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AMPLITUDE-FREQUENCY ANALYSIS OF TRAFFIC FLOW INTENSITY BASED ON PHOTO AND VIDEO RECORDING OF TRAFFIC VIOLATIONS

The information obtained from the video recording systems of traffic violations allows to automatically determine the traffic flow intensity. Dependencies of traffic flow intensity at different averaging intervals on one of the main roads in Perm are collected, and features of traffic flow on the road mentioned above are described. To analyze the features obtained a traffic flow intensity function is expanded in harmonic Fourier series. The amplitude and frequency characteristics of time series are examined. Instead of the traditionally used 'frequency-amplitude' characteristics the 'period-amplitude' characteristics have been proposed as physically more substantial. It is shown that the individual harmonics of the decomposition of the traffic flow intensity into a harmonic series allow us to conditionally identify "sub-streams" that show signs of periodicity. Each such "subflow" has extremes (maximum and minimum) with corresponding periods, whereas the initial intensity of the traffic flow exhibits the properties of a random function of time. It seems appropriate to use the Fourier series expansion of the traffic flow intensity function to predict traffic flows, control the operation of traffic lights, monitor the operation of equipment, as well as in reconstruction, design and construction of roads and road facilities.

Keywords: amplitude-frequency analysis, traffic flow, video recording system.

Introduction

The introduction of technical means of video recording of traffic violations makes it possible to collect and analyze significant volume of information on the characteristics of traffic flows on road sections and intersections, to form correspondence matrices, etc. To analyze traffic flows an intensity indicator is traditionally used [1; 2], that is the number of vehicles passing through the vertical plane perpendicular to the centerline of the road per unit time (it is measured in vph, vehicles per hour).

Modern methods of data processing are successfully used in digital signal processing and video images [3], to identify the energy characteristics of frequency components in the diagnosis of technical systems, in determining the properties of materials [4]. The analysis of amplitude-frequency features of processes and phenomena in various fields of knowledge [5; 6] is successfully applied to the study of time series. Amplitude-frequency analysis [7; 8] electroencephalograms of the human brain make it possible to analyze spectral anomalies caused by errors when driving a car in heavy traffic conditions, since the road accidents is often caused by aggressive or unstable driving. Spectral analysis is used [9] in the study of transport processes safety, assessment of the road network loading, with the monitoring of photo and video fixation means [10], in the transport processes simulation [11–16].

The purpose of the present study is to identify hidden patterns of the traffic flow evolution. As the initial information was data on the motor transport movement obtained with the help of stationary photo and video recording systems located on the road network of a large industrial city.

A review of national and foreign papers indicates a significant interest to use the mathematical apparatus of spectral analysis in a variety of knowledge fields, including different aspects of transport science. The number of national publications devoted to the Fourier analysis of the traffic flows characteristics is very small. The appearance of present paper may help to study the possibility of using amplitude-frequency characteristics in the processing and analysis of traffic flows data.

Materials and Methods

The part of two-lane road chosen for the study on one of the busy roads in Perm. This road is equipped with a measuring software and hardware complex (MSHC) 'Azimut 2' [17], which allows to measure the speed of vehicles in the control area, their average speed, time of passage of the section, etc.

The traffic flow intensity $N(t)$ was determined using the MSHC data with the formula

$$N(t) = \Sigma(t) / \Delta,$$

where $\Sigma(t)$ – is the number of vehicles detected by the MSHC on a specific lane of the road at the time interval $[t - \Delta/2, \quad t + \Delta/2]$; Δ is the duration of the averaging time interval, Δ = 5, 10, 20, 30 and 60 minutes. It is of interest to analyse the traffic flow intensity using the Fourier series expansion of the function $N(t)$ [18]

$$N(t) = a_0 + \sum_{k=1}^{\infty} a_k \cos(2n_k t + \varphi_k),$$

where a_0 is the mean value of the function in question; a_k is the amplitude, φ_k is the phase shift of the harmonic corresponding to frequency n_k. In order to deduce the values of amplitudes, frequencies and phase shifts, the Excel module of Microsoft Office software has been used, which implemented a computational algorithm based on the fast Fourier transform [19; 20].

Results

Dependencies of daily traffic flow intensity on time [21] for different averaging intervals are shown in Fig. 1. According to Fig. 1, *a* at the beginning of the day from 0:00 to 2:00 traffic flow intensity decreases from 252 vph to the least values, and varies from 0 to 85 vph until 6:30. After 6:35 there is a greatly increase in traffic flow intensity up to the maximum (peak) value of 768 vph at 8:32. Between 9:30 and 16:30 the traffic flow intensity varies in the range of 228 to 540 vph, following by a rise to the second peak value of 732 vph at 17:15. However, around 17:00 there is an abnormal decreasing in traffic flow intensity to 108 vph. This is followed by a gradual decrease in traffic flow intensity to 24–96 vph at the end of the daily observation interval.

When increasing the averaging interval to values Δ = 10, 20, 30 and 60 min (Fig. 1, *b*–1, *e*), the behaviour of the curves does not qualitatively differ from that shown in Fig. 1, *a*. Although the maximum (peak) traffic flow intensities decrease and amount to 690, 684, 638 and 579 vph at 8:35, 8:40, 8:45 and 8:30 respectively. The difference between the maximum intensity values determined for Δ = 5 min and Δ = 60 min is 24.6 %.

As a result of processing the data presented in Fig. 1, *a*, the values of amplitudes, frequencies and phase shifts were obtained for the first ten harmonics displayed in Table 1.

Table 2 shows the harmonics with the largest amplitude values a_k of the traffic flow intensity and their corresponding frequencies n_k that are determined at different averaging intervals Δ. These are the harmonics with the highest amplitudes that contribute most to the Fourier series expansion of the analyzed function.

Fig. 2 depicts a comparison of the $N(t)$ function of traffic flow intensity with harmonics 1, 2, 4, 12 and 17 with the largest amplitudes (Table 2) obtained from the Fourier series expansion of this function acquired by processing source data during the averaging interval Δ = 5 min.

To compare the harmonics are located with a shift along the ordinate axis equal to a_0 (shown in Fig. 2), i.e., in the form of

$$a_0 + a_k \cos(2n_k t + \varphi_k).$$

The first harmonic (Fig. 2, *a*) describes qualitatively the presence of declines and rises in the curve of the daily of the traffic flow intensity. Fig. 2, *e*, shows that the first harmonic describes the daily intensity of the traffic flow very satisfactorily when the averaging interval Δ = 60 min is used. The maxima and minima of the second harmonic (Fig. 2, *b*) satisfactorily show the moments of occurrence of global declines and peaks of the daily intensity of the flow of cars.

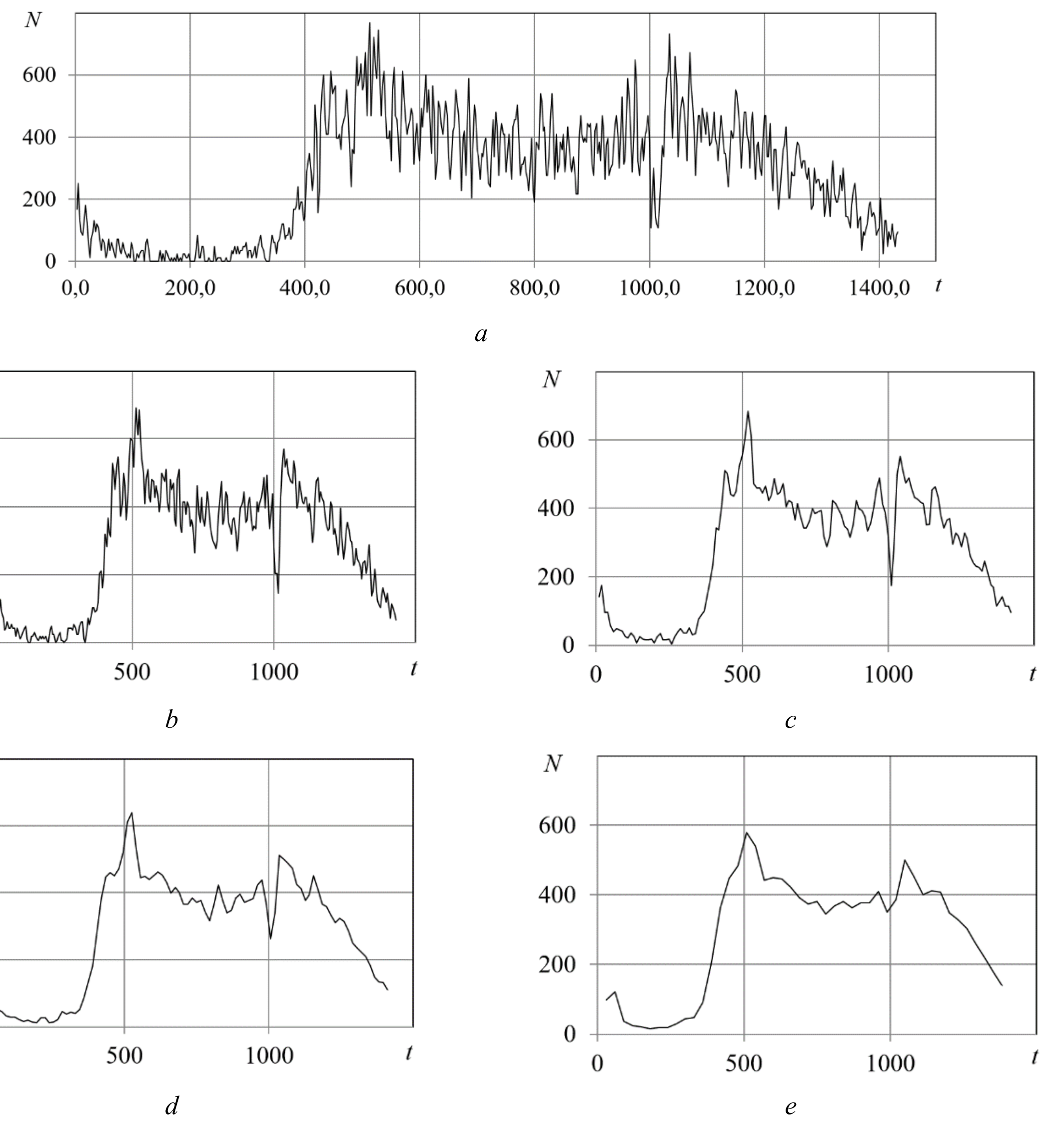


Fig. 1. Dependencies on time *t* (min) of daily traffic flow intensity *N* (vph) at averaging time intervals of 5 min (*a*), 10 min (*b*), 20 min (*c*), 30 min (*d*) and 60 min (*e*) (developed by the authors)

Table 1

Amplitudes a_k (vph), frequencies n_k (min^{-1}) and phase shifts φ_k (rad) of first ten harmonics of traffic flow intensity $N(t)$ when expanded in Fourier series; averaging time interval $\Delta = 5$ min (developed by the authors)

k	Amplitude a_k	Frequencies n_k	Phase shift φ_k
0	291,61	–	–
1	187,42	0,0008	2,338
2	145,87	0,0016	1,279
3	25,94	0,0023	–1,138
4	43,71	0,0031	2,648
5	27,86	0,0039	1,007
6	14,85	0,0047	–0,598
7	12,36	0,0055	1,884
8	15,69	0,0063	1,356
9	9,130	0,0070	2,472
10	11,79	0,0078	–1,295

Table 2

Traffic flow intensity expansion harmonics $N(t)$ with the highest amplitudes a_k (vph) and their corresponding frequencies n_k (min^{-1}) for varying averaging intervals Δ (min) (developed by the authors)

Δ = 5 min		Δ = 10 min		Δ = 20 min		Δ = 30 min		Δ = 60 min	
a_k	n_k	a_k	n_k	a_k	n_k	a_k	n_k	a_k	n_k
187,42	0,0008	187,21	0,0008	186,37	0,0008	234,03	0,0010	229,78	0,0010
145,87	0,0016	145,83	0,0016	145,83	0,0016	98,05	0,0021	100,26	0,0021
43,71	0,0031	43,71	0,0031	42,46	0,0031	49,85	0,0031	43,78	0,0042
31,32	0,0094	31,53	0,0094	30,86	0,0094	45,39	0,0042	42,92	0,0031
28,82	0,0133	27,67	0,0039	27,56	0,0039	25,68	0,0094	23,33	0,0094
27,86	0,0039	27,49	0,0133	26,45	0,0023	17,39	0,0073	16,94	0,0073
25,94	0,0023	26,04	0,0023	26,26	0,0133	17,15	0,0063	16,56	0,0135
19,07	0,0469	18,36	0,0109	17,37	0,0109	14,96	0,0135	15,54	0,0063
18,44	0,0109	15,94	0,0063	16,15	0,0047	11,89	0,0115	14,28	0,0156
17,59	0,0352	15,68	0,0148	15,85	0,0148	11,28	0,0156	14,14	0,0115

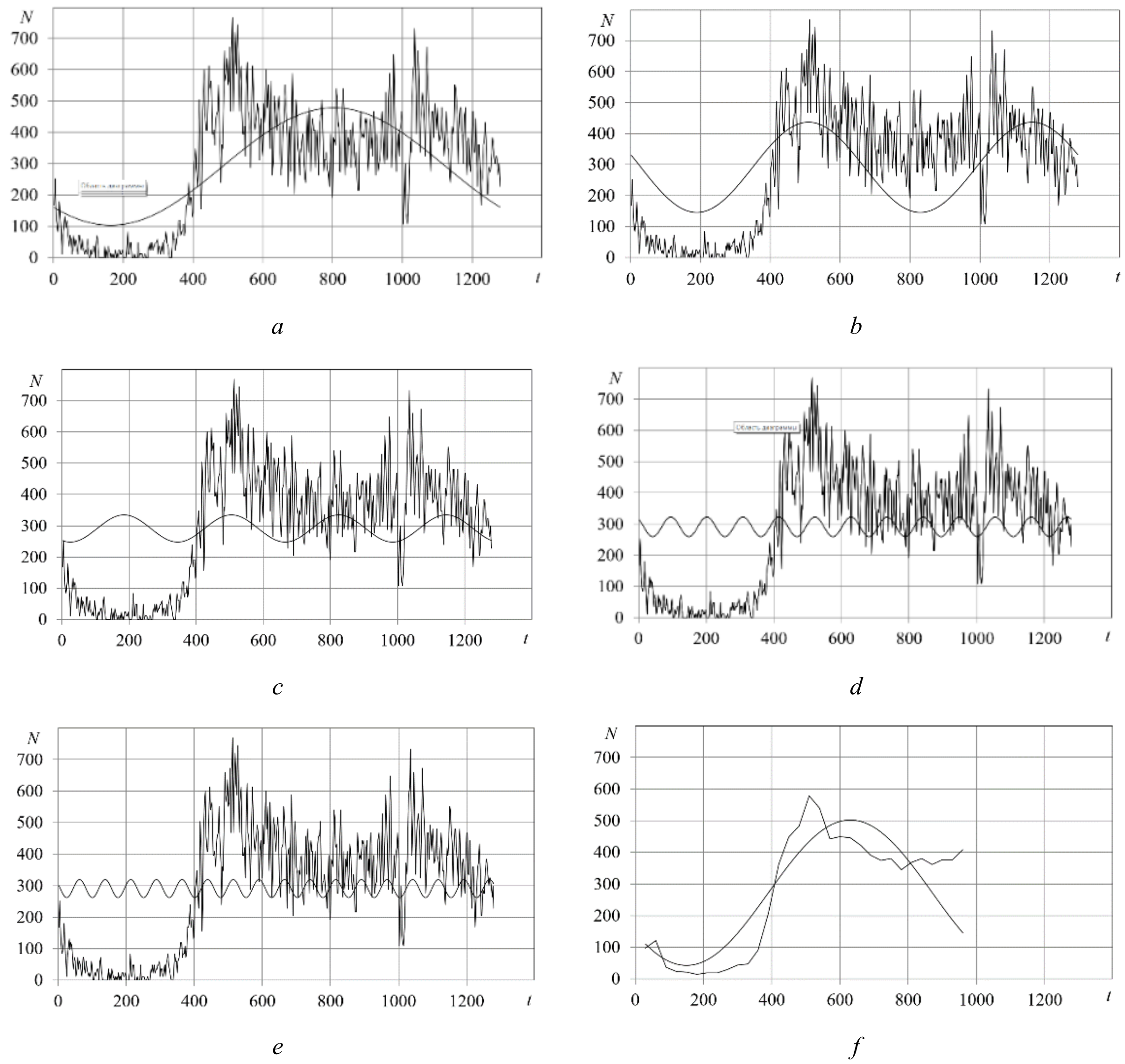


Fig. 2. 1st (*a*), 2nd (*b*), 4th (*c*), 12th (*d*) and 17th (*e*) harmonics of the daily intensity N (veh/h) of traffic flow (——) expansion in Fourier series at averaging interval Δ = 5 min; 1st harmonic (*f*) of the expansion for averaging interval Δ = 60 min (developed by the authors)

The maxima and minima of the fourth harmonic (Fig. 2, *c*) indicate the presence of intermediate maxima and minima of the daily traffic flow intensity with a relatively small periodicity. The maxima and minima of the twelfth and fourteenth harmonics (Fig. 2, *d* and 2, *e*) allow us to identify the positions of local maxima and minima of the daily traffic flow intensity with small amplitudes.

The data compiled in Table 2 demonstrates that the amplitudes for the first and the last harmonics differ by a factor of more than 10–20. Therefore the contribution of harmonics with smaller amplitudes to the decomposition of the studied functions into Fourier series is insignificant, and the error in the representation of functions by series can be estimated at less than 5–10 %.

In Fig. 3 the traffic flow intensity functions, which are obtained by processing source data with processing time intervals of Δ = 5, 10, 20, 30 and 60 minutes, are compared with the representations of the corresponding partial Fourier series drawn using five harmonics with the largest amplitudes.

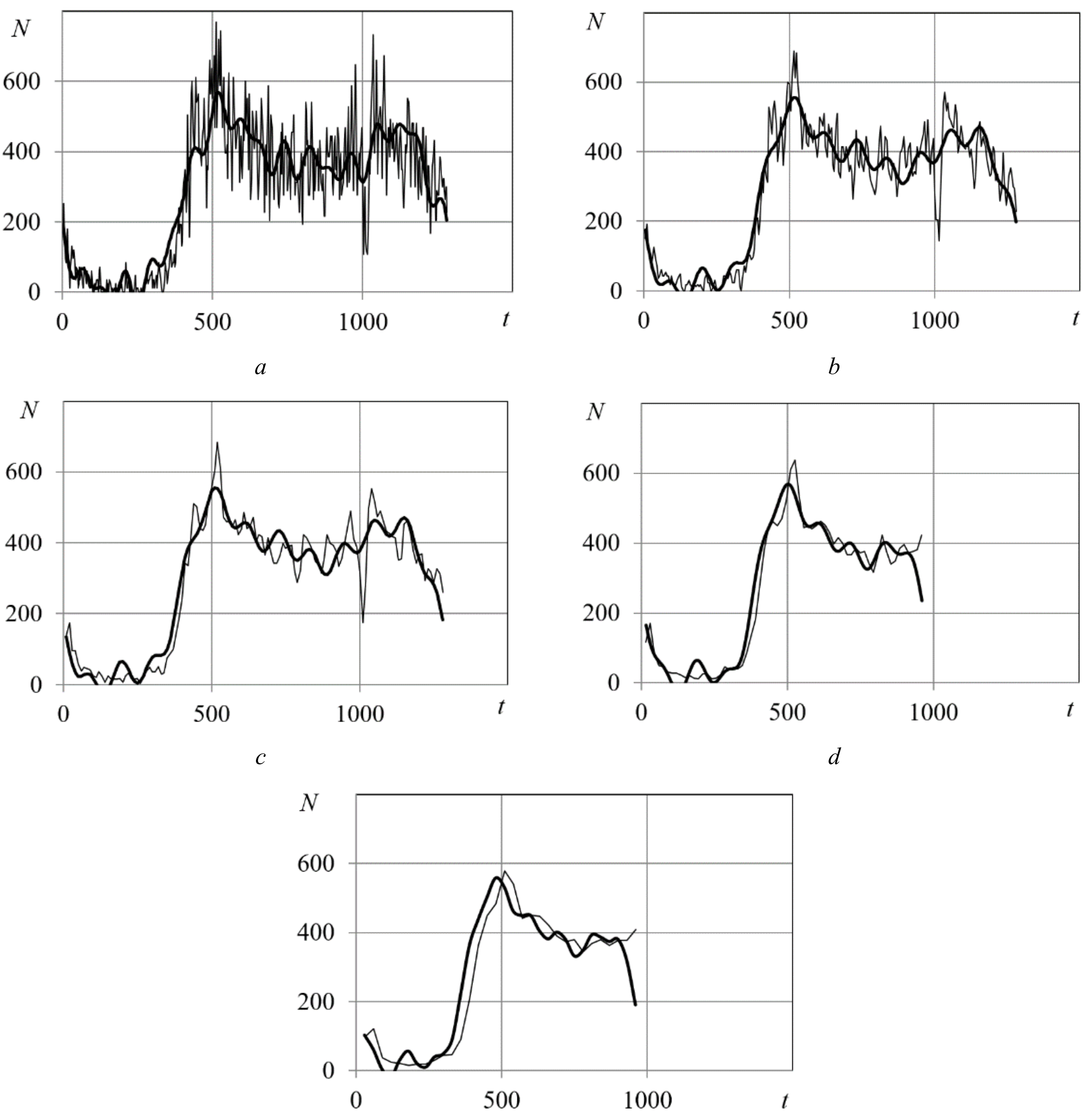


Fig. 3. Time dependencies *t* (min) of daily intensity *N* (vph) of traffic flow (–––) and partial Fourier series (▬▬) at averaging time intervals of 5 min (*a*), 10 min (*b*), 20 min (*c*), 30 min (*d*) and 60 min (*e*) (developed by the authors)

Analysis of the data in Table 2 shows that the amplitude-frequency spectra for the averaging time intervals Δ = 10 and Δ = 20 almost coincide. The coincidence can also be noted for the spectra obtained for the averaging time intervals Δ = 30 и Δ = 60 min. This is confirmed by the closeness of the curves in Fig. 3, *b* and 3, *c*, Fig. 3, *d* and 3, *e,* respectively.

Discussion

Fig. 4*a* shows the amplitude-frequency characteristics of the function of daily traffic flow intensity obtained at averaging interval Δ = 5 min for the data collected by the MSHC 'Azimut 2' on the considered road part.

Analysis of the data presented in Fig. 2 leads to the conclusion that in contrast to the traditionally used amplitude-frequency characteristics, the study of traffic flow intensity may be determined not by the frequencies n_k, but by the periods $T_k = 1/n_k$ of harmonics in the Fourier series expansion of the analyzed intensity function $N(t)$.

It seems appropriate to transform the characteristic 'frequency n_k – amplitude a_k' to a form of dependence of amplitude a_k on the period T_k. The characteristic 'period T_k – amplitude a_k' of daily traffic flow intensity in logarithmic coordinates obtained at averaging interval Δ = 5 min is presented in Fig. 4, *b*. This figure contains over 250 points, only 48 of which (about 20 %) correspond with harmonics with amplitude values ranging from 10 to 200 vph and time periods from 8 min to 21 hours 20 min.

The results given in Table 2 allow to interpret the total traffic flow as a row of separate traffic flows ('subflows') with variable intensity: the largest amplitude a_1 corresponds with a traffic 'subflow' with intensity of 187–188 vph with period of 21–22 hours (more accurately 1280 minutes or T_1 = 21 hours 20 minutes).

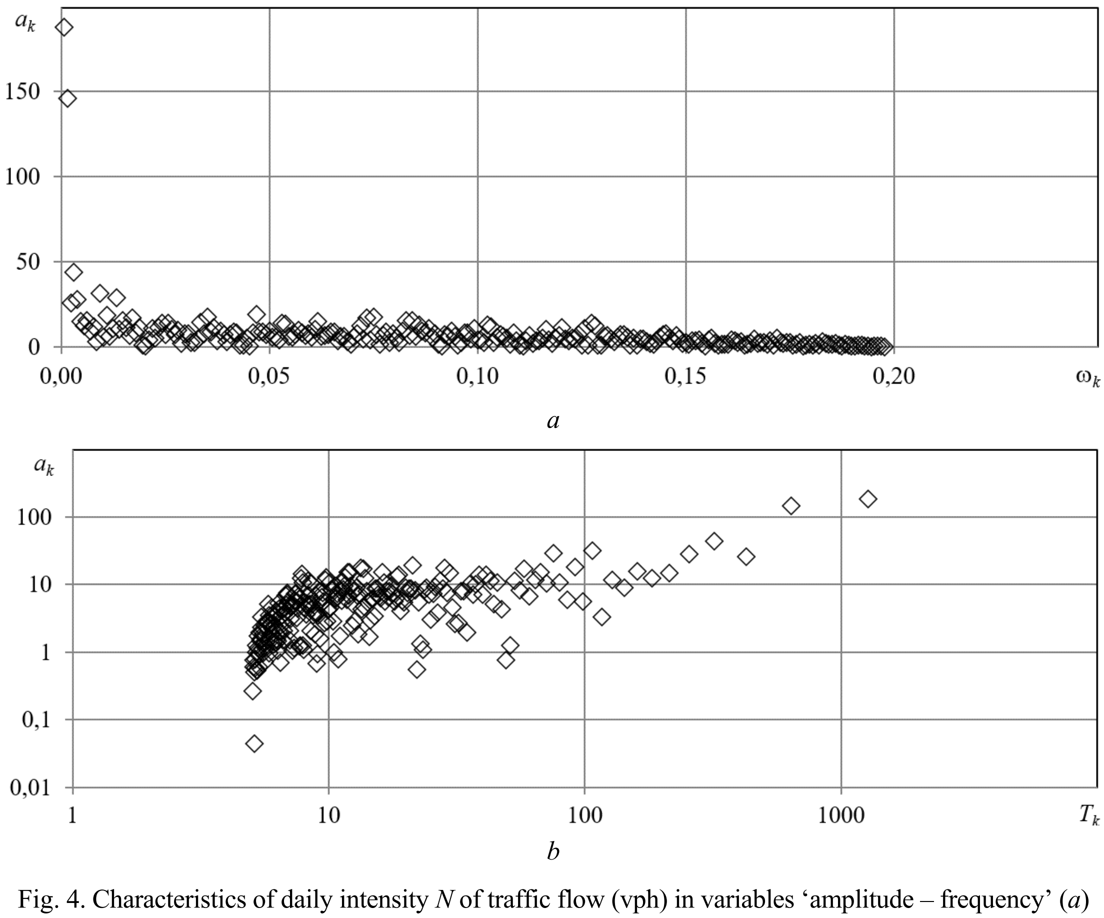
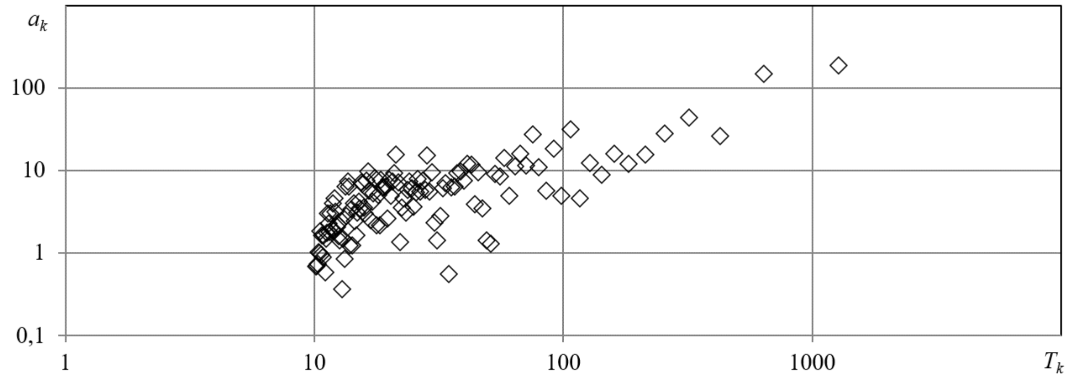
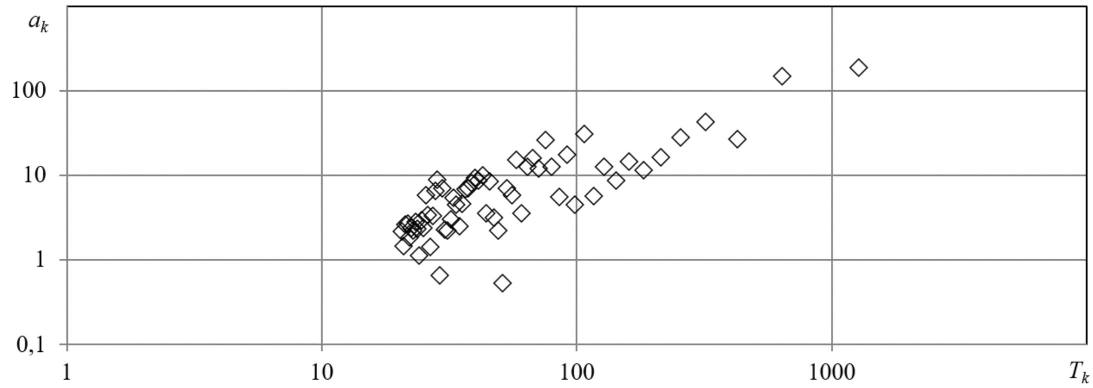


Fig. 4. Characteristics of daily intensity *N* of traffic flow (vph) in variables 'amplitude – frequency' (*a*) and 'amplitude – period' (*b*, in logarithmic coordinates) at averaging interval Δ = 5 min (developed by the authors)



a



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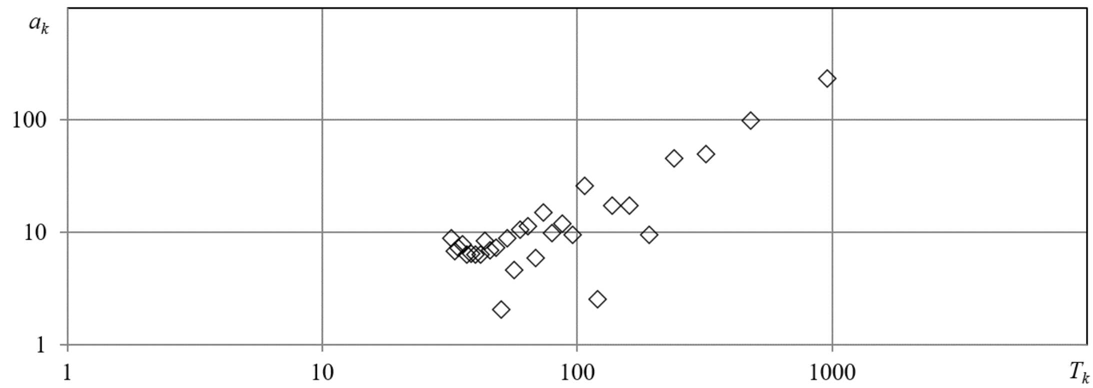

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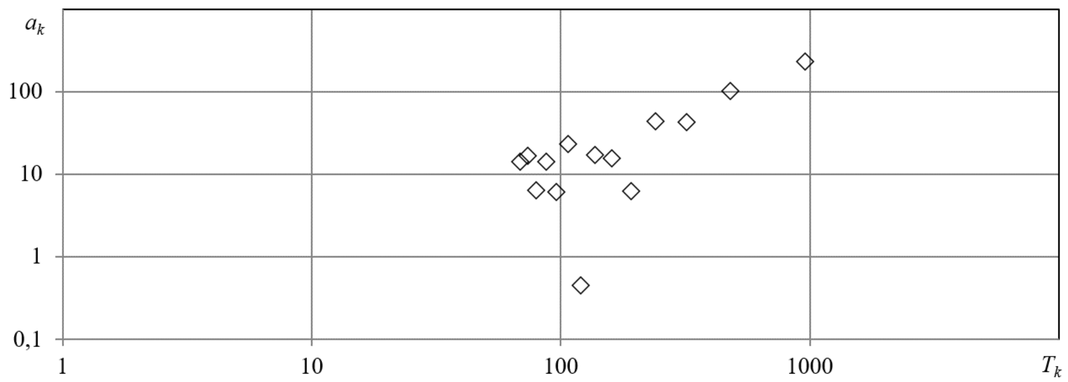

d

Fig. 5. Dependencies ‘amplitude – period’ for daily traffic flow intensity N (vph) at averaging intervals Δ = 10 min (*a*), Δ = 20 min (*b*), Δ = 30 min (*c*) and Δ = 60 min (*d*) (developed by the authors)

Following this is a traffic 'subflow' with the intensity of a_2 = 145–146 vph at intervals of 10–11 hours (T_2 = 10 hours 40 minutes). Then there is a traffic flow with the intensity a_4 = 43–44 vph and period of 5–6 hours (T_4 = hours 22 minutes) etc.

The flow with the lowest intensity of a_{17} = 17–18 vph (Table 2) has a periodicity of 25–30 min (T_4 = 28 minutes and 24 seconds).

Fig. 5 indicates the characteristics 'period T_k – amplitude a_k', in logarithmic coordinates obtained by processing the source data with processing intervals Δ = 5, 10, 20, 30 and 60 minutes, respectively.

The reduction in data volumes in the amplitude spectra is associated with a decrease in the volume of time series of the daily traffic flow intensity due to an increase in the duration of the averaging intervals.

Conclusion

The data collected in real time by different MSHCs allowed to determine the time dependence of the traffic flow intensity on one of the roads of a large industrial city with different duration of averaging time intervals. The possibility of using a series expansion in harmonic functions to analyze the features of the traffic flow intensity function is considered.

Due to the fast Fourier transform the numerical analysis of amplitudes, frequencies, and phase shifts of harmonics in the Fourier series expansion of the function in question was carried out. It was proposed to use 'period-amplitude' dependence instead of the amplitude-frequency spectrum as more substantial considering traffic flow analysis issues. Harmonic analysis of traffic flow is appropriate for forecasting traffic flow intensity, controlling algorithms of traffic lights, as well as using as source data for reconstruction, design and construction of roads and road facilities.

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