The paper presents the results of a statistical analysis of real-world driving cycles recorded in the Poznan agglomeration. The analysis was carried out in order to find out possible relationships between the average speed and other statistics describing speed profiles at the level of individual road sections (e.g. average speed, average acceleration/deceleration, number of stops etc.) in order to create a macroscopic average-speed energy consumption model of an electric vehicle.

Keywords: electric vehicles, energy consumption modelling, urban driving

1. INTRODUCTION

As e-mobility and battery electric vehicles (BEVs) have been gaining more and more focus over the recent years, new challenges have arisen in the area of fleet management. Due to the limited range of electric vehicles, it is necessary to be precise about the expected energy consumption in order to find energy-efficient routes and schedule battery recharging. However, when planning fleet operations, one needs to predict energy consumption without the complete knowledge of speed profiles, which renders microscopic energy consumption models useless. In such cases, the solution are macroscopic energy consumption models, which need limited input data, such as basic vehicle parameters, the average speed driven on certain links (road sections), link parameters or the external temperature. Such macroscopic models can also be applied in macroscopic and mesoscopic traffic flow sim-
ulation, where vehicle dynamics is simplified, thus the exact speed profiles are unavailable.

The goal of the study is to analyse real-world urban driving cycles in terms of calculating energy consumption of electric vehicles in macro/mesoscopic simulators and route planning tools, where speed profiles are unavailable.

2. MACROSCOPIC ENERGY CONSUMPTION MODELS

Modelling energy consumption for electric vehicles is a relatively new research problem, but shares a lot in common with modelling of fuel consumption and emissions, which have been studied for many years. Because of the similarities, all these models can be divided into two major categories, that is macroscopic and microscopic, and then into subcategories depending on the level of detail and aggregation. A detailed classification and description of models for fuel consumption and emissions is presented by Treiber and Kesting [2013].

In the case of managing a fleet at the operational level or running macro/mesoscopic simulation of electric vehicles, where the network is represented as a link-node graph (see Fig. 1), energy consumption has to be estimated for individual vehicles at the level of single links (sections). To take into account the actual traffic on a link, energy consumption may be modelled as a function of the expected/experienced driving speed on a link. Calculating energy consumption on the link level allows to predict/simulate changes in the state of charge (SoC) of a battery for whole routes by decomposing them into links.

![Fig. 1. A graph-based representation of a road network](satellite view image source: Google Maps)
Statistical analysis of real-world urban driving cycles for modelling energy...

Since the average-speed approach takes into account speed fluctuations at the level of single links, calculated energy consumption is expected to be more accurate than that of the constant-speed models [Faria et al. 2012].

3 DATA ACQUISITION AND PROCESSING

3.1. Data acquisition

Driving cycles (velocity profiles) data were obtained by recording GPS coordinates and speed of test vehicles while travelling through or around Poznań, Poland. This data was acquired during normal, everyday driving performed by four drivers. Additional data set was obtained during dedicated driving sessions performed during working days between 10 am and 3 pm.

The data is made up of 53 different trips, with distances varying from 900 m to 13.5 km, with the average of 6.8 km. All the trips were divided into 1.217 sections (i.e. road network links), from 10 m to 2.550 m long, with the average length of 300 m.

<table>
<thead>
<tr>
<th>Section length</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 50 m</td>
<td>50</td>
</tr>
<tr>
<td>50 – 100 m</td>
<td>161</td>
</tr>
<tr>
<td>100 – 200 m</td>
<td>307</td>
</tr>
<tr>
<td>200 – 300 m</td>
<td>218</td>
</tr>
<tr>
<td>300 – 500 m</td>
<td>331</td>
</tr>
<tr>
<td>500 – 1000 m</td>
<td>114</td>
</tr>
<tr>
<td>over 1000 m</td>
<td>36</td>
</tr>
</tbody>
</table>

3.2. Data processing

Each trip velocity profile was divided into sections, each section corresponding to a single link in the network. A special map-matching procedure was developed in order to determine the sequence of link and their enter/exit times when a vehicle moves along a route (Fig. 2).
After partitioning the recorded profiles into sections, the following three steps were carried out (Fig. 3):
1. calculation of the average speed and other statistics for each section,
2. analysis and visualization of different statistics in relation to the average speed (for each section),
3. approximation of statistics as a function of the average speed.

Fig. 3. Driving cycle data processing procedure
The following statistics were calculated for each section and then approximated as a function of time:
– average speed,
– average power,
– energy consumption,
– standard deviation of speed,
– average acceleration (positive and negative),
– number of stops and their duration.

Figure 4 illustrates the average speed calculated for each section within one driving speed profile. For some sections, the average speed is close to the free-float speed, while for other sections, a considerable difference between these speeds can be observed.

3.3. Additional data estimation with a microscopic energy consumption model

Since both energy consumption and power were not measured during test drives, recorded speed profiles were used to estimate these values via simulation of the Backward-Facing Model [Mohan, Assadian and Longo 2012] of longitudinal dynamics of a battery electric vehicle (Fig. 5). A more detailed description is provided in [Ślaski, Ohde and Pikosz 2014]. The model takes into account road resistance power and vehicle on-board systems energy consumption. The battery efficiency, road height and additional electric load (such as lights or heating and air conditioning) are not considered. All the data related to electric power and energy consumption refer to power and energy supplied to the inverter (denoted with $P_e(t)$).
Fig. 5. The Backward-Facing simulation model of longitudinal dynamics of a battery electric vehicle

Fig. 6. Energy consumed for propulsion and vehicle control unit in a simulated driving cycle with speed profile shown on Figure 4 (a), average energy consumed per section (b)
Figure 6 shows the calculated amount of energy consumed over time and the average energy consumption for each section of the analysed speed profile (Fig. 4). Continuous consumed energy is calculated per simulation step (0.1 second), discrete consumed energy is calculated per section. Periods of negative energy consumption (decrease of value of consumed energy) are result of energy recuperation while braking.

3.4. Final data set

The data set obtained through data acquisition and processing includes 1,217 records, each representing one section from the registered speed profiles. Each section is described with a set of computed statistics, e.g. the average speed, power or acceleration (Sec. 3.2). Table 2 presents the number of records in relation to the average speed. There are significantly fewer sections with the average speed above 60 km/h since most data was collected in the urban area with the speed limit of 50 km/h.

<table>
<thead>
<tr>
<th>Average speed [km/h]</th>
<th>Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 10</td>
<td>128</td>
</tr>
<tr>
<td>10 – 20</td>
<td>206</td>
</tr>
<tr>
<td>20 – 30</td>
<td>178</td>
</tr>
<tr>
<td>30 – 35</td>
<td>113</td>
</tr>
<tr>
<td>35 – 40</td>
<td>141</td>
</tr>
<tr>
<td>40 – 45</td>
<td>142</td>
</tr>
<tr>
<td>45 – 50</td>
<td>123</td>
</tr>
<tr>
<td>50 – 60</td>
<td>132</td>
</tr>
<tr>
<td>60 – 70</td>
<td>88</td>
</tr>
<tr>
<td>over 70</td>
<td>6</td>
</tr>
<tr>
<td>sum</td>
<td>1217</td>
</tr>
</tbody>
</table>
4. DATA ANALYSIS

4.1. Speed statistics

Figure 7 shows the maximum and minimum speeds on sections in relation to the average speed (1 data record is represented with 2 points), and the average minimum and maximum speeds as functions of average speed. Different tones of the background illustrate the density of points.

The distance between the minimum/maximum speeds and the average speed depends on the latter:

- the average speed below 10 km/h – the minimum speed equals zero and the maximum speed is relatively low. This is often the case in the “stop&go” traffic
- the average speed between 10 and 20 km/h – the maximum speed is often close to the speed limit (usually 50 km/h) and the minimum speed close to zero. This indicates high variability of vehicle speeds due to heavy traffic or traffic lights
- the mean speed over 35 km/h – the average minimum and maximum speed values are close to the average speed, which is typical for free flow traffic.

![Minimum and maximum speeds in relation to the average speed for each section. Maximum speeds are above the average speed trend line, while the minimum speeds are below.](image-url)
Figure 8 shows the standard deviation of speed in relation to the average speed. For sections with the average speeds below 20 km/h, the standard deviations are relatively high, and the coefficient of speed variation (CV – ratio of the standard deviation to the mean) is above 1.0. Sections with the average speeds above 35 km/h have relatively low standard deviations.

![Data distribution and points with CV = 1](image)

**Fig. 8.** Standard deviation of speed in relation to the average speed (CV = 1 – points with the coefficient of variation equal 1.0)

### 4.2. The number of stops and their duration

The number and duration of stops have a significant impact on the average speed in urban driving, which is confirmed by the share of stop time in the total driving time for each recorded section in relation to the average speed (Fig. 9). Also the number of stops per section is negatively correlated with the average speed (Fig. 10).
Fig. 9. Share of stop time to driving time on a section in relation to the average speed

Fig. 10. Number of stops per section in relation to the average speed
4.3. Average acceleration and deceleration

For a more detailed analysis, the driving cycles were also divided into acceleration, deceleration and constant speed phases. The acceleration phase was used to calculate the average acceleration (positive acceleration) and the deceleration phase was used to calculate the average deceleration (negative acceleration). Figure 11 shows the average acceleration and deceleration are similar in terms of absolute values. The former is negatively correlated to the average speed while the latter is positively correlated. Both statistics are in accordance with the decrease in the number of stops and the standard deviation of speed for higher average speeds.

Fig. 11. The average acceleration (a) and deceleration (b) in relation to the average speed
4.4. Power of resistance forces and power supplied to the inverter

The analysis of the vehicle tractive power focuses on the power of resistance forces acting on a vehicle (the sum of the inertia, aerodynamic and rolling resistance forces multiplied by the vehicle speed) and the electric power supplied to the inverter to overcome the resistance power by the vehicle power train. The former assumes full recuperation when breaking, while the latter only partial recuperation with the efficiency varying relative to vehicle speed and rate of deceleration.

Figure 12 illustrates the average resistance power in relation to the average speed for each section. For these data points, the average resistance power in relation to the average speed is presented (average $P_D$). Additionally, two lines are presented: the average electric power supplied calculated for all sections (average $P_E$), and the theoretical constant-speed drag power ($P_T$). Due to the efficiency of the inverter, motor and gearbox, the values of the average electric power supplied are generally higher than of the average resistance power.

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**Fig. 12.** Average resistance power in relation to the average speed. $P_T$ – theoretical constant-speed drag power, $P_D$ – average power of resistance forces; $P_E$ – average electric power supplied to the inverter
Figure 13 presents the average $P_d$ to $P_T$ and average $P_E$ to $P_T$ ratios. Due to low efficiency of the motor and inverter at low speed and load, the latter ratio is relatively high at low speeds (the electric power is over 2.5 times higher than the theoretical value at speeds below 20 km/h).

![Graph showing the ratios of average drag power to theoretical drag power and average electric power to theoretical drag power.](image)

**Fig. 13.** The ratios of the average drag power and average electric power to the theoretical constant-speed drag power

### 4.5. Energy consumption

In order to ensure comparability, energy consumption calculated for each section was normalized by dividing the section length and expressed in Wh/km. Figure 14 shows the energy consumption in relation to the average speed for all sections (data points) and the approximated average energy consumption (inverter line). The average overall energy consumption including energy losses related to battery charging and discharging is presented as the grid line. The average energy consumption decreases with speed. At higher speeds, the average energy consumption is around 100 Wh/km, whereas at speeds close to 0 km/h it can be more than 200 Wh/km. This confirms the general rule concerning urban traffic that energy consumption per kilometre is higher at lower average speeds. The main reasons are: (a) aerodynamics has little impact at low and moderate speeds, (b) not all energy can be recuperated from breaking (stop&go or heavy traffic), (c) significantly lower efficiency of the electric motor at low rotational speeds, (d) increase of share of energy consumption not related to movement (e.g. on-board devices). For com-
parison purposes, the average energy consumption levels for a set of standard driving cycles measured by Lohse-Busch [2012] is presented as gray diamonds in Fig. 14.

![Graph showing average energy consumption per kilometre in relation to the average speed at the inverter (inverter line) and including energy losses related to battery charging and discharging (grid line). Grey diamonds present the real average energy consumption per kilometre for the following standard driving cycles (from left to right): NEDC Urban, JC08, FTP-72, NEDC, LA92 and NEDC extra urban [Lohse-Busch 2012]](image)

**Fig. 14.** Average energy consumption per kilometre in relation to the average speed at the inverter (inverter line) and including energy losses related to battery charging and discharging (grid line). Grey diamonds present the real average energy consumption per kilometre for the following standard driving cycles (from left to right): NEDC Urban, JC08, FTP-72, NEDC, LA92 and NEDC extra urban [Lohse-Busch 2012]

### 5. CONCLUSION

A methodology for finding relationships between the average speed on a link and energy consumption, acceleration, minimum and maximum speed etc. was proposed and then applied for driving cycles recorded in Poznan. For estimating electric energy consumption, a microscopic model of a drivetrain of an electric vehicle and a model of resistance power was built and used with the recorded speed profiles.

Due to substantial data dispersion observed for records (sections) of similar average speed, the resulting approximations are suitable only for analysis of a high number of vehicles and longer routes (e.g. macro/mesoscopic traffic simulation).

Last but not least, this type of energy consumption model can be applied to route planning and fleet operations. By using the historical statistical data of the
average speed, energy-efficient routes can be found. Additionally, infeasible routes (due to the limited range) can be discarded or modified to include the necessary battery charging.

REFERENCE


