Novel Propulsion & Energy Recharge Architectures for Urban Vehicles

Madhusudan Raghavan\textsuperscript{1}, Raviteja Chanumolu\textsuperscript{2}, Frank Park\textsuperscript{3}

\textsuperscript{1}General Motors Research & Development, Warren, MI, USA, madhu.raghavan@gm.com
\textsuperscript{2}Department of Mechanical Engineering, Indian Institute of Science, Bangalore, India, chraviteja@outlook.com
\textsuperscript{3}School of Mechanical and Aerospace Engineering, Seoul National University, Korea, fcp@snu.ac.kr

Abstract

Electrified propulsion architectures are suitable for urban areas due to their low emissions. Trips in such areas are characterized by short driving distances, low continuous power requirements, long idling times and significant opportunities for regenerative braking due to stop and go traffic. We present results on a novel propulsion architecture and a novel charging system for such urban vehicles. Simulation and experimental results from a novel parallel hybrid configuration consisting of a DC hub motor coupled to an IC engine are described. This configuration adds speed to the wheel output unlike typical configurations which add torque at the wheel output. The addition of speed does not require a complex transmission and may be achieved by simply connecting the output of the IC engine to the stator of an electric hub motor. We extended the study of this “city car” concept beyond the propulsion system, and addressed the problem of convenient recharging of the onboard battery. To this end we created a prototype “hands free” robotic conductive charging device for ease of use. Such a system allows battery recharge without the driver having to manually insert the charging plug. The key research results presented in this context, include a localization algorithm for determining the location of the plug-in receptacle, using low-cost RFID technology. Results are presented from experiments undertaken with a hardware prototype system.

Keywords: hybrid, electric vehicle, city car, robotic charging

1 Introduction

The 2013 International Energy Outlook [1] offers the following forecasts regarding population growth and energy consumption in the future. Global population grows 28\% from 6.9 billion in 2010 to 8.8 billion in 2040. Population remains concentrated in Asia and Africa. Their share of global population is 70\% in 2010 and 72\% in 2040. China’s population peaks in 2025. Most other regions continue to grow through 2040, but their rate of growth slows. Real GDP rises by an average of 3.6\% per year globally from 2010 to 2040. Projected values range from a high of 5.7\% for China to a low of 0.7\% for the Middle East. Total world marketed energy will grow by 56\% from 2010 to 2040, from 524 quads to 820 quads (quad = quadrillion Btu) with transportation sector projected usage shown in Figure 1. A strong demand growth in non-OECD (Organization for Economic Cooperation and Development) countries of 90\% is driven by higher long-term economic growth rates. OECD fuel economy
standards for vehicles will likely be adopted throughout the world and will moderate future growth in liquid fuels consumption. Fuel economy standards and high oil prices will cause petroleum’s share of world energy to fall from 33% in 2010 to 28% in 2040. Worldwide energy-related CO2 emissions rise from about 31 billion metric tons in 2010 to 45 billion metric tons in 2040, a 46% increase (see Figure 2). A steady growth of urbanization increases the standard of living and drives the demand for personal transportation vehicles.

Against this backdrop of increasing population, energy consumption, urbanization, congestion and pollution, we have conducted studies on the architecture of future “city cars” with modular propulsion systems, low emissions, and ease of use. This paper presents simulation of speed addition based electrified propulsion configurations and initial experiments from a laboratory proof-of-concept study. The chosen platform to demonstrate the features and advantages of speed-addition is a three-wheeled vehicle (called an “auto-rickshaw”) very commonly used in urban environments in India and other emerging economies for transporting people and goods. The modified Indian Drive Cycle [2] is used and prior studies have shown that for the three-wheeled vehicle and the modified Indian Drive Cycle, the vehicle power requirement is less than 4 kW for 80% of the time [3]. The additional power, if required, can be supplied by an IC engine. To validate the concept of speed addition and obtain actual experimental data, a test-bed consisting of a single 2kW brushless DC hub motor and a 175 cc IC engine was built in the proposed speed addition configuration.

This novel propulsion architecture study is
complemented by an investigation of a home recharging robot for “hands free” charging of plug-in electric vehicles. Aside from the design of the hardware platform, the main contribution described herein is the development of an RFID localization algorithm for the recharging robot. RFID systems have several well-known advantages: they are low cost, robust to environmental disturbances such as dirt, ice, and operate reliably in poor lighting. Assuming the recharging receptacle is placed on the underside of the vehicle, we have developed two hardware prototypes of the automated charger: a floor-mounted gantry type system, and a wheeled mobile robot platform.

2 Background and Prior Art

We briefly review some recent offerings in the electrified powertrain literature. Robinette and Powell [4], describe the use of a 12V start/stop system to turn the engine off and on during periods of vehicle idle. In particular integration issues such as start ability, noise and vibration, and vehicle launch are discussed in addition to the use of a correlated lump parameter modeling methodology. Hawkins et al., [5] describe General Motors’ recently launched eAssist powertrain, which delivers approximately three times the peak electric boost and regenerative braking capability of GM’s first generation 36V BAS. Key elements include a water-cooled induction motor/generator, an accessory drive with a coupled dual tensioner system, air cooled power electronics integrated with a 115V lithium-ion battery pack, a direct-injection 2.4 liter 4-cylinder gasoline engine, and a modified 6-speed automatic transmission.

An example of a highly successful EVT concept developed at GM is the two-mode hybrid system produced for transit buses and SUVs. Schmidt [6], describes an embodiment with three planetary gear sets coaxially aligned. Gear members of the first and second planetary gear set are respectively connected to the two motor/generators. Their carriers are operatively connected to the output member. The two-mode system innovations provide performance and fuel economy improvements at highway speeds and better trailer towing ability. Grewe et al. [7], describe the General Motors 2-Mode Hybrid transmission for full-size, full-utility SUVs. This system integrates two electromechanical powersplit operating modes with four fixed gear ratios and provides fuel savings from electric assist, regenerative braking and low-speed electric vehicle operation.

Miller et al. [8], describe the Voltec 4ET50 multimode electric transaxle, which introduces a unique two-motor EV driving mode that allows both the driving motor and the generator to simultaneously provide tractive effort while reducing electric motor speeds and the total associated electric motor losses. This new operating mode, however, does not introduce the torque discontinuities associated with a two-speed EV drive. For ER operation, the Voltec transaxle provides both the completely decoupled action of a pure series hybrid, as well as a more efficient powerflow with decoupled action for driving at light loads and high vehicle speed. Additionally, it is worth noting the AUTOnomy concept [9], which was aimed at reinventing the vehicle architecture via a skateboard chassis containing propulsion, transmission, steering systems, and drive-by-wire technology.

3 Principle of Speed & Torque Addition

A hybrid electric vehicle typically consists of two or more power sources connected to the output of the vehicle. The power can be added to the output using either addition of torque or speed. In the following, we discuss our proposed novel concept of addition of speed. For a parallel hybrid system (ignoring losses), the mechanical speed coupler has the property [10]:

$$\omega_3 = k_1 \omega_1 + k_2 \omega_2$$  \hspace{1cm} (1)

where, $k_1$ and $k_2$ are constants associated with the structural and geometric design of the mechanical coupler. For power conservation the torques are linked together by

$$T_3 \omega_3 = \frac{T_1}{k_1} \omega_1 + \frac{T_2}{k_2} \omega_2$$  \hspace{1cm} (2)

We denote the output of the IC engine by $(T_1, \omega_1)$, the output of motor by $(T_2, \omega_2)$, and the resulting output configuration by $(T_3, \omega_3)$. For speed addition, with $k_1$ and $k_2$ as unity, $T_1$, $T_2$ and $T_3$ are equal and the speed of the output is given as

$$\omega_3 = \omega_1 + \omega_2$$  \hspace{1cm} (3)

In the case of torque addition, for $k_1 = k_2 = 1$,

$$T_3 = T_1 + T_2$$  \hspace{1cm} (4)
and the output speed $\omega_3$ must be same as $\omega_1$ and $\omega_2$.

If $k_1$ and $k_2$ are not unity, the output speed and torque can be easily found in terms of $k_1$ and $k_2$. These are given as follows:

for speed addition: $\omega_3 = \frac{\omega_1}{k_1} + \frac{\omega_2}{k_2}$
for torque addition: $T_3 = k_1 T_1 + k_2 T_2$

(5)

The kinematic outline of speed addition is shown in the Figure 3. In this arrangement an internal combustion engine is connected to the wheel output through a hub motor. The output of IC engine is connected to a belt driven CVT and the output of the CVT is connected to the stator of a conventional hub motor through an electromagnetic clutch and a spring loaded electromagnetic brake. For modeling purposes, we use the vehicle parameters listed in Table 1.

![Figure 3: Kinematic Representation of Parallel Hybrid Vehicle with Speed Addition](image)

Table 1: Parameter Values for Simulation

<table>
<thead>
<tr>
<th>Rolling friction</th>
<th>0.015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass</td>
<td>350 kg (including driver weight of 60 kg)</td>
</tr>
<tr>
<td>Radius of rear wheel</td>
<td>0.226 m</td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>0.35</td>
</tr>
<tr>
<td>Frontal area</td>
<td>2.09 m²</td>
</tr>
<tr>
<td>Inclination of road</td>
<td>1 in 20</td>
</tr>
<tr>
<td>Maximum speed reached</td>
<td>50 km/h</td>
</tr>
</tbody>
</table>

![Figure 4: Modified Indian Drive Cycle](image)

We list a few of the important features of the Modified Indian Drive Cycle (Figure 4):
- The cycle is composed of 15 phases.
- The duration of one cycle is 195 seconds.
- The peak acceleration is 1.04 m/sec and the cruising speed is 50 km/h.

![Figure 5: Power Required on the Drive Cycle](image)

Using expressions for the power required for acceleration and cruise, as well as the information in Table 1 and the speeds of Figure 4, the computed tractive power is shown in Figure 5. The negative portion of the power requirement implies that braking occurs at some parts of the drive cycle. One can also observe that for approximately 80% of the time in the drive cycle, 4 kW of power is adequate.

### 3.1 Simulation Results

In this section we summarize key simulation results from Matlab models created to investigate this propulsion architecture in the context of a three-wheeled autorickshaw-type “city car.” Although for a plug-in hybrid the final state of charge of the batteries need not be the same as the initial state of charge of the system, in this...
simulation for the driving cycle, we find that the final SOC is same as that of initial SOC, due to regenerative braking. From simulations, it is observed that the fuel economy is higher in case of speed addition when compared with that of torque addition. The details of this comparison are presented elsewhere [10].

![Figure 6](image)

Figure 6: Output Speed of Engine (Solid Line) and Motor (Dotted Line) in Speed Addition Configuration

Figures 6 shows the output speed of the DC motor and IC engine in the speed addition configuration along the modified Indian Drive Cycle. The DC motor torque is same as the output torque of the IC engine (after the CVT) as expected in the speed addition configuration. The maximum IC engine rpm along the drive cycle is about 5000 in the speed addition configuration.

Figure 7 shows the engine ON/OFF state where ‘0’ indicates engine OFF and ‘1’ indicates engine ON. The engine stays on for 62% time of the driving cycle. Figure 7 also shows the state of charge (SOC) in the battery. It can be seen that the SOC starts from 100% and due to regenerative braking in parts of the driving cycle, finally ends up at 100% at the end of the cycle.

3.2 Test-Bed and Components

The test-bed to validate the above simulations, consists of a 6kW spark ignition IC engine and a 2kW hub motor operating at 48V. An electromagnetic clutch and spring loaded electromagnetic brake are used to switch between electric and hybrid modes. The speed addition test-bed is as shown in Figure 8. In this the IC engine is connected to the DC hub motor stator through the electro-magnetic clutch. The DC hub motor requires 48V and has a maximum torque of 120 Nm and a maximum speed of 3500 rpm.

![Figure 7](image)

Figure 7: Engine ON/OFF and SOC state in speed addition configuration

The spring loaded electromagnetic brake provides a holding torque of 60 Nm to resist the back torque when only the electric motor is in operation (i.e. in the pure electric mode). The power to the electric motor is supplied through slip rings. The Hall effect sensor used to obtain the position of the hub motor is connected through a separate set of slip rings. The output rotor of the hub motor is connected to a water cooled eddy current dynamo meter of 10kW capacity to load the setup and obtain the torque-speed characteristics.

3.3 Experimental Results

As seen in Figure 9, the initial difference in rpm between DC motor alone and DC motor plus IC engine is about 400. As the load increases, due to the change in the ratio of the CVT, the blue and green curves come closer. After a load of 19 N, the CVT ratio does not change any more and one see that both the curves are nearly parallel.)
This demonstrates that addition of power takes place due to the addition of speed. Similar experimental runs at higher DC motor speeds have been conducted and are reported elsewhere [11].

One of the objectives of a “city car” might be to use the electric mode most of the time and switch to the hybrid mode only when the power supplied by the electric motors is not enough or when the battery state of charge is very low. In this section, we have demonstrated some operating modes of an architecture wherein a DC servo motor provides power most of the time and the IC engine power is occasionally used to augment. The experimental results clearly show the shift in the torque-curves along the speed axis consistent with the theory. This shows the feasibility of this concept in small sized automobiles such as an auto-rickshaw. One of the main advantages of the concept is simplicity, via the use of the CVT and the direct coupling of the engine to the stator of the electric motor.

The absence of a gear box reduces the cost and space requirements for smaller vehicles. The proposed architecture can also be used to charge the batteries using the IC engine by coupling the output of the IC engine to a generator. This work is being further extended by running the setup on the Indian Drive Cycle and by using an ECU to control the engine and motor.

4 “Hands Free” Charging

As mentioned in the introduction, with the growth of electric vehicles requiring battery charging from an off-board power source, it would be nice to have an automated recharging system that is economical, reliable, and can be easily installed and operated in a home garage with minimal user intervention. This section reports on the development of a home recharging robot for plug-in electric vehicles. We report on the design and experiments undertaken with a hardware prototype platform.

The objective of localization is to estimate, from 12 RFID tags, the precise location of the recharging plug relative to the vehicle (an RFID card reader is attached at the base of the recharging inlet). The main difficulty is that the RFID measurements taken by a reader can only indicate whether the reader is within the signal radius of a given tag (see Figure 10). An algorithm that can determine the precise location of the reader based on these measurements therefore needs to be devised. In this section, the algorithm for estimating the position and orientation of the reader is described. Twelve tags are attached in a 4×3 array to the lower side of the vehicle, with the recharging inlet at the center as shown in Figure 11, (x∗,y∗). The tags are labelled with numbers as indicated, from 11 to 104. Each tag can be read from within a circle of fixed radius as shown in Fig. 10. The reader can read the numbers for each of the tags within its sensing radius, and produce the sum of all the tags that are read. By labelling the tags with the numbers indicated, the sum indicates which region the reader is placed relative to the RFID tags.

4.1 Position

Using the tag map designed to have distinct tag sums for every combination of 1 to 4 tags, the position of the receptacle can be found. Each tag sum is obtained not only at one point, but also over pre-specified regions. The algorithm finds the center of each region by locating the upper, lower, right, and left limit positions and finding the center.
Fig. 10: RFID Tag Sum of these limits by averaging.

4.2 Orientation

The position of the receptacle \((x^*,y^*)\) is the center of the region in which the surrounding 4 tags \((32+33+102+103 = 270)\) are all read. There are other regions that read 4 tags besides the receptacle position. (e.g. tag sum = 86, 90, 94, 266, 274) Among these, if the position of tag sum=90 \((x_n,y_n)\) is found, the orientation can be estimated by calculating the angle \(\theta\) between the global y-axis and the line from \((x^*,y^*)\) to \((x_n,y_n)\).

4.3 Experiments

Prototypes of two embodiments of the “hands free” charger were constructed (see Figure 12). The first embodiment (Figure 12(a)) is a floor-mounted x-y table with operating range equal to \(520\text{mm} \times 300\text{mm}\) in the X-Y direction. It also has telescoping ability from \(171\text{mm}\) to \(231\text{mm}\) in the Z direction.

The mobile recharging system (Figure 12(b)) has a diameter of 382 mm and the height of 168 mm. The mobile unit is designed under three assumptions. One is that the platform drags the power cable from the wall to the plug-in position. And it uses the line tracing method to get to the tag map reading position. Finally, it should be able to avoid obstacles while driving. Four IR line-tracing sensors are installed between the two front side wheels to track black line that will be drawn on the path to get to the RFID tag map. Seven distance measuring sensors are installed around the mobile platform to measure the distance from obstacles. The mobile recharging system is driven with three wheels called omniwheels to allow for easy maneuvering into position.

And it uses the line tracing method to get to the tag map reading position. Finally, it should be able to avoid obstacles while driving. Four IR line-tracing sensors are installed between the two front side wheels to track black line that will be drawn on the path to get to the RFID tag map. Seven distance measuring sensors are installed around the mobile platform to measure the distance from obstacles. The mobile recharging system is driven with three wheels called omniwheels to allow for easy maneuvering into position.
With this configuration, we compared 2 runs of averaging vs. 3 runs of averaging. For 2 runs of averaging, the time taken was 3 minutes and 47 seconds, with a corresponding average offset from the center of 3.21 mm. For 3 runs of averaging, the time taken was 5 minutes and 7 seconds and the average offset from the center was 3.88 mm. In terms of accuracy, a principal component analysis reveals that 3 runs of averaging leads to improved performance.

4.5 Extreme Position Test with Metal Tags Only

This experiment was conducted with metal tags only. Here we consider situations in which the vehicle is parked off-center at the extreme x-y position limits. Each extreme position is set near a corner of the rectangular X-Y operating range. The first situation is when the vehicle is parked near the right-front corner, so that the initial position of the plug is located at the left rear side of the tag map near tag 101. The second situation is when the vehicle is parked near the left-front corner, and the initial position of the plug is located at the right-rear side of the tag map (near tag 104). The third situation is when the vehicle is parked near the right-rear corner, and the initial position of the plug is located at the left-front side of the tag map (near tag 11). The final situation is when the vehicle is parked near the left-rear corner, and the initial position of the plug is located at the right-front side of the tag map (near tag 14).

The average time taken for 40 total trials was 4 minutes and 40 seconds, with the average offset from the center approximately 2.30 mm. This experiment was conducted using 3 runs of averaging, so the accuracy was improved considerably. Moreover, by using only metal tags, operating times were also improved compared to the runs with only 2 metal tags. Additional testing to investigate robustness of the system to misalignment was conducted [12] and the system appears sufficiently capable of dealing with misalignment.

5 Conclusion

We have presented summary results from two studies we conducted recently; one on creating a simplified modular propulsion architecture for future electrified “city cars,” and the other on creating a novel robotic charging system for such electrified vehicles requiring battery recharging. The proposed novel propulsion architecture relies on speed addition (as opposed to torque addition) to accomplish a simple setup wherein the electric motor provides most of the low power traction and the IC engine is used occasionally to supplement power. The robotic charging system uses an RFID tag system to identify the location of the plug-in receptacle within certain specified error ranges. A specially designed plug with remote center compliance allows the automated plug-in operation once the plug location has been identified. For both system prototypes, it is necessary to conduct further experimentation and development to take these ideas towards product implementation.

Acknowledgments

The efforts of the entire team are gratefully acknowledged.

- IISc.: Prof. Ashtava Ghosal, and P. Sudhir Kumar
- Seoul National University: Hyungan Oh and Byungchul An
- GM R&D: V. Prasad Atluri, Tony Smith, and Ian Sutherland

References


Authors

Madhusudan Raghavan received his B.Tech., degree in Mechanical Engg. from IIT Bombay in 1985, M.S. and Ph.D. from Stanford University in 1987 and 1989, respectively. Since 1989, he has been at the GM R&D Center in Warren, Michigan, where he is currently Group Manager for Global Energy Systems and Hybrid Systems.

Raviteja Chanumolu is currently a Research scholar at the Indian Institute of Science, Bangalore, India. He received his masters from the Indian Institute of Technology, Guwahati in 2009. His research interests are in the field of automobile, dynamics, and vibrations.

Frank C. Park received his B.S. degree in Electrical Engineering from MIT in 1985, and Ph.D. from Harvard University in 1991. From 1991 to 1995 he was an Assistant Professor of Mechanical and Aerospace Engineering at UC Irvine. Since 1995 he has been at Seoul National University, where he is currently Full Professor.