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EXPERIMENTAL COMPARISON OF TWO DIFFERENT HYBRID PROPULSION SYSTEMS

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ABSTRACT –

The three-wheeled vehicle, called an "auto-rickshaw", with a 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 manoeuvrable vehicle and ideally suited for the narrow and traffic clogged streets of urban India. Electric and hybrid vehicles are particularly suited for use in urban areas since city transportation is mainly characterized by relatively short driving distances, low continuous power requirements, long idling times and high availability of regenerative braking energy. These characteristics, when carefully incorporated into the design process, create valuable opportunities for developing clean, efficient and cost effective urban vehicle propulsion systems. A novel, low cost, test-bed for experimenting with hybrid propulsion systems for urban areas is developed and presented in this work. The main objective of this work is to study the performance of a parallel hybrid configuration with a DC hub motor and an IC engine. The hybrid configuration in this case adds speed at the wheel output unlike the normal power split configuration which adds torque. The addition of speed is done by connecting the output of engine and CVT to the stator of an electric hub motor. This novel setup is compared with torque addition where the output of the engine is coupled with the output of the DC motor using a gear transmission arrangement.

INTRODUCTION

It is commonly 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 less developed regions of India, China, South-East Asia, Latin America, Africa and South America.. This increased urbanization and economic growth and the accompanying need for personal transportation and mobility is expected to lead to increased demand for energy, increased emission of CO2 and other greenhouse gasses, increased environmental impact and pollution[2], and result in increased congestion on the existing roads. 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 (HEVs) are the most promising propulsion systems [3-5].

Numerous parallel hybrid configurations have been proposed [6-9]. Parallel HEV, such as a Toyota Prius, consist of a planetary gear train with an electronic control unit to combine the power from both the IC engine and electric motors. The main disadvantage of this type of vehicle is the complexity of the power train. This paper presents a test bed used for validation of novel propulsion architecture for HEV where the power addition is by adding the speeds of both IC engine and electric hub motor. The novel speed addition architecture does not require complex transmission system and, for a DC hub motor, the engine output after a CVT is directly connected to the stator of the hub motor.

The power requirements of vehicle according to modified Indian drive cycles show that the maximum power requirements for an auto-rickshaw is 80% of the time below 4 kW [10], and thus two 2 kW brushless DC hub motors are enough to satisfy power requirements. The test bed consists of a 2 kW DC hub motor and a 175cc gasoline IC engine. The test bed can operate in two different configurations and in a purely electric or a hybrid mode. This paper presents results for the novel speed addition and the more common torque addition configuration. It also presents a comparison of these two configurations.

KINEMATICS OF THE MECHANISM

The test bed has been designed keeping in the mind the eventual application of the technology for an auto-rickshaw.

SPEED ADDITION

Figure 1 shows the schematic of the test bed with speed addition configuration. The crankshaft of the single cylinder IC engine has been connected to a belt driven CVT with a reduction gear at the output of CVT. The output of CVT is connected to an electromagnetic clutch which can be used to connect or disconnect the engine from DC motor while switching between different modes of hybrid configuration. The other end of the clutch is connected to the stator of electric hub motor through a spring loaded electromagnetic brake.

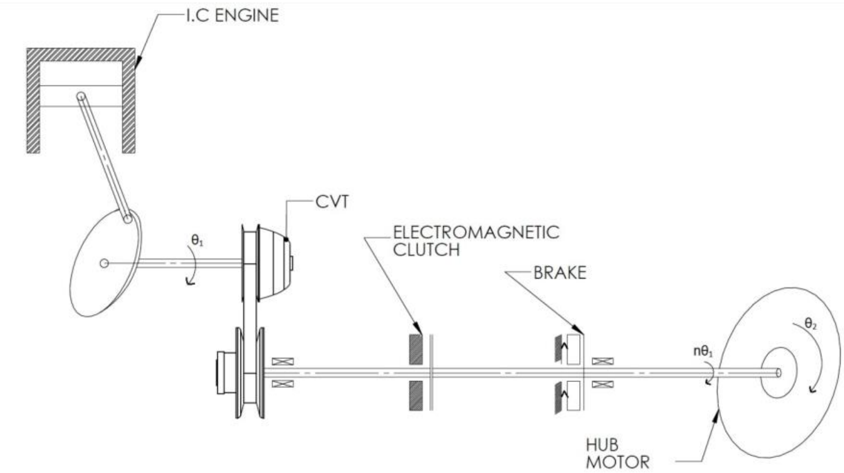

Figure 1: Kinematic diagram of speed addition test bed

Let the output speed of the CVT be denoted by ω_1 and the electric motor by ω_2, and the output of the setup be denoted by ω_3. The mechanical speed coupler can be defined by [11]

$$\omega_3 = k_1\omega_1 + k_2\omega_2 \quad [1]$$

where k_1 and k_2 are constants associated with the structural and geometric design of the coupler which is unity in this case. Among the three speeds ω_1, ω_2 and ω_3, two of them are independent of each other and can be controlled independently. Due to the constraint of power conservation, the torques are linked together by

$$T_3 = \frac{T_1}{k_1} = \frac{T_2}{k_2} \quad [2]$$

The output of IC engine is (T_1,ω_1) and the output of motor is (T_2,ω_2), resulting in the output configuration being (T_3,ω_3). Since k_1 and k_2 are unity in our case, T_1, T_2 and T_3 are equal and the speed of the output are related as

$$\omega_3 = \omega_1 + \omega_2 \quad [3]$$

As seen in equation (3), the speed of the output is the sum of the speeds of IC engine and the DC electric motor.

TORQUE ADDITION

In the torque addition configuration, the output of CVT is connected to a spur gear through a clutch. The clutch is used to switch between electric and hybrid modes. The spur gear connected to the CVT is mated with a spur gear of same specification mounted on the rotor of the hub motor.

Let the output speed of the CVT be denoted by ω_1 and the electric motor by ω_2, and the output of the setup be denoted by ω_3. The mechanical speed coupler can be defined by [11]

$$\omega_3 = k_1\omega_1 = k_2\omega_2 \quad [4]$$

where k_1 and k_2 are constants associated with the structural and geometric design of the coupler which is unity in our case. Among the three speeds ω_1, ω_2 and ω_3, two of them are independent of each other and can be controlled independently. Due to the constraint of power conservation, the torques are linked together by

$$T_3 = \frac{T_1}{k_1} + \frac{T_2}{k_2} \quad [5]$$

The output of IC engine after CVT is (T_1,ω_1) and the output of motor is (T_2,ω_2), resulting in the output configuration being (T_3,ω_3). Since k_1 and k_2 are unity in our case, ω_1, ω_2 and ω_3 are equal and the Torque of the output are related as

$$T_3 = T_1 + T_2 \quad [6]$$

The wheel output speed is same as the speed of IC engine after CVT which is also the speed of the electric motor and the output torque is equal to the sum of torque generated by electric motor and IC engine after CVT.

EXPERIMENTAL SETUP

The experimental setup consists of a 175 cc single cylinder gasoline engine coupled with a CVT.

SPEED ADDITION

The output of CVT is connected to one end of the electromagnetic clutch. The other end of electromagnetic clutch is connected to stator of a 2 kW brushless DC hub motor through a spring loaded electromagnetic brake. The hub motor is connected to the controller using the slip ring for a the main power supply and another slip ring used to connect the hall sensors used to sense the position of the hub motor. The rotor of the hub motor is connected to an eddy current dynamometer. Figure 2 shows the experimental setup used.

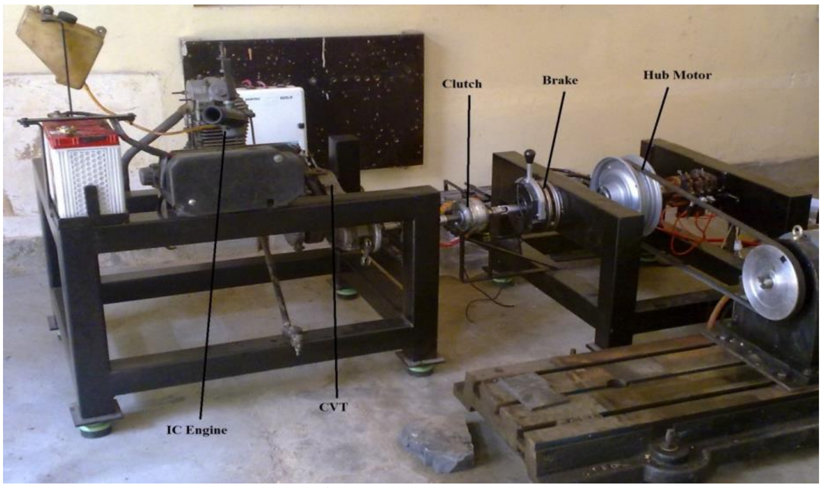

Figure 2: Experimental setup for low cost hybrid propulsion with speed addition

TORQUE ADDITION

The output of IC engine through CVT is connected to one end of the electromagnetic clutch. The other end of electromagnetic clutch is connected to spur gear which is mated with other spur gear of same ratio mounted on the rotor of 2 kW brushless DC hub motor. The hub motor is mounted on a frame and connected to a controller. The rotor of the hub motor is connected to an eddy current dynamometer. Figure 3 shows the experimental setup used for torque addition.

Figure 3: Experimental setup for low cost hybrid propulsion with torque addition

EXPERIMENTAL PROCEDURE

The experiments are done in two modes on both the configurations-- a) electric only b) hybrid. In electric mode for speed addition the power to clutch and brake is disabled. The clutch is disengaged and the brake holds the shaft from rotating due to the counter torque. Whereas in torque addition mode the clutch is disengaged due to the lack of back torque by electric motor the electromagnetic brake is not required. In both the configurations throttle of electric motor is set to the desired value and then the dynamometer is loaded by varying the torque linearly and the change in speed and torques are logged on a computer.

In the hybrid mode the power to clutch and brake is enabled for speed addition and clutch is engaged for torque addition. The clutch is engaged transmitting the power from IC engine to the stator of the brushless DC hub motor in speed addition configuration. The brake is disengaged allowing the shaft to rotate freely. In the torque addition configuration the output of IC engine through CVT is connected to the rotor of the hub motor through a pair of spur gear. The throttle of the IC engine is set to a defined throttle position and the electric motor is set at the same position as in the only electric mode to compare results.

RESULTS AND DISCUSSION

The torque and speed of the engine are the main parameters which define the output power the engine. In this section we show different plots for both speed and torque addition and comparison plot of both speed and torque addition condition for similar engine throttle, motor parameters and dynamometer loading.

PLOTS FOR SPEED ADDITION CONFIGURATION

Figure 4 shows the torque-speed curves of both electric (green) and hybrid (blue) mode. The blue curve is plotted with an initial output engine rpm (after the CVT) of 380 and the motor at an initial rpm of 800. In the electric mode the motor is supplied the same amount current, i.e. the motor rpm is kept same as that in the hybrid mode. From the figure below we can observe that there is a shift in the curve along the speed axes showing that speed addition takes place in this case. The shift in the graph also implies the increase in maximum as well as low power.

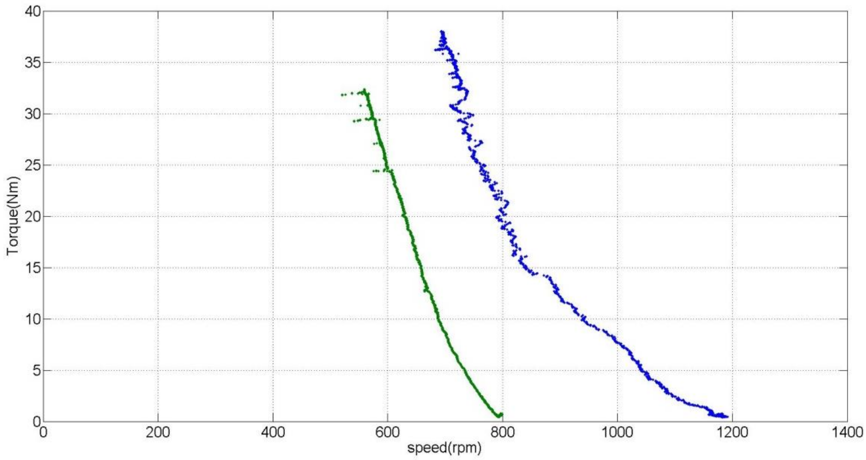

Figure 4: Torque-speed curves with an initial rpm 380 of IC engine and 800 for electric motor.

As seen in figure 4, the initial difference in rpm between DC motor alone and DC motor plus IC engine is 400. As the load increases, due to the change in the ratio in the CVT, the blue and green curves come closer. After a load of 14 N, the CVT ratio do not change any more and one see that both the curves are nearly parallel to each other. *This clearly demonstrates that speed addition is taking place.*

Figure 5 shows the operation of IC engine at lower throttle levels with an initial output rpm after the CVT at a low180 rpm and the electric motor running at full throttle with initial output rpm as 800. Here also we can observe a small shift in the torque-speed curves similar to the figure 4 but the shift is smaller as the throttle opening of IC engine is lower compared to the previous case.

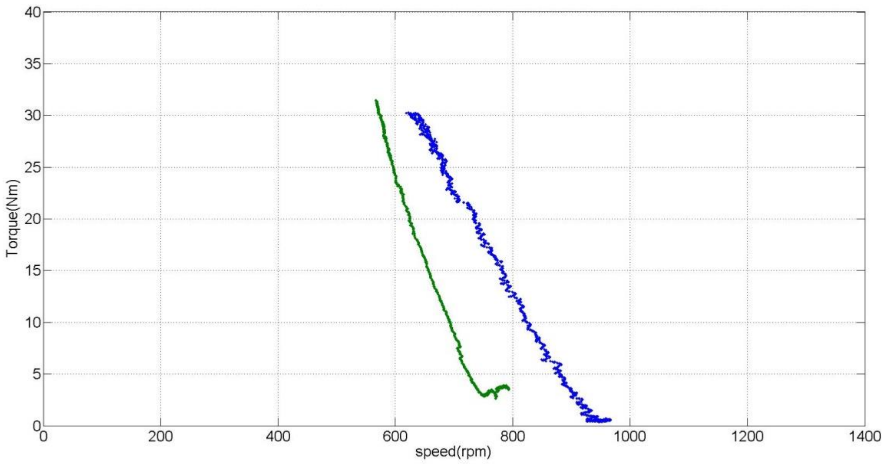

Figure 5: Torque-speed curves with an initial rpm 180 of IC engine and 800 for electric motor

Figure 6 shows the operation of IC engine at approximately 50% throttle with an initial output after the CVT at 560 rpm and the electric motor running at partial throttle with initial output rpm as 640. Here also we can observe a shift in the torque-speed curves similar to the figure 4 and 5 but the shift is relative to the output rpm of the engine which is dependent on the throttle opening of IC engine.

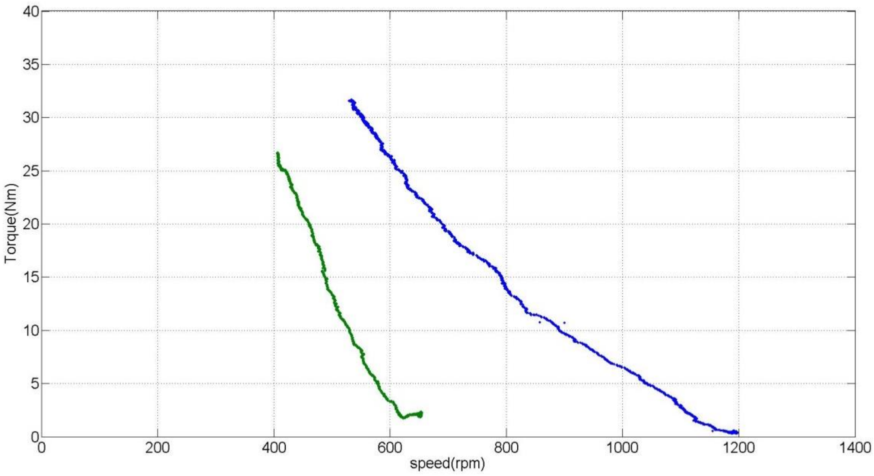

Figure 6: Torque-speed curves with an initial rpm 560 of IC engine and 640 for electric motor

From the above figures 4, 5 and 6 we can observe that the shift in torque-speed curve along speed axis is approximately equal to speed output of the engine. The IC engine used in this case is controlled manually. If the IC engine is controlled by ECU to maintain a constant rpm at the output of CVT the curves are expected to be parallel to each other with an offset equal to the rpm of the engine.

PLOTS FOR TORQUE ADDITION CONFIGURATION

Figure 7 shows the torque-speed curves of torque addition configuraiton. The blue curve represents the torque-speed curve of the experimental setup in hybrid mode with an initial output engine rpm of 430 and the motor at intial rpm of 520. In this case there the power is added by coupling the output of engine to the output of electric motor.

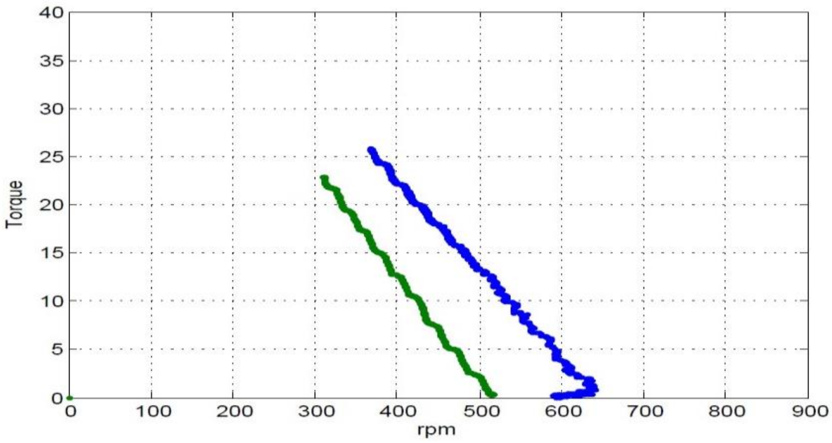

Figure 7: Torque-speed curves with an initial rpm 430 of IC engine and 520 for electric motor

Figure 8 shows the operation of IC engine at lower throttle levels with an initial output rpm after the CVT at a low 280 rpm and the electric motor running at full throttle with initial output rpm as 780. Here also we can observe a small shift in the torque-speed curves similar to the figure 5 but the maximum torque attained is in hybrid mode higher than the maximum torque of the electric motor where as in figure 5 the maximum torque is lower or equal as the power is mainly added due to speed addition in that case.

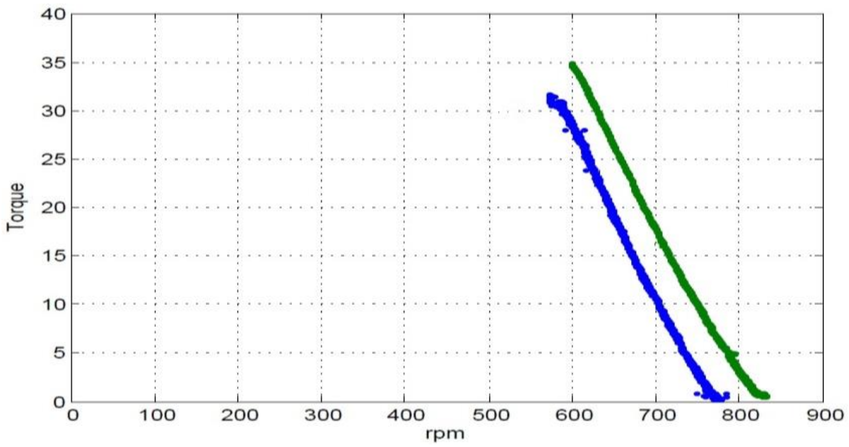

Figure 8: Torque-speed curves with an initial rpm 280 of IC engine and 780 for electric motor

Figure 9 shows the torque-speed curves of both electric (green) and hybrid (blue) mode. The blue curve is plotted with an initial output engine rpm (after the CVT) of 360 and the motor at an initial rpm of 430.

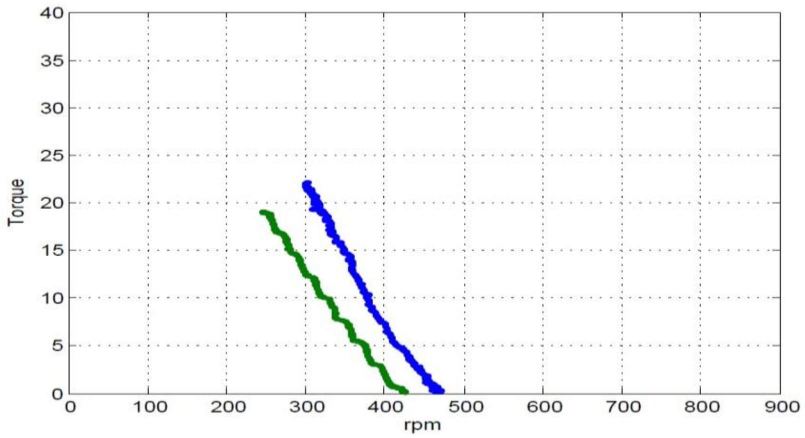

Figure 9: Torque-speed curves with an initial rpm 360 of IC engine and 430 for electric motor

COMPARATIVE STUDY OF SPEED ADDITION WITH TORQUE ADDITION

If we plot the experimental results for both the cases, i.e., speed addition and torque addition at same engine rpm and motor power, the resultant plot is as shown in figure 10. It should be noted that the engine used in both the experimental architectures is same, while the motors used are of same capacity (2 kW). The blue line represents the torque-speed curve in case of speed addition. The red line represents the torque-speed curve for the torque addition architecture. The green and the cyan lines represent the torque-speed curves for only motor in both the architectures. As in both the architectures the motor is run at same rpm i.e., 500 rpm, the lines almost overlap each other. It can also be observed that, for same torques, the speed addition curve (blue) gives a higher rpm, thus being more efficient. At lower torques the difference in powers is notably higher.

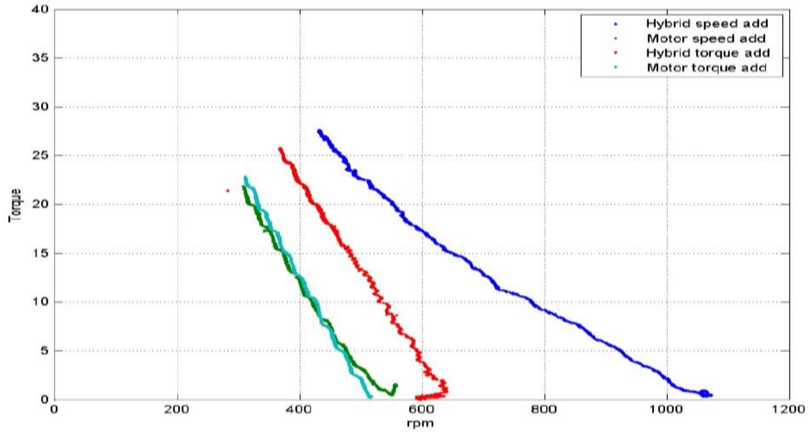

Figure 10: Torque speed curves with an initial rpm 560 of IC engine and 640 for electric motor

CONCLUSIONS

One of the goals of an urban transport is to use the electric mode most of the time and use the hybrid mode when the power supplied by the electric motors is not enough to drive the vehicle or when the battery charge is very low. In this paper, we have demonstrated the feasibility of a concept where a DC servo motor provides power and only when necessary power is added by addition of speed as opposed to traditional addition of torque in common hybrids. We also compare the results obtained from speed addition hybrid configuration with traditional torque addition configuration. The experimental results clearly show the shift in the torque-curves along the speed axis consistent with the theory. The main advantages of the concept is that the direct coupling of the engine to the stator of the electric motor and also higher power output at lower power requirements. This reduces the complexity in power train by avoiding planetary gears and electric control which is required in common hybrids. The absence of a gear box also reduces the cost and space requirements drastically and this type of architecture can be used in smaller vehicles such as auto-rickshaw and small cars. The main disadvantage of the speed addition setup is that the belt type CVT limits the maximum torque that can be transmitted. For further work we plan to use an ECU for a better control of the engine output.

REFERENCES

[1] http://encarta.msn.com/media_701500251/Urban_Population_Growth.html

[2] Sharma, A and Roychowdhury, A., ``Slow murder: the deadly story of vehicular pollution in India'', Centre for Science and Environment, New Delhi, 1996.

[3] Bitsche, O. and Gutmann, G., ``Systems for hybrid cars'', *Journal for Power Sources*, Vol. 127, pp. 8-15, 2004.

[4] Heather, L. M. and Lester, L. B. ``Evaluating automobile fuel/propulsion system technologies'', *Progress in Energy and Combustion Science*, Vol. 29, 2003, pp. 1- 69.

[5] Tate, E. D., Hapster, Michael, O., and Peter, J. S., ``Electrification of the automobile: From conventional hybrid, to plug-in hybrids to extended-range electric vehicles'', *SAE Technical Paper Series*, 2008-01-0458.

[6] Hattori, N., Aoyama, S., Kitada, S., and Matsuo, I., 1999, "Functional design of a motor integrated CVT for a parallel hybrid HEV'', *SAE Paper No. 1999-01-0753*.

[7] Nedungadi, A., Walls, M., and Dardalis, D., 1999, "A parallel hybrid drive train'', *SAE Paper No. 1999-01-2928*.

[8] Severinsky, A. J., 1994, "Hybrid electric vehicle," United States Patent No. 5,343,970.

[9] Welke, K., Ochs, M., and Schmidt-Brucken, H., 1997, "Single shaft parallel hybrid drive system", *SAE Paper No. 970286.*

[10] Ghosal, A., Prasad Atluri, ``Architectural study of hybrid electric propulsion system for Indian cities'', IFToMM World Congress, Mexico, June 2011.

[11] Ehsani, A., Gao, Y., Emadi, A, "*Modern electric, hybrid electric and fuel cell vehicles: Fundamentals, theory and design*", CRC Press.