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HYBRID-ELECTRIC CITY CAR SIMULATION

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Abstract

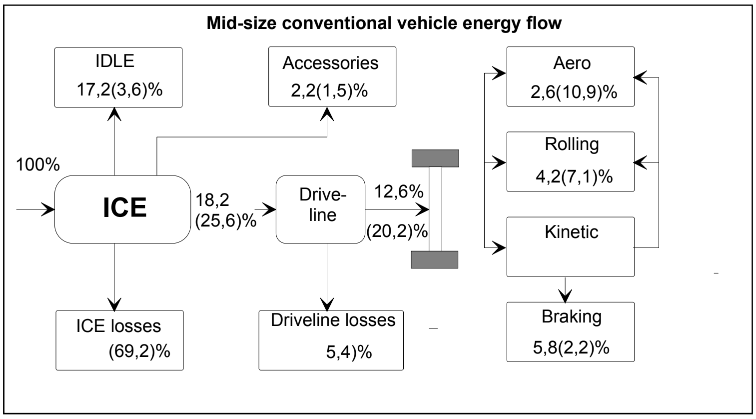
Growing number of motorized vehicles in highly urbanized areas quickly leads to ecological balance disturbance. City traffic with frequent stopping causes energy losses and increases emission without transport effect. The congestion of the city centers by cars, high emission, low traffic efficiency, high conventional city transport costs and high energy consumption are the reasons for the search of solution which would guarantee the comfort of individual short-distance city transport. The small HEV (Hybrid-Electric Vehicle) could be a good solution for such destination. The results of computational simulation of two city car conceptual designs are described in this paper. To ensure comparable conditions, both concepts are based on the same small vehicle body. Powertrains of both series and parallel HEV's are based on a 2-cylinder ICE (Internal Combustion Engine) with 700-ccm cubic capacity. Vehicle body mass is about 550 kg. Simulation models are oriented on the best compromise between energy conversion efficiency and minimum of emission. Procedure of modeling and simulation is performed in Matlab/Simulink environment and Advisor software package.

1. Introduction

Formulated by International Electrotechnical Committee general definition of Hybrid Electric Vehicle sounds as: HEV is a vehicle in which propulsion energy is available from two or more kinds or types of energy stores, sources or converters, and at least one of them can deliver electrical energy. The most popular definition of Hev is: a hybrid vehicle needs to have on board at least two energy sources and it is a necessary condition that one of them is a secondary energy source. The secondary energy source can transform energy from one kind into another in a reversible mode and is able to store energy. Both a combustion engine and a stack of fuel cells are primary energy sources because they convert energy one way: the combustion engine converts the chemical energy of the fuel into mechanical energy of rotational torque and the fuel cells convert the chemical energy of the fuel directly into electric energy. Both combustion engines and fuel cells are unable to store energy. Thus, there are lot of kinds of HEV's, the but most popular is a configuration based on ICE as a primary energy source and battery as a secondary energy source. Main advantage of HEV is to significantly extend driving range if compare with pure electric vehicle (EV).

2. Energy flow control [7]

Every vehicle, to perform movement, have to produce power at the wheels to cover aerodynamic drag, rolling resistance and any resistive gravity forces connected with gradeability. For accelerate, vehicle must overcome inertia forces. Most of the energy delivered for acceleration is then lost during braking. Additionally, energy for lighting, power steering, air conditioning is needed. The work at the wheels in conventional vehicle is taken from fuel as a result of energy conversion. Fig. 1 shows the midsize conventional vehicle energy flow for two driving cycles: urban and highway. Most of fuel energy is lost; only 12,6 % of total energy reaches the wheels during urban cycle, while during highway cycle it is about 20 %.



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Potential energy built up during acceleration the vehicle (box kinetic), include energy lost as heat during braking as well as aerodynamic and rolling energy losses during vehicle deceleration. There are a lot of energy flow control strategies, but main keys of control are:

- maximum fuel economy,
- minimum emission,
- minimum costs,
- good driving performance.

Hybrid vehicles, comparing to conventional vehicles, can save energy due to the unique characteristics:

- Regenerative braking. Energy always lost in CV during braking, in HEV can be capture and store in secondary energy source (battery or ultracapacitor). Regenerative braking is the process by which some of the kinetic energy stored in the vehicle's translating mass is stored in the vehicle during decelerations. Energy recovering is possible by operating the electric motor as a generator, providing braking torque to the wheels and recharging the traction batteries or ultracapacitor. In big city traffic through the energy regeneration one can even obtain up to 15% savings.
- Optimal point of ICE operation.
- Lower size of ICE.
- Potential of nonconventional, advanced primary energy sources. (gas turbine, CIDI, SIDI, Fuel Cells)
- Hybridization drawbacks:
- Higher weight tendency. Mainly due to high battery weight.
- Electrical losses occuring. Electric motors have lower efficiency at the low rotational speed and load – in urban driving normal state.

3. Hybrid vehicle efficiency

Typically, the energy efficiency of a battery is in the range of 55-75 %; charge efficiency – 65-90%. Overall hybrid system energy efficiency is obtained as:

$$\eta = \frac{AERO_{loss} + ROLL_{loss}}{FC_{in} - ES_{in}}$$

where
AERO – aero energy loss,
ROLL – rolling energy loss

FC – fuel converter input energy
ES – energy storage input energy

Prime mover in series HEV configuration (ICE) can operate in optimal point or area, thus average efficiency is the same as nominal (in this simulation 33%). Efficiency of ICE in parallel configuration varies with the level of hybridization and energy conversion strategy.

For 01 level of hybridization ICE energy conversion efficiency amount 28%, while for 02 level of hybridization amount 26%, and for 03 level of hybridization amount 25%. These values are significantly lower than in series type of HEV.

4. Hybrid city vehicle concept [1], [2], [3]

The city hybrid car concept is based on chassis of mass-produced, 3-door, small vehicle. Vehicle mass, without specific powertrain, is about 550 kg and it is a good base for assembling a not too heavy hybrid vehicle equipped with different kinds of powertrains. The results of simulations of two basic configurations of HEV are presented in this paper. The first vehicle is series HEV with SI ICE, and the second one is vehicle with Fuel Cell stack supplied with pure hydrogen. This vehicle operates also in series configuration. It is assumed that the city car has to be compatible with current demands for mass and volume, high efficiency without decrease of performances, minimum of emission and extended durability. Each of powertrain subsystems has to be consistent with demands for minimal essential power. The minimal essential power from a source of energy depends on many factors and is described with general formula:

$$P = \int \left(\frac{1}{\eta_p} \left[m_v C + A + B_r \right] v_v + P_a \right) dt$$

where

$$C = C_r g \cos(\alpha) + \frac{dv_v}{dt} + g \sin(\alpha) \qquad A = \rho_a C_d A_v (v_v - v_a)^2$$

In this case, vehicle mass (without drivetrain and gear) is about 550 kg. Powertrain of series and parallel HEV are based on a 2-cylinder combustion engine with the cubic capacity of 700 cm^3 and power of 23 kW. NiMH Ovonic battery was used as a secondary energy source. Battery sizing in parallel configuration depends on hybridization level. A number of modules depends on the level of hybridization, and varies from 50 modules for parallel 01 to 34 modules for hybrid 03. In series configuration it is 25 modules. Each module is characterized by followed parameters:

- Nominal Voltage = 6V
- Nominal Capacity (C/3) = 28Ah
- Dimensions (L * W * H) = 195mm X 102mm X 81mm
- Weight = 3.6kg
- Volume (modules only) = 1.6L
- Nominal Energy (C/3) = 175 Wh
- Peak Power (10s pulse - 50%DOD - 35 ºC) = 1.6kW

5. Components

5.1. Batteries [5]

Specific energy is a key parameter to assess the suitability of a battery for the desired driving range. Specific power is a key parameter to assess the suitability of a battery for the desired gradeability and acceleration. State of Charge (SOC) refers to a battery's residual charge capacity on a scale from 0 (empty) to 1 (full). SOC is not directly measurable on an actual battery, but for some battery technologies, including Lead Acid and Lithium Ion, there is a correlation between the SOC of a battery and the battery voltage. When the battery is decharged, the battery's SOC is depleted. When the battery is charged, the battery's SOC increases. In order to account for energy that the battery has remaining, one must also consider the voltage and time during which that charge is delivered.

$$SOC = \frac{Q_{\max} - Q_{used}}{Q_{\max}} \cdot 100\%$$

Q_{max} – maximum capacity (nominal) of battery Ah,
Q_{used} – the difference between the nominal and current capacity Ah,
SOC – State Of Charge.

Table 1. Parameters of batteries for HEV's [7]

	Specific energy Wh/kg	Energy density Wh/l	Specific power W/kg	Cycle life
Lead-acid	30-45	60-90	200-300	400-600
Ni-Cd	40-60	80-110	150-350	600-1200
Ni-MH	60-70	130-170	150-300	600-1200
Zn/Air	230	269	105	not available
Li-Polymer	155	220	315	600
Li-Ion	90-130	140-200	250-450	800-1200

Lead-acid batteries represent mature technology; they are cheap and have high specific power and low specific energy. Ni-Cd batteries – mature technology, high specific power, low specific energy, cancirogenicity. Ni-MH batteries – High specific power and energy, short life cycle, very high potential for HEV applications. Zn/Air batteries – low cost, machanically rechargeable, very high specific energy and low specific power. Li-Polymer batteries – very high specific energy, high specific power. Li-Ion batteries – very high specific energy and power, high costs.

5.2. Internal Combustion Engines. [3], [4], [8]

The combustion engine as a primary energy source guarantees confidence of functioning in every conditions. Moreover, in series HEV solutions it enables the recharging of the battery in areas without zero emission requirements and purely electrical functioning of the propulsion in the areas with zero emission requirements. The advantage of combustion engines is also their low cost ensuing from mass production. Because of limitations of conversion of chemical energy of the fuel into thermal energy ensuing from Carnot cycle, combustion engines are characterized by low efficiency. Even under ideal conditions, a heat engine cannot convert all the heat energy obtained from the fuel into mechanical energy. Significant part of the heat energy is lost in engine cooling subsystem. Their disadvantages are noisiness and most of all long chain of energy conversion: chemical energy into thermal one, then thermal one into mechanical one and lastly mechanical one into electrical one, however using an external generator. Another disadvantage is also lack of possibility of fulfillment of strict requirements of exhaust gases toxicity norms and large losses of friction due to many moving parts. The compression ratio limited due to knock combustion also affects the efficiency. In hybrid solutions it is also possible to use both advanced construction SI engines and modern engines with compression ignition. Highest harmful ICE emission appears directly after cold start. Maximum efficiency of combustion engines reaches 34% at high power (0.6-0.8 maximum power). Powertrains of both series and parallel HEV's are based on a 2-cylinder ICE (Internal Combustion Engine) with 700-ccm cubic capacity.

6. Simulation tools [1], [2], [8], [9]

ADVISOR, software packet developed by National Renevable Energy Laboratory (NREL), is a set of models and data files for use with MATLAB/SIMULINK environment. Advisor models based on data from laboratory stand are empirical and quasistatic. Advisor gives possibilities for tentatively estimate performance of vehicle, which exists only as a concept. The user has to configure a vehicle, by selecting all of components: fuel converter (engine, fuel cell stack), energy storage (battery, ultracapacitor, flywheel), transmission, motor, generator etc. Each component is described by mathematical model and file with empirical data. It is very difficult to obtain full set of those data for each kind and type of fuel converter.

All vehicles are tested under special driving conditions, called driving cycle. UDDS (Urban Dynamometer Driving Schedule) is equivalent to the first two bags of the Federal Test Procedure (FTP-75) and represents city driving conditions. It is used for light duty vehicle testing (from EPA). To obtain full battery charge and discharge cycle, according to applied control strategy, the test cycle is repeated five times. ECE-EUDC cycle duration is 1224 s, and it is an equivalent of 10.59 km road section. UDDS cycle duration is 1369 s, and it is an equivalent of 11.99 km road section. In this simulation, the combination of two US driving cycles has been chosen. First test, called "do_pracy", contains one highway cycle HWFET followed by one urban cycle UDDS. The second test, called "z_pracy", contains one urban cycle UDDS followed by one highway cycle HWFET. Those cycles are equivalent of european driving tests, like ECE+EUDC. The cycle is used for emission certification of light duty vehicles in Europe. The entire cycle includes four ECE segments, repeated without interruption, followed by one EUDC segment. Before the test, the vehicle is in the rest for at least 6 hours at a test temperature of 20-30°C. It is then started and allowed to idle for 40s. In year 2000 idling period was eliminated, i.e., engine starts at 0 s and the emission sampling begins at the same time. Emissions are sampled during the cycle and expressed in g/km for each of the pollutants (from EEC Directive 90/C81/01). In the case of applying this cycle to vehicles without a manual gearbox there is a minor error caused by gear shifting not being taken into account. For series hybrid vehicle configuration, the thermostat control strategy has been chosen. In this simulation it means that the ICE is turned off when present battery SOC reaches 0.8 of full charge, and ICE is turned on when present battery SOC drops to 0.4 of full charge.

The thermal model of the engine breaks the engine assembly into four temperatures: the cylinder, the engine block, the exterior engine accessories, and the hood of the vehicle. The coolant operates as a thermostat, with the setpoint set by the user. Heat is generated by combustion, conducted to the engine block, and removed through forced liquid cooling, conduction, natural convection, and radiation.

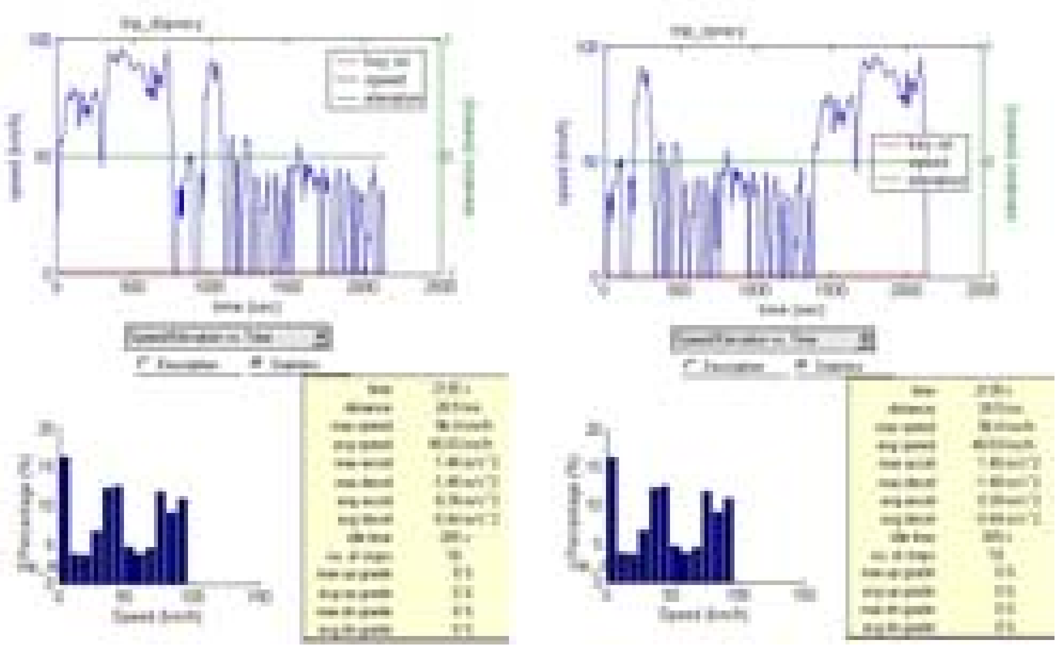

Fig. 2. Driving cycles "do_pracy" and "z_pracy".

7. Simulation results

Parallel HEV's provide a wide range of chices in the level of hybridization. Greater hybridization results in a vehicle with a smaller primary energy source (ICE) and a larger secondary energy source (battery). If the level of hybridization is 0, then vehicle is called mild hybrid. If the level of hybridization is between 0 and 1, then vehicle I called moderate hybrid. Level 1 means extreme hybrid vehicle.

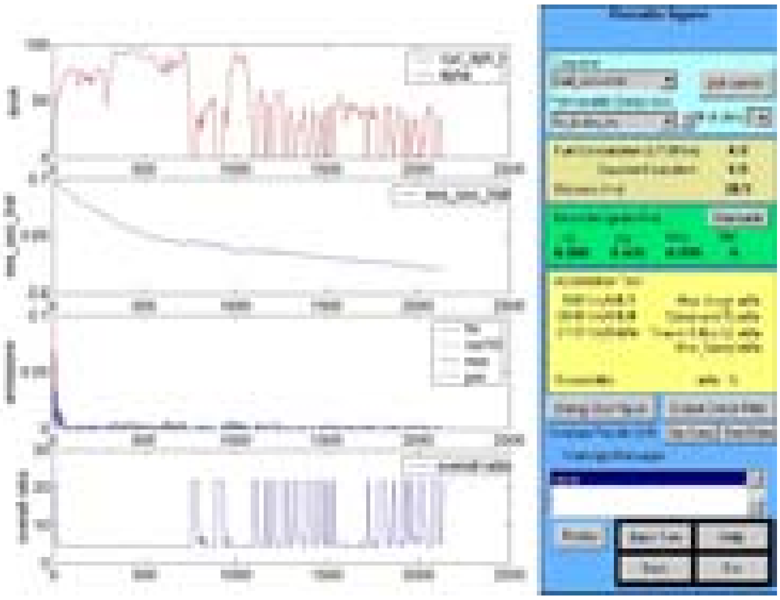

Fig.3. Results of simulation of parallel vehicle.

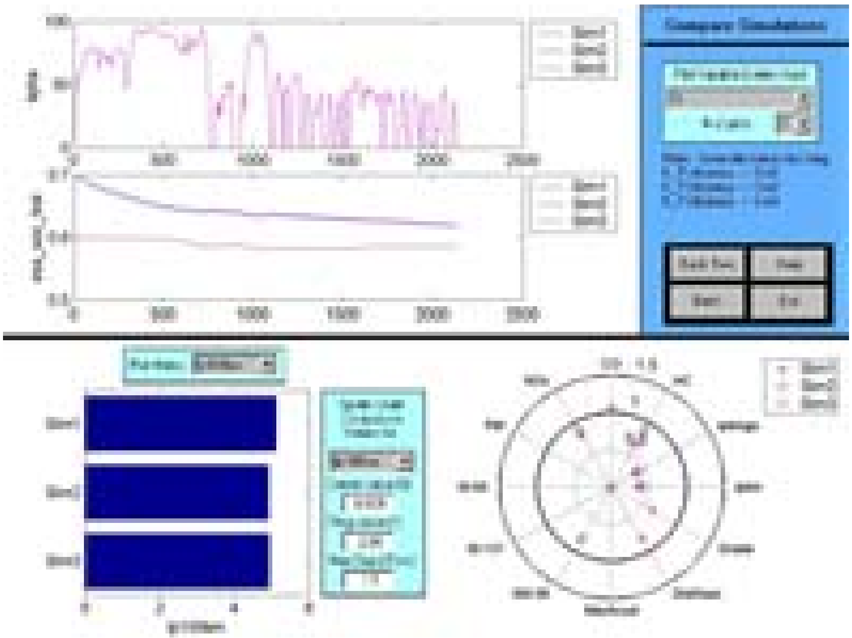

Fig.4. Comparison of simulation efects of 3 parallel vehicles.

From the above comparison some conclusion can be drawn: the parallel hybrid vehicles have good acceleration parameters, but the results of fuel consumption are not very satisfy. The parallel vehicles are cheaper than the series ones [7]. The overall energy conversion efficiency in simulation is lower than in the series case. But the only market existent and succeeded HEV's: Toyota Prius and Honda Insight are based on parallel concept of hybrid vehicle.

Table 2. Parallel HEV simulation results comparison.

Vehicle	Eff. %	Trip direction	Fuel consumption l/100km	Emission			Acceleration time	
				HC g/km	CO g/km	Nox g/km	0-60 km/h	60-90 km/h
P1	14,6	do_pracy	5,1	0,105	1,031	0,200	6,8	7,7
		z_pracy	5,1	0,103	0,829	0,118		
P2	14,3	do_pracy	4,9	0,088	0,426	0,099	6,1	5,8
		z_pracy	4,9	0,088	0,418	0,106		
P3	14,3	do_pracy	4,9	0,088	0,427	0,100	6,0	5,8
		z_pracy	5,0	0,089	0,417	0,107		

Table 3. Series HEV simulation results comparison.

Vehicle	Overall Efficiency %	Fuel consumption l/100km	Emission			Acceleration time	
			HC	CO	NOx	0-60	60-90
S1	15,9	4,8	0,057	0,186	0,095	NA	NA
S2	18,4	3,8	0,063	0,239	0,086	22,5	14,1
S5	14,9	4,7	0,075	0,295	0,103	NA	NA

The fuel consumption of series hybrids is better than parallel hybrids. Acceleration and gradeability is poor, but in a city car these parameters are not crucial. The proper battery sizin is very important, because it is then effective in frequent or rare internal combustion engine swiching on. Series HEV can operate as a zero emission vehicle in areas with specific environmental requirements [6].

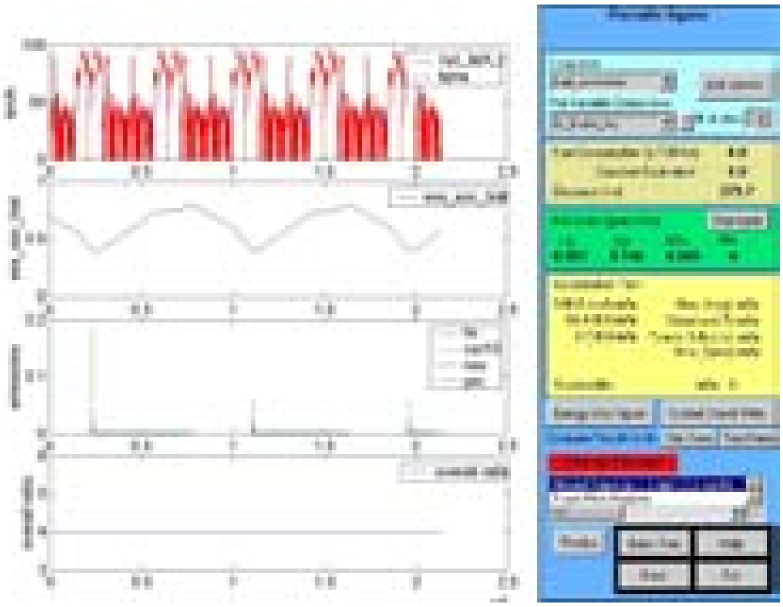

Fig.5. Results of simulation of series vehicle.

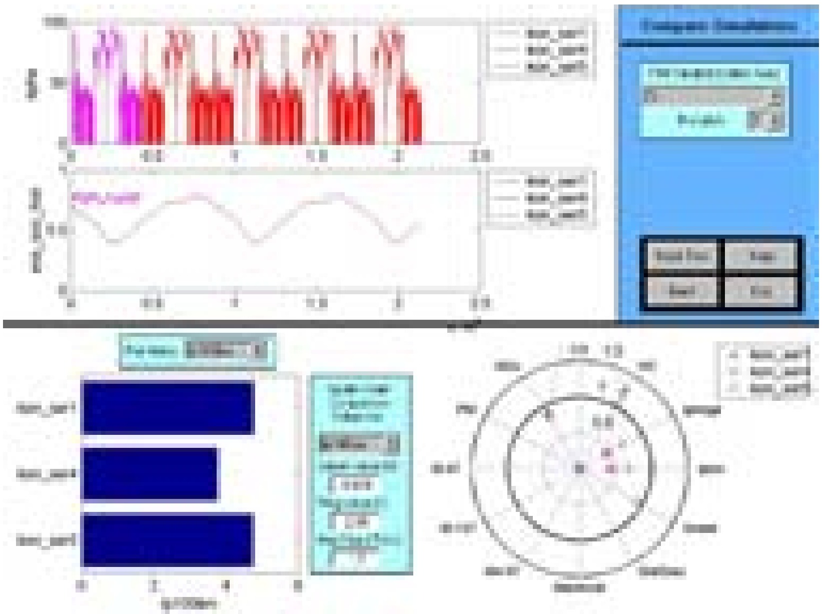

Fig.6. Comparison of simulation efects of 3 series vehicles.

8. Conclusion

Low price and ease of assembling are main advantages of series HEV. In areas with zero-emissions requirements such a vehicle can use pure electrical propulsion and in others areas it can use internal combustion engine for storage battery charging. Control can be highly optimized as internal combustion engine in series HEV configuration operates with constant rotational velocity and narrow torque range. This causes high efficiency and lowered emission. In a city car both acceleration and gradeability are not crucial. More important is to aim at lowering the total mass of the vehicles. In a series HEV a smaller internal combustion engine can be used as the APU. After mounting the APU with ICE and the storage battery in a rather small chassis, there is enough room left for a small luggage space and quite comfortable room for 2 passengers. Both the series and parallel HEV's are promising because of the possibility of regenerative braking, which is especially significant in city traffic. The main problem is the mass of both devices and their size, which causes difficulties in assembling in comparatively small chassis and costs – actually higher then conventional vehicle.

9. References

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

P	powertrain power demand
η	powertrain efficiency
m_v	vehicle mass
C_r	wheels rolling resistance
g	gravity (9.8 m/s^2)
α	road angle
ρ	air density
C_d	vehicle drag coefficient
A_v	vehicle cross-sectional area
v_a	air velocity
v_v	vehicle speed
B_r	resistance due to braking
P_a	accessory loads
ICE	Internal Combustion Engine
SI	Spark Ignition
HEV	Hybrid Electric Vehicle
SOC	State Of Charge
CIDI	Compression Ignition Direct Injection Engine
SIDI	Spark Ignition Direct Injection Engine