Journal of civil engineering and transport **transEngin**

2023, Volume **5** Number **3** **ISSN 2658-1698, e-ISSN 2658-2120**

DOI: 10.24136/tren.2023.009

ESTIMATION OF ROUTE SPEED PARAMETERS DESIGNED FOR ELECTRIC BUSES

Zbigniew **Czapla** [1]

[1] Silesian University of Technology, Faculty of Transport and Aviation Engineering, Krasińskiego 8, 40-019 Katowice, Poland, email: zbigniew.czapla@polsl.pl, https://orcid.org/0000-0001-6733-8995

Reviewed positively: 20.11.2022

Information about quoting an article:
Czapla Z. (2023). Estimation of route speed parameters designed for electric buses. Journal of civil engineering and transport. 5(3), 9-20, ISSN 2658-1698, e-ISSN 2658-2120, DOI: 10.24136/tren.2023.009

Abstract – The paper presents a method for the estimation of speed parameters on urban bus routes designed for the use of electric buses. The considered bus route is divided into stopping and running sections. The bus stops are the stopping sections. The running sections connect two neighbouring bus stops. A bus equipped with the GPS receiver moves along the urban bus route at a variable speed. The GPS receiver records at a constant frequency location data that include current bus position and the measurement time. The location data enable the estimation of the time of varying speeds for the running sections and the stop time for the stopping sections. The speed parameters for the sections involve the specification of time periods assigned to the defined speed ranges. Measurement data were recorded on the selected bus route in off-pick and pick hours. The results obtained allow estimation of speed parameters for individual sections and by aggregation for the entire bus route considered. The speed parameters of the bus route correspond to the energy consumption of electric buses and can be applied to determine the properties of the urban bus routes on which electric buses are introduced.

Key words – bus route sections, electric buses, GPS data, speed parameters

JEL Classification – Q47, R41, R58

INTRODUCTION

Urban bus routes are increasingly operated with electric buses supplied by traction batteries. The introduction of electric buses results in reduction of exhaust emissions and allows a decrease in air pollution in cities where collective bus transport is used. The main limitation of electric buses is their relatively short range. The range of electric buses depends on the capacity of the traction batteries and the energy consumption. The energy consumption of electric buses is changing and depends on the driving time and speed parameters achieved on a bus route. The driving time and speed parameters on the bus route are the result of various factors. The topology and height profiles of the road, traffic conditions and driving style, and ambient temperature influence the energy consumption of electric buses.

The consumption of electric energy can be predicted using the kinetic parameters of the vehicle trips. To determine the correlation between kinetic parameters and energy consumption, models based on real-world date on the energy consumption of electric vehicles are constructed [1]. The amount of energy spent by an electric bus varies for a different route. The energy consumption of the electric bus can be analysed on the basis of the simulation results obtained using the simulation platform including the representation of the electric bus and its interaction with the various bus routes [2]. The ambient temperature has a significant impact on the energy consumption of electric buses. In winter, under harsh weather conditions, the energy consumption increases considerably and this increase affects the operation of electric buses [3]. The performance properties of battery electric vehicles can be assessed by comparing the energy consumption of the same type vehicles, propelled by electric and combustion engines. Measurement data are obtained within a city and outside a city, under various traffic conditions, and with various driving styles. [4].

A comparison between the diesel bus fleet and the battery electric bus fleet can be made taking into consideration the costs incurred. The costs of a battery electric fleet include the bus lifecycle, the charging infrastructure, and electricity and maintenance costs [5]. The operation of electric buses requires charging infrastructure. The dynamic optimization model of charging infrastructure for electric buses, which enables optimization of charger location and analysis of charging time, presents [6]. Traction battery of electric bases needs an appropriate long charging time. The charging infrastructure of electric buses can be based on battery exchange stations. The approach to scheduling electric buses with the assumption of a single depot and battery exchange stations shows [7]. The methods of planning and scheduling designed for electric buses take into account various limitations of the operation of electric buses. The approaches to planning and scheduling considering planning levels, properties of the electric bus fleet, charging infrastructure, the scheduling problems concern electric vehicles and charging presents [8]. Electric buses can be charged at the depots and at the charging station located at the terminal stops. The scheduling model that assumes fixed location of chargers, limited operational range of electric buses, and partial charging at multiple locations shows [9].

Travel time can be used to describe the travel properties of urban bus routes. There are several factors that influence the travel time on an urban bus route. The bus travel time depends on the location and topology of a bus route, changes in elevation along a bus route, timetables, dwell time, characteristics of the speed and the stops of the bus, and also on the frequency of occurrence of queuing and bunching on a bus route. In [10], a method for analysing the bus travel time is presented. The presented method is based on automatic measurements, and uses bus location data and vehicle counter data. The data collected enable the determination of fluctuation of the travel time, and travel time modelling. In [11], a method for the bus travel time description using historical profiles is presented. In the presented method, short term travel time is predicted on the basis of historical behaviour and current travel time is determined at passed points of interest.

GPS data can be used for determination of travel parameters. In [12], various machine learning methods are used for bus speed prediction using GPS data obtained from GPS devices installed on buses. For prediction of bus speed, artificial neural networks, support vector regression, Bayes networks, and mixed model are used and compared. In [13], the support vector machine is applied for the prediction of the bus travel time. The proposed method uses GPS data and is based on the prediction of the bus travel time between stations. The considered road section is divided into segments for which an average travel time is predicted. In [14], various models applied to the prediction of the bus travel time utilizing GPS data are presented. The bus travel time is predicted using a historical average of travel time model, a Kalman filtering model, and an artificial neural network model applied to sections of varying length. The models considered are compared according to accuracy and robustness.

The accuracy of GPS data obtained from GPS receivers is limited. In [15] inaccuracy of the GPS system is considered and the methods that improve vehicle location accuracy are analysed. Measurement accuracy obtained can be improved using reference station networks, Kalman filtering, and perceptive GPS. GPS data can be used for estimation of the speed parameters of the bus. In [16], accuracy and reliability of various types of GPS receivers are analysed. For determining the accuracy and reliability of selected GPS receivers, stationary data measured in open and built up areas, and data obtained at fixed speed on a carriageway and in a built up area are used.

The proposed method of estimating the speed parameters of the bus route is based on GPS data. The considered bus route is divided into stopping and running sections according to the location of bus stops on a bus route. The ranges of the bus speed are fixed. For each section, the driving times at the speed from the individual speed ranges are determined. The speed parameters are also determined for the entire bus route. Estimation of the speed parameters of the bus route allows assessment of the suitability of the considered bus route for the use of electric buses.

1. Estimation of speed parameters

Estimation of route speed parameters is based on analysis of GPS data recorded by a GPS receiver placed on a bus. The GPS receiver on the bus moving along a bus route records location data of consecutive track points. The location data recorded are stored in a GPX file. The GPX file contains GPS data in an XML schema. The recorded track consists of the location data of consecutive track points. Track points are denoted by position numbers. The starting track point has position number 0. The current track point denoted by the position number n is described by the set of parameters

$$P_n = \{n, lat_n, lon_n, ele_n, dat_n, tim_n\}. \qquad (1)$$

The set of parameters describing the current track point comprises the number of position denoted by n, a latitude and a longitude in decimal degrees denoted by lat_n and lon_n, respectively, an elevation in meters denoted by ele_n, the current date denoted by dat_n, and the current time denoted by tim_n. Assuming that the circumference of the equator is equal to 40075.704 km, the distance in meters between the current track point with the number n greater than 0 and the previous directly track point can be expressed as

$$d_n \approx \frac{40075.704 \cdot 10^3}{360} \sqrt{\left(lat_n - lat_{n-1}\right)^2 + \left(lon_n - lon_{n-1}\right)^2 \cos^2 lat_n} \,. \tag{2}$$

When the difference between the time of the current track point and the time of the previous directly track point is expressed in seconds, and the distance between these track points is expressed in meters, then the instantaneous bus speed in meters per second at the current track point is given by the equation

$$v_n = \frac{d_n}{tim_n - tim_{n-1}} \,. \tag{3}$$

The considered bus route is divided into bus route sections. There are two types of bus route sections, stopping sections and running sections. The regular bus stops are the stopping sections. The running sections of the bus route stretch between two directly neighboring bus stops. Each track point is assigned to exactly one section, either the running section or the stopping section.

For all track points, the set of parameters describing the single track point is supplemented by four various pointers of speed ranges: the pointer of the zero speed range denoted by zv_n, the pointer of the low speed range denoted by lv_n, the pointer of the medium speed range denoted by mv_n, and the pointer of the high speed range denoted by hv_n. After supplementation, the set of parameters describing a single track point takes the form

$$P_n = \left\{n, lat_n, lon_n, ele_n, dat_n, tim_n, zv_n, lv_n, mv_n, hv_n\right\}. \tag{4}$$

For the single track point of the stopping section, the pointer of the zero speed range is set to 1 and the other pointers of the speed range are set to 0

$$zv_n = 1 \,, \quad lv_n = mv_n = hv_n = 0 \,. \tag{5}$$

For the single track point belonging to the running section, the pointer of the zero speed range is set to zero

$$zv_n = 0, \tag{6}$$

while the pointers of the low speed range, medium speed range, and high speed range are set to 1 or 0 according to the speed conditions that are satisfied. For the bus speed at the current track point less than or equal to the maximum speed defined for the low speed range, the low speed range pointer is set to 1, whereas to 0 otherwise

$$lv_n = 1 \quad \text{if} \quad v_n \le v_{lmax}, \quad \text{otherwise} \quad lv_n = 0. \tag{7}$$

For the bus speed at the current track point greater than the maximum speed defined for the low speed range and less than or equal to the maximum speed defined for the medium speed range, the pointer of the medium speed range is set to 1, while to 0 otherwise

$$mv_n = 1 \quad \text{if} \quad v_{lmax} < v_n \le v_{mmax}, \quad \text{otherwise} \quad mv_n = 0. \tag{8}$$

If the bus speed at the current track point is greater than the maximum speed defined for the medium speed range, the pointer of the high speed range is set to 1, and to 0 otherwise

$$hv_n = 1 \quad \text{if} \quad v_n > v_{mmax}, \quad \text{otherwise} \quad hv_n = 0. \tag{9}$$

In the set of parameters describing the single track point, only one pointer of the zero speed range, low speed range, medium speed range, and high speed range pointers is set to 1, while the others are set to 0. The pointer equal to 1 points the speed range to which the track point is classified.

2. EXPERIMENTAL RESULTS

The experimental results have been obtained on the number 297 bus route in Katowice city. The selected bus route is representative of the Upper Silesian conurbation and contains sections in and outside the city centre with different traffic volumes in off-pick hours and in pick hours. Currently the 297 bus route is operated with electric buses. The number 297 bus route starts at the bus terminal in the centre of Katowice city and leads towards south until the Odrodzenia housing estate in the Piotrowice district is reached. Next, the bus route goes around the Odrodzenia housing estate and returns to the city centre. The number 297 bus route ends at the same bus terminal where it starts. The considered bus route encompasses the sections in the city area of intensive traffic, mainly in the city centre and its vicinity, and the sections of low traffic, mainly in the Odrodzenia housing estate. Measurements have been performed in both off-pick hours and pick hours. The sections of the bus route in areas of intensive traffic are usually susceptible to congestion, especially during pick hours. Table 1 includes the list of the running sections of the number 297 bus route supplemented by ordinal numbers of bus stops in parentheses and the approximate length of the individual running sections.

The number 297 bus route includes 27 bus stops, excluding request bus stops. Request bus stops are regarded as a part of the appropriate running section and therefore stoppings at them are classified as a result of current traffic conditions. The bus stops are classified as the bus stops in the direction to the housing estate (the bus stops numbers 1 to 14) and the bus stops in the direction to the city centre (the bus stops numbers 14 to 27). As bus stops are the stopping sections, hence the number 297 bus route includes 27 stopping sections that determine 26 running sections. In the direction to the housing estate, there are 13 running sections, and the same number of the running sections leads back to the city centre. Bus stops of numbers 12 to 16 are located in the Odrodzenia housing estate. The bus stop of number 1 is located at the bus terminal and is both the starting bus stop and the last bus stop.

A bus that runs the bus route is equipped with a GPS receiver. The GPS receiver records GPS data of track points every second in a file in the GPX format. The GPS data of the consecutive track points constitute the bus track.

Table 1. Running sections of the number 297 bus route

Running section	Length [m]
(1) Katowice Dworzec – (2) Katowice Mikołowska	600
(2) Katowice Mikołowska – (3) Katowice AWF	550
(3) Katowice AWF – (4) Brynów W. Pola	1000
(4) Brynów W. Pola – (5) Brynów Dworska	1400
(5) Brynów Dworska – (6) Brynów Kościuszki	650
(6) Brynów Kościuszki – (7) Brynów Pętla	250
(7) Brynów Pętla – (8) Ochojec Wapienna	850
(8) Ochojec Wapienna -(9) Ochojec Sadowa	550
(9) Ochojec Sadowa – (10) Ochojec Ziołowa	350
(10) Ochojec Ziołowa – (11) Piotrowice Tyska	400
(11) Piotrowice Tyska – (12) Odrodzenia Radockiego	800
(12) Odrodzenia Radockiego – (13) Odrodzenia Łętowskiego	350
(13) Odrodzenia Łętowskiego – (14) Odrodzenia Bażantów	300
(14) Odrodzenia Bażantów – (15) Odrodzenia Kościół	450
(15) Odrodzenia Kościół – (16) Odrodzenia Szewska	500
(16) Odrodzenia Szewska – (17) Piotrowice Osiedle	500
(17) Piotrowice Osiedle – (18) Ochojec Ziołowa	350
(18) Ochojec Ziołowa – (19) Ochojec Sadowa	500
(19) Ochojec Sadowa – (20) Ochojec Wapienna	550
(20) Ochojec Wapienna – (21) Brynów Kościuszki	950
(21) Brynów Kościuszki – (22) Brynów Dworska	900
(22) Brynów Dworska – (23) Brynów W. Pola	1150
(23) Brynów W. Pola – (24) Katowice AWF	1000
(24) Katowice AWF – (25) Katowice Mikołowska	400
(25) Katowice Mikołowska – (26) Katowice Mikołowska Sąd	500
(26) Katowice Mikołowska Sąd – (27) Katowice Dworzec	300

The GPS data of a single track point comprise the number of the track point, the latitude and the longitude expressed in decimal degrees, the elevation given in meters, the current date and the current GMT time. Each track point is classified into one of the sections of the bus route, either the running section or the stopping section. Processing of the recorded data obtained for the track points results in the determination of the instantaneous speed assigned to the individual track points.

Based on the obtained speed values, each track point classified within the running section is assigned to one of three fixed speed ranges. The low speed range includes track points of the speed not exceeding 10 km/h. The medium speed range gathers track points of a speed above 10 km/h and not exceeding 30 km/h. The high speed range comprises track points of the speed above 30 km/h. All track points classified within the stopping sections are assigned to the zero speed range. The time during which a bus stays at bus stops is defined by the moments of opening and closing of the bus doors.

The data obtained concern two runs denoted by Ride 1 and Ride 2. Ride 1 data have been recorded in off-pick hours, whereas Ride 2 data in afternoon pick hours. Both the GPX file of Ride 1 and Ride 2 comprise over 4000 recorded track points. Because the track points are recorded with an interval of 1 second, the number of the track points corresponds to the bus driving time expressed in seconds at the speed from the appropriate range. For Ride 1, in off-pick hours, the numbers of track points in low, medium, high speed ranges, and their sum for individual running sections are presented in Table 2. For the same Ride 1, in off-pick hours, the numbers of track points for the stopping sections are contained in Table 3. Similarly, for Ride 2 in pick hours, the numbers of the track points in the speed ranges for the running sections and the stopping sections are presented in Table 4 and Table 5, respectively.

Table 2. Track points in the speed ranges for the running sections in off-pick hours (Ride 1)

No.	Running section	Low speed range [s]	Medium speed range [s]	High speed range [s]	Driving time for section [s]
1.	Katowice Dworzec – Katowice Mikołowska	191	87	5	283
2.	Katowice Mikołowska – Katowice AWF	110	101	0	211
3.	Katowice AWF – Brynów W. Pola	15	25	64	104
4.	Brynów W. Pola – Brynów Dworska	106	58	95	259
5.	Brynów Dworska – Brynów Kościuszki	12	45	34	91
6.	Brynów Kościuszki – Brynów Pętla	55	40	2	97
7.	Brynów Pętla – Ochojec Wapienna	87	77	40	204
8.	Ochojec Wapienna – Ochojec Sadowa	78	125	0	203
9.	Ochojec Sadowa – Ochojec Ziołowa	15	26	19	60
10.	Ochojec Ziołowa – Piotrowice Tyska	33	55	2	90
11.	Piotrowice Tyska – Odrodzenia Radockiego	34	62	45	141
12.	Odrodzenia Radockiego – Odrodzenia	10	14	25	49
13.	Odrodzenia Łętowskiego – Odrodzenia	10	16	20	46
14.	Odrodzenia Bażantów – Odrodzenia Kościół	9	13	31	53
15.	Odrodzenia Kościół – Odrodzenia Szewska	14	14	41	69
16.	Odrodzenia Szewska – Piotrowice Osiedle	62	34	26	122
17.	Piotrowice Osiedle – Ochojec Ziołowa	12	17	27	56
18.	Ochojec Ziołowa – Ochojec Sadowa	18	59	11	88
19.	Ochojec Sadowa – Ochojec Wapienna	32	29	41	102
20.	Ochojec Wapienna – Brynów Kościuszki	84	59	52	195
21.	Brynów Kościuszki – Brynów Dworska	64	52	58	174
22.	Brynów Dworska – Brynów W. Pola	50	50	77	177
23.	Brynów W. Pola – Katowice AWF	25	13	60	98
24.	Katowice AWF – Katowice Mikołowska	23	40	19	82
25.	Katowice Mikołowska – Katowice Mikołowska	36	42	26	104
26.	Katowice Mikołowska – Sąd Katowice Dworzec	244	38	0	282
	Total for running sections 1-26	**1429**	**1191**	**820**	**3440**

Table 3. Track points for the stopping sections in off-pick hours (Ride 1)

No.	Stopping section	Zero speed range [s]	No.	Stopping section	Zero speed range [s]
1.	Katowice Dworzec	17	15.	Odrodzenia Kościół	10
2.	Katowice Mikołowska	9	16.	Odrodzenia Szewska	10
3.	Katowice AWF	15	17.	Piotrowice Osiedle	14
4.	Brynów W. Pola	13	18.	Ochojec Ziołowa	9
5.	Brynów Dworska	10	19.	Ochojec Sadowa	12
6.	Brynów Kościuszki	26	20.	Ochojec Wapienna	10
7.	Brynów Pętla	34	21.	Brynów Kościuszki	74
8.	Ochojec Wapienna	19	22.	Brynów Dworska	11
9.	Ochojec Sadowa	11	23.	Brynów W. Pola	12
10.	Ochojec Ziołowa	8	24.	Katowice AWF	15
11.	Piotrowice Tyska	13	25.	Katowice Mikołowska	45
12.	Odrodzenia Radockiego	153	26.	Katowice Mikołowska Sąd	15
13.	Odrodzenia Łętowskiego	8	27.	Katowice Dworzec	20
14.	Odrodzenia Bażantów	9		**Total for stopping sections 1-27**	**602**

Table 4. Track points in the speed ranges for the running sections in pick hours (Ride 2)

No.	Running section	Low speed range [s]	Medium speed range [s]	High speed range [s]	Driving time for section [s]
1.	Katowice Dworzec – Katowice Mikołowska	240	98	0	338
2.	Katowice Mikołowska – Katowice AWF	63	74	17	154
3.	Katowice AWF – Brynów W. Pola	22	21	71	114
4.	Brynów W. Pola – Brynów Dworska	59	161	56	276
5.	Brynów Dworska – Brynów Kościuszki	35	33	42	110
6.	Brynów Kościuszki – Brynów Pętla	21	25	8	54
7.	Brynów Pętla – Ochojec Wapienna	658	129	0	787
8.	Ochojec Wapienna – Ochojec Sadowa	279	79	6	364
9.	Ochojec Sadowa – Ochojec Ziołowa	9	12	27	48
10.	Ochojec Ziołowa – Piotrowice Tyska	22	52	6	80
11.	Piotrowice Tyska – Odrodzenia Radockiego	22	39	54	115
12.	Odrodzenia Radockiego – Odrodzenia Łętowskiego	14	18	23	55
13.	Odrodzenia Łętowskiego – Odrodzenia Bażantów	11	13	24	48
14.	Odrodzenia Bażantów – Odrodzenia Kościół	12	13	32	57
15.	Odrodzenia Kościół – Odrodzenia Szewska	9	16	37	62
16.	Odrodzenia Szewska – Piotrowice Osiedle	82	45	18	145
17.	Piotrowice Osiedle – Ochojec Ziołowa	11	36	12	59
18.	Ochojec Ziołowa – Ochojec Sadowa	28	46	20	94
19.	Ochojec Sadowa – Ochojec Wapienna	16	15	45	76
20.	Ochojec Wapienna – Brynów Kościuszki	112	52	58	222
21.	Brynów Kościuszki – Brynów Dworska	44	92	44	180
22.	Brynów Dworska – Brynów W. Pola	14	32	88	134
23.	Brynów W. Pola – Katowice AWF	28	46	64	138
24.	Katowice AWF – Katowice Mikołowska	22	43	12	77
25.	Katowice Mikołowska – Katowice Mikołowska Sąd	103	90	0	193
26.	Katowice Mikołowska – Sąd Katowice Dworzec	227	45	0	272
	Total for running sections 1-26	**2163**	**1325**	**764**	**4252**

Table 5. Track points for the stopping sections in pick hours (Ride 2)

No.	Stopping section	Zero speed range [s]	No.	Stopping section	Zero speed range [s]
1.	Katowice Dworzec	25	15.	Odrodzenia Kościół	9
2.	Katowice Mikołowska	14	16.	Odrodzenia Szewska	11
3.	Katowice AWF	13	17.	Piotrowice Osiedle	10
4.	Brynów W. Pola	10	18.	Ochojec Ziołowa	17
5.	Brynów Dworska	11	19.	Ochojec Sadowa	4
6.	Brynów Kościuszki	10	20.	Ochojec Wapienna	11
7.	Brynów Pętla	11	21.	Brynów Kościuszki	9
8.	Ochojec Wapienna	11	22.	Brynów Dworska	10
9.	Ochojec Sadowa	10	23.	Brynów W. Pola	9
10.	Ochojec Ziołowa	10	24.	Katowice AWF	9
11.	Piotrowice Tyska	12	25.	Katowice Mikołowska	8
12.	Odrodzenia Radockiego	12	26.	Katowice Mikołowska Sąd	15
13.	Odrodzenia Łętowskiego	12	27.	Katowice Dworzec	18
14.	Odrodzenia Bażantów	36		**Total for stopping sections 1-27**	**337**

The number of track points classified into the appropriate speed ranges for the sections of the bus route corresponds to the bus driving time in the running and stopping sections expressed in seconds. This time depends on various factors for the individual sections and on traffic conditions. Based on the distribution of the number of track points along the bus route, the speed parameters of the considered bus route can be determined.

3. SPEED PARAMETERS

The speed parameters can be determined for both individual sections and the entire bus route. The total driving time included in tables 2 and 4 for all running sections of the bus route in off-pick hours and in pick hours is presented in Figs. 1 and 2 respectively.

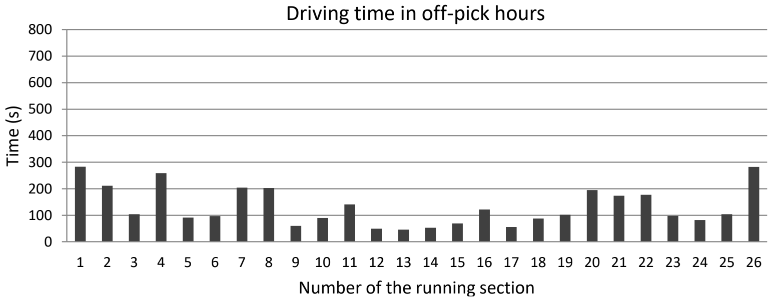

Fig. 1. Distribution of the driving time for the running sections in off-pick hours (Ride 1)

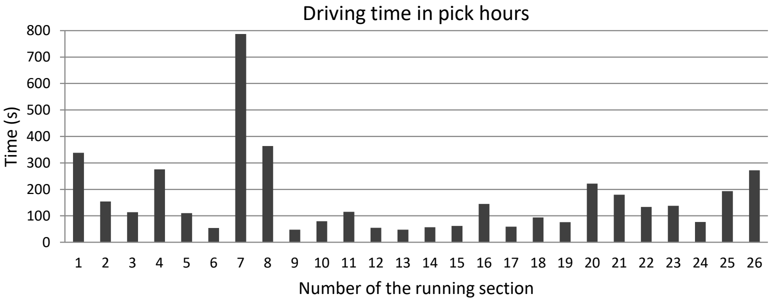

Fig. 2. Distribution of the driving time for the running sections in pick hours (Ride 2)

In off-pick hours, the driving time changes from 46 seconds for section 13 to 283 seconds for section 1. In pick hours, variability of the driving time is from 48 seconds for sections 9 and 13 to 787 seconds for section 7. The total driving time for all running sections is 3440 s (about 57 min) in of-pick hours and 4252 s (about 1 h 11 min) in pick hours. The total stop time for all stopping sections is 602 s (about 10 min) in off-pick hours and 337 s (about 6 min) in pick hours. The addition of the time in the stopping sections to the time in the running sections gives the travel time of the bus route. The travel time of the considered bus route is 4042 s (about 1 h 7 min) in off-pick hours, while in pick hours the travel time is 4589 s (about 1 h 16 min). The driving time for the running sections is the basis for the determination of the speed parameters as related values of the driving time at the speed from the low speed range, the medium speed range, and the high speed range.

The low speed range contains the number of track points at which a speed is below 10 km/h. The driving time in the low speed range from Tables 2 and 4 in off-pick hours and pick hours for all running sections is presented in Figs. 3 and 4, respectively.

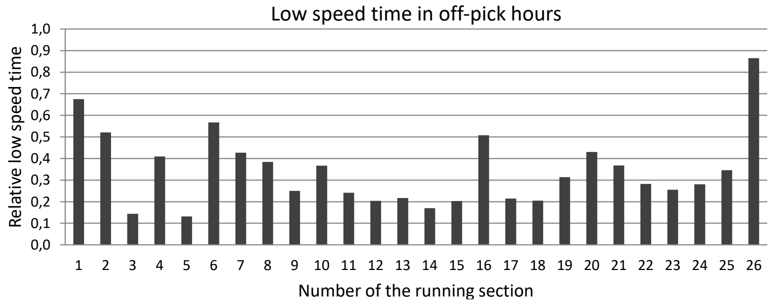

Fig. 3. Distribution of the low speed time for the running sections in off-pick hours (**Ride 1**)

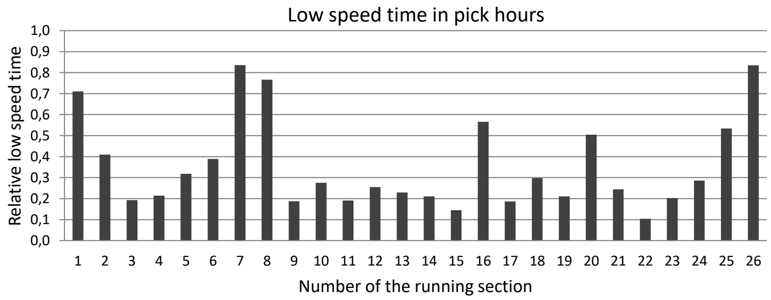

Fig. 4. Distribution of the low speed time for the running sections in pick hours (**Ride 2**)

The relative low speed time is the time of the low speed range related to the total driving time determined for the appropriate running section. The significant increase in the driving time at the speed from the low speed range in pick hours is noticeable for sections 7, 8, and 25. For the other sections, the driving time is similar in off-pick hours and in pick hours.

The medium speed range contains the number of track points at which a speed is above 10 km/h and up to 30 km/h. The driving time at the medium speed from tables 2 and 4 for all running sections in off-pick hours is shown in Fig. 5, and in pick hours in Fig. 6. The relative medium speed time denoted the time of the medium speed range related to the total driving time of the appropriate running section. In pick hours, the clearly shorter driving time at the speed from the medium speed range has been recorded for sections 7, 8, 9, and the clearly longer for sections 4 and 17.

The high speed range contains the number of track points for which a speed is above 30 km/h. The driving time of the high speed from tables 2 and 4 for all running sections is presented in Fig. 7 in off-pick hours and in Fig. 8 in pick hours. The relative high speed time is the time of the high speed range related to the total driving time calculated for the appropriate running section. In pick hours, the clearly shorter driving time at the speed from the high speed range is noticeable for sections 7, 17, and the clearly longer for sections 9 and 22.

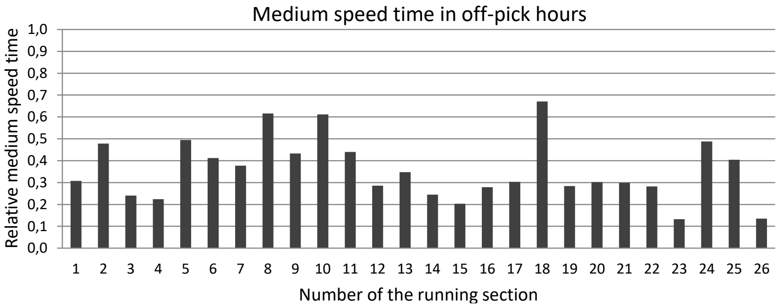

Fig. 5. Distribution of the medium speed time for the running sections in off-pick hours (**Ride 1**)

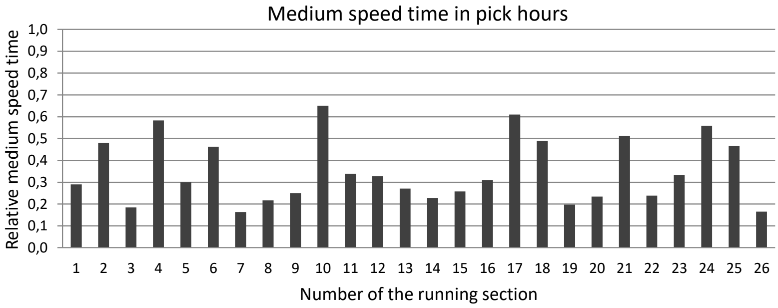

Fig. 6. Distribution of the medium speed time for the running sections in pick hours (**Ride 2**)

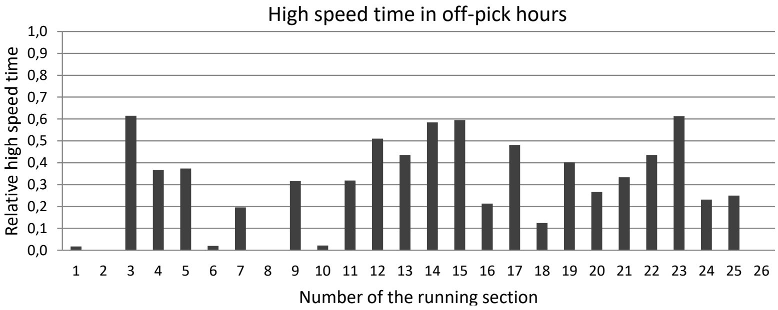

Fig. 7. Distribution of the high speed time for the running sections in off-pick hours (**Ride 1**)

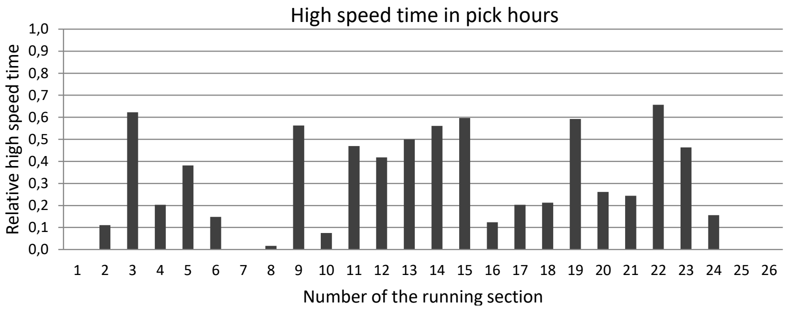

Fig. 8. Distribution of the high speed time for running sections in pick hours (**Ride 2**)

For all running sections in off-pick hours, the low speed time is 1429 s (about 24 min), the medium speed time is 1191 s (about 20 min), and the high speed time is 820 s (about 14 min), while in pick hours the low speed time is 2163 s (about 36 min), the medium speed time is 1325 s (about 22 min), and the high speed time is 764 s (about 13 min). The percentage share of the speed ranges for all running sections in off-pick hours is 41.6% of the low speed range, 34.6% of the medium speed range and 23.8% of the high speed range, whereas in pick hours this percentage share is 50.9% of the low speed range, 31.1% of the medium speed range, and 18.0% of the high speed range.

The zero speed range contains the track points within the stopping sections. For all track points in the stopping section, the bus speed is equal to 0 km/h. For all stopping sections in off-pick hours, the zero speed time is 602 s (about 10 min), and in pick hours 335 s (about 6 min).

The travel time of Ride 1 in off-pick hours is 4042 s (about 1 h 7 min) of which 85% are the track points of the running sections and 15% track points of the stopping sections. For Ride 2 in the pick hours, the travel time is 4589 s (about 1 h 16 min) and consists of 93% of track points belonging to the running sections and 7% track points to the stopping sections.

4. Discussion

The description of time and speed enables the assessment of suitability of the bus route for operation with electric buses considering the energy consumption. The most beneficial speeds to the energy consumption are in the medium speed range. The increase in bus speed results in an increase in energy consumption, and, therefore, speeds from the high speed range are less beneficial. The least beneficial speeds are in the low speed range. Low speeds are usually the result of traffic conditions that force frequent stoppings, startings, and drivings up. Stopping time expressed by the zero speed time also impacts on energy consumption. Although a traction engine does not consume electric energy, other electrical equipment working in the bus work causes energy consumption, particularly devices used in heating and cooling systems.

The accuracy of the determined speed values results from the accuracy of location data. Analysis of the location data shows that for an unmoved bus at a bus stop, the distance determined between two consecutive track points is below 1 m. The location data have been recorded with a frequency of 1 Hz, thus the accuracy of a speed can be estimated as below 1 m/s. Speed inaccuracy can be taken into account in the selection of the limits of the speed ranges.

In pick hours, the travel time increased by 13.5% relative to the travel time in off-pick hours (approximately from 1 h 7 min to 1 h 16 min). For the running sections, the share of track points in the medium speed range decreased by 3.5 % (from 34.6% to 31.1%), while the share of track points in the low speed range increased by 9.3% (from 41.6% to 50.9%) and the share of track points in the high speed range decreased by 5.8% (from 23.8% to 18.0%). The total stop time for the stopping sections in the pick-hours relative to the total stop time in off-pick hours reduced by about 44.0% (approximately from 10 min to 6 min). Moderate congestion in pick hours on a few running sections in the city centre causes noticeable changes in distribution of speeds for the entire bus route.

The novelty of the proposed approach consists in the description of travel of a bus along the urban bus route by the time of a speed classified to the fixed speed ranges. The guideline for the operation of electric buses on urban bus routes is the appropriate level of electric energy consumption. The energy consumption of an electric bus depends on the speed of the bus and the travel time. Determining the driving time at the speed from the selected ranges allows estimation of energy consumption using the appropriate model of an electric bus for individual sections and the entire bus route. The estimation of energy consumption can be performed and then comprises considering various urban bus routes under varying traffic conditions.

Conclusions

The presented method of estimation of speed parameters is designed for assessing the suitability of the considered bus routes for the use of electric buses. The division into sections enables the estimation of the speed parameters for individual sections and further analysis of speed properties of the chosen parts of the considered bus route. The use of a GPS receiver allows efficient measurement data collection. GPS data collected along the bus route at a constant frequency form a GPS track that is used for the calculation of speed parameters at each track point recorded. The track points assigned to the low, medium, and high speed ranges correspond to the driving time at the speed defined for these speed ranges. The number of GPS points in the speed ranges determines the speed properties of the individual sections.

Measurements carried out in off-pick hours and in pick hours enable estimation of the influence of traffic conditions on speed parameters of the considered bus route. The impact of the changeability of traffic conditions in off-pick and pick hours is more noticeable for the sections located in the city centre. For some running sections in the city centre, total driving time increased significantly in pick hours, which was expressed by the increase in the number of track points from the low speed range. Analysis of speed parameters enables the determination of the susceptibility of individual sections of the considered bus route to traffic congestion. Estimation of route speed parameters performed at selected times of the day allows the assessment of the typical electric energy consumption for the individual sections and entire bus route under varying traffic conditions.

ABBREVIATIONS

1. **GPS** - Global Positioning System;
2. **GPX** - Global Positioning System Exchange Format;
3. **XML** - Extensible Markup Language.

OKREŚLENIE PARAMETRÓW SZYBKOŚCIOWYCH NA LINIACH AUTOBUSOWYCH PRZEZNACZONYCH DLA AUTOBUSÓW ELEKTRYCZNYCH

W artykule przedstawiono metodę określania parametrów szybkościowych na miejskich liniach autobusowych, na których wykorzystywane są autobusy elektryczne. Rozpatrywana linia autobusowa jest podzielona na odcinki postoju i jazdy. Przystanki autobusowe są odcinkami postoju. Odcinki jazdy łączą dwa sąsiednie przystanki autobusowe. Autobus wyposażony w odbiornik GPS przemieszcza się po linii autobusowej ze zmienną szybkością. Odbiornik GPS rejestruje ze stałą częstotliwością dane lokalizacyjne zawierające bieżącą pozycję i czas pomiaru. Dane lokalizacyjne umożliwiają określenie parametrów szybkościowych na odcinkach jazdy i czas postoju na odcinkach postoju. Parametry szybkościowe odcinków obejmują specyfikację okresów czasu przyporządkowanych do zdefiniowanych przedziałów szybkości. Dane pomiarowe zostały zarejestrowane na wybranej linii autobusowej poza godzinami szczytu i w godzinach szczytu. Otrzymane wyniki pozwalają na określenie parametrów szybkościowych dla pojedynczych odcinków oraz, przez agregację, dla całej rozpatrywanej linii autobusowej. Parametry szybkościowe linii autobusowej związane są ze zużyciem energii przez autobusy elektryczne i mogą być stosowane do wyznaczania właściwości miejskich linii autobusowych, na których wprowadzane są autobusy elektryczne.

Słowa kluczowe: autobusy elektryczne, dane GPS, odcinki linii autobusowej, parametry szybkościowe

REFERENCES

[1] De Cauwer C., Van Mierlo J., Coosemans T. (2015) Energy Consumption Prediction for Electric Vehicles Based on Real-World Data. *Energies*, 8(8), 8573-8593. https://doi.org/10.3390/en8088573.

[2] Perrotta D., Macedo J.L., Rossetti R.J.F., Freire de Sousa J., Kokkinogenis Z., Riberio B., Alfonso J.L. (2014) Route planning for electric buses: a case study in Oporto. *Procedia - Social and Behavioral Sciences*, 111, 1004-1014. https://doi.org/10.1016/jsbspro.2014.01.135.

[3] Vehviläinen M, Lavikka R, Rantala S, Paakkinen M, Laurila J, Vainio T. (2022) Setting Up and Operating Electric City Buses in Harsh Winter Conditions. *Applied Science*, 12(6): 2762, 1-19. https://doi.org/10.3390/app12062762.

[4] Braun A., Rid W. (2017) Energy consumption of an electric and an internal combustion passenger car. A comparative case study from real word data on the Erfurt circuit in Germany. *Transportation Research Procedia*, 27, 468-475. https://doi.org/10.1016/j.trpro.2017.12.044.

[5] Quarles N., Kockelman K.M., Moatz M. (2020), Costs and Benefits of Electrifying and Automating Bus Transit Fleets. *Sustainability*, 12(10): 3997, 1-15. https://doi.org/10.3390/su12103977.

[6] Xylia M., Leduc S., Piera Patrizio P., Silveira S., Kraxner F. (2017) Developing a dynamic optimization model for electric bus charging infrastructure. *Transportation Research Procedia*, 27, 776–783. https://doi.org/10.1016/j.trpro.2017.12.075.

[7] Zhu C., Chen X. (2013) Optimizing Battery Electric Bus Transit Vehicle Scheduling with Battery Exchanging: Model and Case Study. *Procedia - Social and Behavioral Sciences*, 96, 2725-2736. https://doi.org/10.1016/jsbspro.2013.08.306.

[8] Perumal S.S.G., Lusby R.M., Larsen J. (2021) Electric bus planning & scheduling: A review of related problems and methodologies. *European Journal of Operational Research*, 301(2), 395-413. https://doi.org/10.1016/j.ejor.2021.10.058.

[9] Janovec M., Koháni M. (2019) Exact approach to the electric bus fleet scheduling. *Transportation Research Procedia*, 40, 1380-1387. https://doi.org/10.1016/j.trpro.2019.07.191.

[10] Comi A., Nuzzolo A., Brinchi S., Verghini R. (2017) Bus travel time variability: some experimental evidences. *Transportation Research Procedia*, 27, 101-108. https://10.1016/j.trpro.2017.12.072.

[11] Cristobal T., Padron G., Quesada-Arencibia A., Alayon F., de Blasio G., Garcia C.R. (2019) Bus Travel Time Prediction Model Based on Profile Similarity. *Sensors*, 19(13): 2869, 1-18. https://doi.org/10.3390/s19132869.

[12] Julio N., Giesen R, Lizana P. (2016) Real time prediction of bus travel speeds using traffic shockwaves and machine learning algoritms. *Research in Transportation Economics*, 59, 250-257. https://doi.org/10.1016/j.retrec.2016.07.019.

[13] Junyou Z., Fanyu W., Shufeng W. (2018) Application of Support Vector Machine in Bus Travel Time Prediction. *International Journal of System Engineering*, 2(1), 21-25. https://10.11648/j.ijse.20180201.15.

[14] Fan W, Gurmu Z. (2015) Dynamic Travel Time Prediction Models for Buses Using Only GPS Data. *International Journal of Transportation Science and Technology*, 4(4), 353-366. https://doi.org/10.1016/s2046-0430(16)30168-x.

[15] Thin L.N., Thin L.Y., Husna N.A., Husin M.H. (2016) GPS Systems Literature: Inaccuracy Factors and Effective Solutions. *International Journal of Computer Networks & Communication*, 8(2), 123-131. https://doi.org/10.5121/ijcnc.2016.8211.

[16] Rychlicki M., Kasprzyk Z. Rosiński A. (2020) Analysis of Accuracy and Reliability of Different Types of GPS Receivers. *Sensors*, 20(22): 6498, 1-14. https://doi.org/10.3390/s20226498.