INFLUENCE OF TRAFFIC CONDITIONS ON THE ENERGY CONSUMPTION OF AN ELECTRIC VEHICLE

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Resume

Traffic conditions are constantly changing when driving in urban areas. Depending on the hour the vehicle is moving, the drive is more or less smooth. The aim of this study is to determine how the traffic conditions affect the energy consumption of an electric vehicle. Simulations carried out in AVL Cruise software, based on real-world testing, were used to determine this issue. The methodology for conducting the research and performing the simulations is also described. The energy consumption of the vehicle, on each route and during the hours studied, was compared to each other based on the results from the simulation software. The results of the study showed that the influence of traffic conditions on the vehicle energy consumption is significant. Simulations have shown that the need for numerous stops and driving at low speeds requires increased energy consumption.

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1 Introduction

Electric vehicles have varying energy consumption, which is affected by many factors. This is particularly important for EV (Electric Vehicle) drivers who are concerned about discharging their vehicle while driving. Papers [1-2] present the phenomenon of range anxiety, which is directly related to vehicles energy consumption. Paper [3] outlines how to plan a route in relation to range concerns. To this end, an algorithm was created that takes into account the driver's feelings to create a route where the risk of unexpected events is low.

The energy consumption of electric vehicles is one of the core areas of electric vehicle testing. The methods for its analysis usually include simulation based on the real data or simulation only.

The authors of the paper [4] used the AVL Cruise simulation software to investigate the energy consumption of an electric vehicle. For this purpose, well-known, ready-made cycles such as NEDC (New European Driving Cycle) and JC08 (Japan Cycle) were used. The range resulting from the simulations was compared for both cycles and two different vehicles. A similar approach was used by the authors of [5], who used the NEDC, WLTP (Worldwide Harmonized Light Vehicle Test Procedure) and highway cycle in the AVL Cruise software for simulations. In addition, different ambient temperatures, vehicle load and battery state of charge were introduced into the simulation. Paper [6] simulates the energy consumption of electric vehicles based on geographical route data. The road model and its characteristic points were created based on geographical information, a map and GPS.

A different approach was used by the authors in the paper [7]. They collected actual data based on driving in Shanghai. Based on those, they created a real driving cycle, which was used to simulate energy consumption using the ADVISOR software. In paper [8], vehicle testing on a chassis dynamometer was used. This data was used to create a simulation that provided information on the factors affecting the energy consumption of an electric vehicle.

In paper [9], real data collected in Beijing was used to estimate energy consumption. The route information was collected by driving a Nissan Leaf. Energy consumption was estimated using mathematical models.

***Table 1** A literature review of factors influencing vehicle energy consumption*

Factors influencing energy consumption	Reference	Results of studies on the factor
Ambient conditions	Air temperature [10]	The authors showed that the influence of temperature on energy consumption varied, particularly above 30 °C and below 10 °C. An interaction between ambient temperature and the use of a heater or air conditioner was demonstrated. The rational use of these devices will save around 10% of energy.
	Air temperature [11]	The air temperature was measured over a period of four years of research. The results show that specific energy consumption is almost twice as high when the temperature is around 0 °C as when it is close to 19 °C. This dependency mainly applies to short trips.
	Wind [12]	The authors showed that wind is clearly relevant to the energy consumption of electric vehicles. Based on analyses of routes in the UK, the difference in energy demand was shown to be 14% more for a flat route without varying speed limits on a windy day than compared to a non-windy day. For a hilly route with numerous speed restrictions, the demand was 5% higher than on a day with no wind.
Route characteristics	Road gradient [13]	The influence of the road gradient on energy consumption was investigated. The results showed that the energy increases almost linearly with increasing absolute gradient. Electric vehicles are more efficient than conventional vehicles in mountainous areas due to the possibility of energy recovery.
	Road gradient [11]	Results from real-world tests have shown that an increase in gradient increases energy consumption. For a gradient of 3%, specific energy consumption is 50% higher than when driving on a flat road. When the gradient decreases to -3%, the specific energy consumption is reduced by 80% compared to a flat road.

The energy consumption of a vehicle is affected by certain factors. Those may be related to external conditions, the characteristics of the route, the way the vehicle is driven or directly to the vehicle. A literature review, related to factors affecting the energy consumption of an electric vehicle, is presented in Tables 1 and 2. They summarize the type of factor that was analyzed and its results. The vehicles tested in the given literature sources are not the same as in this paper. The main aim of the literature review was to determine the scope of the influence of various traffic conditions on the energy consumption of an electric vehicle.

It is important to remember that other factors, such as braking energy recovery, the initial state of charge of the battery or its general condition, also affect the amount of energy consumed after a trip. Table 3 summarizes the factors that affect the energy efficiency of an electric vehicle.

The problem of energy management does not only concern individual vehicles driven by “casual” drivers. It also appears in larger concentrations, i.e. in fleets. In the paper [20], the authors presented the problem of route planning for electric vehicle fleets. A model is presented, including route, speed, braking and power transmission system information. A numerical experiment based on the Gothenburg routes, was also carried out. What was important in the authors’ approach was the listing of junctions and the detailed presentation of the road topography. The results show that the estimation error of energy consumption is 2.28% and of time is only 3.48%.

The aim of this paper was to determine the influence of traffic conditions on the energy consumption of an electric vehicle based on simulations performed under the real-world conditions. This study of the topic offers the possibility of further research and simulations related to other conditions under which the vehicle moves, e.g. changes in land elevation, road curvature etc. By creating simulations, it is possible to determine the range of the vehicle while driving in urban areas.

In this study, an approach is used that allows seeing how the vehicle energy consumption changes as a function of route alignment and traffic conditions. It is extremely important that the research was carried out using actual trip data. With the information used, it is possible to take advantage of the opportunities offered by AVL Cruise.

2 Research methodology

2.1 Real-world study

The research involved taking actual measurements of speed, distance and time using a test vehicle. This data was used as input in the AVL Cruise simulation software.

The trip was made in the area of Kielce, a medium-

***Table 2** A literature review of factors influencing vehicle energy consumption 2*

Factors influencing energy consumption	Reference	Results of studies on the factor
	Type of road and travel time [14]	The paper shows the difference in energy consumption related to travel time and road type. Travel times increase during the peak traffic periods. In addition, stopping at red lights, sharp bends and speed bumps can increase energy consumption by up to several hundred percent. This is especially true for drivers with an aggressive driving style
	Traffic conditions [11]	The authors showed that on shorter routes, specific consumption is about 9.7% higher than on long distances. In addition, the greater the proportion of stops and the lower the average travel speed, the higher the specific consumption (up to 19%), especially on short routes.
	Differentiation of cycles [5]	In this paper, the authors compared energy consumption based on known driving cycles in the AVL Cruise software. The results for the NEDC, WLTP and highway cycle test were compared to each other for different values of vehicle load, ambient temperature and battery charge. It has been shown that as the average vehicle speed per cycle increases, energy consumption also increases. In addition, the simulation showed that negative temperatures increase energy consumption by around 24% in relation to driving at 20 °C.
Driver's driving style	[11]	The authors considered the influence of driving conditions on the specific energy consumption of an electric vehicle, based on actual data. The driving method was determined on the basis of the product of acceleration and speed. If 9 5% of the calculated values were above 75% of the dynamic work limit, then driving was defined as aggressive. If the values were below 25% of the dynamic work limit, then driving was defined as passive. The results showed that the more aggressive the driving, the more energy is consumed. Compared to calm driving, the difference is 16%, while moderate driving is 7.1%.
	[14]	The study compared aggressive, normal and eco-driving styles of drivers. The driving method was determined on the basis of the values of acceleration, braking, driving speed, lateral acceleration and the effectiveness of regenerative braking. The difference between the most dynamic and economical driving is relatively around 17% and changes with increasing speed. When accelerating, an aggressive driver uses up to 25-30% more energy.
Vehicle-related factors	Vehicle weight [12]	The paper shows that vehicle weight significantly affects the energy consumption of an electric vehicle. This is particularly related to overcoming the resistance to motion and the route the vehicle takes.
	Use of auxiliary equipment [15]	The use of equipment to heat or cool the interior of an electric vehicle has been shown to reduce its range. The percentage reduction in range varies from 35 to 50% and is related to the weather conditions outside. Analysis of ranges in individual cities in the US shows that milder seasons result in less energy being used to heat the vehicle, resulting in a greater range.
	Battery weight [16]	The paper shows how the weight of the battery affects the energy consumption of the vehicle. Batteries with more weight have been shown to consume more energy.

***Table 3** A literature review of factors influencing energy efficiency*

Factors influencing energy efficiency	Reference	Results of studies on the factor
SOC	[17]	The authors of the study highlighted the relationship between the state of charge of the battery and energy consumption. According to them, if the SoC level increases, the power consumption decreases. Maintaining a constant power output is possible by consuming more energy with a reduced battery state of charge.
Regenerative braking	[18]	The paper examines how driving with energy recovery affects energy efficiency. According to the results, energy flow efficiency increased by 41.09%, while driving range increased by 24.63%.
SOH	[19]	The authors used a method that allows the remaining life of the battery to be determined based on information related to its health.

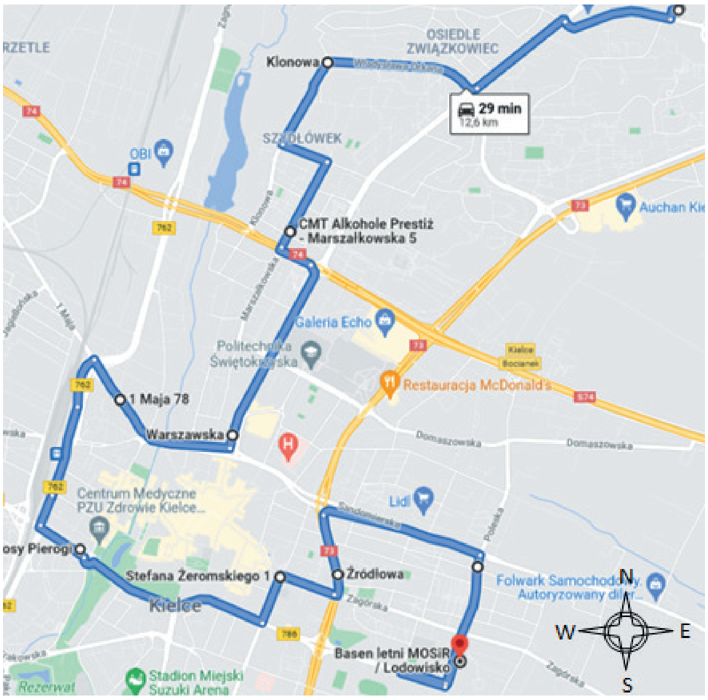

Figure 1 *Route surveyed in Kielce (Poland)*

Figure 2 *Test vehicle - Ford Transit*

sized city, three times a day due to the different traffic conditions. The times chosen were 7.30 a.m., 11.30 a.m. and 3.30 p.m., as these are the most characteristic time slots found in the city. Carrying out the road tests made it possible to record the actual driving parameters. This approach allowed to determine the actual speed, braking, acceleration, stopping time or duration of the trip. The information recorded by the measuring devices on the Ford Transit made it possible to simulate a vehicle with an electric drive under the same driving conditions. A similar methodology for route and time of day selection was used by the authors in [21-22].

There are three routes, designated as T1 (Figure 1), T2 and T3, running from the northeast to the southeast of Kielce. The route T2 ran in the same way as the T1 route, shown in Figure 1, but in the opposite direction. The T3 road was a loop of the T1 and T2 routes.

Kistler brand equipment was used to prepare the measurements, consisting of a TAA KCD15911 acceleration module, a Datron S-350 optoelectronic sensor, a Kistler GPS CDA module and a KIDAQ 5501A Data Acquisition Station. The equipment was mounted on a Ford Transit test vehicle (Figure 2), which is available at the laboratory of the Kielce University of Technology. This type of measuring device and vehicle was used by the authors in the studies described in [23-24], to determine the parameters of vehicle movement and the driver's manner of driving under different road conditions.

2.2 Simulation studies

The simulation was carried out using AVL Cruise, a product of the Austrian company AVL List GmbH. The tool allows both electrified and conventional vehicles to be analyzed from the point of view of, among other things: fuel and energy consumption, power distribution,

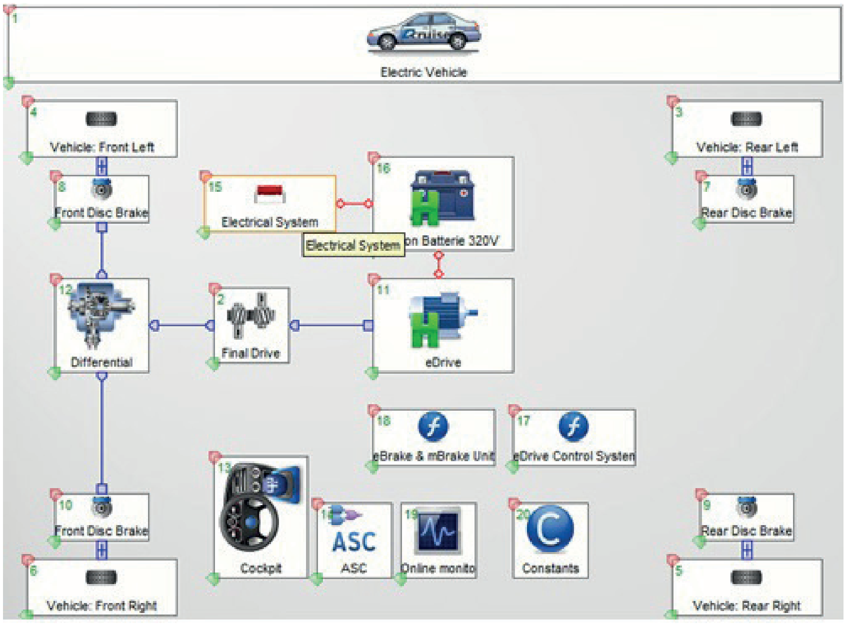

Figure 3 *Electric vehicle model in AVL Cruise software*

Table 4 *Characteristic parameters of the driving cycle on each route at indicated times*

Route	T1			T2			T3		
Hour	7.30 a.m.	11.30 a.m.	3.30 p.m	7.30 a.m.	11.30 a.m	3.30 p.m	7.30 a.m.	11.30 a.m.	3.30 p.m.
Route length [km]		11.45			11.59			23.04	
Time of travel [s]	2248	1805	3002	1756	1685	2657	4004	3490	5659
Average speed [km/h]	18.3	22.8	13.7	23.8	24.7	15.7	20.7	23.8	14.7

hill climbing, braking, power loss, exhaust emissions or gear ratios. The AVL Cruise allows using commonly known driving cycles, as well as introducing a custom cycle. The software gives the possibility to use already prepared vehicles, change their parameters, as well as to build the model of the actual vehicle by oneself [25]. The findings of simulation studies using it are described in paper [26], where the software was used to simulate range changes under the well-defined conditions during the WLTP cycle. Based on the simulation, the vehicle's driving capabilities were determined. The authors in [27] used the capabilities of the software to show how the gear ratios or engine parameters affect vehicle performance and how they can be optimized. In [28], a simulation was carried out to determine the carbon monoxide emissions and energy consumption of a taxi fleet in Brazil. The forecasts were based on replacement of the rolling stock from conventional to electric and energy production conditions.

The vehicle used in the simulation is a front-wheel drive electric car. Its mass during the simulation was 1300 kg. The frontal area of the vehicle is 1.97 m^2, while the drag coefficient is 0.284. The vehicle model (Figure 3) contains all the necessary vehicle components, i.e. the electric motor, clutch, gearbox, electrical components, etc. The battery is characterized by parameters such as an initial state of charge of 95 %, a voltage of 350 V and an energy capacity of 47.5 Ah. Furthermore, the battery consists of five rows of compartments, one cell in each.

3 Analysis of the results obtained

3.1 Analysis of the speed profiles

Based on the measurements obtained, parameters related to the driving cycle on each route were determined (Table 4). The length of route T1 was 11.45 km, for T2 it was 11.59 km and for T3 it was 23.12 km. The routes are characterized by varying travel times and average speeds. On route T1, the fastest trip was at 11.30 a.m., while the longest was at 3.30 p.m. A similar dependency occurred on routes T2 and T3. When analyzing the average speed, the relationship between the highest and lowest values is analogous to that for the travel time.

For the routes studied, speed profiles were drawn up as a function of time, showing the dynamics of speed changes during travel. In addition, it was also possible to create a speed distribution from the data collected. Figures 4-6 show the speed profiles and distributions for routes T1, T2 and T3 in the analyzed time intervals.

A significant reduction in traffic speeds is evident in the graphs for the 7.30 a.m. and 3.30 p.m. travels on route T1 (Figures 4a, c). During the afternoon peak, the

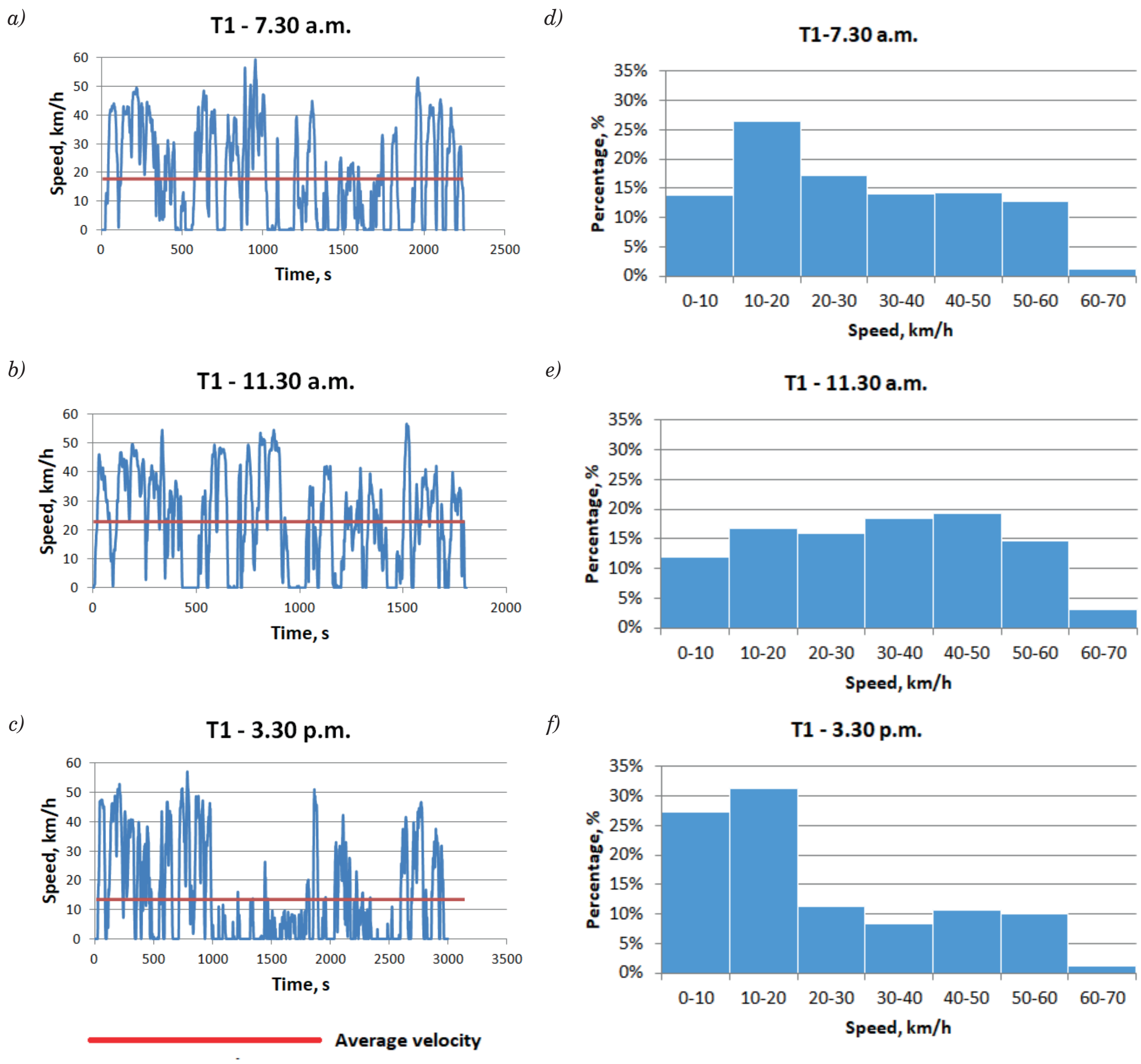

Figure 4 *Vehicle speed characteristics for route T1 in each of the analyzed hours: a - Vehicle speed profile at 7.30 a.m., b - Vehicle speed profile at 11.30 a.m., c - Vehicle speed profile at 3.30 p.m.; d - Vehicle speed distribution at 7.30 a.m., e - Vehicle speed distribution at 11.30 a.m., f - Vehicle speed distribution at 3.30 p.m.*

vehicle often stopped or moved at much lower speeds as evidenced by an average speed of about 13.7 km/h (Figure 4c). At 11.30 a.m., traffic was relatively at its smoothest and, even despite the repeated stops, the average speed reached its highest value (Figure 4b). Meanwhile, it can be seen that at this time of day the shares of the different speed ranges are most evenly distributed (Figure 4e). The distributions for 7.30 a.m. and 3.30 p.m. are significantly different in this respect, where the proportion of speeds below 20 km/h is 40 and 60 % respectively (Figures 4d, f).

For route T2 (Figure 5), the speed profiles are characterized by more dynamic changes in the speed curve. Comparing the lines on the graph, it can be seen that the vehicle accelerated and braked more frequently. However, in this case, the low speeds and frequent stops characteristic of driving on a congested street, occur less frequently than on route T1. On route T2, the conclusions regarding the average speeds recorded for route T1 were qualitatively confirmed. Again, the highest average speed of around 25 km/h was recorded at 11.30 a.m. (Figure 5b), slightly lower at 7.30 a.m. (Figure 5a) and the lowest in the afternoon peak at 3.30 p.m. (Figure 5c). The distribution of speeds clearly shows the changes that occurred from hour to hour and it can be seen that speeds of 30-50 km/h dominate at 11.30 a.m. (Figure 5e).

The longest route, T3, is characterized by strongly varying profiles where it is noticeable that the vehicle was traveling at a below average speed at times of heavy traffic. The lowest average speed occurred during the 3.30 p.m. trip, as confirmed by the speed distribution (Figure 6f), where speeds of 0-20 km/h have the largest share. The vehicle was traveling at its highest average speed at 11.30 a.m. The distribution of speeds is relatively evenly distributed (Figure 6e), with the most common speeds being the 30-50 km/h range.

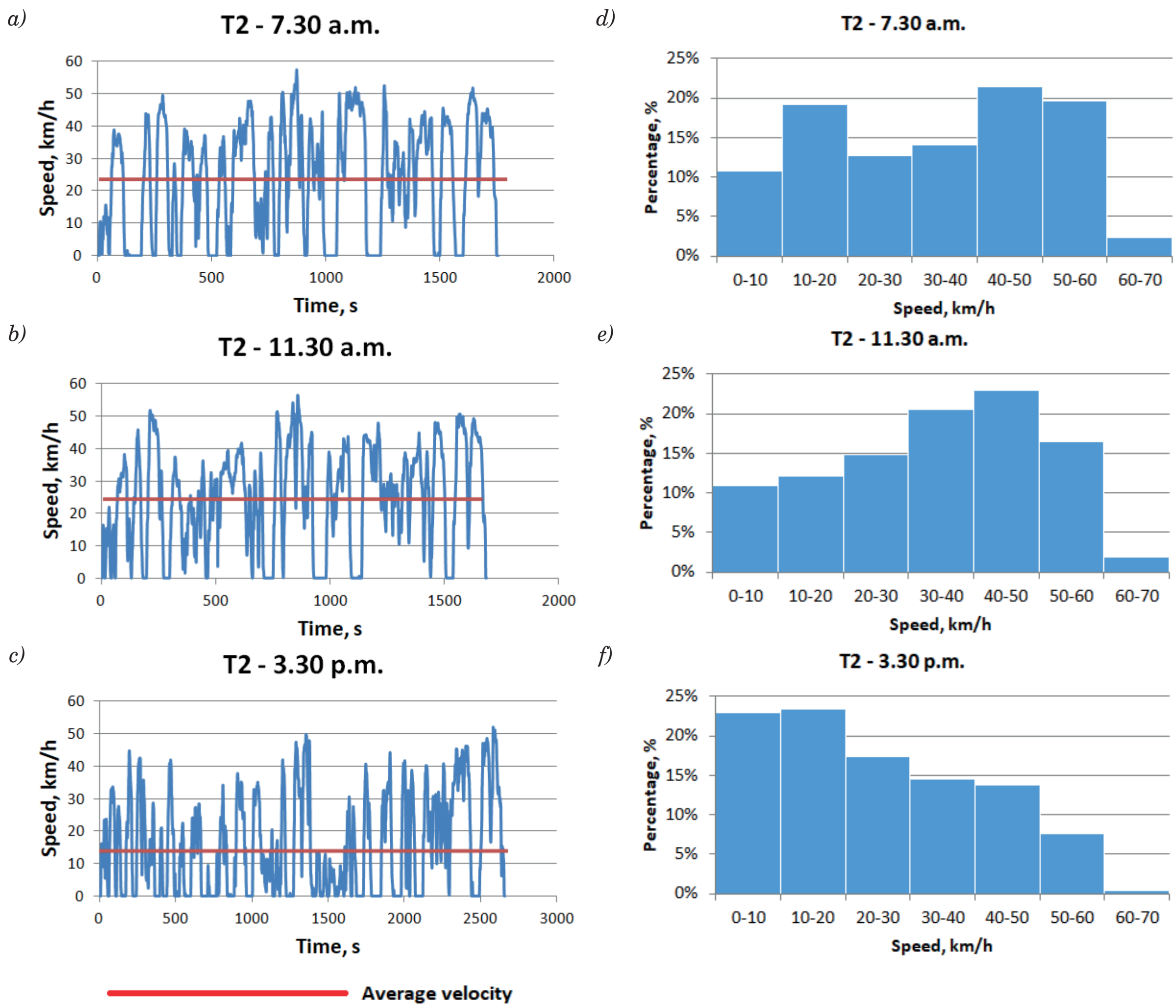

Figure 5 *Vehicle speed characteristics for route T2 in each of the analyzed hours: a - Vehicle speed profile at 7.30 a.m., b - Vehicle speed profile at 11.30 a.m., c - Vehicle speed profile at 3.30 p.m.; d - Vehicle speed distribution at 7.30 a.m., e - Vehicle speed distribution at 11.30 a.m., f - Vehicle speed distribution at 3.30 p.m.*

3.2 Energy consumption analysis

The results of the tests, related to obtaining the real speed profiles, allowed simulations to be performed in the AVL Cruise software. In order to obtain the results, data related to driving time and speed had to be imported into the software. Based on suitable algorithms, the software calculated, among other things, the energy consumption per kilometer, the energy lost and recovered during the trip and the battery charge at the end of the trip.

Figure 7. shows a comparison of the output and input energy consumption curves that were calculated during the simulation and a comparison of their final values. The energy output is the energy that was used to propel the vehicle, whereas, the energy input is the energy that the vehicle has recovered from braking during the trip.

For route T1, the level of energy lost was the highest at 3.30 p.m. and the lowest at 11.30 a.m. The difference between the energy consumption was 8%. The energy recovered by the vehicle, on the other hand, was similar in each hour and oscillated around 1900 kJ. The test graph (Figure 7d) shows that the input energy has a more flattened character than that of the output energy. The shorter the route, the steeper the change in energy consumption. It can be seen that initially the lines of the graph (Figure 7d) coincide for both types of energy, while the visible differences start after about a half of the route. The energy lost is more than twice as high as the energy recovered.

On route T2, the output energy reached its highest value during the trip at 3.30 p.m. The vehicle also recovered the least amount of energy during the drive at this time. The input and output energies for the 7.30 a.m. and 11.30 a.m. trips are similar. The difference between the highest and lowest energy consumption is 5%. This can also be seen in the graph showing the curve of energy consumption. The lines in the graph (Figure 7e) overlap, showing slight differences at the start phase and at the end of the route, due to the length of the trip.

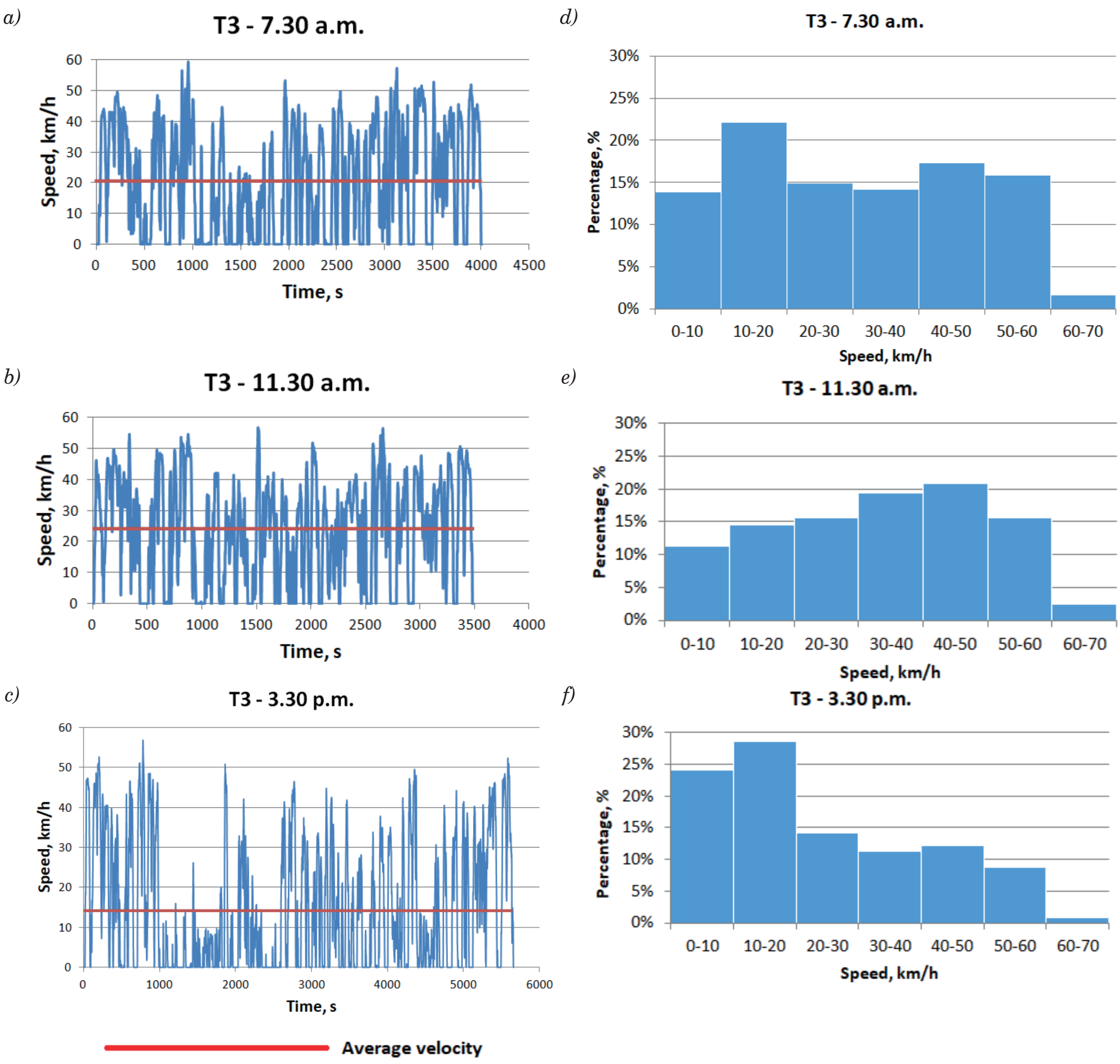

Figure 6 *Vehicle speed characteristics for route T3 in each hour analyzed: a - Vehicle speed profile at 7.30 a.m., b - Vehicle speed profile at 11.30 a.m., c - Vehicle speed profile at 3.30 p.m.; d - Vehicle speed distribution at 7.30 a.m., e - Vehicle speed distribution at 11.30 a.m., f - Vehicle speed distribution at 3.30 p.m.*

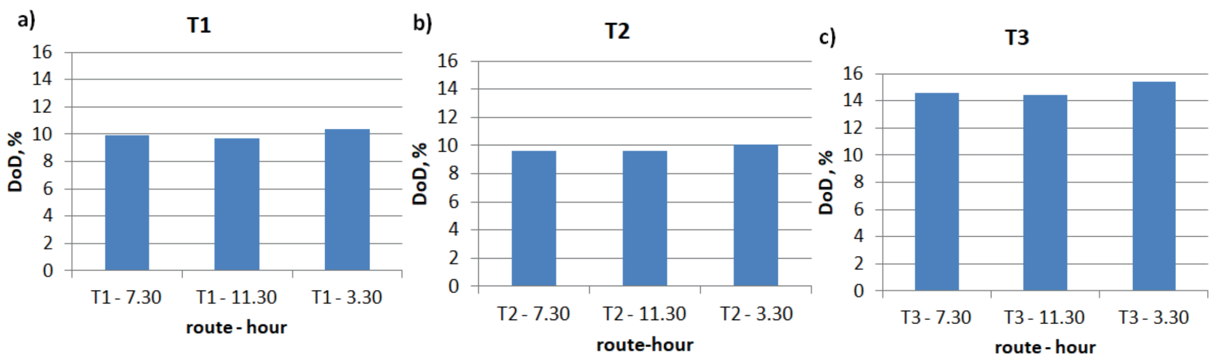

Figure 8 *Battery depth of discharge in the analyzed hours after completing routes a) T1, b) T2, c) T3*

For route T3, as for routes T1 and T2, the highest value of energy lost was calculated at 3.30 p.m. and the lowest at 11.30 a.m. The vehicle therefore used 6% more energy in the afternoon. The energy recovered oscillates around a similar value of 3700 kJ for all of the times of the day studied, but it is the lowest in the afternoon. The

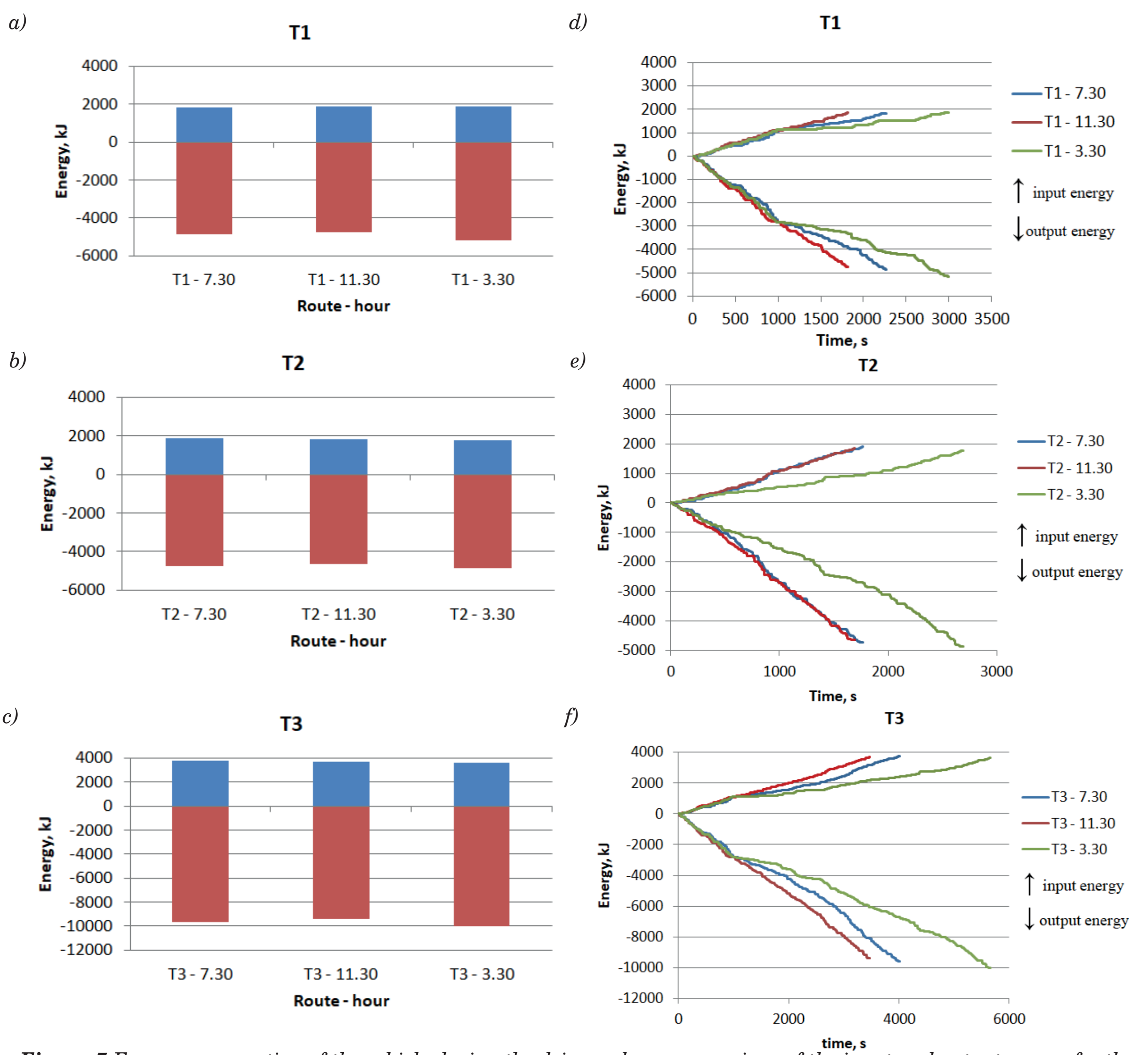

Figure 7 *Energy consumption of the vehicle during the drive: a, b, c - comparison of the input and output energy for the routes T1, T2 and T3, respectively in the tested hours, e, f, g - the curve of the input and output energy consumption for routes T1, T2 and T3, respectively*

input and output energy consumption patterns are the most varied of all the collated routes. There is a small overlap between the lines in the graph (Figure 7f). It is noticeable that there are no sudden collapses and that changes occur smoothly.

The amount of energy absorbed to complete each route was also represented by the depth of discharge (DoD) of the battery. This value is expressed as a percentage and represents, in percentage terms, the amount of energy consumed from the battery per trip. For routes T1, T2 and T3 the depth of discharge is shown in Figure 8.

The depth of discharge of the battery on route T1 is the highest at 3.30 p.m. and is 10.4%. The vehicle then covered the specified distance in the longest time, in addition to often standing in traffic congestion or traveling at low speed. The battery was discharged the least at 11.30 a.m., which is when the trip took the shortest time. In the afternoon, the battery discharge was relatively 7% higher than at midday.

On route T2 the depth of battery discharge was the greatest in the afternoon. In contrast, for the two earlier trips the value of this parameter is similar. The trip, took place under similar conditions, which can also be seen in the curve of energy use (Figure 7).

A very similar relationship to the results for route T1 is shown in the graph for route T3. The depth of discharge of the battery at 3.30 p.m. is the greatest, while at 11.30 it is the least. The depth of discharge was relatively 5% greater.

Energy consumption was also presented on a per kilometer basis, in the form of an hour-by-hour comparison on a given route (Figure 9).

When comparing the graphs to each other, it can be seen that the highest energy consumption occurred on route T1 at 3.30 p.m., reaching a value of almost 350 kJ/km. This is relatively 28% more than during the least energy-consuming trip on road T1. The relative difference between the highest and lowest consumption for route T2 is 9% and for the route T3 is 12%.

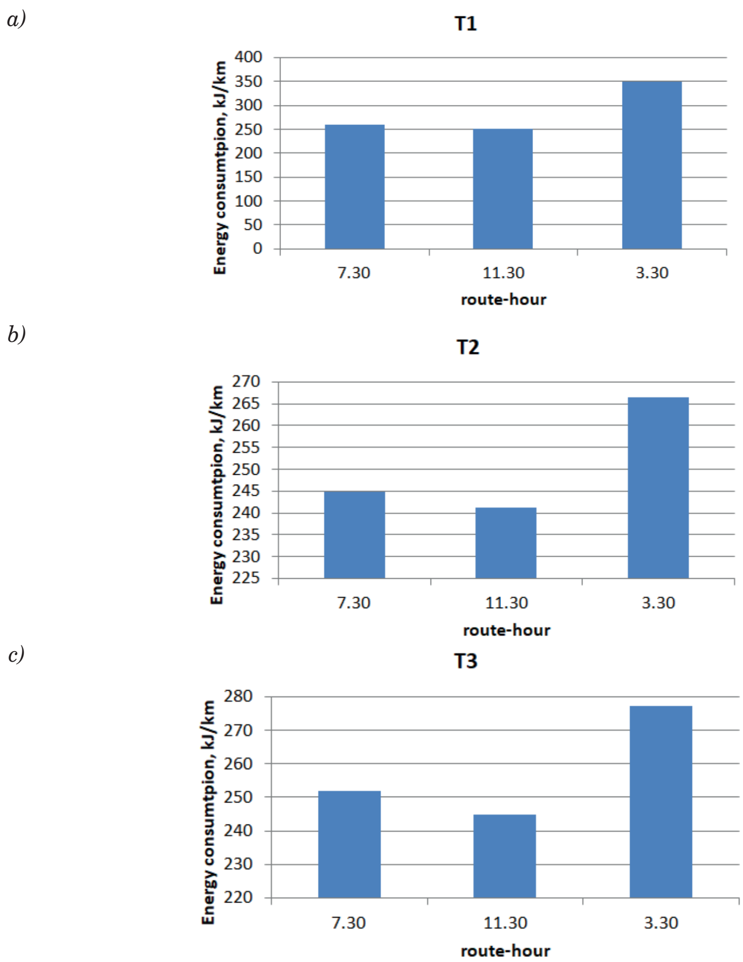

Figure 9 *Energy consumption in different traffic conditions per 1 kilometer for routes: a) T1, b) T2, c) T3*

4 Conclusions

In summary, the energy consumption of a vehicle varies depending on the conditions under which the vehicle is driven. This is confirmed by every parameter calculated from the simulation software. The reason for differences is mainly due to the time of day the vehicle traveled and the road conditions. On each route, the afternoon trip around 3.30 p.m. was the longest and was characterized by the long stopping times or driving at low speeds, typical of urban rush-hour driving. This is when the amount of energy that an electric vehicle needs is the greatest and the battery discharges the most.

The complete opposite was recorded for the 11.30 a.m. trip, where the traffic flowed most smoothly. From the analysis of the speed distribution and profile, it can be seen that the car traveled the route under similar conditions. The speed distribution was more uniform. The vehicle repeatedly braked and accelerated, while then the proportion of stopping time was small. These driving conditions affected energy consumption. The amount of energy used or the depth of discharge of the battery were the lowest.

The 7.30 a.m. driving time combined features of the midday and afternoon driving conditions. The vehicle moved quite smoothly and the stops or periods of slow driving that occurred were much shorter than at 3.30 p.m. This has resulted in average values that lie between the highest typical values of 3.30 p.m. and the lowest characteristic values of 11.30 a.m. The exception is the result obtained for the morning and midday cycle on route T2. The speed distribution and its profile indicate that the route was driven in very similar conditions, hence the values for energy consumption or the battery discharge were very similar.

Performing simulations based on the real-world testing has produced very specific analyses and conclusions. It can therefore be seen that the more difficult the traffic conditions on the road, involving traffic jams, stop or slow driving, the more energy-consuming the electric vehicle becomes. This kind of information is extremely important for drivers who own an electric vehicle that they drive around town. This allows for planning the steps involved in charging and driving in rush hour. With this information, the driver will be able to avoid being stressed about the vehicle's range and possible battery drain while driving.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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