Review of propulsion types in hybrid electric vehicles

Keywords: range extender; hybrid; propulsion

Abstract: Worldwide fuel consumption increases continuously and the Earth’s natural resources are finite. These ecological aspects combined with the economy and the traffic flow pose many challenges for new vehicles and their propulsion systems. The automotive sector and academic researchers seek, test, develop and examine numerous configurations of propulsion systems. This paper presents a classification of propulsion systems based on the hybrid vehicle power train configurations. Advantages and disadvantages of serial, parallel or power-split/series-parallel hybrids are discussed. An overview of concepts used in different drive train types in hybrid vehicles, as well as a description of internal combustion engines used as range extenders are also presented.

1. Introduction

With a plethora of news about diminishing natural resources, noise, air pollution and consumer awareness, it is impossible not to notice that the automotive industry all the time reveals and supplies the market with vehicles using electric propulsion systems. On the other hand, despite the fact that consumers across six major markets claim that they are generally favorable towards electric vehicles (EVs), the vast majority still buys automobiles with internal combustion engines (ICE) (DeVeaux, 2013).

2. Hybrids

Analyzing the efficiency of processing a barrel of oil into the energy that drives wheels (Table 1.), one may notice that overall efficiency for combustion and electric propulsion is very similar. This means that using EVs does not bring significant benefits of reducing consumption of natural resources, because majority of electric power – about 70% (Factbook 2011-2012: Economic, Environmental and Social Statistics, 2011) – comes from fossil fuels (gas, coal and oil).
Tab. 1. Comparison of the overall efficiency of transforming the energy from a barrel of oil to the driving wheels propulsion (Stachura, 2011).

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<thead>
<tr>
<th></th>
<th>Combustion propulsion</th>
<th>Electric propulsion</th>
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<tr>
<td></td>
<td>Efficiency [%]</td>
<td>Efficiency [%]</td>
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<tr>
<td></td>
<td>Max.</td>
<td>Min.</td>
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<tr>
<td>Oil barrel</td>
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<tr>
<td>Refinery (gasoline)</td>
<td>90</td>
<td>85</td>
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<tr>
<td>Refinery (Diesel fuel)</td>
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<tr>
<td>Distribution to petrol stations</td>
<td>99</td>
<td>95</td>
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<td></td>
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<tr>
<td>ICE</td>
<td>22</td>
<td>20</td>
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<tr>
<td>Gearbox / Drive shaft</td>
<td>98</td>
<td>95</td>
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<tr>
<td>Driving wheels</td>
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<tr>
<td>Overall efficiency</td>
<td>19</td>
<td>15</td>
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However, electric power transmission loss may be omitted by onboard power generation. Among many such propulsion systems, the most popular combination is the synergy of an ICE combined with a generator. Such automobiles are known since 1900, when Ferdinand Porsche developed the first hybrid vehicle: The Lohner-Porsche Mixte Hybrid. Though, almost a hundred years passed before its mass production begun.

3. Propulsion structure

Developing the technology of combining an ICE with an electrical generator owes a lot to the railway industry. This kind of power transmission is used on railways by diesel electric locomotives and diesel electric multiple units, as electric motors are able to supply full torque at 0 RPM. Moreover, it helps avoid costs and problems related to maintenance of long distance electric traction. Locomotives and Porsche’s propulsion have serial structure, but nowadays numerous vehicles utilize parallel or power-split/series-parallel systems. All these kinds of hybrids are characterized by various advantages and disadvantages, depending on application.
3.1. Serial

Initially, hybrid propulsion had a serial structure. Nowadays, such vehicles are designed so as to be run mostly on a battery, but have a petrol or diesel generator to recharge the battery when going for a long drive.

In a series-hybrid system, the ICE drives the electric generator instead of directly driving the wheels. The generator provides power for the driving electric motors.

Fig. 1. Structure of a series-hybrid vehicle propulsion system.

Advantages:

• the ICE is not running all the time – this increases average efficiency:
  – off at idle (reducing toxic emissions – with the exception of NOx)
  – off with full battery, when the battery power is sufficient to overcome resistance to motion;

• the ICE can operate in narrow (optimal) range of load and speed:
  – avoiding sudden speed and engine load changes;
  – higher durability, endurance, longer lifetime and less maintenance costs;
  – lower emissions of toxic components;
  – high fuel efficiency;

• some serial systems do not require a mechanical transmission (i.e. Hi-Pa Drive):
  – simple structure – it eliminates the need for complex gears and power transmission systems;
  – no mechanical loss;
  – less weight;

• the possibility of active torque control for each wheel;
• a large range may be achieved even with a small engine-generator unit;
• the ICE can be put almost anywhere in the vehicle or even outside;
• using appropriate electric motors enables energy recovery during braking, then storage in batteries or ultra-capacitors;
in addition, due to the possibility of work in “only electric mode”, vehicles may be used in cities and areas with increased environmental requirements.

Disadvantages:
- requires the use of at least two high power electric machines;
- individual units work in a series – their efficiency must be multiplied;
- the serial hybrid configuration offers less power than the parallel, because driving wheels are supplied only by an electric motor;
- the benefits of lower fuel consumption are connected with higher operating costs;
- the use of batteries makes the entire system much heavier than the conventional one;
- batteries require more space limiting the usable space of the vehicle;
- complex recycling;
- at steady state conditions (motorway traffic, cruising speed) benefits are negligible and efficiency is lower in comparison with parallel systems.

3.2. Parallel

Presently, most of the commonly produced hybrid vehicles have a parallel structure. An ICE and an electric motor are coupled. In short, in a parallel system power from the engine may be mechanically delivered directly to the drive shaft and wheels. Batteries may be charged from the propulsion system or the electric generator/motor. Moreover, power may be delivered simultaneously from both units – in such a case their powers sum up. During braking the electric motor works as a generator. Effectiveness and desirability of using this type of propulsion depends mainly on the driving cycle, vehicle type, and above all, the construction of the hybrid parallel system. Minimizing the power demand from the primary source (power-gen set) may be achieved by:
- appropriate cooperation between primary and secondary sources (batteries);
- selection of the appropriate scope of work of each of them;
• capacity of the battery.

A parallel hybrid vehicle may work in several modes: electric only, hybrid/electric assist, battery charging, combustion only and regenerative braking. To manage such a system appropriate electronic control unit is necessary. It has to collect and process data from particular units, environmental conditions sensors and send the appropriate signals to the actuators, depending on the driver’s intentions.

![Fig. 3. Structure of a parallel-hybrid vehicle propulsion system.](image)

Advantages:
• the driver has more power at his disposal, because the vehicle can be supplied by both engines at the same time;
• high power is available at low fuel consumption;
• it is not necessary to install the generator to charge the battery;
• a driving cycle characterized by frequent starts and stops creates favorable conditions for accumulation of energy;
• using appropriate electric motors enables energy recovery during braking, then storage in batteries or ultra-capacitors;
• in comparison with series system, there is no need to install a large battery pack;
• full ICE power is available in case of failure of the electric components and regardless to the battery status;
• it is not necessary to convert mechanical energy into electrical energy – this provides higher energy efficiency in steady conditions i.e. while cruising on a highway.

Disadvantages:
• the ICE must be coupled with the propulsion system and it is not possible to install it in any place;
• batteries cannot be charged when the propulsion is using energy stored in them – in the parallel system the electric generator is missing;
unfavorable conditions for optimal operation of the ICE in city driving;
increased vehicle weight;
complex structure;
the use of a number of planetary gears makes the structures complicated, increases the mass and failure frequency, slightly reduces the overall efficiency and shortens longevity.

3.3. Power-split or series-parallel hybrid

This kind of hybrid combines the features of a parallel and a serial drive. It incorporates power-split devices, allowing power paths (from the engine to the wheels) to be either mechanical or electrical. A variation of this drive type is the e4WD solution, which is an independent four-wheel drive vehicle. Advantages of this solution are flexibility and functionality of the drive (Stachura, 2011).

Fig. 4. Structure of a power-split/series-parallel hybrid vehicle propulsion system.

It must be remarked that this structure solves the problem of charging batteries when the vehicle is using the electric power path. Unfortunately, this is achieved by complications of the system and installation of an additional generator.

4. Range Extender

The demographic situation in the beginning of the 21st century in Europe shows interesting figures on car utilization (Stan, 2001):

- 80 % Europeans live in towns;
- from this, 50 % drive less than 5 km per day;
- respectively, 80 % drive less than 50 km per day.
It means that a car with a range of 50 km would be suited for 64% of European population. Furthermore, cars for the urban traffic are generally compact, light and their mean power requirement (in a European city traffic) is not higher than 25 kW (Stan, 2001). A small urban EV is sufficient to meet such requirements, though it is not suitable for occasional long distance travel.

Vehicle electrification technology is now one of the industry’s hottest topics and the technology is constantly evolving. Automobiles driven by hybrid or purely electric propulsion have the advantages provided by an electric motor – almost perfect for automotive applications speed-torque characteristic and a high torque potential from the start. Therefore, such a vehicle has good drivability and can accelerate better in comparison with conventional propulsion concepts.

Unfortunately for EVs, the limited energy density of battery systems remains an unsolved problem. To enable a driving range of 500 km, with modern lithium-ion batteries reaching about 0.15 kWh / kg, a vehicle would need a battery system with an estimated mass of 600 kg (Jürgen et al., 2014). On the other hand, the energy density of gasoline fuel is about 12.8 kWh / kg. To provide the same range (500km) an estimated mass, including the tank system and the fuel, is less than 50 kg (Jürgen et al., 2014).

Therefore, utilization of series hybrids that are also able to recover a great amount of energy from frequent braking seems to be the most efficient solution. In urban conditions for typical distances up to 50 km the vehicle may work in fully-electric mode and use the energy stored in the batteries while plugged-in to the power grid. In case of flat batteries or necessity of long travel, a small combustion unit may start working in order to supply the electric motor with energy and recharge the batteries.

Despite good utility properties, such a concept may also have both economic and environmental advantages. Using the opposed piston (OP) engine may be a good choice as it has the most efficient, uniflow scavenging. This, in modern engines, results in higher trapping efficiency and faster load change. Moreover, such configuration eliminates the cylinder-head and valve-train components of conventional engines. The engine can work under higher pressures and temperatures, which significantly increases its thermal efficiency. Developed in 1959, Coventry Climax H30, also an OP engine (28kW), has an efficiency of 33.3% (Pirault and Flint, 2010). With the growth of displacement of the engine its efficiency increases as well. This is one of the reason why Sulzer 3Z G9, the 56 kW OP engine developed earlier (in 1946) had brake thermal efficiency of 36% (Pirault and Flint, 2010).

Nowadays, several teams are working on developing such an OP engine. For example, FEV and Advanced Propulsion Technologies (APT), Porsche (flat horizontally opposed pistons) and EcoMotor. The last one established an R&D Center with Hu-nan University to Develop OPOC Technology in China. The two primary investors in EcoMotors are Khosla Ventures and Bill Gates.

At present, a 25 – 60 kW ICE, operating at a narrow range of load and speed, may achieve an efficiency of 40% – this is one of goals for the R&D Barrel Engine Team from Warsaw University of Technology (WUT). The team at WUT is now developing a new engine under a Polish-Norwegian Research Program. A prototype engine, PAMAR-4 will be designed as a Range Extender with the ability to work on a variety of fuels (gaseous and liquid) and ignition types (SI, CI, HCCI/CAI). This is a successor of PAMAR-3, 340 kW, 3 dm³ barrel engine for aviation purposes that
at the test bench achieves an efficiency of 44% (specified fuel consumption of 197 g/kWh). PAMAR-3 has successfully worked on propane, indirectly and directly (200 bar) injected CNG and gasoline, and directly injected (1600 bar) diesel fuel. Thanks to the collected data and the gathered experience, the new engine will be prepared to work with different fuels as well.

Fig. 5. Example of barrel engine model developed by Mazuro and Teodorczyk (2008).

Extended Range Electric Vehicles (EREVs) have a much better weight-to-range ratio. Furthermore, an overall efficiency, discussed in paragraph 2, is similar if compared to EVs.

In this context, it has also to be remarked that, in comparison with an ICE vehicle, such a concept has not only better efficiency, but also better drivability. Purchase cost will be higher, but this difference will be covered during operation by expenditure cuts on fuel bills and in some areas, due to legal aspects, fiscal benefits and tax credits (Stachura, 2011).

5. Hi-Pa drive

Another advantage of the EREVs hybrid power train is the possibility of implementing the High Power drive system. This follows a new direction in drive control – torque vectoring – which may advance drivability of the vehicle. Such a solution has the potential not only to improve cornering, but also to partially decouple the requirements for ride and handling (Olsson, 2014).

6. Conclusion

Consequently, new concepts and new technologies are being developed to produce efficient electric vehicles suited for both individual and public mobility and for goods distribution. A large development of vehicle electrification in the near future is to be expected. This will result in better parameters and performance together with lower production costs.
Tab. 2. Overall efficiency for Extended Range Electric Vehicle.

<table>
<thead>
<tr>
<th>Hybrid propulsion - EREV</th>
<th>Efficiency [%]</th>
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<tr>
<td></td>
<td>Max.</td>
</tr>
<tr>
<td>Oil barrel</td>
<td></td>
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<tr>
<td>Refinery (Diesel fuel)</td>
<td>97</td>
</tr>
<tr>
<td>ICE efficiency</td>
<td>40</td>
</tr>
<tr>
<td>Generator</td>
<td>95</td>
</tr>
<tr>
<td>Battery charging</td>
<td>90</td>
</tr>
<tr>
<td>Battery (lead acid)</td>
<td>75</td>
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<tr>
<td>Motor / controller</td>
<td>85</td>
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<tr>
<td>Gearbox / Drive shaft</td>
<td>98</td>
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<tr>
<td>Driving wheels</td>
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<td>Overall efficiency</td>
<td>21</td>
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</table>

At present, batteries are a major technological challenge for the automotive industry. Energy density of battery systems remains an unsolved problem and this is one of the reasons why ICE will still be in use for many years. Nevertheless, its main role may change from being the main drive shaft power supplier into the range extender.

Fig. 6. Torque vectoring effect on absolute yaw moment change (Olsson, 2014).
for EVs. Such solution will increase ICE’s efficiency, but has an even more important advantage – it can use high density energy from fuel to power electric motors driving the wheels. It provides good drivability, acceleration and energy utilization with a possibility of a long travel with a lightweight vehicle.

References


Mazuro, Paweł and Andrzej Teodorczyk (2008), Mechanical efficiency and losses of internal combustion engines with cylinder axes parallel to drive shaft axis, Hokkaido University, COMODIA, Sapporo.


