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THEORETICAL EVALUATION OF THE EFFECT OF OPERATING PARAMETERS ON ELECTRIC VEHICLE ENERGY CONSUMPTION AND DRIVING RANGE

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Abstract

The paper presents theoretical evaluation of the effect of operating parameters on electric vehicle energy consumption and driving range. The objective of this study was to analyse the effect of temperature (at constant pressure) and traction properties on the energy consumption and driving range related to it of a chosen electric vehicle. The test methods assumed the analysis of parameters of the test object based on a simulation model. The evaluation involved a Nissan Leaf vehicle equipped with an electric motor, the torque characteristic curve of which was used in the test model. The values of basic and additional resistance to motion for the adopted conditions: external temperature and pressure-dependent air density, and vehicle technical parameters, such as its weight, capacitance of batteries, vehicle dimensions, type of drive system, drag coefficient and tyre dimensions, were determined. Basing on these data and the characteristic curve of engine torque, electric vehicle energy consumption and driving range were determined. The following relationships were obtained because of the analysis: vehicle energy consumption / vehicle driving range and external temperature, vehicle energy consumption / vehicle driving range and vehicle acceleration, vehicle energy consumption / vehicle driving range and acclivity slope. It was proven that the operating parameters could considerably increase the energy consumption and the driving range of an electric vehicle.

Keywords: *energy consumption, vehicle-driving range, electric car*

1. Introduction

Implementation of the future carbon dioxide emission limits (95 g/km is expected for motor vehicle in Europe in 2020 [10, 14]) assumes utilisation of modern technical solutions. One of these construction concepts is an electric vehicle, being already produced at present in different drive system configurations [3, 10, 11].

The intake of electric energy, being required for electric vehicle movement, from the mains is associated with its production. In Poland, the production of electric energy is mainly based on fossil fuels (first of all from hard coal). It is a main reason for a negative assessment of electric vehicles with regard to pollutant emissions in the Well-to-Wheel analysis [4-6, 8, 9]. The results of the analyses of energy consumption by an electric vehicle weighing 1549 kg and being powered by lithium-ion batteries have corresponded to the measured value being equal to 15 kWh/100 km [6]. Also the specific energy consumption of an electric car has been analysed and the results of the measurements of this indicator for an electric vehicle weighing 1360 kg and with the drag coefficient $c_x = 0.5$, based on urban cycle test (UDDS, Urban Dynamometer Driving Schedule), extra-urban cycle test (HWFEDS, Highway Fuel Economy Driving Schedule, called also HWFET, Highway Fuel Economy Test), and US 06 driving test (SFTP, Supplemental Federal Test Procedure), have corresponded to the following values: 137 Wh/km, 165 Wh/km, and 249 Wh/km, respectively[2]. Similarly, this parameter for specific energy consumption in a Zilent Courant electric vehicle has been in the range of 155 Wh/km to 223 Wh/km [2]. The experiments referring to vehicle energy consumption have been also performed based on the driving cycles under laboratory conditions, using the NEDC test, and the results of these measurements for different types of electric vehicles are presented in Fig. 1 [16].

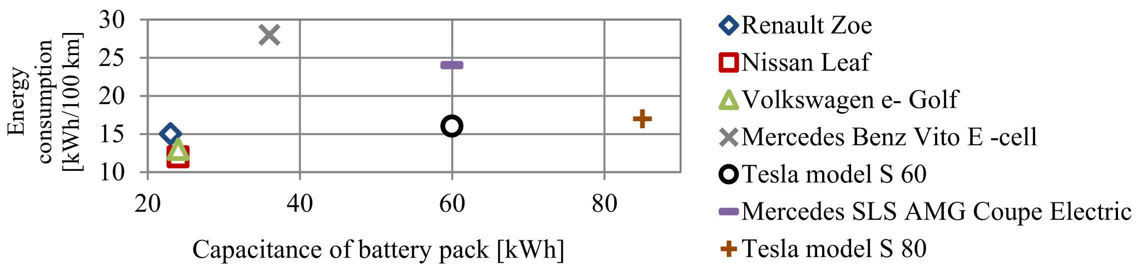


Fig. 1. Energy consumption for selected electric vehicles [16]

Energy consumption (Fig. 1) affects the vehicle driving range, which depends on the capacitance of battery pack [10]. The battery control system monitors the battery's state of charge (SOC), determining the minimum charge level and the maximum one [10, 15] and limiting its effective capacitance. For example, in the case of a Nissan Leaf vehicle being equipped with batteries with capacitance amounting to 24 kWh, their effective capacitance amounts to 21.3 kWh and this is about 88% of total battery capacitance [12]. The low capacitance of traction battery significantly limits the driving range of electric vehicle. The so-called economy mode driving, with a considerable speed limit, allows this distance to be increased [2]. The value of vehicle energy consumption and driving range resulting from it depends on different factors (Fig. 2).

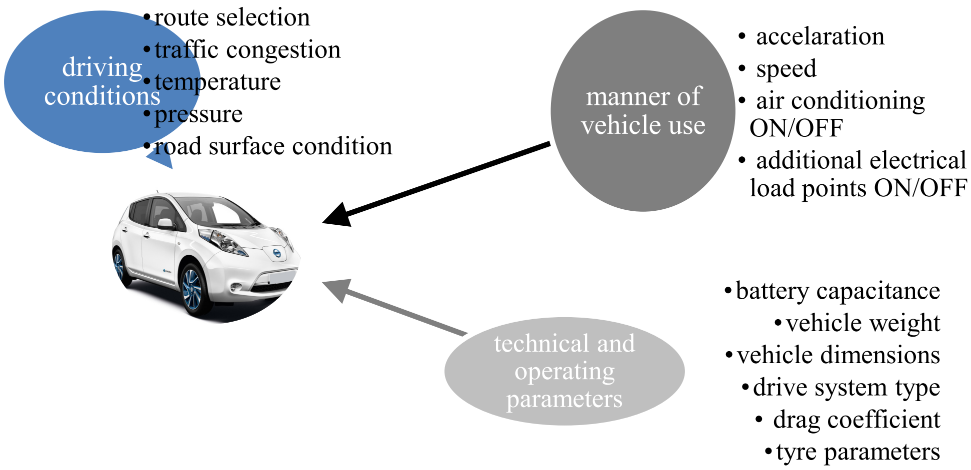


Fig. 2. Operating parameters affecting vehicle energy consumption

These include operating parameters, to which driving conditions, manner of vehicle use and car technical and operational characteristics belong.

2. Study objective

The objective of this study was to analyse the effect of operating parameters, such as temperature and car traction properties, on the energy consumption of electric vehicle and the driving range related to it.

3. Test methods

The test methods assume the use of the test object based on a simulation model of tests.

3.1. Test object

The test object was a Nissan Leaf electric vehicle, the technical data of which are presented in Tab. 1.

Tab. 1. Technical parameters of a Nissan Leaf vehicle [6, 8, 12]

Vehicle data	Value	Unit
motor type	synchronous, AC	
maximum motor power P^d	109 / 80	[KM/kW]
rotational speed range for maximum power n_P	3000-10000	[rpm]
maximum motor torque T_{tq}	254	[Nm]
rotational speed range for maximum torque n_{Ttq}	0-3000	[rpm]
type of battery applied	Lithium-ion	
battery capacitance E	24	[kWh]
type of drive system	locked front-wheel	
power transmission	no clutch, helical gear	
	fixed gear, 7.9377:1	
vehicle weight m	1550	[kg]
height H	1.549	[m]
width B	1.770	[m]
aerodynamic drag coefficient c_x	0.28	–
tyre size	205/55R16	
wheel rolling resistance coefficient	0.012	
energy consumption – additional electrical load points		
vehicle control systems during its starting	280	W
pre-cooling / air conditioning-stabilised cooling	2000 / 1800	W
pre-heating (minimum … maximum) / stabilised heating (minimum … maximum)	4000…6000 / 2000…4000	W

3.2. Simulation test model

The following driving conditions were adopted for simulation tests: a) passenger and load weight – 250 kg; b) external temperature = 25°C, 20°C, 10°C, 0°C, –10°C, c) external pressure = 101.3kPa, d) air density (temperature-dependent) = 1.168 kg/m^3, 1.189 kg/m^3, 1.247 kg/m^3, 1.293 kg/m^3, 1.342 kg/m^3. The simulation model assumed the determination of vehicle energy consumption and driving range. These parameters were determined from the following relationships [13]:

$$E = \frac{E_a \cdot 100}{s} = \frac{E_a \cdot 100}{3.6 \cdot v \cdot t} = \frac{10^5 \sum P_{ak}}{3.6 \cdot v}, \tag{1}$$

$$\sum P_{ak} = P_r + P_{odb} = \frac{P^d}{\eta_{SE}} + P_{odb} = \frac{P_K}{\eta_{SE} \cdot \eta_{PG}} + P_{odb} = \frac{F_{op} \cdot v}{\eta_{SE} \cdot \eta_{PG}} + P_{odb} = \frac{(F_t + F_p + F_a) \cdot v}{\eta_{SE} \cdot \eta_{PG}} + P_{odb}, \tag{2}$$

$$\sum P_{ak} = \frac{\left[f_t \cdot (m_1 + m_2) \cdot g + \frac{\rho_P}{2} \cdot c_x \cdot A \cdot v^2 + (m_1 + m_2) \cdot \delta \cdot g \right] \cdot v}{\eta_{SE} \cdot \eta_{PG}} + P_{odb}, \tag{3}$$

where:
E – energy consumption [kWh/100 km],
E_a – effective capacitance of battery pack = 21.3 kWh,

s – driving range [km],
v – vehicle speed [m/s],
t – time [h],
$\sum P_{ak}$ – battery load [W],
P_r – resistance to motion power [W],
P_{odb} – power consumed by electrical load points [W],
P^d – electric motor power [W],
P_K – power on wheels [W],
η_{SE} – electric motor efficiency,
η_{PG} – final drive efficiency,
F_{op} – resistance to motion [N],
F_t – wheel rolling resistance [N],
F_p – air resistance [N],
F_a – inertia resistance [N],
f_t – wheel rolling resistance coefficient,
m_1 – complete vehicle kerb weight [kg],
m_2 – passenger and load weight [kg],
g – gravitational acceleration [m/s^2],
ρ_P – air density [kg/m^3],
c_x – air resistance coefficient,
A – vehicle frontal area [m^2],
δ – coefficient of rotating masses.

The vehicle energy consumption and driving range were determined for three modes of power utilisation by vehicle electrical load points (Fig. 3) [1, 7].

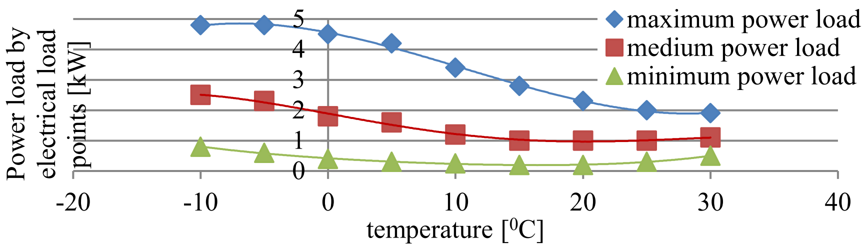


Fig. 3. Power intake by vehicle electrical load points [1, 7]

The strategy of loading the battery with the power of electrical load points assumed the following load modes:

– maximum – control systems, lights, car radio, GPS, air conditioning / heating maximum load,
– medium – control systems, lights, car radio, GPS, air conditioning / heating minimum load,
– minimum – control systems, lights, car radio, GPS, air conditioning / heating switched off.

Using the data and the adopted model, the simulation characteristic curves of vehicle energy consumption and vehicle driving range as a function of ambient temperature (assuming a constant pressure equal to p = 101.3 kPa), vehicle acceleration, and acclivity slope being climbed by the vehicle, were determined.

4. Relationship between vehicle energy consumption / vehicle driving range and external temperature

From the adopted test model, the characteristic curves of vehicle energy consumption and driving range versus vehicle speed as a function of external temperature were obtained (Figs. 4-6, next site).

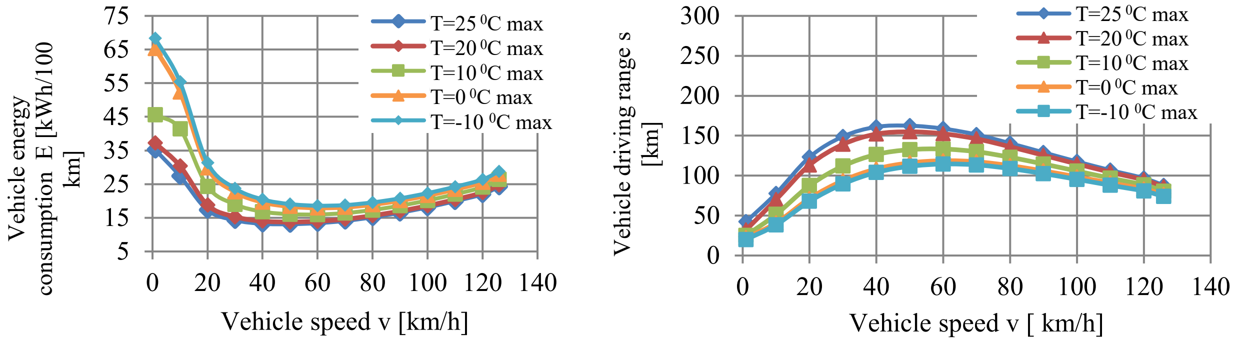


Fig. 4. Vehicle energy consumption and vehicle driving range versus vehicle speed (different external temperature) – electrical load points of maximum power intake

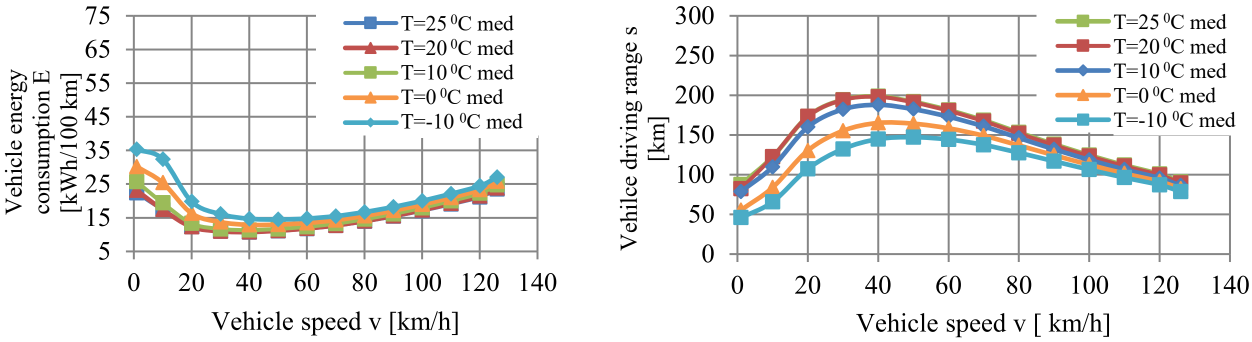


Fig. 5. Vehicle energy consumption and vehicle driving range versus vehicle speed (different external temperature) – electrical load points of medium power intake

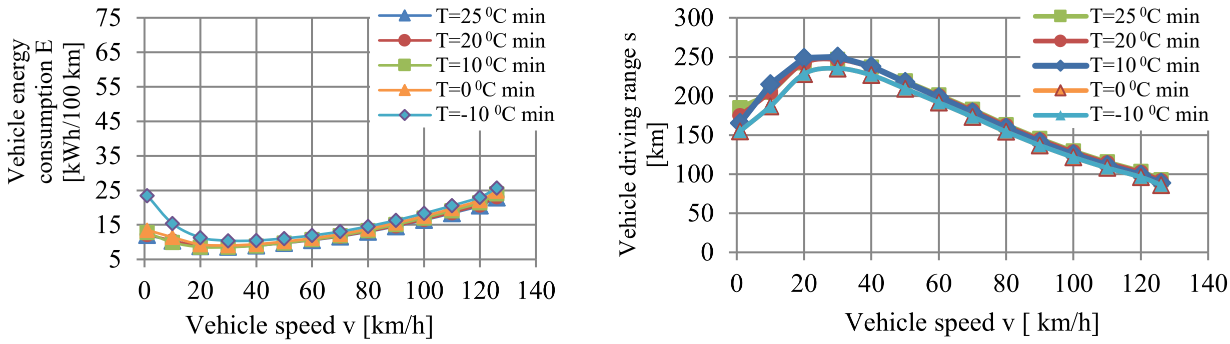


Fig. 6. Vehicle energy consumption and vehicle driving range versus vehicle speed (different external temperature) – electrical load points of minimum power intake

A temperature change (in maximum load mode) from 25°C to 20°C induces an increase in energy consumption from 2 (for the vehicle speed of 126 km/h) to 10% (for the vehicle speed of 10 km/h). A temperature change from 20°C to 10°C induces an increase in energy consumption from 6 (v = 126 km/h) to 36% (v = 10 km/h). A difference in energy consumption for temperatures –10 and 10°C is higher, from 9 to 36%. The longest driving range of electric vehicle occurs for the temperature of +25°C and amounts to 246 km (for minimum load mode), 198 km (for medium load mode), and 161 km (for maximum load mode).

Energy consumption from batteries by electrical load points in maximum load mode (for example, for the vehicle speed of 1 km/h) is by 57% higher than in medium load mode and as much as by 163% higher than that in minimum energy disposal mode. The lowest energy consumption for each of the these model occurs within the vehicle speed range of approximately 30 to 60 km/h (which results in the longest vehicle driving range under urban driving cycle conditions, assuming the omission of traffic congestion phenomenon).

For the vehicle speed of 50 km/h (vehicle motion, T = 25°C), the vehicle driving range for minimum load mode is by 14% higher than that for medium energy disposal mode by electrical load points and by 35% higher than that for minimum energy disposal mode by electrical load points.

5. Relationship between vehicle energy consumption / vehicle driving range and vehicle acceleration / acclivity slope

Based on the motor characteristic curve [8] and the technical and operational characteristics of vehicle, the characteristic curve of motor torque was determined with the curves of inertia resistance and grade resistance being applied to them. The lines $F_t + F_p$ and the dotted lines on both diagrams (Fig. 7) describe the utilisation of motor torque versus vehicle speed for specific acceleration values (0.5, 1, 1.5, 2, 2.5 m/s^2) or for specific road slope values (5, 10, 15, 20, 25, 30, 35, 40, 45%). Using the characteristic curve from Figure 7 (on the left), the diagrams showing the vehicle energy consumption and the vehicle driving range versus its speed were made for different acceleration values according to the utilisation of electrical power intake points (Fig. 8-10).

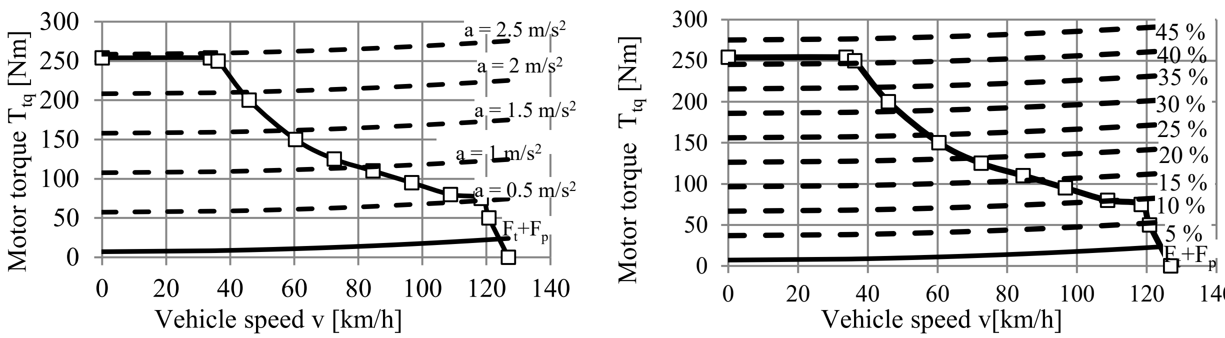


Fig. 7. Motor torque with the inertia resistance curves (on the left) and the grade resistance curves (on the right)

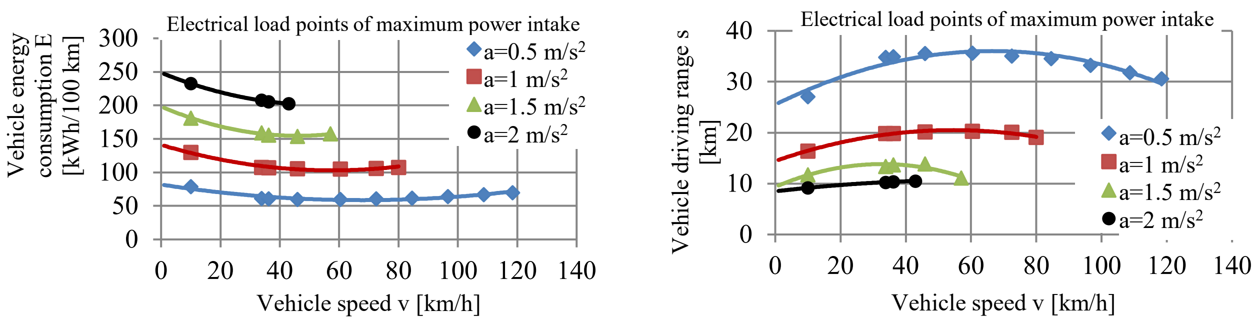


Fig. 8. Vehicle energy consumption and vehicle driving range versus vehicle speed (different vehicle acceleration) – electrical load points of maximum power intake

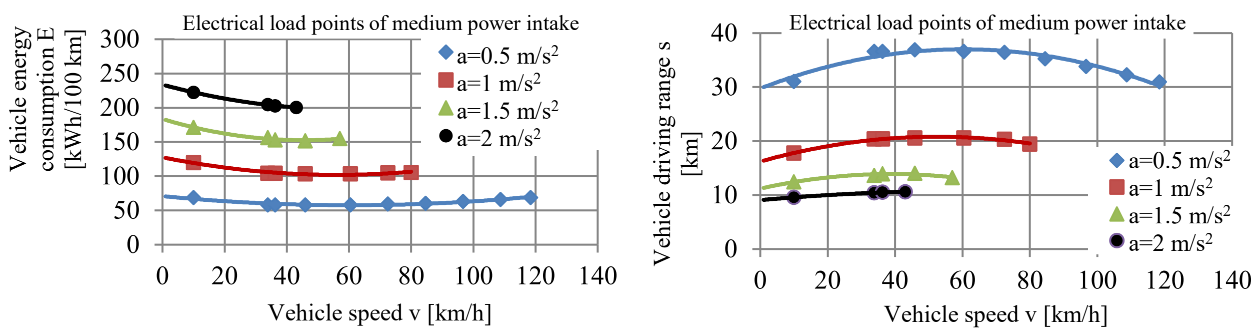


Fig. 9. Vehicle energy consumption and vehicle driving range versus vehicle speed (different vehicle acceleration) – electrical load points of medium power intake

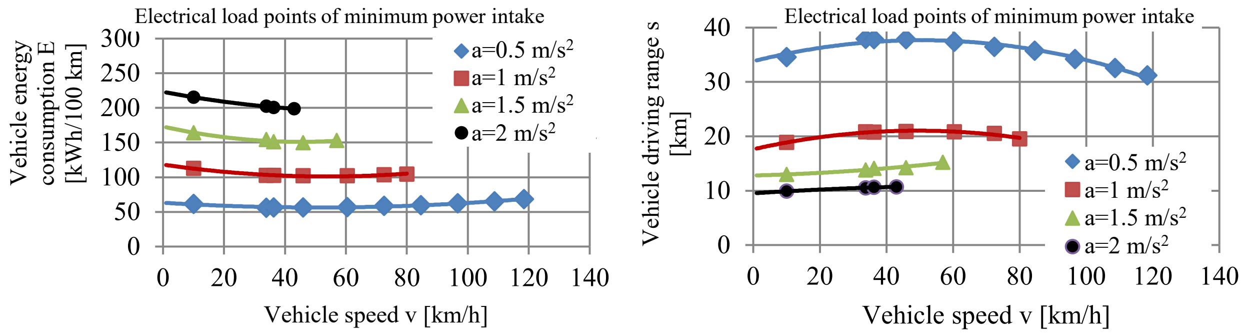


Fig. 10. Vehicle energy consumption and vehicle driving range versus vehicle speed (different vehicle acceleration) – electrical load points of minimum power intake

The highest energy consumption amounted to 249 kWh/100 km with the driving range of 9.16 km (for the vehicle speed of 1 km/h and the acceleration value equal to 2 m/s^2, i.e. maximum power intake by electrical load points), while the lowest value of this parameter was equal to 56.12 kWh/100 km with the driving range of 37.9 km (for the vehicle speed of 34 km/h and the acceleration value equal to 0.5 m/s^2, i.e. minimum power intake by electrical load points).

Based on Fig. 7 (on the right), the diagrams showing the relationship of vehicle energy consumption and vehicle driving range versus its speed were made for different road slope values for different modes of the utilisation of electrical power intake points (Fig. 11-13).

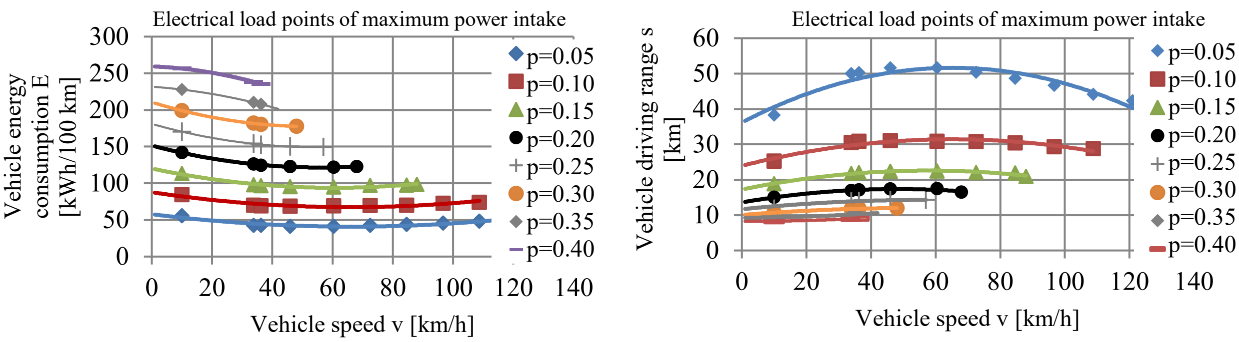


Fig. 11. Vehicle energy consumption and vehicle driving range versus vehicle speed (different slope acclivity) – electrical load points of maximum power intake

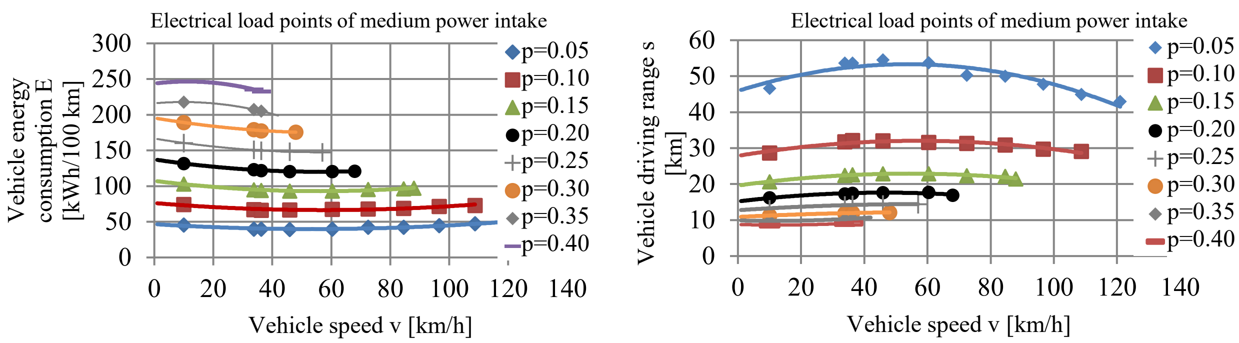
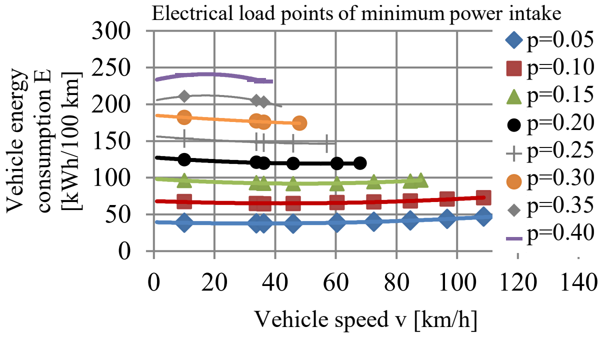


Fig. 12. Vehicle energy consumption and vehicle driving range versus vehicle speed (different slope acclivity) – electrical load points of medium power intake

The highest energy consumption of 256.45 kWh/100 km (vehicle driving range of 8.30 km) was observed for the vehicle speed of 10 km/h and the road slope value equal to 40%, while the lowest value of this parameter was equal to 37.53 kWh/100 km (vehicle driving range of 56.74 km) for the vehicle speed of 46 km/h and the acclivity slope equal to 5%.



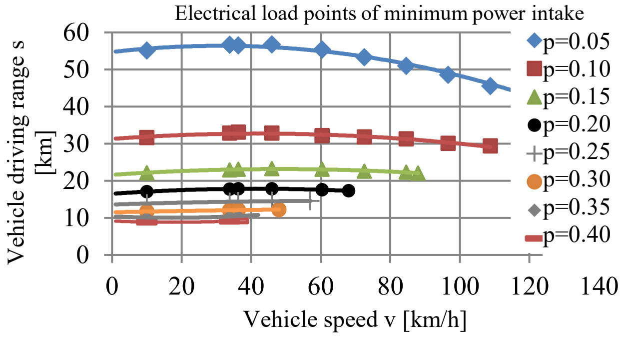


Fig. 13. Vehicle energy consumption and vehicle driving range versus vehicle speed (different slope acclivity) – electrical load points of minimum power intake

6. Conclusions

A slight change in temperature induces a change in vehicle energy consumption and driving range be a few percent. A decrease in temperature by 20°C may result in increased energy consumption even to about 40%. The advantage of the control system is that in the case of low level of available capacitance of a battery pack the system switches off different electrical load points (having no effect on driving safety), such as air conditioning or heating, which results in minimum power intake by equipment and decreased energy consumption and considerably extension of driving range (depending on temperature even to about 100 km more).

Reasonable utilisation of vehicle capacity to accelerate also allows the energy consumption and driving range of electric vehicle to be reduced. The driving technique consisting in aggressive acceleration (close to the value of 2 m/s^2) is associated with several times higher energy consumption in comparison with acceleration of a car in a manner similar to economy driving (acceleration value equal to 0.5 m/s^2). The advantage of the control system is maximum speed reduction in order to decrease vehicle energy consumption and increase its driving range.

Based on the driving conditions, and hence on the route characteristics, being described, among others, by acclivity slope, it is possible to observe a similarity in vehicle energy consumption in relation to its capacity to accelerate. In increase in acclivity slope induces increased energy consumption (a difference in the value of this parameter between a five-percent acclivity slope and a fourty-percent one can be even several times greater).

A positive aspect of electric vehicle is the control system, which aims to reduce its energy consumption and increase its driving range depending on the varying conditions of vehicle operation. A negative aspect, associated with the operating conditions, is battery capacitance, which limits the driving range of electric vehicle.

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