Study of a Parallel Electric Hybrid Three-Wheeled Motor Taxi

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ABSTRACT
The three-wheeled motor taxi, often termed as "auto rickshaw" is very popular in India and serves as the most affordable means of transportation to the local people. Due to its small size, it is well suited for the narrow crowded streets in Indian cities. One of the main concerns of this vehicle has been its large emissions of green house gases and other toxic particulates, thereby causing severe air pollution. This paper presents a survey of relevant literature on the need for a low-cost Parallel Electric Hybrid Three-Wheeled Motor Taxi or Parallel Electric Hybrid Rickshaw (PEHR). Extensive simulation studies are carried out on a Bajaj RE auto rickshaw equipped with a two stroke engine on the modified Indian Driving Cycle by making it electric hybrid capable of managing its regenerative braking energy. The main focus has been the study of brake recovery energy and its management to increase the fuel economy delivered by the PEHR.

Keywords
Parallel Electric Hybrid Rickshaw (PEHR), Indian Driving Cycle, Drive Power Demand, Fuel Economy, Regenerative Braking Energy

1. INTRODUCTION
Most of the cities in developing countries are highly polluted. The main reasons are the air and noise pollution caused by transport vehicles, especially petrol-powered two and three-wheelers. Besides causing pollution, these vehicles consume barrels of petrol and diesel due to which the country has to pay dearly when it comes to foreign exchange outflow. The auto rickshaws in India are no exception to these. Since the introduction of auto rickshaws in India in the late 1950s, these vehicles have become an indispensable aspect of urban mobility for millions of people. Most of these auto rickshaws are owned by people constituting the lower income groups in society. Hence within this paper, the objective has been to make the existing auto rickshaws more efficient and affordable by reduction of fuel consumption. The project objectives include:

- CO_2-emission reduction of auto rickshaws;
- Increasing fuel economy of auto rickshaws;
- Improvement of air quality in cities;

According to study [2], the population of Indian cities is expected to grow from 340 million (2008) to 590 million (2030). These cities have 4 to 16 auto rickshaws serving every 1000 people. On an average if we consider 10 auto rickshaws per 1000 people and assuming the population in these cities to be around 375 million (2013), there are 3.75 lac auto rickshaws running on urban streets. If we assume an auto rickshaw to be running 100 km/day with a fuel consumption of around 20 km/l, then the fuel consumption would be roughly 5 l/day. The corresponding CO_2 emissions are 5 l/day X 2.4 kg/l = 12 kg/day. The total CO_2 emissions of 3.75 lac auto rickshaws amount to 4.5 million kg/day. So the main motive of this paper has been to reduce these emissions and increase fuel economy of these vehicles by making it parallel electric hybrid.
The outline of the paper is as follows: The vehicle model and specifications of the vehicle under study are mentioned in Section 2. These specifications have been adopted from literatures [3] and [14]. Section 3 deals with the driving cycle under study i.e. the urban part of the modified Indian Driving Cycle [13] and the modeling of the PEHR in Simulink, MATLAB. In Section 4, the drive power demand and regenerative braking energy is studied and analyzed on the Indian Driving Cycle for component sizing. The simulated results and the fuel economy improvements are listed in Section 5. The paper is concluded with a Conclusion and scope for future work in Section 6.

2. VEHICLE MODEL AND SPECIFICATIONS
The vehicle is equipped with a two-stroke 145.45 cc single cylinder SI engine with a maximum crankshaft power of 5.24 kW. The transmission consists of a four speed manual gearbox with a reverse gear, and a wet-plate clutch. The kerb weight of the vehicle is 284 kg and the maximum Gross Vehicle Weight (GVW) of the vehicle is 610 kg. For the study, the maximum GVW of the vehicle i.e. M_v = 610 kg is considered. Table 1 gives an overview of technical specifications adopted from literatures [3] and [14].

Figure 1: Bajaj RE 2S auto rickshaw

Table 1: Specifications of Bajaj RE 2S

Part	Values
Engine	
Type	Single Cylinder, 2 stroke
No. of cylinders	One
Displacement	145.45 cc

Max. Power, P_{max}	5.24 kW @ 5000 rpm
Max. Torque, T_{max}	12.17 Nm @ 3500 rpm
Clutch	
Type	Wet multidisc
Transmission	
Type	4 Forward, 1 Reverse
Gear ratios, G_t	[5, 2.93, 1.84, 1.12]
Primary ratio, G_p	1.13
Final drive ratio, G_{fd}	4.125
Tyres	
Front and Rear, R_w	4.00-8, 4PR
Electrical System	
System Voltage	12 V
Dimensions	
Overall width, W	1300 mm
Overall length, L	2625 mm
Overall height, H	1710 mm
Wheelbase	2000 mm
Rear track	1150 mm
Ground clearance	180 mm
Assumptions	
Drag Coefficient, C_d	0.45
Rolling resistance, C_r	0.01
Frontal area, A_f	2.09 m^2

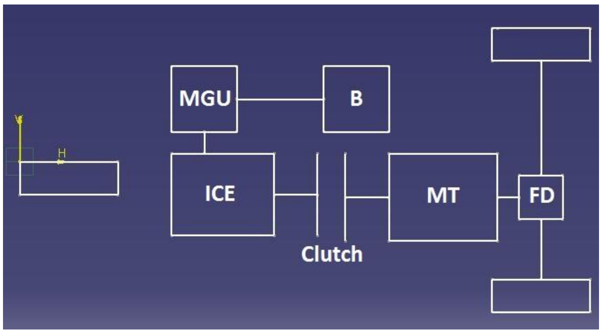

Figure 2: Layout configuration of PEHR in CATIA V5 ICE-Internal Combustion Engine, MT-Manual Transmission, FD-Final Drive, MGU- Motor/Generator Unit, B-Battery

3. DRIVE CYCLE AND MODELING

The simulations are performed on the urban part of the modified Indian Driving Cycle [13] since the study is carried out for Indian cities. The driving cycle is shown in Figure 3:

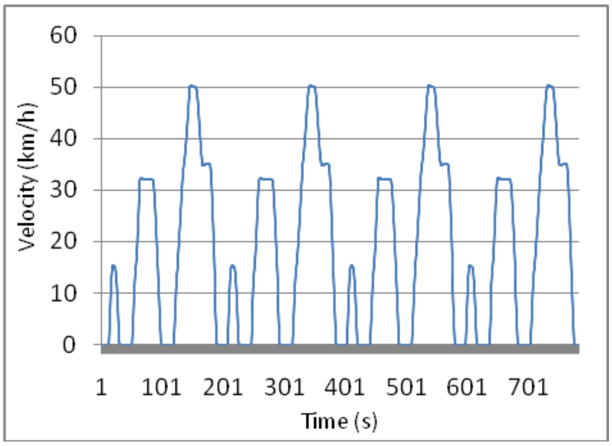

Figure 3: Urban part of modified Indian Driving Cycle

Some of the main features of the cycle are as follows:

- Duration: 781s
- Distance Travelled: 2.52 mile or 4.06 km
- Maximum speed: 50.2 km/h
- Peak acceleration: 1.03 m/s^2
- Average speed: 18.74 km/h which corresponds to average traffic conditions in cities

The modeling of the conventional auto rickshaw and PEHR has been performed in Simulink, MATLAB. While modeling, the transmission and final drive efficiencies are considered to be 95% and 97% respectively. The gear shifts for the drive cycle have been implemented based on the vehicle speed, v :

$$v = \frac{120\pi N R_w}{1000G} \tag{1}$$

Where,
N = speed of engine (rpm)
G = total gear ratio at the wheels
The simulated results are shown in the succeeding sections.

4. DRIVE POWER DEMAND AND COMPONENT SIZING

4.1 Drive Power Demand

The drive cycle and the vehicle specifications listed in Table 1 can be used to calculate the wheel torque, T_w as follows:

$$T_w(t) = C_r \cdot M_v \cdot g \cdot R_w + \frac{1}{2} \cdot \rho \cdot C_d \cdot A_f \cdot \omega_v(t)^2 \cdot R_w^3 \tag{2}$$

Where,

g = gravitational acceleration

ρ = air density (1.225 kg/m^3)

and wheel speed,

$$\omega_v(t) = \frac{v(t)}{R_w} \tag{3}$$

The drive power demand is,

$$P(t) = T_w(t) \cdot \omega_v(t) \tag{4}$$

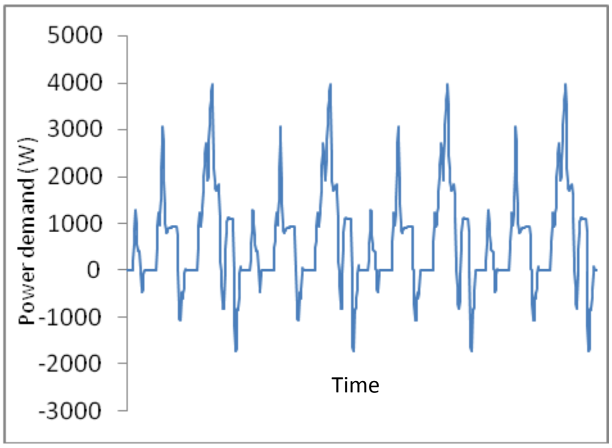

Figure 4: Drive Power demand

In Figure 4, the drive power demand is calculated at each instant for the entire duration of the drive cycle using equation (4). The drive power demand study is used to calculate the amount of braking energy that is available for recovery and hence determine the size of the energy storage system.

If we consider one braking event to be from the time when the power demand just becomes negative to the time when the power demand just becomes positive, there are total 16 braking events in the urban part of Indian Driving Cycle. The energy, E can be calculated from the power demand by the following relation:

$$E(t) = \sum_{0}^{T} P(t) \cdot \Delta t \quad (5)$$

The energy required to accelerate / maintain velocity can be calculated by summing up the positive power demands at each instant. The energy available for recovery i.e. the regenerative braking energy can be calculated by summing up the negative power demands. Figure 5 shows the regenerative braking energy available at 16 braking events. The total energy required to accelerate / maintain velocity comes out to be around 550 kJ for one drive cycle. The energy available for recovery under braking is the summation of all the braking energies in 16 events and comes out to be around 91 kJ. Hence under ideal conditions, if the entire braking energy is recovered and used to propel the vehicle, the energy saving would be:

Energy saving = (90.84/550.05) X 100 = 16.5 %

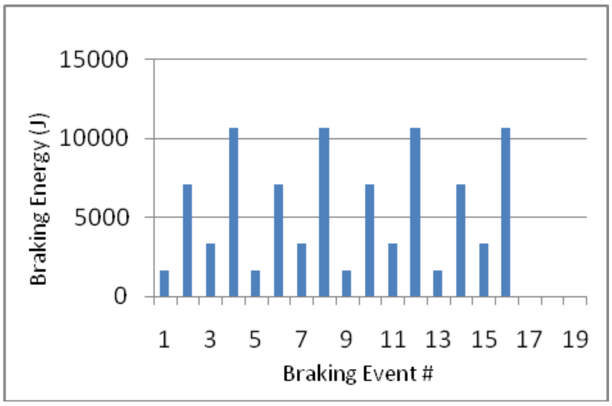

Figure 5: Energy available for recovery at discrete braking events

If all the braking energy is recovered, the energy saving is 16.5 %. However, in real situations due to drag losses, rolling losses, road grade losses, etc., the energy is never completely recovered.

4.2 Component Sizing

The power demand gives an estimate of the Motor/Generator Unit (MGU) required in PEHR. The peak braking power over the drive cycle is 1.8 kW. Assuming 70 % of this power to be recoverable, we choose a 1.2 kW motor for our purpose. This motor suffices to extract most of the available power at all instants. The total energy available for recovery under braking is around 91 kJ over one drive cycle. Assuming an auto rickshaw to be running 100 km/day, it will undergo roughly 25 drive cycles (one drive cycle = 4.06 km). The total energy available for recovery per day = 91 X 25 = 2275 kJ. Considering 50 % recovery of this regenerative braking energy, a 24 V 15 Ah battery has been chosen for storing this amount of energy. There are many different battery technologies available in the market, e.g., NiCd, NiMH, Li-ion, Li-polymer battery technologies. While NiMH battery has good efficiency and is widely used in hybrid vehicles, it is more expensive. Li-ion batteries have high energy and power densities but have low tolerance to high voltages and have low battery life. The lithium iron phosphate batteries ($LiFePO_4$) are characterized by faster charging times and longer life cycles. They are also available in Asian market and hence are suitable in our case. The stored energy can be used for propulsion of the vehicle in the form of launch assist, boost or other optimized control strategies as depicted in Section 5.

5. FUEL ECONOMY IMPROVEMENTS

The model has been simulated for fuel economy improvement by implementation of various control strategies. Using the start-stop feature which shuts off the engine during idling phases, around 16 % of fuel consumption can be saved. There are 237 idle seconds in the urban part of the modified Indian Driving Cycle. The fuel consumption in case of PEHR reduces to 0 g/s during idling phases while the conventional vehicle continues to consume fuel at the rate of 1 g/s. So there is a saving of 23.7 g or approximately 1027 MJ of fuel energy (LHV of gasoline = 43.3 MJ/g). Figure 6 shows improvement in fuel economy through various strategies. There is a fuel economy improvement of around 17 % over the conventional auto rickshaw if the stored braking energy of PEHR is used to propel the vehicle at times of low vehicle speeds (v<=4 km/h) along with the start-stop feature. The stored energy can be used to start the vehicle due to low torque demands (T_w) (calculated from (2)) at low speeds and the engine is made to run only after the vehicle reaches the speed of 4 km/h. The boost feature comes into play when the torque demand is high. Due to sudden high torque demand, the fuel consumption by the engine increases and the efficiency of the engine goes down. Thus, a boost feature is implemented in PEHR that gets activated only when the torque demand is higher than 7 Nm (60 % of peak torque) and delivers a torque of 3 Nm. This relieves the engine from high torque demand values and the fuel consumption decreases.

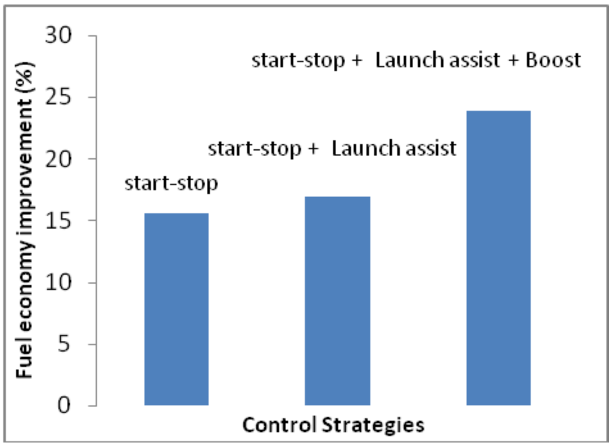

Figure 6: Fuel economy improvement through various control strategies

Keeping engine away from sudden high torque demands also increases engine life due to low fatigue stresses. The boost feature can be controlled by torque demand pattern on different roads. In our case, it provides a reasonable fuel economy improvement of around 24 % or around 4.3 km/l over conventional vehicle for one cycle of Indian Driving Cycle. The vehicle travels approximately 100 km or 25 drive cycles per day. With a mileage of around 18 km/l at full load conditions in city streets, the conventional vehicle consumes 5.5 l of gasoline per day whereas the PEHR consumes 4.45 l of gasoline daily. The fuel consumption of one auto rickshaw reduces by around 1.05 l per day. The total reduction in fuel consumption of 3.75 lac auto rickshaws is 3,75,000 X 1.05 = 3,93,750 l/day. The corresponding reduction in CO_2 emissions in these cities is 3,93,750 l/day X 2.4 kg/l = 9,45,000 kg/day i.e. close to 1 million kg/day.

6. CONCLUSION

This paper presents the fuel economy improvements of a three wheeled motor taxi for urban environment by making it parallel electric hybrid. Using basic control strategies, the component sizing is determined and fuel economy improvements upto 24 % are noted. Due to rapid urbanization and growing population in Indian cities, pollution has become a prime concern. Thus, the need of a PEHR is justified in future if these emissions are to come down and the same have been argued and justified by means of statistics. In future research, the vehicle model has to be refined by optimizing the efficiencies of engine and motor/generator curves simultaneously. Optimized controlled management of regenerative braking energy is also a future part of research.

7. ACKNOWLEDGMENTS

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