

# Refueling strategies of autonomous hybrid vehicles

M Zöldy<sup>1\*</sup>, S Szalay<sup>1</sup>, Z Szalay<sup>1</sup> and I Zsombók<sup>1</sup>

<sup>1</sup>Budapest University of Technology and Economics, Department of Automotive Technologies, 6 Sztoczek street, Building J, Floor V, 1111 Budapest, Hungary

mate.zoldy@auto.bme.hu

**Abstract.** Fuel consumption prediction and recharging strategies are crucial fields of autonomous hybrid vehicles. In our paper based on literature review the currents trends of hybrid vehicles are compared and working principals of hybrid strategies created for different types of hybrid drivetrains were described. The fuel management, basics of the range estimation in hybrid vehicles are displayed. Analyzations of the factors affecting the fuel consumption and energy management were made, along with an estimation of the order of magnitude of these factors, based on experiments done by EPA. Main fuel consumption influencers are listed and a real word test is carried out in a highway measurement. It was focusing on the affection on the fuel consumption, caused by the additional consumers of the vehicle has been carried out. Evaluation of this measurement was made and conclusions were drawn about the efficiency changes of the vehicle.

## 1. Brief history and relevance of the hybrid vehicles

Hybrid vehicles were present in automotive history from the beginning. At the last years of the XIX century, electric drive systems took a significant role. At this time, more electric vehicles were manufactured than the ones with internal combustion engines, so the opportunity was given to combining the two powertrains. In the first two decades of the XX century, the development of petrol-powered cars sky-rocketed, halting the development of the hybrid automobiles until the 1960s [1], [2].

The growing fuel prices during the oil crisis of 1973 and reduction plans of the harmful exhaust gas emissions during the 1980s meant a new start for the hybrid car development [1]. In the last few years the market-leading manufacturers started revealing plans of the full electrification and hybridization of their model lineup. The hybrid drive means a powertrain, where the energy required to propel the car is ensured by two or more power sources with different operating principles. The powertrain solutions can be seen today mostly use a combined system of an internal combustion engine and an electric motor [3].

The ICE-powered vehicles provide outstanding performance and long range, using the excellent energy density of their fuel. On the negative side, they aren't fuel efficient and are polluting. Electric cars have their advantages as well, such as better energy efficiency and extremely low harmful emissions while running, however their range per charge ratio is weak, because of the lower energy density of their batteries.

## 2. Categories of the hybrid systems

The power output of the electric drive, is the basis of categorization of hybrid systems. Hybrid systems with the smallest power output are micro-hybrids. In this case the typical performance of the electric motor is 2-3 kW. The electric motor, functioning as a starter and generator is connected to the internal

combustion engine mediateley, by a V-belt drive. Beneficially the ICE and the powertrain remains basically unchanged, so the system can be easily implemented even into a production-ready drivetrain.

Next step is the mild hybrid system, where the electric motor is directly connected to the powertrain. The ICE and the e-motor rotate together, as the two units are disconnectable, their torques add up. The electric machine can provide up to 10-15 kW of power [1]. Systems above 15 kW e-motor power output are full-hybrid, these can run without local emission. The electric drivetrain system operates on a voltage of 200-350 V. Plug-in hybrids are full-hybrids, chargeable not only by internal regeneration, but from an external power source [4].

Basic variations of the hybrid powertrains are series and parallel systems. Both have their advantages and disadvantages, which are combined with Series-Parallel hybrid systems. The series hybrid is a system, which uses two power sources to drive an electric motor which propels the vehicle. As its most significant benefit, the operation of the internal combustion engine is completely independent of the drive requirement of the vehicle, so it can be used in any range of its revolution-torque characteristics so it can be held at the range of its top efficiency. This drivetrain is the most variable and has the best opportunities to reduce emissions. On the downside, the energy given by the ICE is transformed at least twice, the efficiency is multiplied, so the total drivetrain loss can be significant [4].

The combined system architecture is basically the same as the series one, but the ICE can directly power the vehicle by using a clutch. In case of a power-split system, the internal combustion engine performance is split in a planetary gear set, one half powers the vehicle, the other half charges the battery or powers the car through the electric motor [5].

### **3. Parts of a hybrid drivetrain**

As an internal combustion engine, modern petrol engines and turbocharged direct injection diesel engines can be used. After all, using an ICE of a traditional powertrain unchanged is not enough to operate a hybrid drivetrain efficiently. The ICE of a hybrid can be more straightforward and smaller, as it does not have to operate economically in the whole range of operation. However, the average load of the ICE is higher than an ordinary vehicle, needing optimization for the higher load. This will decrease the efficiency in case of a part load state but with using a suitable strategy, the scale of these states can be minimized [1], [5]. As a transmission, the shiftless (CVT) transmission is considered the best for the optimal efficiency. In hybrids using power split system, planetary transmissions are usually used.

For hybrid powertrains, proper energy storage is a key, the used solution depends on the features of the hybrid system. The possibly smallest and lightest battery must be able to handle the quickly changing charging and discharging processes. The dynamic features of the vehicle depend on the power density, the emission-free range depends on the energy density of the battery [1].

### **4. Hybrid drive modes**

Depending on the use and torque demand the ICE and the electric motor usage may vary. The hybrid system ECU determines the torque distribution between the two power sources, considering the throttle pedal angle, the battery state of charge and data provided by the other systems of the vehicle.

The hybrid strategy determines the sequence of the drive modes. The purpose of the hybrid strategy is to operate the vehicle using the optimal drive combination. This could mean minimized fuel consumption or the best dynamics. The strategy is aligned to the operating states of the internal combustion engine, for example evading the less economical part load state. Depending on the system layout, the power output of the ICE can be different or the same as the momentary power need of the vehicle [1]. In the age of advanced driver assistance systems, GPS-technology and neural systems, development of predictive hybrid strategies are a possibility. These strategies are not only able to adapt to the driver, but they can also generate an optimal hybrid strategy by prediction using the data from the GPS and ADAS. Predictive strategies can reduce the fuel consumption and the swing of the battery state of charge, causing the potential reduction of the battery pack size [6].

### **5. Factors affecting fuel consumption**

In case of an everyday car only the 12-30 % of the energy of the fuel is utilized to move the car, depending on the driving cycle. This proportion is 21-40 % in a hybrid vehicle, based on the city (FTP-75) and highway (HWFET) cycles used by EPA [7]. Overall energy losses are around 65-69 %. In Otto-engines, more than 62 % of the energy of the fuel is lost. Internal combustion engines have an extremely low efficiency altering the chemical energy of the fuel to mechanical energy, caused by friction, heat and pumping losses [8], [9].

Parasitic losses are around 4-6 %. It covers the energy required to power the water pump, fuel pump, oil pump, ignition, ECU, etc. Idle losses are negligible. While driving in a city a tremendous amount of energy is lost in idle state. This loss can be reduced by using a Start-Stop system. Auxiliary losses - air conditioning, power steering, headlights, etc. also use the energy produced by the internal combustion engine - are in the range of 0-3 %. The transmission and the other parts of the drivetrain cause losses as well. The magnitude of them is around 3-5 % Modern solutions such as continuously variable transmissions and double clutch gearboxes can adequately reduce these losses.

Aerodynamic drag is altogether 10-15 %. A rolling vehicle uses energy to conquer the resistance surrounding the medium. The energy used to that increases progressively with the speed growth. The aerodynamic drag is closely connected to the shape of the car, the shrinkage of the end-surface and the shape factor causes smaller energy consumption [10]. Rolling resistance is a force, which is needed to roll the wheels, and is directly proportional to the wheel load. It is approximately 10 %. Optimized tire tread area and use of materials can reduce rolling resistance effectively. The magnitude of overcoming inertia and brake loss could reach even 8-12 %. Energy recoverable by regenerative braking is around 5-9 %. Regarding energy efficiency, the amount of energy retrievable from the acceleration and moving is an important question [11, 12, 17, 18, 19]. Energy can be regenerated via braking, this time the electric motor used to drive works as a generator, charging the batteries and its torque can be used to slow the vehicle down [7, 8, 13, 14, 15]

## 6. Description of the measurement

The test vehicle uses the Honda IMA (Integrated Motor Assist), which is a parallel, mild hybrid system. Main parameters of the vehicle are presented in Table 1. The internal combustion engine is a 1,5 l, 4-cylinder power equipment, with variable valve timing. As a transmission, serves a 6-gear manual gearbox. Between these two a brushless DC motor is placed, which also serves as a starter, rated at 10 kW. The system output is 90 kW. The battery is a Li-ion pack, with a capacity of 0,6 kWh, consisting of 84 cells, with a voltage of 12V individually [11], [12], [13].

**Table 1** Technical specifications of the measured vehicle [16]

Engine	1.5 i-VTEC	
Displacement (cm <sup>3</sup> )	1499	
Bore (mm)	73	
Stroke (mm)	89.4	
Maximum Power (kW (LE)) /revolutions (1/min)	83(114) /6100	
Maximum Torque (Nm)/revolutions(1/min)	145/4800	
Compression ratio	10.4:1	
Maximum speed(km/h)	200	
Acceleration (0-100 km/h)	9.9	
Empty weight (kg)	1147	
Fuel consumption (l/100km)	city	4.4
	highway	6.1
	mixed	5.0

The way of the measurement was the following: the vehicle's cruise control was set at 110km/h speed, and we tested it in ECON and Normal modes. Measured on-board consumers were air condition, headlights and audio system.

The decrease of the range estimated by the vehicle on a 2 km long highway distance has been investigated. In every mode, we carried out 2 measurements with every consumer, and we measured 2 reference values with every consumer turned off. This data and the fuel consumption estimated by the vehicle gives the chance to calculate the added energy need of each consumer. When determining the performance of the environmental forces, I choose to consider the highway terrain flat, because determining the exact elevation angles would have gone far beyond this dissertation.

Analyzing the measurement, the fuel consumption increase caused by the consumers is not high for each but when summed, it is considerable. The effect of the air conditioning considering the inaccuracy of the own sensors of the vehicle is numerous, 0,2-0,3 l/100 km. Heating generated only 0,05 l more consumption than prior. The fuel consumption raising the effect of the radio and the lights are marginal according to the results. The environmental effects are severally significant [6, 18]. As a result of the distortions caused by the terrain, in Normal mode while all the consumers were turned off, the fuel consumption raised to 6,4 l/100 km. The fuel consumption on the plain road was 4,5-5 l/100 km, compared to this, the terrain can cause up to 30 % difference.

**Table 2** Fuel consumption differences caused by the additional consumers

consumer	fuel consumption difference - ECON (l/100km)	fuel consumption difference - Normal (l/100km)
reference value	0	0
AC	0.3	-0.2
heating	0.35	-0.1
lights	-0.1	-0.8
audio center	-0.35	-1.05
all consumers	1	-0.7

## 7. Evaluation of the measurement

The fact that the board computer rounds the data to whole caused inaccuracy in the measurement of the range decrease. The range estimation of the own system of the car was accurate in half of the cases. When no consumers or low-powered consumers were turned on, the range decrease was only 2 km during the 4 km long measurement, and only twice did the range decrease by 5 km, so it can be said, that the board computer of the car miscalculates to the safety side.

The effective efficiency results were lower than expected, the performance of the resistance forces was 21 % of the engine performance. The calculated productive efficiency is in the range of 17-30 %, but if the measurement is carried out on a longer distance, it will be more representative, because the distortion caused by the environmental conditions will be negligible. The efficiencies for confident consumers were in the range of 22-27 %. In ECON mode the vehicle operated with 3 % better efficiency than in normal mode.

At ECON mode the use of the air conditioning worsened the efficiency by 1,6 %, so did the heating. Regarding the audio system and the lights, the efficiency was roughly the same. When turning on all consumers, the efficiency decreased by 5 %. At Normal mode the measurement when all consumers were turned off was distorted by an ascent. The use of air conditioning caused a 2,9-4,2 % decay in efficiency compared to the headlights and audio system.

## 8. Conclusions

Predictability of fuel and energy consumption effect of vehicle onboard consumers is the basis of the hybrid strategies of autonomous vehicles. In our work the necessary tests were done to measure different consumers effect on fuel consumption. The results showed that the use/non-use of these devices has a remarkable effect on vehicle fuel consumption. From the investigated equipment's the highest influence had the air conditioning on the fuel consumption of the hybrid test vehicle. The magnitude of the

onboard consumer's influence on energy consumptions is a potential tool for autonomous vehicles to influence the driving distance and the used energy mix.

### Acknowledgments

The research was supported by the Hungarian Government and co-financed by the European Social Fund through the project "Talent management in autonomous vehicle control technologies" (EFOP-3.6.3-VEKOP-16-2017-00001).

### References

- [1] Emőd I, Tölgyesi Z and Zöldy M 2006 *Alternative Vehicle Propulsion systems* (in Hungarian: Alternatív Járműhajtások), Maróti Plc, Budapest
- [2] Berdman 2011 *History of Hybrid Cars*, <https://www.hybridcars.com/history-of-hybrid-vehicles/>
- [3] Varga Z and Sauter F 2014 *Alternative und future drivetrains* (In Hungarian: Jövőbeli és Alternatív Járműhajtások), TÁMOP 2.1.4, Győr
- [4] Hofmann P 2014 *Hybridfahrzeuge*, Springer, ISBN 978-3-7091-1780-4
- [5] Polak F 2018 *E-REV's Hybrid Vehicle Range Modeling*, Journal of KONES Powertrain and Transport, Vol. 25, No. 2 pp. 281-286 DOI: <https://doi.org/10.5604/01.3001.0012.2814>
- [6] Szalay Z, Tettamanti T, Esztergár-Kiss D, Varga I and Bartolini C 2018 *Development of a Test Track for Driverless Cars: Vehicle Design, Track Configuration, and Liability Considerations*, Per. Pol. Transportation Engineering, 46(1), pp. 29-35. doi: <https://doi.org/10.3311/PPtr.10753>
- [7] Rhodes K, Kok D, Sohoni P, Perry E 2017 *Estimation of the Effects of Auxiliary Electrical Loads on Hybrid Electric Vehicle Fuel Economy*. SAE Technical Paper 2017-01-1155, <https://doi.org/doi:10.4271/2017-01-1155>.
- [8] Široký J, Schröder S and Gašparík J 2017 *Comparison of operational and economic aspects of direct road transport and continental combined transport*. Communications - Scientific Letters of the University of Zilina. 19. 109-115.
- [9] Zöldy M and Zsombók I 2019 *Influence of External Environmental Factors on Range Estimation of Autonomous Hybrid Vehicles*. System Safety: Human - Technical Facility - Environment, 1(1), pp. 472-480. Retrieved 6 Apr. 2019, doi: <https://doi.org/10.2478/czoto-2019-0061>
- [10] Zöldy M and Zsombók I 2018 *Modelling fuel consumption and refueling of autonomous vehicles*, MATEC Web Conf. 235 00037 DOI: <https://doi.org/10.1051/matecconf/201823500037>
- [11] Mitran T, Chioreanu N, Chioreanu C, Rus AI, Beles H 2017 *A Propulsion System for Means of Transport with Non-autonomous Electrical Traction* CONAT 2016: International Congress of Automotive and Transport Engineering, Pages: 491-496, DOI: 10.1007/978-3-319-45447-4\_54, Published: 2017. Publisher: Springer Int Publishing AG, Switzerland, ISBN: 978-3-319-45447-4
- [12] Thomas J 2014 *Drive Cycle Powertrain Efficiencies and Trends Derived from EPA Vehicle Dynamometer Results*. SAE Int. J. Passeng. Cars - Mech. Syst. 7(4):2014, doi: <https://doi.org/10.4271/2014-01-2562>
- [13] Carlson R, Wishart J and Stutenberg K 2016 *On-Road and Dynamometer Evaluation of Vehicle Auxiliary Loads*. SAE Int. J. Fuels Lubr. 9(1):2016, doi:<https://doi.org/10.4271/2016-01-0901>
- [14] Chioreanu N, Mitran T, Rus AI, Beles H 2014 *Numerical Simulation of Thermal-Hydraulic Generators Running in a Single Regime*. Central European Journal of Engineering, Volume 4, Issue 2, June 2014, Pages: 119-124. Publisher: Springer-Verlag Wien, DOI: 10.2478/s13531-013-0145-2, ISSN: 18961541
- [15] Baalen J V 2005 *Optimal Energy Management Strategy for the Honda Civic IMA*, Master's Thesis, University of Eindhoven, DCT 2005.148
- [16] Honda 2011 CR-Z Powertrain, Honda North America, 1919 Torrance Boulevard, Torrance, CA 90501 <http://www.hondanews.com/releases/2011-honda-cr-z-powertrain?l=en-US>
- [17] [https://en.wikipedia.org/wiki/Honda\\_CR-Z](https://en.wikipedia.org/wiki/Honda_CR-Z)
- [18] Shah F 2013 *Delving into the details* <http://paultan.org/2013/02/22/delving-into-the-details-interview-with-norio-tomobe-large-project-leader-of-the-new-facelifted-honda-cr-z/>
- [19] Török Ad, Török Ar and Heinitz F 2014 *Usage of Production Functions in the Comparative Analysis of Transport Related Fuel Consumption*. Transport and Telecommunication Journal. 15(4), pp. 292-298. <https://doi.org/10.2478/ttj-2014-0025>