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Low-pollution three-wheeler autorickshaw with power-assist series hybrid and novel variable DC-link voltage system

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Abstract

Hybrid cars, i.e. cars with two sources (electric and petrol) for the drive train, are generally accepted as a solution for consumption and pollution reduction compared to normal combustion engines. While in the beginning public and industries favored pure electric or even fuel cell cars, time has shown that at the moment neither of these two can realize as many benefits as the hybrid car solution.

The three wheeler autorickshaw is commonly used in Indian cities as taxi and for commercial transportation. It is an old technology, very easy to repair and very robust, but contributes largely to the known pollution problems in larger Indian cities. A study shows that over 72% of the pollution in New Delhi was caused by transportation, a large part of it by the autorickshaws and two wheelers, before the current anti-pollution regulations came into force. This situation is still prevalent in other Indian cities. At the same time the study does notice the rise of an Indian middle class which wants to replace their traditional two wheeler transportation means with a small car.

Since 1996 the Biel School of Engineering, together with Centre for Electronics Design and Technology of the Indian Institute of Science in Bangalore, has worked on the concept of a new and simple low pollution drive concept for the autorickshaws. The goal of this new drive train concept was to propose a viable alternative for the autorickshaws as well as to show how to satisfy the need for a small commuter car for the India of tomorrow. After a general overview of the possible solutions, the paper will focus on the CEDT/ARGE CH simple hybrid solution, called LP3W, to show that hybrid solutions also make sense for smaller cars in Indian cities.

Keywords: Hybrid car, series hybrid, small urban car, variable DC-link, Indian city car.

1. Introduction

The oil crisis of the 70s and growing environmental concern have forced the negative impacts of automobile transport, especially air quality, into the political spotlight. Fleet emission standards and regulation have forced automobile manufacturers to produce more environmentally friendly motors. The introduction of catalytic converters and unleaded gasoline have had positive impact on air quality. However, it is estimated that the number of automobiles on the road will triple in the next 50 years making it imperative that the

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automobile industry stimulates and encourages the use of sustainable and environmentally friendly mobility.

The increase of automobiles is directly coupled to the growth of population and the increase of CO_2 emissions. The world population will grow up to 11 billion people in 2050 and as this will happen mostly in non-OECD countries, the rise in energy consumption will even be higher.

Serious research on hybrid cars therefore began in the late 70s. Hybrids have been looked at as a possible solution to resolve consumption and pollution problems without having to reduce performance or range compared to a normal car. Especially, Volkswagen started a longer series of hybrid car developments, having its peak in the small scale production of a hybrid car based on the popular Golf platform, called Hybrid II.

The success of the hybrid has been plagued with doubts regarding complexity, reliability and cost. Nevertheless, it appears that these challenges are being overcome. It is reported that since entering the Japanese market in December 1997 Toyota hybrid car, the 'Prius' sales have been so brisk that production has been ramped up from the projected 1000 cars per month to 2000.

2. Hybrid topologies

A normal drive train configuration will couple a combustion engine to a transmission and then to the wheel. For an average car only 16% of the fuel's total energy will be actually used at the wheel as illustrated in Fig. 1.

The pure electric car will replace the combustion engine with an electric motor and uses no or only a one-stage gear box. The battery will power the electric motor with the help of power electronics. The advantage of the electrical drive system is the superiority of the electrical motor in terms of efficiency and torque at lower speed.

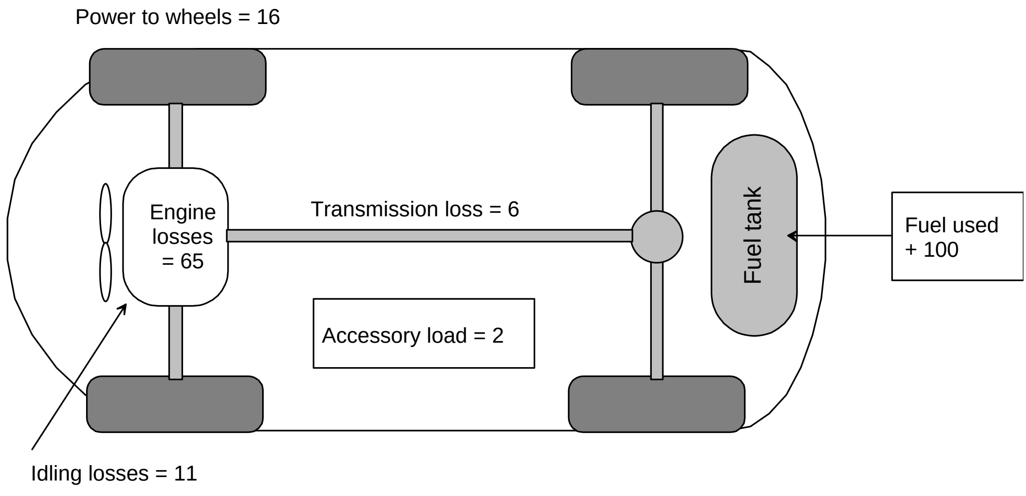

FIG. 1. Consumption in normal internal combustion engine (ICE) vehicle.

Table I
Comparison of the most commonly used motor types for automotive drive trains

	DC brush	Brush-less PM	IM	SRM
h	85	95	90	<90
h@10% load	80	85	70	78
Max. rmp	<6000	10000	>15000	>15000
$/kW	10	15	7.5	10
Cost of control	1	1.5	1.5	1.5
Ruggedness	Good	Good	Excellent	Good
Reliability	Fair	Good	Excellent	Good

Table II
Comparison of battery types

Type	Wh/kg	W/kg	°C	Life cycles	$/kwh	Avail-ability
Lead acid	35	100	amb	500	90	y
Ad–LA	40	350	amb	1000	135	y
Ni–Cd	40	110	amb	700	450	y
Ni–MH	70	200	amb	2000	600	y
Sod–Sul	100	150	350	800	300	y
Li–Ion	130	200	450	1000	–	n

The battery has to be recharged after a driving during a longer recharging period (typically 5–7 hours).

If measured at the entry of the electrical energy into the car only, the electric car has the lowest power consumption of all possible solutions as seen from Figs 3 and 4. If the production and transport of the energy is taken into account the overall consumption and emissions unfortunately are even worse than for most of the gasoline cars, if we consider only thermal power source. However, as shown in Fig. 2.

- Electricity for electric vehicles (EVs) can be produced from various sources for which certain countries like India have natural resources and do not need to depend upon import of oil.
- Electric Vehicles consume less than 50% of the energy of gasoline vehicle and hence will save the countries tremendous amount of energy.
- Night time charging of EVs will help balance the load and improve power plant efficiency.
- Electricity from nonconventional energy sources cause no pollution and pollution from conventional sources of energy can be controlled better at the source than on each individual vehicle.

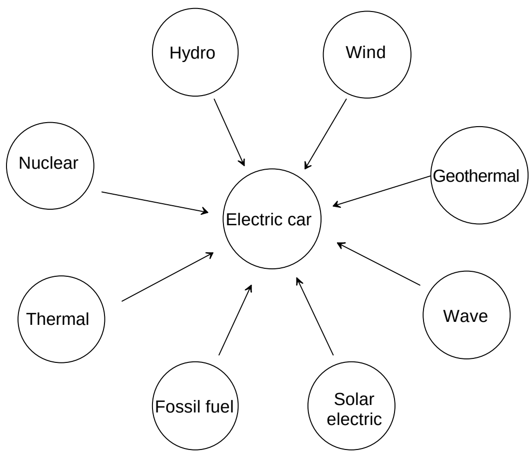

FIG. 2. EVs–Long-term energy sustainability for countries like India.

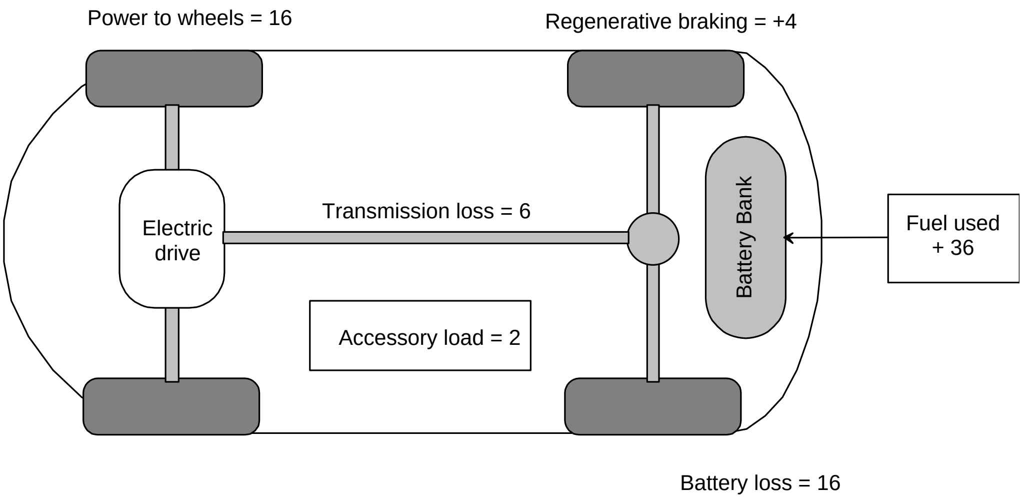

FIG. 3. Normal electric vehicle configuration.

The effective utilization of two different types of power plant in combination has considerable potential in terms of reducing both emissions and fuel consumption. The emerging motor and power electronics technologies are permitting improved and more effective control of such hybrid systems. Intelligent controlling strategies have recently realized benefits in terms of vehicle fuel consumption of up to 50% compared with other models of similar engine size (Toyota, 1997 and Swan, 1998). The PNGV (Partnership for a New Generation of Vehicles) program perceives the hybrid electric vehicle (HEV), with a compression ignition direct injection as the most promising technology to meet its near term fuel consumption targets of 80 mpg (34 km/l).

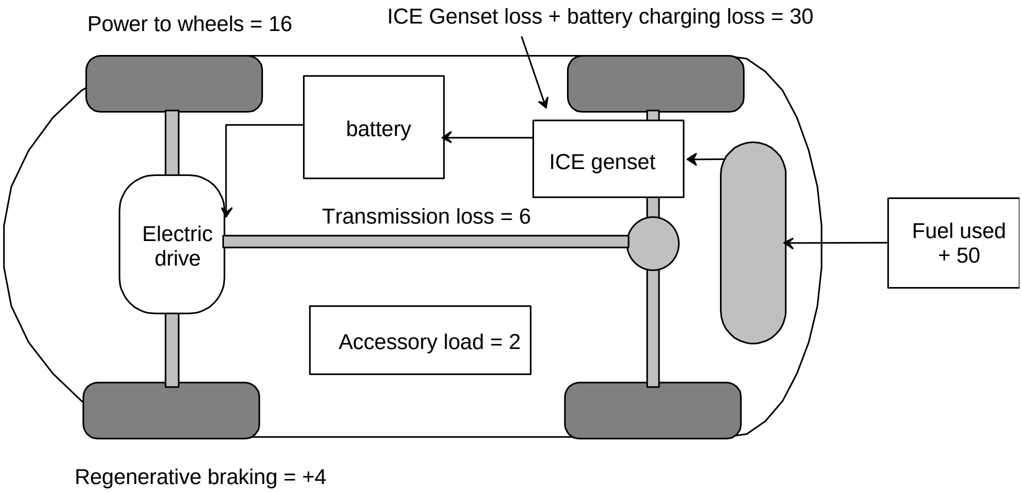

FIG. 4. Series hybrid configuration.

There have traditionally been two main hybrid power train configurations; the series and parallel. The series configuration consists of an engine which drives a generator, producing electricity to drive the motor. This system operates a small engine at its most efficient condition, resulting in good fuel economy and low emissions.

Series HEVs can be mechanically less complex than conventional vehicles, as the multi-speed transmission can be eliminated and the starter and standard alternator replaced with a single alternator. If multiple traction motors are used the differential and possibly even the drive axles can be eliminated.

The parallel configuration permits both the engine and the motor to drive the vehicle through a torque coupler. The system is designed for the engine to work under high load conditions where the internal combustion engine offers its maximum efficiency. Such a vehicle could operate as a battery-powered EV in urban areas or at low speeds. On the highway the engine would be the prime means of power with the electric drive offering power assistance when accelerating. The motor can also act as a generator and be used for regenerative braking or feeding energy to the battery when not all of the engine power is being utilized. Most of the parallel hybrid configurations use a full-sized combustion motor and a much smaller electric motor. Toyota started in 2001 the sales of such a typical parallel hybrid solution which it called “Mild Hybrid”.

3. The CEDT–ARGE CH

Under a study contract from DEZA, the Arbeitsgemeinschaft Schweiz (ARGE CH) carried out a “Pre-feasibility study for introduction of electrified rickshaws in India”. The study collected data, quantified the very high levels of air pollution in Indian cities and found that over 65% of the air pollution in a city like Delhi was caused by emissions from the transportation sector. The air pollution distribution in New Delhi is illustrated in Fig. 5. Two-

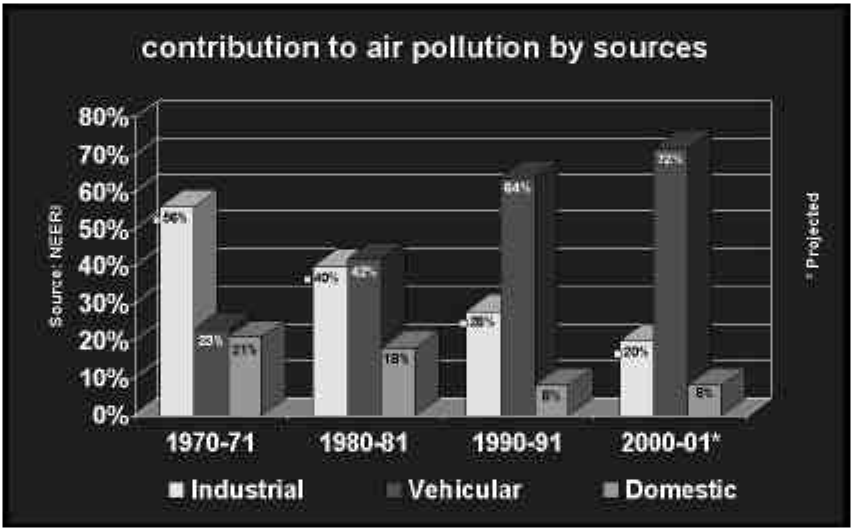

FIG. 5. Air pollution distribution in New Dehli, 1970–2000.

stroke engines used in two-wheelers and three-wheeler autorickshaws contribute a very significant part of these emissions, especially pollutants such as nonburnt hydrocarbons and SPM, suspended particulate matters. Apart from local pollution, the transportation sector also produces about a quarter of the CO_2 emissions in India.

The study concluded that the ultimate solution to urban pollution lies in an integrated long term approach covering:

1. Better urban planning to reduce transportation needs
2. Efficient and adequate public transportation systems
3. Computerized traffic control systems
4. Smaller, lighter, more efficient and properly maintained vehicles
5. New technologies and fuels which produce less pollution and lower GHG emissions.

Short-term action was, however, also urgently needed to reverse the trend of the ever increasing pollution. The three-wheeler autorickshaws were identified as one of the major culprits but it was concluded that they could be modified to significantly reduce pollution and CO_2 emissions. The report looked at the pure electric drive and concluded that while the payback period of a battery-driven three wheeler was quite attractive, the presently available batteries did not permit adequate mileage between charging cycles which limited its market potential significantly. The relatively short battery life, the correspondingly high recycling and waste management requirements of the system, and the scarcity and unreliability of the electricity supply for battery charging were identified as the other barriers to the pure battery system.

4. The simple hybrid

The goal of this new simple hybrid drive train concept was to propose a viable alternative for the autorickshaws as well as to show how to satisfy the need for a small commuter car for the India of tomorrow. In the first phase, over 1000 autorickshaw owners were interviewed and the data analyzed to determine the required performance of such a new car. The results summarized in Table III showed that only a very simple solution, which needs neither special knowledge nor additional infrastructure to run and which maintains a high ratio between the no load and payload weight of the car would be accepted. A slightly higher price would be accepted if the return on investment would pay off after two years. The

Table III
Results of the survey

Three-wheelers	Units
No. of vehicles	1084
Distance covered/day	97.45 km/day
On road duration	4.69 h/day
Fuel consumption	4.73 l/100 km
Maintenance cost/month	~ Rs 600/month
Fuel cost/month	~ Rs 550/month
Cost/km	~ Rs 5.70/km

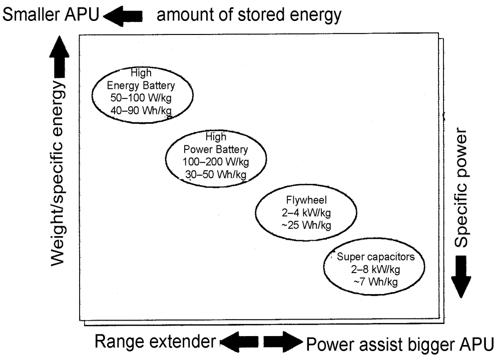

FIG. 6. Power assist vs range extender mode.

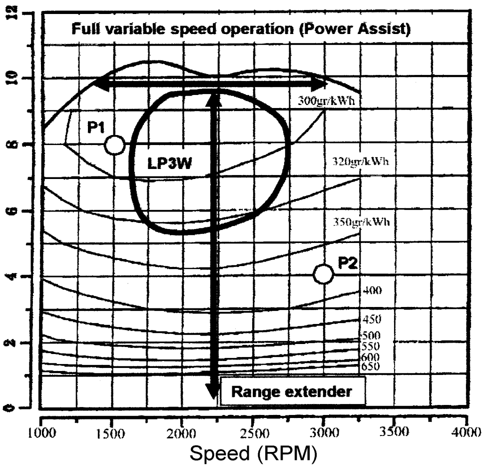

FIG. 7. The low-pollution three-wheeler motor control strategy, which allows using direct rectification of the generator output.

average distance covered in a day was seldom more than 100 km and the average speed clearly below 25 km/h. Maximum speeds of higher than 50 km/h were seldom reached.

The drive train concept did focus therefore on a simple power-assist series hybrid: Power assist was the choice to reduce the battery weight to a bare minimum, allowing just to use the regenerative energy from braking to be stored several times, to accelerate the car without having to over dimension the IC-engine and to allow the IC-engine to recharge the battery in case of low load from the car, thus increasing the efficiency point of the motor.

The series hybrid allowed a total decoupling of the motor rpm from the rpm of the car wheel. Therefore the energy management strategy tries to stay in the higher torque field of the IC engine even if it means to lower the rpm. The simple hybrid concept uses no boost converter from the generator but has instead a variable DC-link voltage. The speed variation has to be limited and power variation is attained trough modulation of the throttle. As long as the additional losses in the IC engine will be lower than the losses of the boost DC/DC converter this is the better approach as cost are lower.

To find the specifications of the rpm an extended simulation has been done based on actual road measurements in India. Figure 8 shows the total energy used for different power levels. As it is clear from Fig. 8, not only the average power output of the combustion motor does have to meet the average power but also it can be very interesting to use a bigger sized motor to cover the power demand above the average, as a considerable amount of energy is transferred in this region too.

The battery really should only cover excessive power peaks and should be able to take braking energy during a short period for several consecutive times. This will also considerably reduce the battery weight. As will be shown later, the battery can be reduced up to three times compared to a pure range extender solution. The energy storage strategy for the hydride is shown in Fig. 6, and for the ICE control in Fig. 7.

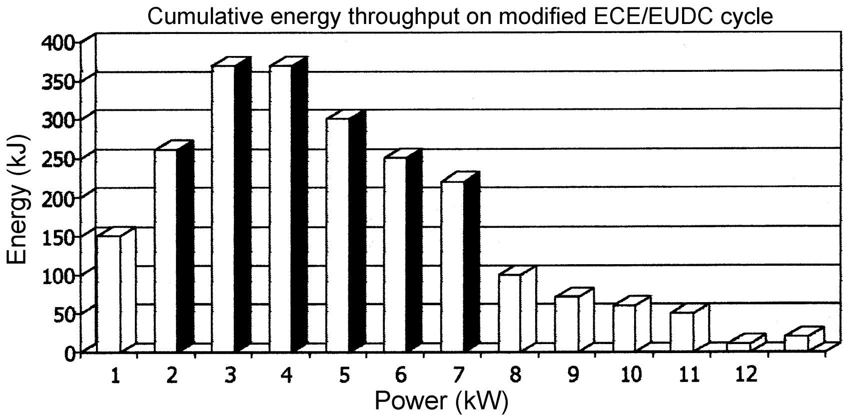

FIG. 8. Defining the optimal combustion motor power.

From the energy point of view the low-pollution three wheeler is independent from the grid; the energy content of the small battery is completely managed by the EMS (energy management system). The battery used is an Indian lead acid battery with high power density and moderate energy density. It is maintenance free.

As the LP3W uses a permanent magnet generator, which is coupled only with a passive rectifier bridge to the DC-link, the output voltage of the APU varies with the speed of the IC engine. As low power demand means lower speed, the DC-link voltage decreases too. Higher power demand means higher speed and higher DC-link voltage. This is an advantage as the voltage needed for the asynchronous motor for the wheels is also variable. At lower power demand the systems reduce the DC-link voltage and therefore goes in an automatic field weakening mode to reduce excitation-related losses in the machine. Furthermore, the switching losses of the inverter are reduced at the same time. Therefore, the system has a very good efficiency even at lower speed, especially important for city traffic. The power flow in the battery and APU is shown in Fig. 9.

The consumption, which was over 4.5 l in a conventional autorickshaw, could be reduced by around 40% as also the emission drastically with the use of a newer four-stroke IC en-

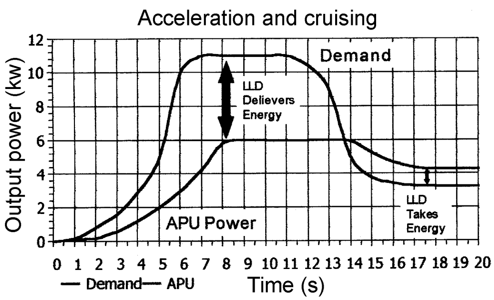

FIG. 9. Power flows in battery and internal combustion motor.

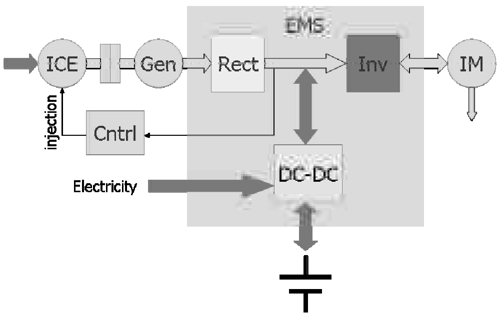

FIG. 10. The simple hybrid concept.

Table IV
Simulation results comparing different EMS strategies

Strategy	Original rickshaw	Range extender rickshaw	Power-assist rickshaw on/off	Power-assist rickshaw without on/off	Power-assist rickshaw idle off	Power-assist rickshaw variable DC-link
Consumption (l/100 km)	4.46	2.19	2.29	2.5	2.4	2.4
Battery weight (kg)	–	>150	>150	<50	<50	<50
IC-genset power (kW)	–	<2	<4.5	<4.5	<4.5	<4.5

gine. The concept was realized during the period 1998–2002 with collaboration between CEDT and Biel School of Engineering. Figure 10 gives the Hock schematic of the simple hybrid concept.

5. Simple hybrid implementation

Figure 11 shows a typical vehicle drive cycle in Bangalore city. The average speed is around 20 kmph, and a major portion of the drive consists of acceleration and deceleration. In a conventional ICE vehicle, the energy during deceleration is lost as heat, whereas in an EV or HEV it is put back into the battery due to the presence of the regenerative braking mechanism.

The energy flow in an ICE vehicle weighing about 1000 kg is shown in Fig. 12. For 1 km travel, about 80 Wh is needed at the wheels. For this 615 Wh is required to be given as input to the vehicle. This in general is given in the form of a fossil fuel like petrol. Out of this input energy, about 20 Wh is lost in transmission and a whopping 515 Wh goes off as heat in the engine.

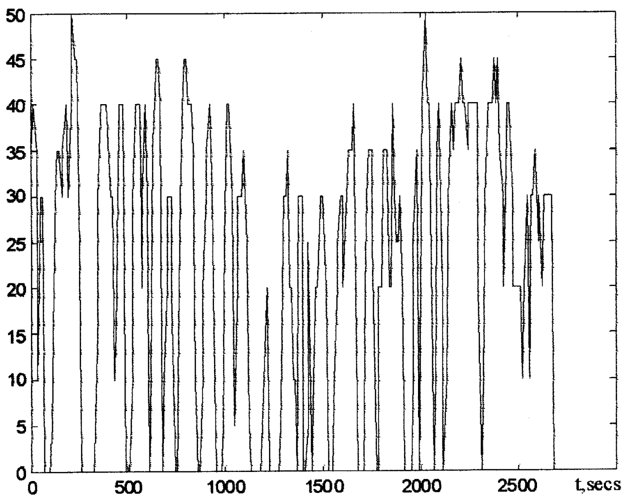

FIG. 11. Typical Bangalore city drive cycle, time vs speed in kmph.

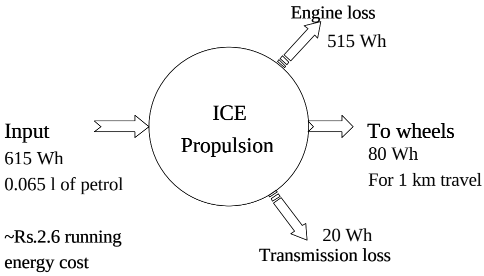

FIG. 12. Energy budget for ICE vehicles.

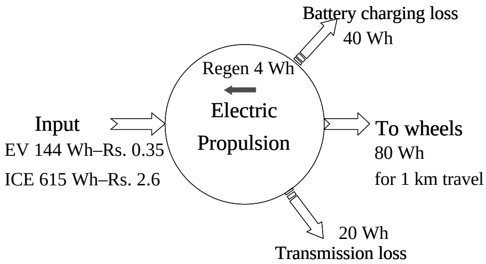

FIG. 13. Energy budget for EV.

In contrast, the energy budget for the EV is as shown in Fig. 13. Here, for a similar vehicle which demands 80 Wh at the wheels, 144 Wh is required from the input. Further, because of regenerative braking, 4 Wh is given back to the input. Therefore, effectively, only 140 Wh is required at the input. The extra Wh of energy accounts for transmission and battery charging losses.

Referring to the ICE vehicle's energy budget, approximately 0.065 l of petrol is needed to generate 615 Wh of input energy. At the present petrol prices, the running cost will come to Rs. 2.60 per km run of the vehicle. In contrast, the EV propulsion which requires only 140 Wh of electrical input, would cost only Rs. 0.35 per km.

One can consider the electric propulsion as one end of the spectrum and the ICE propulsion as the other (Fig. 14). EV has the disadvantage of limited range, whereas the ICE of emissions and higher running cost. Therefore, it is prudent to look for a solution which gives the best of both worlds. The hybrid electric vehicle is the bridging technology, which will make todays ICE vehicles meet with tomorrows EVs. Figure 14 shows three curves. One is the efficiency curve which is higher for the EV as compared to the ICE vehicles. The other is the specific energy curve which is higher for the ICE vehicles as compared to the EVs. The third curve gives the product of the efficiency and the specific energy curves. The maximum point of this efficiency-specific energy product curve would be the optimal compromise between the ICE and the EV. Sixty per cent of ICE and 40% EV in terms of power rating would be the optimal compromise for today's HEV.

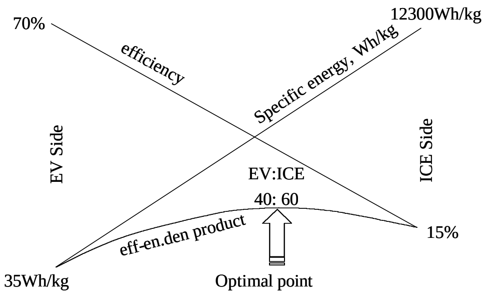

FIG. 14. Optimal EV–ICE compromise.

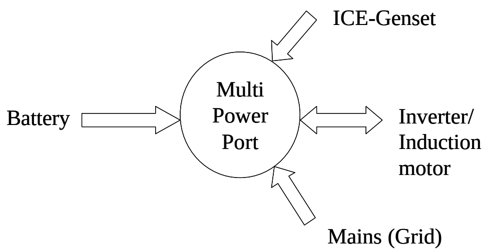

FIG. 15. Power flow in MPPC.

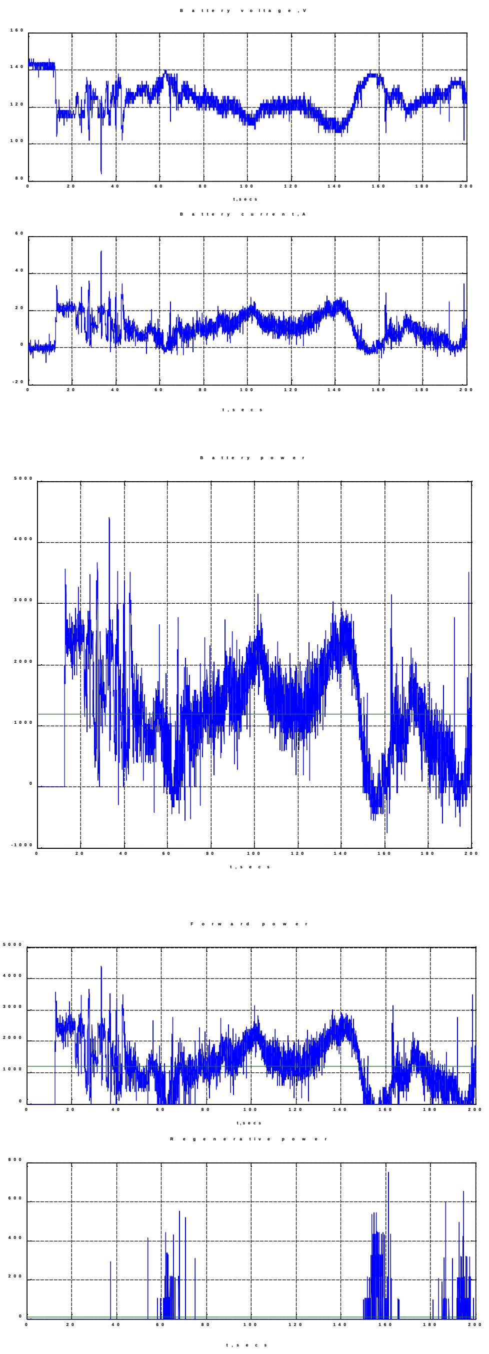

FIG. 16(a). Experimental waveforms for range extender mode of operation of the series hybrid prototype.

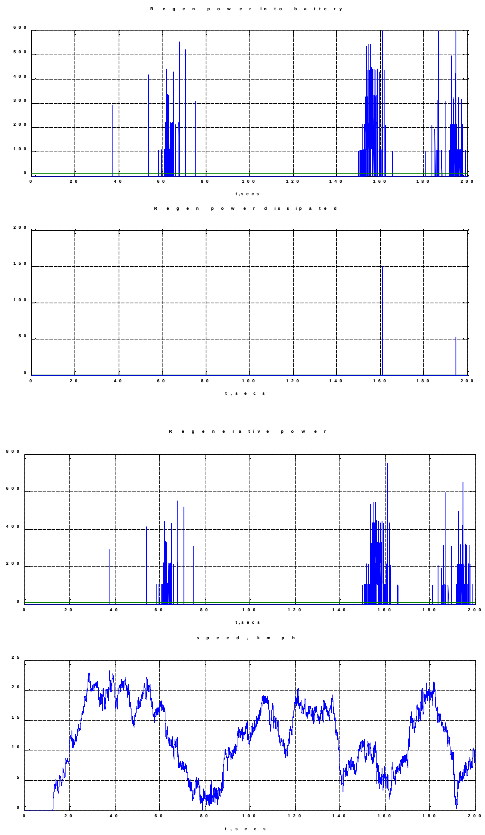

FIG. 16(b). Experimental waveforms for the range extender mode of operation of the series hybrid prototype.

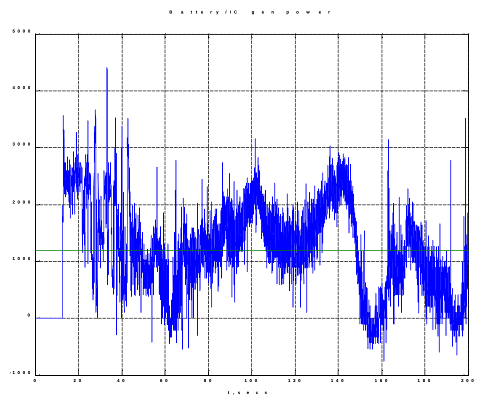

FIG. 17(a). The instantaneous battery power when IC generator power is maintained at a constant value.

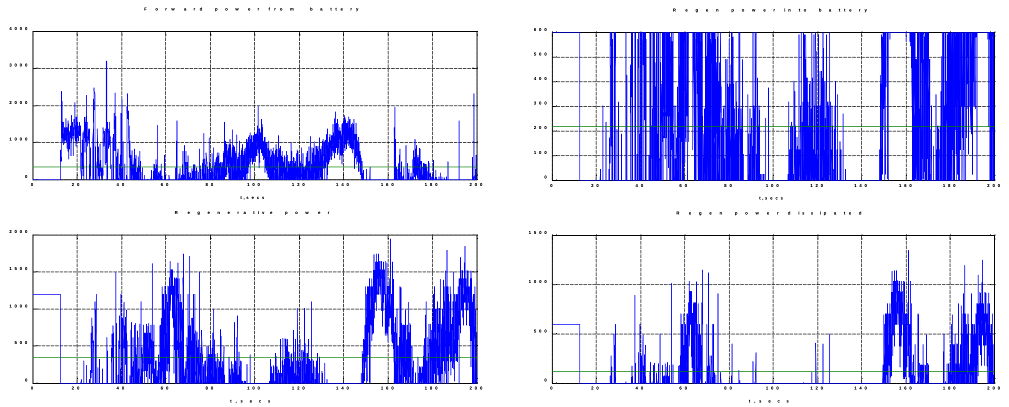

FIG. 17(b). The forward and the regenerative power during power-assist mode of operation.

Series hybrid vehicle can be separated in two subgroups: The range extender and the power assist (Figs 16 and 17). The power assist gets all energy from the IC-generator group. It has a small battery pack for high power situations, as accelerations. The range is nearly infinite, because the IC-Generator group can deliver the average power needed on the wheels. With a power assist it is not possible to have a zero emission mode, because the battery power is too small. A range extender has a very small IC-genset that is only switched on if the state of charge of the battery is low. For that reason the battery will be significantly bigger than in a power assist and must be able to deliver full power. With a range extender a zero emission mode is possible.

Figure 10 shows the complete block schematic of the series hybrid electric that has been implemented. A prototype based on the above series hybrid schematic has been designed, fabricated and tested (Fig. 18). An induction motor is used for the electric propulsion (Fig. 10). This needs an inverter and associated controller which is built using a digital signal

FIG. 18. The simple hybrid prototype at CEDT.

processor (DSP). The energy inputs are taken from the petrol–ICE combination and/or the battery. An energy management unit controls the ratio of energy that is drawn from the ICE unit or the battery at every instant of time so that the ICE is operating at its maximum efficiency at all times. Another important unit is the multi power port converter (MPPC) which controls the flow of power from battery to the wheels, the wheels to the battery during regenerative braking, the ICE-Genset to the battery and the ICE-genset to the wheels. Further, the MPPC is also used to charge the battery from the mains grid avoiding the need for an external charger. The power flow directions of the MPPC is shown in Fig. 15.

6. Experimental results

Tests were conducted on the prototype shown in Fig. 18. Figures 16 and 17 show the experimental results measured during test rides on IISc roads.

Summary of test results

Range extender mode summary		
Motor power	:	5 KW
Forward power	:	1200 watts
Regenerative power	:	10 watts
Battery average power	:	1190 watts
Battery AH	:	20 AH
K Wh/km	:	0.10361
Battery Wh/kg	:	9.6
Battery weight/vehicle weight	:	0.375
Acceleration ratio, kmph/sec	:	2
gradient performance @10kmph and 250 kg payload	:	1:7
Average battery power	:	110 watts
Gear drive ratio	:	0.079365
Power-assist mode projections		
IC operating point power	:	1200 watts
Forward power	:	325 watts
Regenerative power	:	335 watts
Maximum Regeneration setting	:	600 watts
Regenerative power dissipated	:	120 watts
Regenerative power into battery	:	215

7. Conclusions

Hybrids have been around for a long time now. Big advances have been made since serious development began in the early seventies of the last century. Actually, the hybrid concept is the only alternative concept for normal passenger cars, of which 10,000 units have been sold, as in the case of the Toyota Prius. The ongoing progress and new models, e.g. from Toyota and Honda, will make this concept even more successful.

In the case of the Indian market, the proposed solutions still have the disadvantage of a too high price. Also the proposed segment (a four seater middle class car) does not really fulfil the needs of the Indian society and does not meet the requirements of a typical Indian city either.

The proposed solution from CEDT/ARGE CH is based on extensive market research in India. It does meet the basic requirements and targets a large existing class of vehicles (autorickshaw), which has to be replaced in the coming decade if the Indian cities want to overcome their pollution problem.

The solution was designed to meet very low production costs without compromising too much on the efficiency. The variable voltage DC-link has two big advantages: The DC-DC converter in the main energy path has been eliminated, lowering cost and increasing efficiencies at the same time. At the same time, the efficiency of the drive (power electronics and motor) can be improved considerably for lower speeds.

The cost of the additionally needed DC-DC converter between the battery and the DC-link is more than compensated as it allows to keep the battery at a smaller size without having to reduce the capacity to very small and hardly controllable capacities.

This paper gives an objective comparison of the ICE vehicle and the EV. The HEV as the bridge technology is elucidated. The energy budgeting for the EV and the HEV is described which shows that the HEV is today competitive alternative to the ICE vehicles. A series hybrid technology is built and tested on a prototype. The range extender and power-assist mode of operation were tested and the results reported. It is found that the HEV is a viable alternative transport solution today.

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