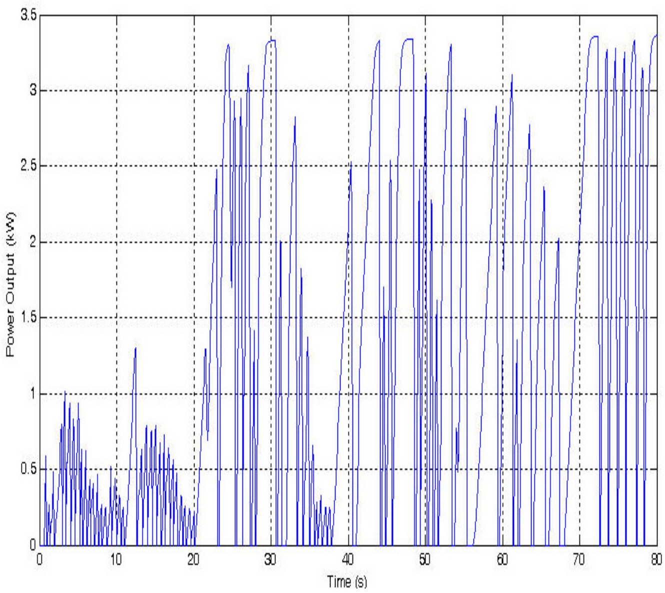

Figure 5: FC output versus time for LP FC model on daytime drive cycle

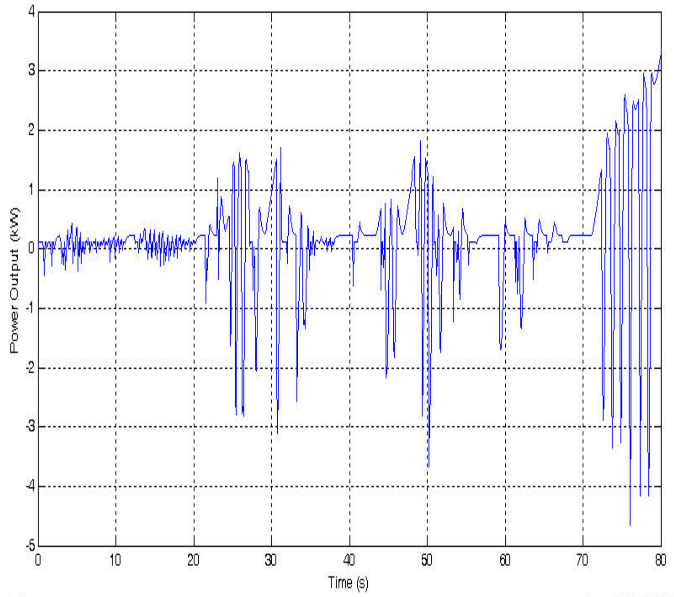

Figure 6: Battery output versus time for LP FC model on daytime drive cycle