https://doi.org/10.55343/CogSust.96

Investigating energy management of hybrid vehicle technologies to promote sustainable mobility paradigms

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Abstract

Analysing contemporary passenger cars' energy consumption and environmental impacts is a critical research area. This is particularly relevant in urban transport's dynamic and unpredictable environment, where vehicles' fuel consumption and emissions vary considerably. An in-depth understanding of such fluctuations is essential for innovative, efficient, environmentally friendly vehicle technology. In the present research, I investigated a 1.4-litre petrol hybrid vehicle, focusing on its energy supply chain under real-world urban driving conditions. The study focuses on policies that can promote the development of sustainable mobility, improve energy efficiency and reduce environmental pollution. The results can help to optimise hybrid vehicle technologies in an environmentally conscious way and explore possible new avenues for sustainable transport solutions.

Keywords

consumption, driver behaviour, hybrid vehicle efficiency, sustainable mobility

1. Introduction

Modern vehicle on-board diagnostic (OBD) systems provide a sufficient quantity and quality of data to accurately measure and monitor vehicle condition, fuel consumption and other key parameters. Extracting and analysing this data provides deeper insights into the vehicle's internal energy flows and the underlying reasons for their fluctuations. The use of CAN data for better understanding vehicle behaviour is a key element in increasing the cognitivity of mobility (Zöldy and Baranyi, 2023). Using the data collected via the OBD connector allows us to objectively assess vehicle performance and efficiency in different driving scenarios (Szabó M., 2022).

One of the main aims of this research was to explore the impact of driver behaviour on vehicle energy consumption. Driving style, such as acceleration, gear changes and braking habits, significantly influences vehicles' fuel consumption and emissions. Conducting measurements and analyses under real traffic conditions enabled a comparison of how these factors affect vehicle energy flow and overall performance.

The following section presents the research methodology, the data collection and analysis process, and a detailed analysis of the results. The aim is to provide a comprehensive picture of how we can influence the energy efficiency of vehicles by consciously modifying driving behaviour and how the data that can be extracted through OBD can help reduce the environmental footprint of vehicles.

In simple terms, to calculate the overall efficiency (η) of any given car, it is necessary to consider several factors that determine the overall efficiency of the vehicle's energy use. The calculation of the overall efficiency allows a comparison of the vehicle's energy consumption and the resulting work (1):

$$\eta = (\text{Output mechanical energy} / \text{Input energy}) * 100\%, \quad (1)$$

where 'Output mechanical energy' is the work or energy that the vehicle eventually converts into kinetic energy, and 'Input energy' is the total energy that the vehicle derives from fuel or electric battery. This formula helps us understand how efficiently the vehicle can convert energy into useful work, such as moving the vehicle (Hartlieb, 2009).

A vehicle's overall efficiency results from the interaction between vehicle characteristics and technology, the driver, the environment and the road. This means that in addition to the technical parameters of the vehicle, such

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as the efficiency of the engine and drivetrain, the driver's driving style (Török, 2011), environmental conditions, and the characteristics of the route (Meszaros, Torok, 2014). also play a significant role (Yeom, 2022), (Fig 1):

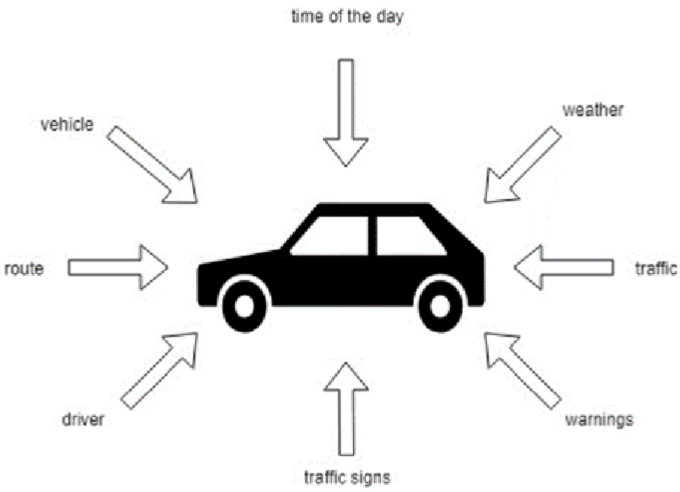

Fig. 1 External factors affecting consumption
Source: Zöldy, Zsombók 2019

These factors presented in Fig. 1 are analysed in more detail below. Vehicle characteristics and technology refer to the design and efficiency of vehicle components, including the engine, transmission, aerodynamics and tyre condition.

Driver: the driver's driving style, including acceleration and braking, can significantly impact fuel consumption and vehicle efficiency.

Environmental conditions such as temperature, wind, and road affect energy consumption.

Route: route characteristics, including hills, curves and traffic density, also affect the overall efficiency of the vehicle.

To conclude the effectiveness of performance-enhancing measures in the overall context of vehicles, it is necessary to consider a wide range of influencing factors due to their highly complex nature. In contrast to simulation studies (Tollner and Zöldy, 2023), where all parameters can be freely specified, real-world street conditions offer fewer variables that can be controlled and measured. Traffic, weather conditions, and traffic light behaviour can be measured and observed but cannot be controlled or held constant. However, it is precisely these factors that make street measurements particularly comparable to consumer driving habits, which simulation studies often ignore. Even though these tests occur in real-life conditions, they occur in an artificially created environment, i.e., within a measurement journey. Therefore, the conditions must be defined by an appropriate test design so that the data collected are representative of the test object (Zhang et al., 2023).

The parameters to be considered for a realistic test include the choice of vehicle, route and participants and the conditions under which the test is conducted. Given that this study aims to represent findings accurately, the study design is largely driven by European car traffic statistics. In the vehicle selection, the vehicle class, energy efficiency, powertrain and power-to-weight ratio had to be defined so that the selected vehicle corresponds to the representative data for European passenger cars as indicated in the paper (Table 1):

Table 1 Parameters of the tested vehicle

Vehicle class	middle category
Weight/power	0.069 kW/kg
Consumption (factory)	12.7 kWh/100 km
Drive chain	hybrid, DSG gearbox

Similar requirements apply to the route, which must correspond to the average car user's profile. Roads are divided into internal, external, highway and motorway sections. A mean distribution is defined for these road types

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based on vehicle use surveys on roads around Budapest. On this basis, a test track with all road types in the Budapest area was defined for the measurement (Fig 2):

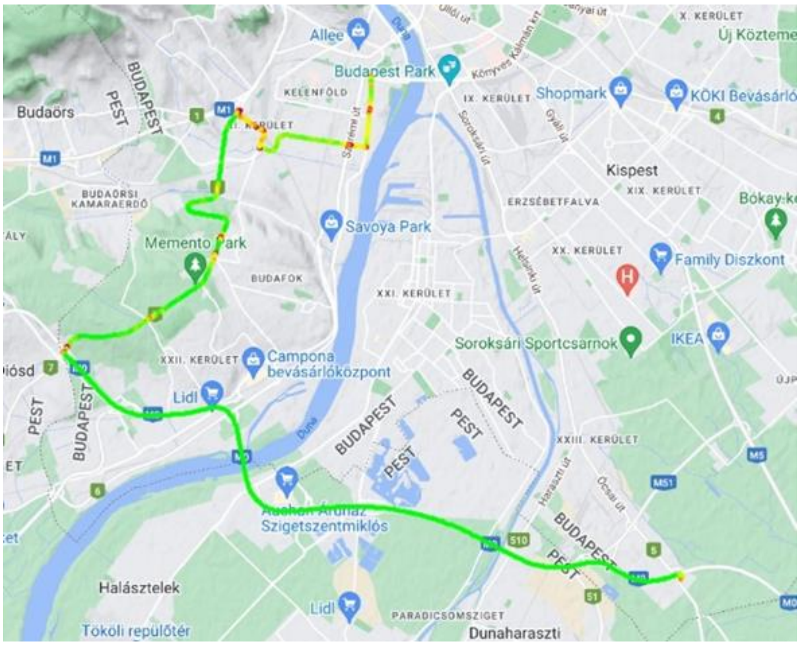

Fig. 2 The test route
Source: own edition

The third parameter is the size and nature of the group of participants. Here, it is important to balance the number of participants needed and the feasibility of the measurement trips to provide a good representation of European motorists based on the selected characteristics. These characteristics should be selected so that they can be determined before the participants are selected. A specific distribution can already be taken into account during the acquisition process. Age, gender, and annual management performance are used as characteristics by managers. These characteristics are divided into two or three categories. The representation of these characteristics for European car drivers is shown in Fig 3 and provides a guide for selecting test subjects (Zsombok and Zöldy, 2023):

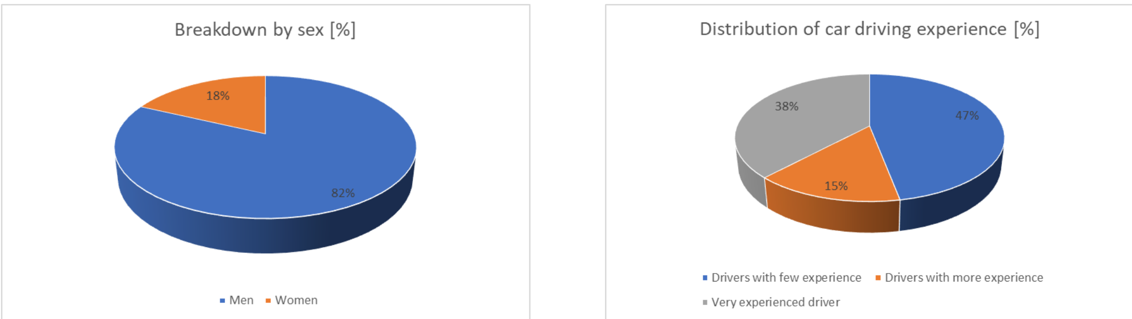

Fig. 3 Characteristics of test characteristics for European car drivers

The number of participants required is a function of the permutation of the characteristics, the precision required for the test, and the time needed to carry out the measurement paths. Permutation also allows for a representative distribution of characteristics when constructing subgroups. The required sample size is determined based on a prior assumption of the expected effect size under the hypothesis of a uniform distribution to achieve the desired precision (Bortz, 2005). The effort estimate is derived from the study design and depends mainly on the number of measurement runs that can be performed in one day. Other factors that influence the study's outcome are the effects of vehicle and participant habituation and conditioning and the variation in traffic according to the time of day. To minimise habituation effects, participants make two trips after the introduction. In addition, to ensure the

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same vehicle and traffic conditions for all participants, the measurement trips were always carried out at the same time of day after the vehicle had been preconditioned. The tests were carried out during the morning hours. The drivers were asked to drive according to their normal driving habits. Only the driver was sitting in the car during the measurements. All tests were repeated five times.

2. Power flow and resistance measurements in the participants' experiment

An HEV was used for the study, and data recording devices were used to record thermal, electrical, and mechanical power flows, resistances, vehicle position, and data from the vehicle environment and driver-vehicle interaction. All signals are recorded synchronously over time in two data acquisition systems. While measuring these data individually or on a test bench is standard practice, measurement trips in real traffic have specific requirements and conditions that must be considered. It is particularly important to process the different data synchronously (Li et al., 2024).

To minimise calculation errors in determining power flows, signals should be corrected to consider the sometimes significantly different transmission times. Since the repetition of measurement paths is practically impossible or only possible at a high additional cost, the risk of instrument outages should be minimised by using redundancies. Power flows were balanced for the whole vehicle, from fuel energy content to the power measured on the wheels. Fuel energy duration was determined using a measurement system for fuel volume variation and temperature measurements (Duhr et al., 2021).

The energy conversion heat losses of the internal combustion engine were derived from data measured at the temperature measurement points of the cooling system and the exhaust system. The energy required to operate the auxiliaries was determined from the torque data of the respective consumers. Here, in addition to the power data on the pulley on the main shaft, the air conditioning compressor shaft and the steering servo pulley, it was impossible to measure the alternator torque directly due to installation constraints. The power consumption was therefore determined by comparing the power required to operate the pulley on the crankshaft, the air conditioning compressor, the power steering pump and the engine auxiliaries. In the electrical on-board network, the electrical output power of the relevant consumers, the battery, and the alternator were determined by point current and voltage measurements (Fig. 4):

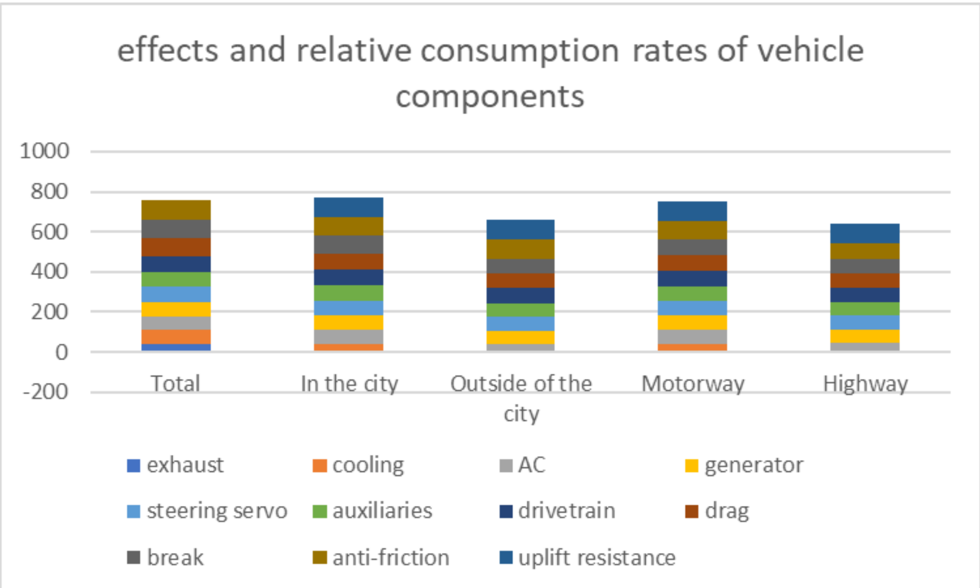

Fig. 4 Relative consumption distributions of each component and countermeasure

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$$P_{\text{fuel}} + (P_{\text{mode}}) = P_{\text{effective}} + P_{\text{cooler}} + P_{\text{exhaust}} + P_{\text{aux}} + P_{\text{steering control}} + P_{\text{Drive chain loss}}, \tag{2}$$

where:

- P_{fuel} – Fuel power: the power provided by the fuel.
- P_{mode} – Operating power: the power added by the air.
- $P_{\text{effective}}$ – Effective power: the effective power of the engine.
- P_{cooler} – Cooling capacity: the power dissipated by the cooling system.
- P_{exhaust} – Exhaust power: the power carried by the exhaust gases.
- P_{aux} – Ancillary equipment power: the power consumed by the ancillary equipment.
- $P_{\text{steering control}}$ – Servo losses: losses of the servo pump.
- $P_{\text{Drive chain loss}}$ – Drivetrain losses: losses in the transmission system.

The significant driving resistances and power loss during braking are quantified according to the equation. The rising values are compared to the measured power of the car on the axle. The air pressure was corrected for the measured outside temperature and ambient pressure to determine the drag. The road slope was calculated by integrating the vehicle's roll rate with the body roll angle, measured and corrected using a laser inclinometer. Rolling and acceleration resistance were derived from the vehicle's brake pad parameters and measured driving dynamics data. The skid resistance was determined from the wheel slip and torque combination measured at the wheel hubs. Brake energy was determined by measuring brake torques and wheel speeds.

$$P_{\text{wheel}} = P_{\text{air resistance}} + P_{\text{rolling resistance}} + P_{\text{pitching resistance}} + P_{\text{sliding resistance}}, \tag{3}$$

3. Power flows and consumption fluctuations under real traffic conditions.

The research was conducted between September and October 2023, with 12 participants. The study analysed energy losses during car use and distribution along different road sections. The average values of the consumption shares from vehicle components and driving resistances were calculated based on the distance travelled by the participants on each road. The results reflect the average values of typical driving behaviour under the test conditions.

The findings reveal that 33% of energy is lost across all road types, 8% is lost due to the operation of auxiliary equipment, and 2% is lost due to mechanical friction in the drivetrain. Of the 23% of energy remaining at the wheel, 6.5% is distributed to rolling resistance, 8% to drag and 8.5% to losses during braking. Of the auxiliaries, 2% is consumed by the air conditioning compressor, 2% by the power steering servo and 2% by the alternator. In the vehicle's electrical system, the biggest energy consumers are the air-conditioning fan (0.2%) and the cooling fan (0.1%), while the other electrical devices together account for 1% of the energy consumption.

Variations in consumption rates can be observed on each road section. Particularly high rates of braking losses are observed in urban and peri-urban areas. In urban areas, this is due to the high frequency of braking, while in peri-urban areas, it is due to the high kinetic energy, which is reduced by braking at the beginning of settlements and intersections. In addition, road sections outside urban areas tend to be more sloping overall, leading to a negative sign of slope resistance. The drag shows a characteristic behaviour depending on speed, leading to increasing consumption values on road sections with higher average speeds. The auxiliaries have lower energy consumption on such road sections, resulting from the almost constant energy demand of the equipment and the increasing total energy demand depending on the road section speed. A comparison of the different road sections shows that 17% more fuel is used in urban areas, 6% less in peri-urban areas, and 4% less on motorways. The relative variations in consumption between participants are shown in Figure 6.

For all road sections, the relative fuel consumption ranges from 33% overall, with a deviation of +/-6.5%. The variation varies according to the type of road, with the largest variation of +/-10.2% in the extra-urban areas, with a range of 55%, and the smallest variation on the national roads. The fluctuations show an asymmetric distribution towards higher consumption regardless of the road type. This can be explained by the fact that consumption can theoretically be increased indefinitely while there is a lower limit to the minimum consumption. The energy-loss

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group presents relative consumption fluctuations. The "Energy conversion" group includes losses that occur during the conversion of the chemical energy of the fuel into mechanical energy, including exhaust gas and cooling losses, as well as the energy demand of auxiliary power equipment. This group shows the largest variance of all the road sections studied (Fig. 5):

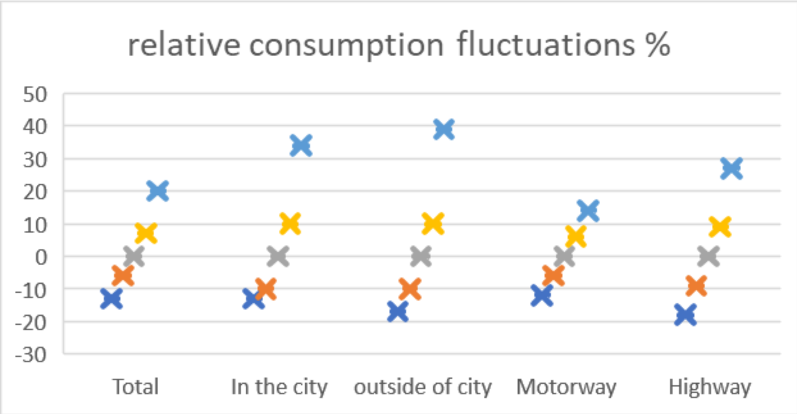

Fig. 5 Relative consumption differences by route type, test series are marked with different colours
Source: own measurement

Resource losses correlate with the amount of fuel consumed, reflected in the fluctuations. In contrast to the low variability in driveline and transmission losses, high variability in braking losses is observed between participants, especially on extra-urban and motorway sections. For losses due to comfort and safety (auxiliaries and on-board network), the effect of reduced energy consumption of auxiliaries on higher speed road sections is again observed, which also affects the consumption variations. The fluctuations due to passing resistances are low and are dominated mainly by the speed-dependent effect of air resistance, leading to higher fluctuations when the speed range on the road type is wider.

4. Summary and outlook

In a series of measurements, average values for European passenger car traffic were determined to examine the distribution of losses in real-world use of an actual conventional vehicle.

In addition, the average values of the consumption variations between different drivers on the same route were also determined. The distribution of losses shows that an average vehicle's "tank to wheel" efficiency is around 23% over average wear and tear. The influence of drivers on average consumption is +/-6.5%, with a maximum variance of 33%. These variations depend on driving style and variations in consumption effects from braking.

The dispersion of consumption values can be considered conservative. The value of the inter-participant variation in fuel consumption indicates the range of theoretically achievable values for the average driver's consumption-optimised driving style.

Further studies have tested the usefulness of exploiting such potentials using driver assistance functions. For this purpose, driving data collections from real-world measurement trips can be used as input for a simulation in which different consumption optimisation functions are implemented, and the effects of the functions can be inferred by comparing them with the original driving data. In addition to the consumption-saving potentials, the time demand and the constraints on individual driving styles resulting from the intervention of different assistance functions can be evaluated.

https://doi.org/10.55343/CogSust.96

References

Bortz, J. (2005). *Statistik Human Sozialwissenschaftler* 6th edition. Springer Verlag, Berlin.

Duhr, P., Christodoulou, G., Balerna, C., Salazar, M., Cerofolini, A., Onder, C. H. (2021). Time-optimal gearshift and energy management strategies for a hybrid electric race car. *Applied Energy*. 282, Part A. 115980. DOI: https://doi.org/mpk6

Hartlieb, S (2009).: Untersuchung von Fahrversuchsdaten auf demographisch signifikante Merkmale zur Identifikation von Fahrern und Situationen, Studienarbeit am Institut für Verbrennungsmotoren und Kraftfahrwesen, Universität Stuttgart, November 2009

Li, C., Xu, X., Zhu, H., Gan, J., Chen, Z., Tang, X. (2024). Research on car-following control and energy management strategy of hybrid electric vehicles in connected scene. Energy. 293, 130586. DOI: https://doi.org/mpk7

Meszaros, F., & Torok, A. (2014). Theoretical investigation of emission and delay based intersection controlling and synchronising in Budapest. Periodica Polytechnica Transportation Engineering, 42(1), 37-42. DOI: https://doi.org/mpk8

Tollner D., Zöldy M. (2023). Dynamic Data extraction from vehicles through OBD connector. *2023 IEEE 2nd International Conference on Cognitive Mobility (CogMob)*. 189–194.

Török, Á. (2011). Investigation of road environment effects on choice of urban and interurban driving speed. International Journal for Traffic and Transport Engineering, 1(1), 1-9.

Yeom, K. (2022). Learning model predictive control for efficient energy management of electric vehicles under car following and road slopes. *Energy Reports*. 8, Supplement 15. 599–596. DOI: https://doi.org/mpk9

Zhang, H., Peng, J., Dong, H., Tan, H., Ding, F. (2023). Hierarchical reinforcement learning based energy management strategy of plug-in hybrid electric vehicle for ecological car-following process. *Applied Energy*. 333, 120599. DOI: https://doi.org/gr9gch

Zöldy, M., Baranyi, P. (2023). Definition, Background and Research Perspectives Behind The Cognitive Mobility Concept. *Infocommunications Journal*, Special Issue: Internet of Digital & Cognitive realities. 35–40. DOI: https://doi.org/j4pc

Zöldy, M., Zsombók, I. (2019). Influence of external environmental factors on range estimation of autonomous hybrid vehicles. *System Safety: Human-Technical Facility-Environment*, 1(1), 472-480. DOI: https://doi.org/mpmb

Zsombok I. (2021) Járművek fogyasztása és hatótáv becslő rendszerei , OGÉT 2021.04.18. URL: https://ojs.emt.ro/oget/article/view/453

Zsombok, I., Zöldy, M.(2023). Modelling, Simulation and Validation of Hybrid Vehicle Fuel Consumption. *Acta Polytechnica Hungarica*. 20(5). 61–74. DOI: https://doi.org/kv2x