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Analysis of speed limit and energy consumption in electric vehicles

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This paper presents an analysis of the mileage energy consumption for an electric passenger vehicle in terms of introducing numerous speed limits. Regulations concerning the limiting of vehicle speed to30 km/h in cities or residential areas are particularly common. This restriction is intended to increase traffic safety, but at the same time introduces increased mileage fuel or energy consumption in electric drivetrain. Regardless of the energy carrier, any increase in energy causes negative effects for the environment. The analysis was focused on the mileage energy consumption of electric passenger cars for a constant speed under real traffic conditions. During the tests, the tested vehicles' speed on a specially designated road section was changed gradually by 10 km/h, simultaneously recording the car's traction parameters and mileage energy consumption. An analysis of the mileage energy consumption was then carried out for the assumed fleet of cars travelling one after another (in a so-called traffic jam), while maintaining a safe distance. This allowed for the calculation of the environment's energy burden caused by a fleet of vehicles travelling on a given road section, indicating that a reduction in vehicle speed causes an increase in the vehicles' energy consumption. Both total and mileage energy consumption of electric vehicles were analysed during the tests.

Key words: *energy consumption, constant speed, safe driving distance*

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1. Introduction

The reduction of carbon dioxide (CO_2) emissions and other components resulting from the combustion of hydrocarbon fuels to power vehicles and machinery is a global issue for the 21st century's civilization. It derives not only from global norms, but also due to the passenger vehicles sector, where the mobility of society has become a common phenomenon. For this reason, the passenger vehicles manufacturing sector is one of the most growing areas of the economy, and in many countries the passenger car saturation rate per 1,000 inhabitants exceeds the magic number of 700 units. This value represents a high degree of mobility in society, meaning that there are more cars on the market than opportunities for people to use them on the road at any one time. Powering these passenger cars requires an energy carrier in the form of fossil fuels, gaseous fuels, alternative fuels [3, 5] or electric energy in the case of electric drive units. Electric drive units are equipped with energy storages known as traction batteries, powered by the mains electricity supply or supplemented by energy recovered during the car's deceleration process. In Poland, electricity is produced [6] mostly from fossil fuels. This makes passenger vehicles neutral in terms of emissions on the road, but their environmental burden is transferred to the location of electricity production. This is beneficial for urbanised areas, but in terms of supplying energy to the wheels in the so-called "Well-to-Wheels" system, the final efficiencies are comparable (Table 1).

The final efficiency of electric drive units depends less on the drive unit itself, which is an electric machine with a high specific field efficiency, but more on the traffic conditions in which the vehicle operates. It is the driver's speed profile that has a significant impact on the electric drive unit's performance. At the same time, under real traffic conditions, the performance deviates from that measured in the WLTP cycle, similarly as in the case of internal combustion drive systems of passenger cars [1]. Hence, the range in real traffic conditions is shorter by several to over a dozen percent in the case of many electric vehicles as the range declared by the manufacturer [12]. This paper includes an analysis of the performance of an electric drive unit, achieved while driving at a constant speed under road conditions.

Table 1. Well-to-Wheel efficiency for battery electric vehicles (BEV) and internal combustion engine vehicles (ICEV)

	Well	**T**ank	Tank to **W**heel	
Drive unit	Production	Transport	Energy Conversion efficiency	**WTW Efficiency**
BEV	**35–60%** Depends on different methods of electricity production	**81–85%** Power transmission + charging efficiency	**65–82%** Losses during energy conversion, motion, friction of the drive unit	**18–42%**
ICEV	**82–87%** Extraction of fossil fuels and refining processes	**99%** Low energy losses during transport as a result of evaporation or sticking to tanks	**19–25%** Most of the energy is lost as heat. included efficiency of a drive unit featuring a combustion engine	**16–20%**

2. Mileage energy consumption and vehicle speed

A direct manner of improving the safety of road traffic and also the safety of other road users is usually a speed limit introduced by traffic regulations. This is implemented through signs or the introduction of speed-limit zones on city streets, with the speed limit being 30 km/h. Such regulations work well in terms of safety and this is not disputed by the authors in terms of energy, however consumption varies over a wide range. The simulated mileage energy consumption under different traffic conditions for an electric passenger vehicle is presented in paper [7], which shows a large spread of mileage energy consumption (Fig. 1).

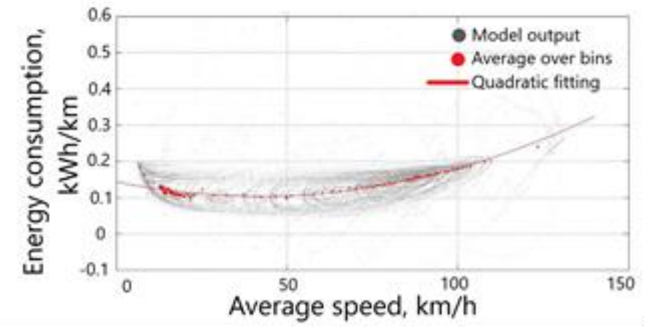

Fig. 1. Mileage energy consumption of an electric passenger vehicle [7]

The electric energy consumption shown varies for an average speed of 50 km/h from 5 kWh/100 km to 18 kWh/100 km with an average consumption of 10.5 kWh/100 km. This variation is caused by the simulated traffic conditions on different road sections when travelling at different speeds [16, 17]. The points highlighted in grey are the unit values and those in red correspond to the average mileage energy consumption. The average values shown for the mileage energy consumption indicate minimum consumption at speeds in the range of 30 to 45 km/h. In the same work, the authors compared the mileage fuel consumption for an internal combustion drive unit, as shown in Fig. 2.

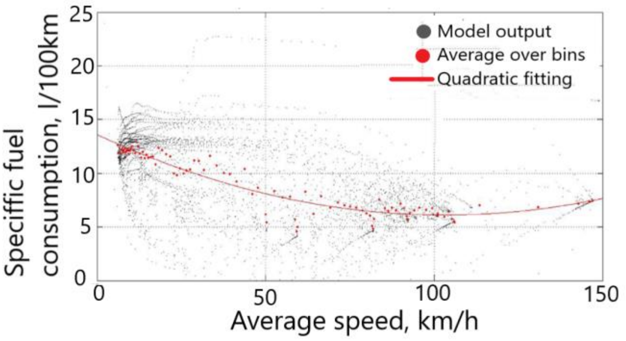

Fig. 2. Mileage fuel consumption of combustion drive units [7]

Internal combustion vehicles have a significantly greater spread of fuel consumption and their average value is in the range of 90 to 100 km/h. It is interesting that the different drive unit designs (BEV and ICE) feature minimum mileage fuel and energy consumptions that occur at a given speed. Attention should be paid to identical vehicle parameters related to weight, tire type, drag coefficient c_x or frontal surface area. It is not correct to directly compare the presented mileage fuel and energy consumption. Therefore, in paper [8], the authors compared the electricity consumption and fuel consumption per unit of electricity for travels made under real road conditions.

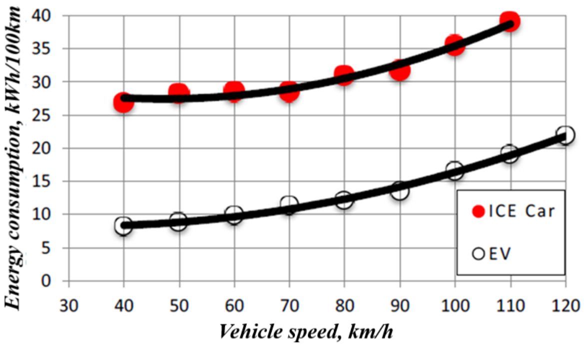

Fig. 3. Mileage energy consumption for various passenger vehicle drive units [13]

A similar comparison can be found in paper [8, 10], where the difference in the mileage energy consumption of an internal combustion engine and an electric engine is substantial. However, the authors of this paper compared the variation in the aforementioned drive units' energy carrier consumption depending on the driver. The results of energy carrier consumption for a random selection of 10 vehicles over a period of at least one year are presented in Fig. 4.

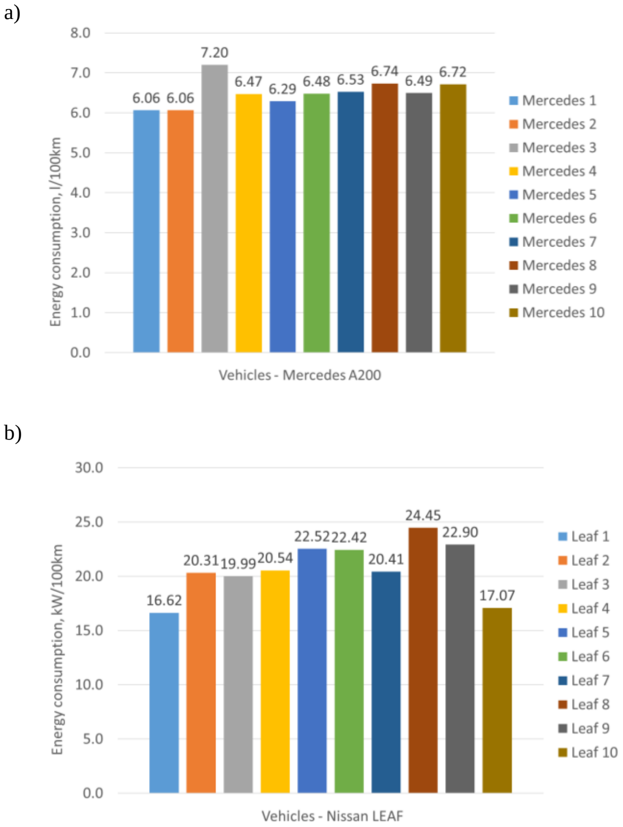

Fig. 4. Differences in energy carrier consumption for different drive units: a) internal combustion, b) electric

The reason for these differences is the operation period of over 12 months, in which the vehicles covered a maximum distance of 31,000 km for the electric drive unit and 34,000 km for the internal combustion drive unit. The spread of results is significantly greater for electric drive units for which the standard deviation is in the range of 1.5 to 12.8 (Fig. 5), while for the internal combustion drive unit, this value does not exceed 0.7.

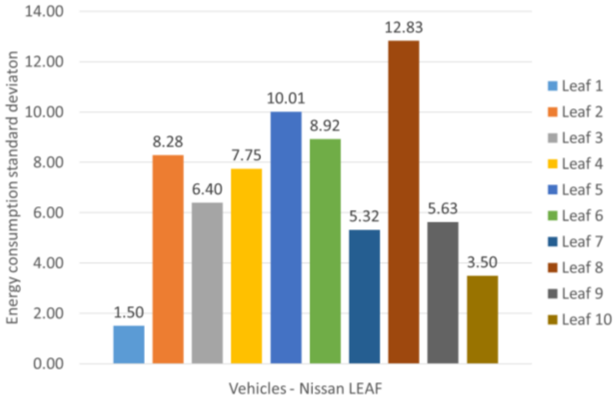

Fig. 5. Standard deviation of an electric drive unit

Therefore, the internal combustion engine's consumption is characterised by a significantly smaller spread in the average mileage fuel consumption. In the case of the electric drive system, the driver's driving style is important in terms of the ability to recover energy from the deceleration process and in terms of the average vehicle speed [11]. In paper [10], the authors presented the energy consumption at an average speed of an electric engine. The differences are significant and amount from 135 to 420 Wh/km.

3. Mileage energy consumption and constant vehicle speed

The electric drive unit's mileage energy consumption is measure of the energy expended on a given road section at a given speed. Due to the fact that vehicle speed depends on the driver's will and on the environmental conditions (road topography, weather conditions, other road users' manoeuvres) or the legal conditions that regulate traffic in a given area. The regulations introduced to limit the speed to 30 km/h result in an increased fuel consumption, according to the information shown in Fig. 7a. From the information presented, it is possible to conclude that the minimum mileage energy consumption occurs at a well-defined electric vehicle speed. In Mitrović's paper [14], it is possible to find confirmation of the above information for an internal combustion vehicle with an assumed speed limit on a limited length road section. Under these assumptions, a vehicle moving at a very low speed $V \rightarrow 0$ will have a fuel consumption rising to infinity (Fig. 6) due to the internal combustion engine's operation in its low-efficiency range resulting from idling Q_0 and under such traffic conditions the travel time also increases to $\tau \rightarrow \infty$. This shows that the time τ [h] and fuel consumption Q [l] are very high for a very low vehicle speed, Eq. (1).

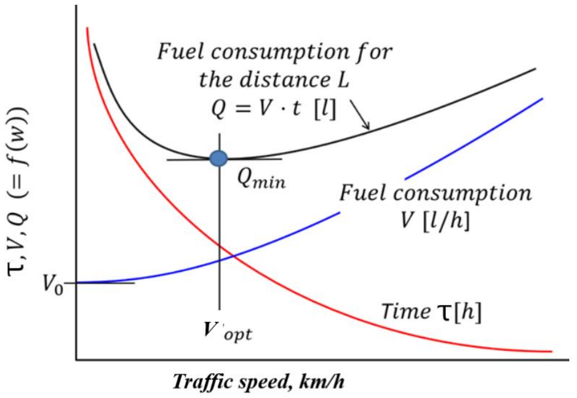

Fig. 6. Analysis of the vehicle's traction variables in road traffic at limited speeds

Low vehicle speed:

$$V \rightarrow 0\ \{(\ Q_p\ [l/h] = Q_0;\ \tau \rightarrow \infty)\}:\ Q\ [l] \rightarrow \infty,\ \text{large} \qquad (1)$$

High vehicle speed:

$$V \rightarrow \text{large}\{(Qp\ [l/h] = \text{large};\ \tau \rightarrow \text{small})\}:\ Q\ [l] \rightarrow \text{finite}\ (2)$$

In the second extreme position for high speeds, the fuel consumption increases, but the travel time decreases greatly (2). In this case, the fuel consumption, treated as the product of high-intensity fuel flow Q_τ [l/h] and short travel time τ [h], will provide a finite fuel value in Q [l] (3).

$$Q\ [l] = Q_\tau\ [l/h] \cdot \tau\ [h] \qquad (3)$$

It was assumed that similar dependencies apply to electric vehicles. Hence, energy consumption was measured for selected vehicle models under traffic conditions. The difference in mileage energy consumption derives from the differences in the drive units.

4. Mileage energy consumption under road conditions

The energy consumption of an electric passenger vehicle was analysed on a selected road section of 2.5 km with a good bituminous road surface, sheltered from the wind and the road slope was close to zero. The tests were carried out at similar temperatures of 5^{o}C.

The traction and energy parameters were monitored using a measurement platform developed at the Department of Vehicles of the Opole University of Technology [9]. The platform enables the measurement of traction parameters from several data sources simultaneously including, among others, the on-board diagnostic (OBD) network or the on-board CAN Bus data transmission network. In addition, for Mercedes-Benz vehicles, the authors used the company's software that enabled a continuous preview of the following data: energy storage capacity, total distance travelled, travel time, average speed and energy expenditure as the mileage electricity consumption. The aforementioned data were systematically recorded in the database and then analysed.

The technical data of the analysed electric vehicles is presented in Table 2.

Table 2. Tested vehicle parameters

Manufacturer	Renault	Mercedes-Benz	Mercedes-Benz
Type	ZOE	CLA	A250e
Electric engine's output	68 kW	75 kW	75 kW
Electric engine's max. torque	220 Nm	330 Nm	300 Nm
Engine assembly	Front, transverse	Front, transverse	Front, transverse
Engine system type	EV	PHEV	PHEV
Transmission system	1 gear	Automatic – 8 gears	Automatic – 8 gears
Battery capacity	41.1 kWh	–	15.6 kWh
Vehicle mass	1445 kg	1325 kg	1817 kg
Vehicle travel range	255 km	80 km	75 km
Vehicle energy consumption	165 Wh/km	190 Wh/km	209 Wh/km

The energy consumption was analysed for the vehicle's real operating conditions at a preset constant speed from 30 km/h to 130 km/h, with the speed being changed gradually by 10 km/h once the energy consumption had stabilised. It should be noted that two hybrid vehicles equipped with an additional combustion engine were among the analysed drive units. However, in the case of both aforementioned vehicles, the analysis was carried out solely on the basis of a forced electric drive. For the Renault ZOE, tests were carried out for two drive unit control modes ("Normal" and "ECO"). The "ECO" mode limits the drive unit's available output to 38 kW, maximum vehicle speed to 96 km/h and cockpit temperature to 21^{o}C.

Figure 7 shows the mileage energy consumption as a function of the vehicle's speed. The results shown are the averaged values recorded at the measurement points (constant speed). For each recorded mileage energy consumption, its minimum values can be determined for a given constant vehicle speed. In the case of the analysed vehicles, these values were as follows:

- Renault ZOE, ECO mode; V – 37 km/h → 12.2 kW/100 km
- Renault ZOE, normal mode; V – 50 km/h → 14.50 kW/100 km
- Mercedes-Benz CLA; V – 40 km/h → 11.5 kW/100 km
- Mercedes-Benz A250e; V – 60 km/h → 15.7 kW/100 km.

There is a noticeable effect of speed on energy consumption, which increases below and above the set speed. The Mercedes-Benz CLA has the lowest energy consumption, but the drive unit's output required to drive the analysed vehicles is similar, as shown in Fig. 8. These values are in line with the research presented in another paper [4] on the analysis of fuel consumption in an internal combustion drive unit. Despite the significant differences in the vehicles' drive units, its output at a constant speed is similar and is approximately 20 kW for the 100 km/h vehicle speed. In contrast, significant differences were registered in torque. Regardless of its operating mode, Renault ZOE has a similar torque as both Mercedes-Benz, which share the same drive unit (Fig. 9). The drive unit of the Mercedes-Benz vehicles uses an eight-speed transmission, which affects its torque, unlike the ZOE, which has a fixed transmission ratio in its drive units.

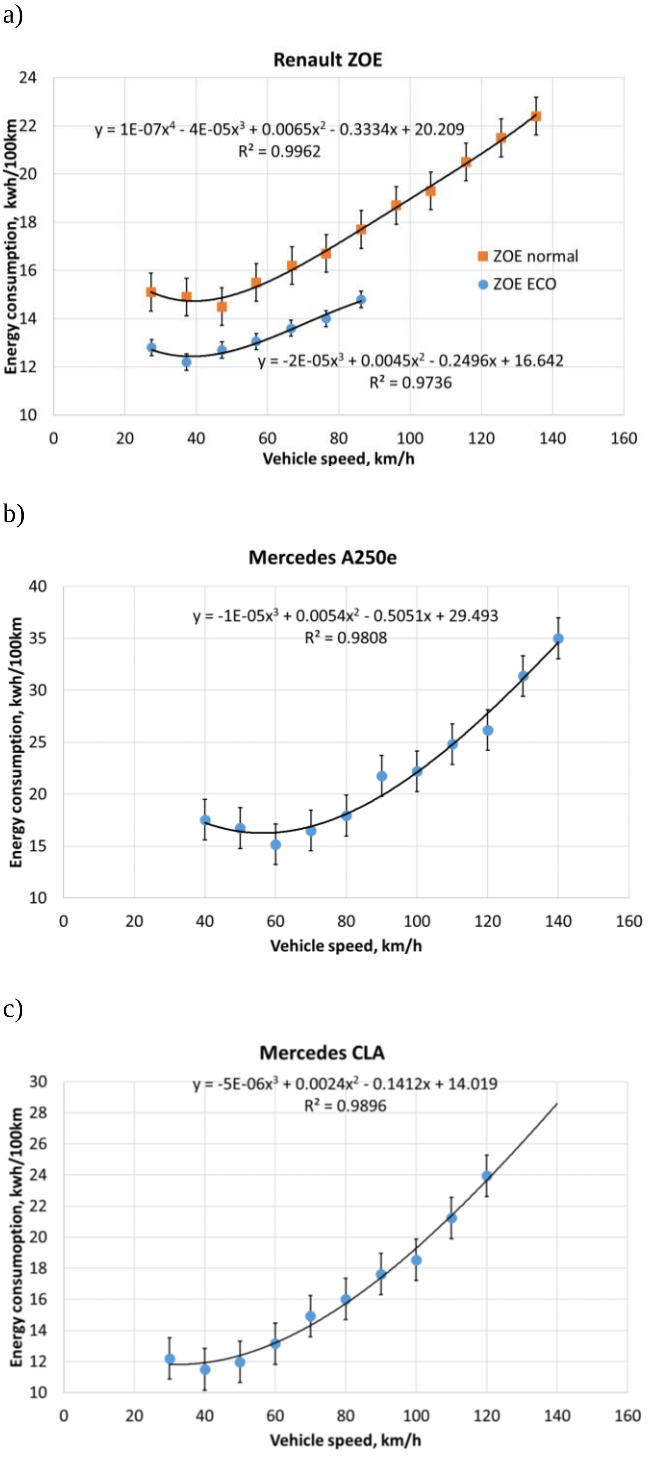

Fig. 7. Mileage energy consumption for the analysed electric vehicles: a) Renault ZOE, b) Mercedes-Benz A250e, c) Mercedes-Benz CLA

The values shown above for the vehicle's electric drive unit are determined empirically for a constant vehicle speed. The values are similar in terms of mileage and characteristics for internal combustion drive units widely reported in the literature, but also presented in Chapter 2.

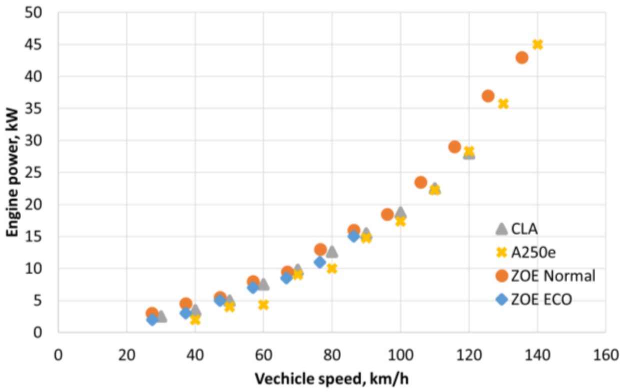

Fig. 8. Drive unit output at constant vehicle speed

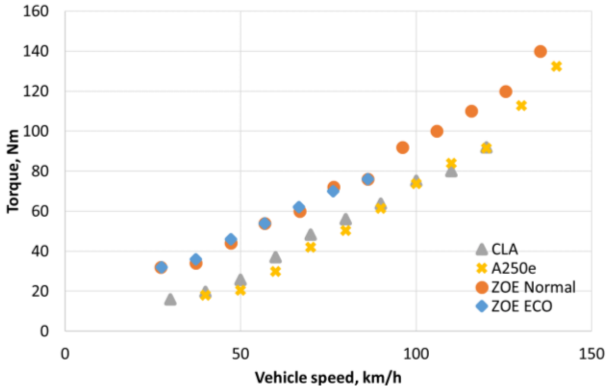

Fig. 9. Drive unit torque at the constant vehicle speed

5. Energy consumption for the vehicle fleet

The electric energy consumption Q_e [kWh] was analysed for the following vehicle movement pattern on the road at a constant speed. The pattern refers to the vehicles' travel on road section L [km] from points A to B, while maintaining a safe distance between the vehicles. The safe distance is not a fixed value and is not precisely defined. It is generally acknowledged that this distance ensures the driver's safety in the event of emergency braking, both in front of and behind the vehicle. The term is not precise due to the use of the words "safe distance" in the context of two conditions related to braking distance and the driver's reaction time. The braking distance depends on many conditions, such as the road type, the vehicle's condition and even its type, brand or weather conditions. Reaction time is the driver's subjective ability to respond to an occurring traffic event and refers to the driver's psychomotor properties, experience and even the force with which the driver presses on the brake pedal. In practice, the driver's reaction time is between 0.5 and 1.5 seconds and can therefore be three times as long. For safety reasons, the response time is assumed to be 3 seconds and is preferred by the Polish road manager, i.e. the General Directorate for National Roads and Motorways. The Road Traffic Law defines the safe distance in Article 19, paragraph 3a as "the minimum distance between the driver's vehicle and the vehicle in front of him in the same lane. This distance, expressed in meters, shall be defined as not less than half the number representing the driver's vehicle's speed, expressed in kilometers per hour". The minimum safe distance at 30 km/h is therefore 15 m and at 100 km/h – 50 m.

Therefore, the number of vehicles is variable for a queue of vehicles moving one after the other, without interruption, on the same road section at a constant speed. This is important in terms of minimising the vehicle fleet's energy consumption, which requires determining the grid energy demand for minimum values at the recommended speed in terms of energy consumption and that resulting from legal regulations. Each energy consumption $Q > Q_{min}$ increases the intake of grid energy and is adverse for the environment. It is therefore important to estimate the difference $\Delta Q = Q - Q_{min}$, and for the analysed vehicle, e.g. Renault ZOE, the difference is presented in Fig. 10.

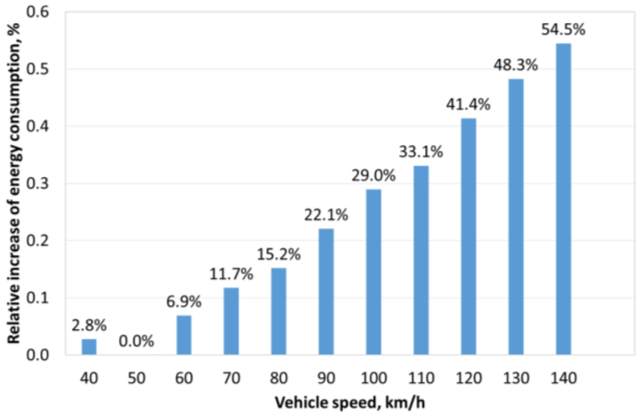

Fig. 10. Relative energy gain compared to its minimum value for Renault ZOE

Each travel at a speed V that differs from V_{opt} ($V \neq V_{opt}$), featuring a minimum energy consumption, increases energy consumption. A plot describing the dependency between consumption and travel time over a 10 km distance for the selected electric vehicle (Renault ZOE) is shown in Fig. 11. It corresponds to Fig. 6, presented in Mitrović's paper [14] for the internal combustion drive unit.

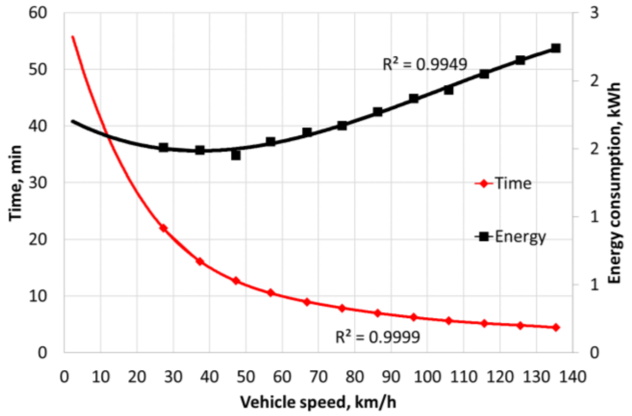

Fig. 11. Approximate energy consumption and time values for the analysed road section of 10 km

The energy consumption determined this way was used to calculate the energy consumption of a fleet of electric vehicles travelling at a constant speed, assuming a safe distance between them is maintained as required by traffic regulations, as shown in Fig. 12.

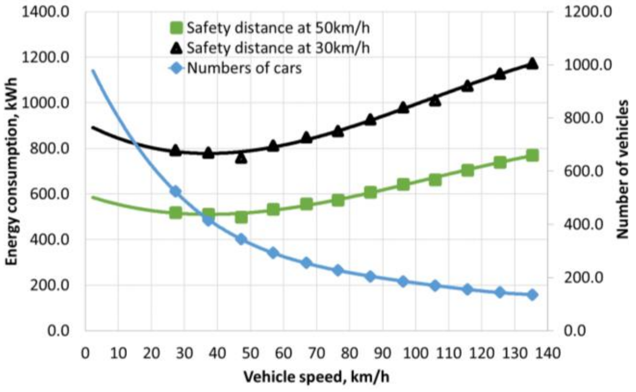

Fig. 12. Dependency of energy consumption for a fleet of electric vehicles at a constant speed of 30 km/h and 50 km/h while maintaining a safe distance

The number of vehicles in the fleet decreases as the speed increases, because the distance between vehicles increases along with an increase in speed, for which the vehicle's length must also be taken into account (4.08 m in the case of Renault Zoe). The number of vehicles travelling over a distance of 10 km at a constant speed of 30 km/h is 524 and 184 vehicles at 100 km/h. By calculating the energy consumption directly (Fig. 11) for the moving fleet, it turns out that the consumption amounts to 791.4 kWh at 30 km/h, 498.6 kWh at optimum speed (50 km/h) and 354.8 kWh at 100 km/h. The reduction in energy consumption is due to the decreasing number of vehicles in the fleet along with the increasing speed on a given road section. A detailed analysis was carried out for energy consumption if the fleet of vehicles was to cover the 10 km distance at the optimum speed (50 km/h) and at the speed limit derived from legal restrictions (30 km/h). The representative fuel will then be derived from the consumption at a given speed and number of vehicles, as shown in Fig. 12.

The energy consumption shown in the figure by the green line is presented for a fleet of 349 vehicles travel-ling at the optimum speed (50 km/h) while maintaining a safe distance. In contrast, the black line shows the consumption for a fleet travelling at 30 km/h. The differences in consumption are significant and at 50 km/h amount to ΔQ = 52.8% of the relative value, while at 30 km/h, ΔQ = 58.7%, and at 100 km/h – nearly 100% (precisely 96%).

In terms of the energy consumption of a fleet of vehicles travelling in the city, the ultimate aim should be making traffic smoother. At the same time, all the electric vehicles analysed have a significantly lower constant speeds that guarantee minimum energy consumption when compared to the internal combustion drive unit presented in papers [2, 10].

In paper [14], Mitrović pointed out that an increase from 30 km/h to 100 km/h in the case of the internal combustion drive unit results in a 93% increase in fuel consumption. A similar increase was recorded for the analysed Renault ZOE, which amounted to 90.3% and was mainly due to the vehicles' drag resistance, as shown in Fig. 7.

6. Summary

An analysis of the results obtained allows for the conclusion that the introduction of a 30 km/h speed limit causes an increase in the energy consumption of vehicle fleets. Regardless of the form of energy generation (coal, nuclear or RES), an increase in consumption always has an adverse effect on the environment. For example, it causes greater thermal and CO_2 emissions in the case of conventional coal energy, greater thermal emissions for nuclear energy and requires using more windmills or solar panels for RES. At the same time, the introduction of speed limits results in a 7.8% decrease in the number of road accidents, according to data provided by insurance companies [15].

In summary:

- 30 km/h speed-limit zones should only be introduced in particularly dangerous areas
- a reduction in speed below that which ensures minimum energy consumption results in an increased energy consumption
- the analysis carried out for a fleet of electric vehicles travelling at a safe distance from one another results in more traffic at a reduced speed, which is dangerous in itself. Therefore, these restrictions should also take traffic congestion into account
- higher energy consumption also has economic effects which should be taken into consideration.

Only a comprehensive way of considering the introduction of 30 km/h speed limits will be effective in reducing the energy consumption of electric vehicles.

Nomenclature

BEV	battery electric vehicle
ICEV	internal combustion engine vehicle
OBD	on-board diagnostic
Q	fuel consumption [l]
Qe	electric energy consumption [kWh]
Qτ	fuel flow [l/h]
V	vehicle speed [km/h]
V_{opt}	optimum speed
WLTP	Worldwide Harmonized Light Vehicles Test Procedure
WTW	well-to-wheels
ΔQ	differences in fuel consumption
τ	time [h]

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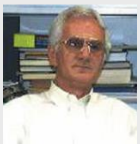

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