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Duration of Car Movement in the Flow as a Traffic Congestion Indicator

Mikhail G. BOYARSHINOV

Alexander S. VAVILIN

Mikhail G. Boyarshinov [1]***, Alexander S. Vavilin*** [2]
Perm National Research Polytechnic University, Perm, Russia.
✉ [1] *mgboyarshinov@pstu.ru.*
[1] *ORCID 0000-0003-4473-6776; Web of Science Researcher ID: ACE-0166-2022; Russian Science Citation Index SPIN-code: 5958-2345; Russian Science Citation Index Author ID: 79853.*
[2] *ORCID: 0000-0003-4473-6792; Russian Science Citation Index Author ID: 566592.*

ABSTRACT

The relevance of studying traffic congestion is determined by the need to find a scientifically based criterion for its emergence, development and elimination using modern methods of processing information about car flows. The objective of this study is to reveal a quantitative criterion for emergence and evolution of traffic congestion based on a deterministic estimate of time of movement of individual vehicles in the general flow between control boundaries as a random variable of mean value, mode, median, standard deviation, variation indicators, asymmetry, and kurtosis.

The subject of the study related to the patterns of evolution of the listed deterministic indicators of traffic flows, which can be used for operational forecasting of formation, development, and elimination of traffic congestion. The initial data were obtained using hardware and software systems for fixing traffic violations installed on the urban street-and-road network. As a result of the study, it was found that for the same section of the road, the listed deterministic indicators of a random variable differ significantly during free movement of road transport and in case of a traffic jam. It seems promising to use the average value of duration of movement of cars to identify the stages of emergence, development, and disappearance (liquidation) of traffic congestion. The proposed indicator can serve as a basis for developing a mechanism for real-time assessment of the likelihood of emergence of traffic jams, as well as for developing recommendations for the rapid response of transport services to prevent and eliminate them.

Keywords: *road transport, traffic congestion, traffic jam, traffic flow, traffic intensity, duration of movement on the road.*

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INTRODUCTION

The study on factors and consequences of emergence of traffic congestion, mathematical and computational modelling and simulation, and further forecasting of emergence of traffic congestion is rather a relevant problem that has not found till now adequate solution in Russian or global research. Till recently the term of traffic congestion has been interpreted by the authors in rather a free manner, as this has been revealed in works [1–3] and other papers. It is to note that domestic regulatory definition of traffic congestion first appeared in GOST [State standard] R 55691–2013/ISO/TS 15624:2001. The ambiguity of defining traffic congestion resulted in missing of a reliable quantitative scale to classify, record, and measure this phenomenon, to determine the time of emergence, duration, and end time of traffic congestion. Consequently, there is no possibility to automatically track the location and the time of concentration of vehicles (traffic jam) in the streets of modern city.

The analysis of vehicle flows operates with indicators of uniformity and speed of transport [4; 5], street-road network congestion [6–8], hourly and daily traffic intensity [9–13], as well as deterministic characteristics of random variables [14–16]: mean value, mode, median, variance, standard deviation, indicators of variation, asymmetry and kurtosis, and others. The conduct of field surveys to increase the efficiency of road use, as well as to prevent traffic jams, reduce accidents and negative impact on the environment involves direct observation and study of video recordings[1] of movement of cars in the traffic flow, mobile road laboratories [17], unmanned aerial vehicles [18], satellite monitoring tools [19; 20], vehicle acoustic emission recorders [21], built-in (intrusive) sensors on the roads, probe vehicles equipped with accelerometers, ultrasonic emitters and receivers of the global navigation satellite system, software and hardware complexes for video recording of traffic violations [22–25]. In addition, there is a need for effective technologies for collecting, storing and processing information about the situation on the roads [26; 27], high-performance data processing and analysis algorithms based on multidimensional scaling, methods of statistical, regression, cluster, harmonic, wavelet and other types of analysis, which allows collecting and studying real-time information about development of the main indicators of traffic flow over time on the road network for various time intervals, on separate sections of roads and their intersections, to build origin-destination matrices, and so on.

The problem of traffic congestion is a priority for the transport system [10; 28; 29]. The reasons for their emergence relate to general increase in the number of cars [17], traffic accidents [30], a decrease in road capacity [31–33], an increase in the density of cars on a road section [34], an increase in the truck fleet and transportation volume [35; 36], the presence of unregulated intersections, entrances and pedestrian crossings [37], the installation of traffic lights with a large number of phases [38], the inconsistency of their work [39], construction and repair work [40], irrational organisation of the work of toll collection points [41], the human factor [26; 37; 42] and other factors.

Traffic congestion leads to a decrease in speed and an increase in travel time [43], an increase in fuel consumption and transportation costs [12], an increase in polluting emissions into the environment, accidents and noise levels, health hazards [26], a decrease in labour productivity and in quality of transport services, in safety of road users [44], deterioration of the psychological state of drivers and passengers.

To detect the presence of a traffic jam and determine the degree of congestion of the road network, in some cases, the average time for passing a section of the road, determined using the software of car navigators, is used[2] [29]. Since traffic flows as objects of study are stochastic, the works [45; 46] considered the influence of the random nature of the traffic flow on the degree of saturation of controlled intersections and duration of delay of vehicles. A stochastic model of a system of technical means for monitoring and controlling compliance with traffic rules is presented in [47] to assess the effectiveness of managing a traffic safety system. The model [48] of a regulated intersection with several random traffic flows was used in the calculation of traffic light regulation to reduce the likelihood of traffic jams on the street-and-road network.

[1] GOST 32965-2014. Public automobile roads. Methods for accounting for traffic intensity. Moscow, Standartinform publ., 2019, 18 p. [Electronic resource]: https://docs.cntd.ru/document/1200132267. Last accessed 17.04.2023.

[2] How Yandex.Traffic jams works. [Electronic resource]: https://yandex.ru/company/technologies/yaprobki. Last accessed 15.11.2022.

On sections of the road network with high traffic intensity and volatility, adaptive approaches are most effective [35; 49], based on the analysis of traffic congestion and allowing changing the phases of the traffic light in real time, automatically adjusting to the traffic flow, reducing traffic delays, travel time and emissions of pollutants into the atmosphere. The need to develop a methodology for managing traffic flows based on monitoring and predicting the queues of vehicles due to the increased load on the road network is substantiated in [50]. The introduction of intelligent transport systems [51] is aimed at reducing and eliminating traffic congestion by regulating movement of vehicles. The theory of cognitive transport systems [52] involves introduction of mechanisms for continuous research and self-learning of both the transport systems themselves and the transport infrastructure due to the automated collection of data on traffic accidents, their processing in real time for prompt response to changes in the transport situation.

Currently, in the Russian Federation, the concept of traffic congestion is enshrined in the standard[3]: «Congestion (traffic impediment): a congestion of vehicles forced to significantly reduce speed of movement up to its complete cessation within one or more lanes due to any traffic obstruction». It should be noted the predominantly qualitative nature of this definition and the absence at present of a quantitative indicator that makes it possible to assess the stages of the existence of a traffic jam.

It should be expected that during emergence, evolution and elimination of a traffic congestion as a result of a traffic accident, repair of the roadway, violation of the speed limit or traffic rules, causes of an accidental (spontaneous) nature or due to other circumstances, the main indicators of the traffic flow take on specific (critical) values that distinguish them from the «normal» values unique to each specific section of the road network. The rapid detection of such specific values will allow operators of traffic control services to make informed decisions in a timely manner and take rational actions to manage traffic flows to eliminate the negative consequences of traffic congestion.

[3] GOST R 55691-2013/ISO/TS 15624:2001. Transport management and information systems. Traffic Impediment Warning Systems (TIWS). System requirements. Moscow, Standartinform, 2014, 24 p. [Electronic resource]: https://docs.cntd.ru/document/1200107272. Last accessed 28.02.2023.

To correctly determine the specific values of the traffic flow, indicating emergence (evolution, elimination) of a traffic jam, it is necessary:

• To collect data on «normal» traffic flow indicators in the studied area (density, intensity and speed of traffic flow, travel time and other indicators typical for free movement of cars).

• To determine anomalous (critical) values of the main parameters of the traffic flow during formation, development, and elimination of traffic congestion, when there is traffic impediment.

• To perform comparison and analysis of traffic flow indicators in case of free movement of road transport and in case of traffic congestion.

• To develop criteria for detecting anomalous values of traffic flow indicators to assess the probability of emergence of traffic congestion.

The quantitative, scientifically substantiated indicator, suggested by the authors, will allow classifying types of congestions, tracing the fact of emergence of traffic congestion, its starting time, duration, end time, and will be useful to prevent and promptly reveal the conditions for emergence of the traffic congestion on the street-and-road network, will serve as a reference basis to develop recommendations for transport organisations permitting them to rapidly intervene to prevent or neutralise traffic congestions.

Given the above, the *objective* of this study is to identify a quantitative indicator of emergence and evolution of traffic congestion based on the analysis of random values of duration of movement between the control lines of all cars in the observed traffic flow based on revealing of deterministic estimates of time of their movement, including the average value, mode, median, standard deviation, indicators of variation, asymmetry and kurtosis, using modern *mathematical tools of statistical analysis*. It is advisable to compare these deterministic indicators with each other in terms of effectiveness of detecting a traffic jam.

RESULTS

Vehicle Traffic Intensity

The study of emergence and evolution of a traffic jam was carried out on a section of the road 2,2 km long, free from intersections (Pic. 1). The selected section is characterised by spontaneous traffic jam formation, which usually takes place in the afternoon. Observations were carried out during May 8 (there was no traffic jam during the day) and May 9, 2022 (traffic jam

Pic. 1. The section of the road selected for the study; markers indicate observation lines, an arrow indicates the direction of traffic [developed by the authors using resources of 2GIS of LLC «DoubleGIS» [Electronic resource]: https://2gis.ru/perm. Last accessed 28.02.2023].

was recorded from 20:00 to 22:00). The initial data for the study were obtained using hardware and software systems for photo and video recording of traffic violations.

Pic. 2 shows the daily dependences of intensity of the traffic flow on the considered section of the road on May 8 (Pic. 2, *a* – the entrance line) and May 9 (Pic. 2, *b* – the entrance line, *c* – the exit line). There are no fundamental differences in the behaviour of intensity of the traffic flow in the absence of a traffic jam on May 8 and its presence on May 9 in the interval from 20:00 (1200 min) to 22:00 (1320 min).

Anomalies in the behaviour of intensity of the traffic flow, which could indicate formation of a traffic jam, were not identified. There are also no fundamental differences that could indicate the presence or absence of a traffic jam in the probability density distribution of the flow intensity values on the specified days at the control boundaries of the considered road section (Pic. 3).

The deterministic indicators of random functions of intensity of the traffic flow on May 8 and 9 (Table 1) also do not allow detecting signs of a traffic jam. Thus, the analysis of the intensity function of the traffic flow on the road section under consideration did not make it possible to distinguish between traffic situations with and without a traffic congestion.

Duration of Movement of Cars in the Flow of Vehicles

It is advisable to consider another indicator of the traffic flow of vehicles related to the regulatory definition of the traffic congestion.

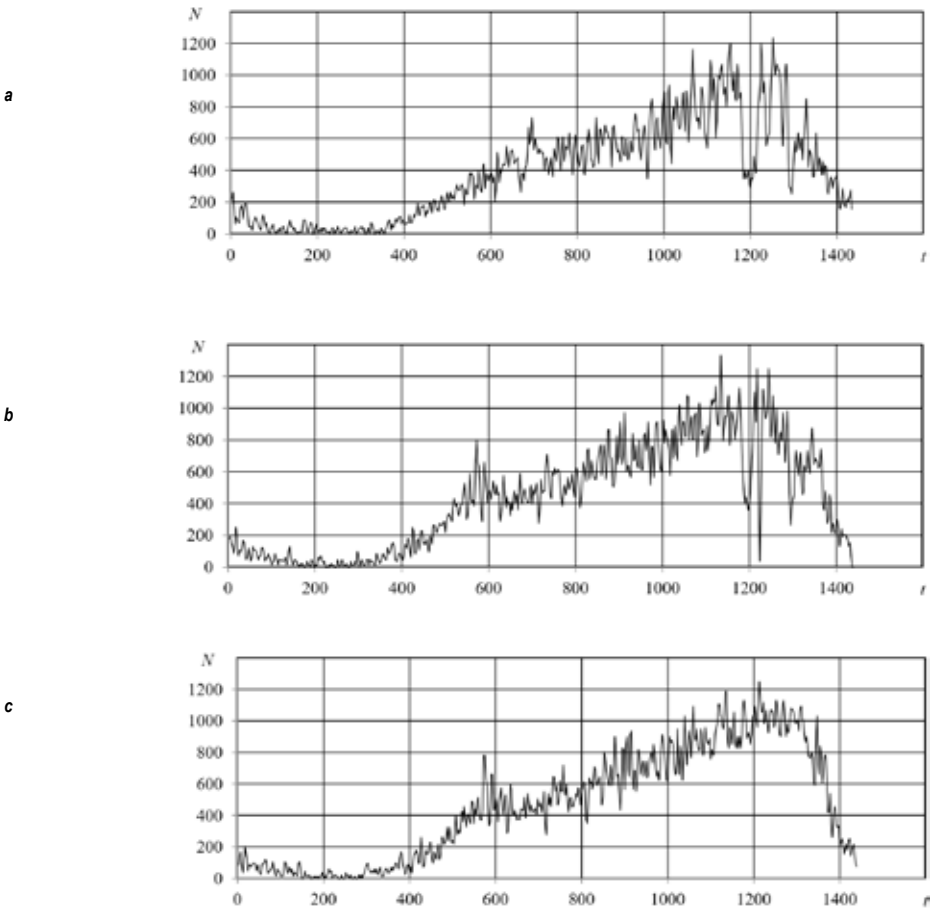
It follows from the definition that the quantitative basis for constructing the traffic congestion criterion can be the speed of vehicles in the traffic flow, changing from the maximum allowed value up to zero, that is, to a complete stop. It is impossible to determine true, or instantaneous speed of the car at any given time without the use of special technical means in modern conditions.

Since the hardware-software complexes for photo and video recording of traffic violations make it possible to record the state registration plate (that is, to identify a specific car), the moments of the beginning and end of its movement along the studied area, this makes it possible to determine the average speed of each car moving between control lines.

The average speed v_i^{av} and time T_{i} of the *i*-th car passing between the control lines are equivalent in terms of informativeness and are related by the relation $v_i^{\text{av}} = S / T_{\text{i}}$, where S is the distance between the control lines. However, from the point of view of efficiency of the computational part of the complex, it is advisable to limit ourselves to determining time T_{i} and not to overload the processor with the calculation of v_i^{av}.

Pic. 4 shows the dependence of duration T_{i} of movement between the control lines of individual cars on time *t* of their appearance at the beginning of the section from 0:00 to 24:00 (data obtained from the complex of photo and video recording of traffic violations for May 9, 2022). The sharp increase in duration of movement of cars in the period from 20:00 to 22:00 reflects the formation of a traffic jam on the road.

The duration T_{i} of movement of individual cars can be considered as a function of time t, which is a time series, which made it possible to perform harmonic analysis (Fourier analysis) [53], wavelet analysis [54], the study of the Hurst exponent [55] of the data presented in Pic. 4. The results of the performed analysis make it possible to identify anomalies indicating emergence of a traffic congestion, but the approaches



Pic. 2. Dependences of intensity of the traffic flow N (car/hour) on time t (min) on May 8 (a – entrance line) and May 9, 2022 (b – entrance line, c – exit line) [developed by the authors].

themselves turned out to be cumbersome and uneconomical in terms of computational costs.

The method based on the statistical analysis of the time series (Pic. 4) using the «sliding window» turned out to be rational and economical.

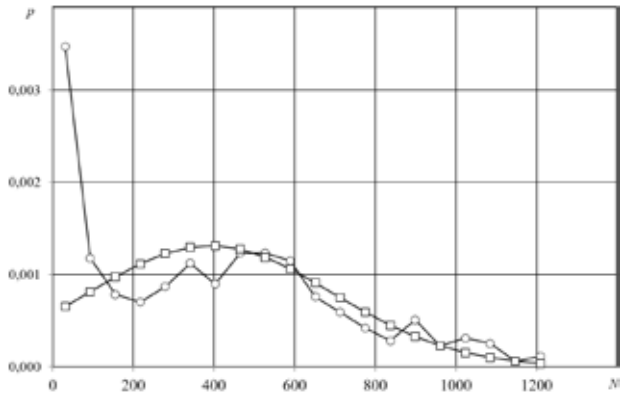
Pic. 5 shows the average duration T_{av} of movement of cars along the studied section of the road during the day, depending on the time of their appearance t at the initial boundary, according to the data obtained for May 8 (no traffic jam) and May 9 (traffic jam recorded) 2022. Averaging was carried out over ten-minute time intervals with a successive shift of these intervals by 1 minute («sliding» averaging interval). The formation of a traffic jam is detected by a rapid increase in the average duration T_{av} of movement of cars between the control lines. The elimination of traffic congestion

Table 1

Statistical indicators of traffic intensity on May 8 and 9, 2022 [developed by the authors]

Traffic flow intensity indicators	Date		
	08 May	09 May	
	Entrance line	Entrance line	Exit line
Total number of cars per day, units	9518	10591	11312
Average value, car/hour	396,58	441,29	471,33
Median, car/hour	372,00	438,00	456,0
Standard deviation, car/hour	304,10	325,98	353,22
Variation coefficient, %	76,68	73,87	74,94
Asymmetry	0,53	0,30	0,22
Excess	-0,56	-1,03	-1,27

a



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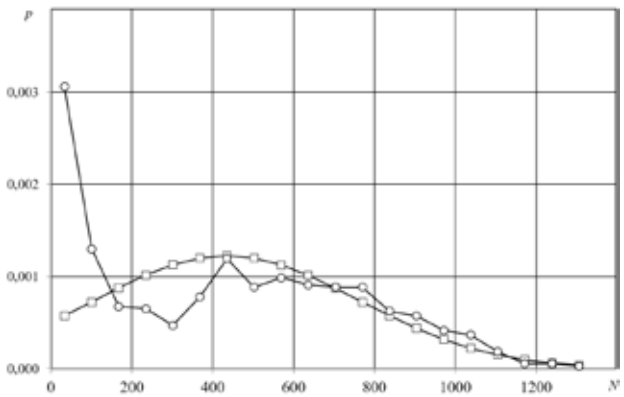

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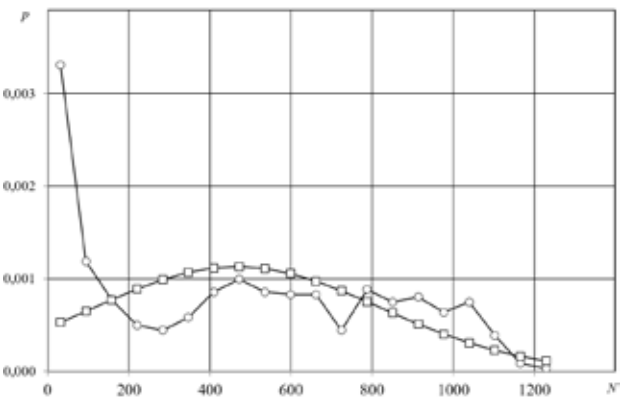
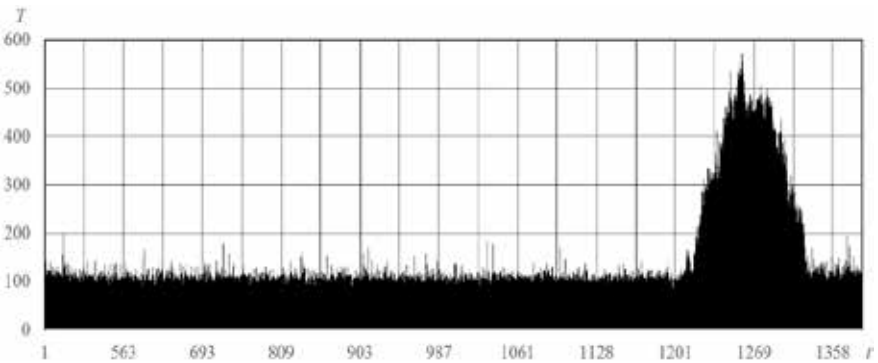
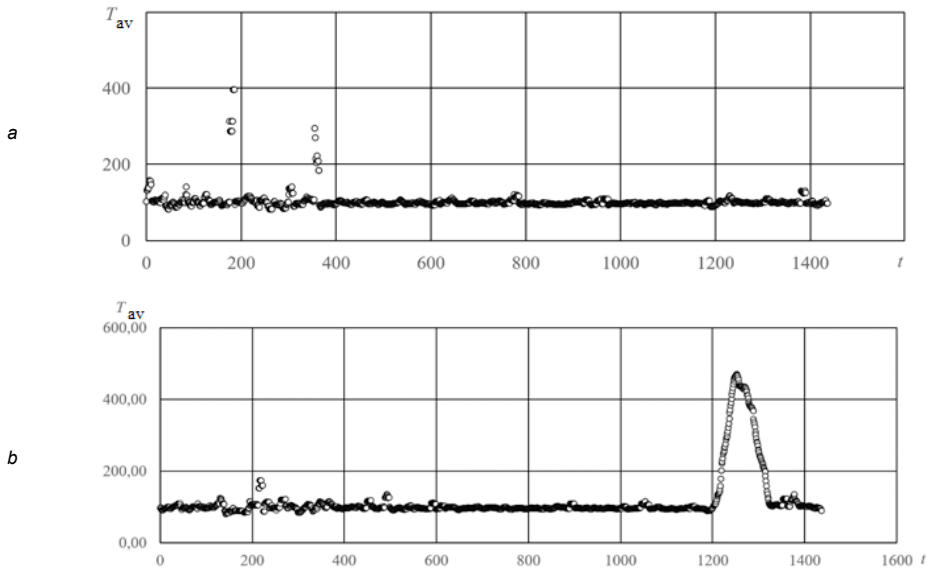


Pic. 3. Density distributions p of the probability of the intensity N of the traffic flow on May 8 (a – entrance line) and May 9, 2022 (b – entrance line, c – exit line); experimental (–o–) and theoretical (–▫–) distribution curves [developed by the authors].



Pic. 4. The dependence of duration T_i(s) of movement of individual cars on time t (min) of the appearance of cars at the beginning of the section during the day on May 9, 2022 [developed by the authors].



Pic. 5. Averaged durations <<Eqn281.eps>> (s) of movement of cars depending on time t (min) of appearance of cars at the beginning of the section on May 8 (a) and May 9, 2022 (b) [developed by the authors].

Table 2

Statistical characteristics of distribution of duration of movement of cars along the road section for different observation periods on May 9, 2022 [developed by the authors]

Statistical indicators	Observation periods, hours		
	00:00–24:00	00:00–20:00	20:00–22:00
Average value T_{av}, s	130,81	95,62	317,48
Mode, s	96,00	94,50	435,50
Median, s	98,53	95,21	332,78
Standard deviations, s	95,07	12,73	125,47
Variation coefficient, %	72,68	13,31	39,52
Asymmetry	2,60	0,29	-0,30
Kurtosis	5,62	0,23	-1,11

can also be recorded by return of the duration of movement of cars to the established average value characteristic of this section of the road.

Comparison of pictures 2 and 5 makes it possible to explain the high values of T_{av} at the beginning of the day from 0 to 3:20 in the morning, which, apparently, are associated with the low speed of individual cars in the dark and are due to the psychological characteristics of the drivers of these cars, since the traffic volume at this time is negligible.

Data given in Table 2 made it possible to compare the main indicators of distribution of the random variable of duration T_i of movement of cars between the control lines in the absence (00:00–20:00) and the presence (20:00–22:00) of a traffic congestion on the road section selected for observation:

• Average value of duration T_{av} of movement of cars in the presence of a traffic jam increased by 3,32 times compared to movement of cars in its absence.

• Mode has increased by 4,61 times.

• Median has changed by 3,5 times.

• Dispersion has increased by 97,13 times.

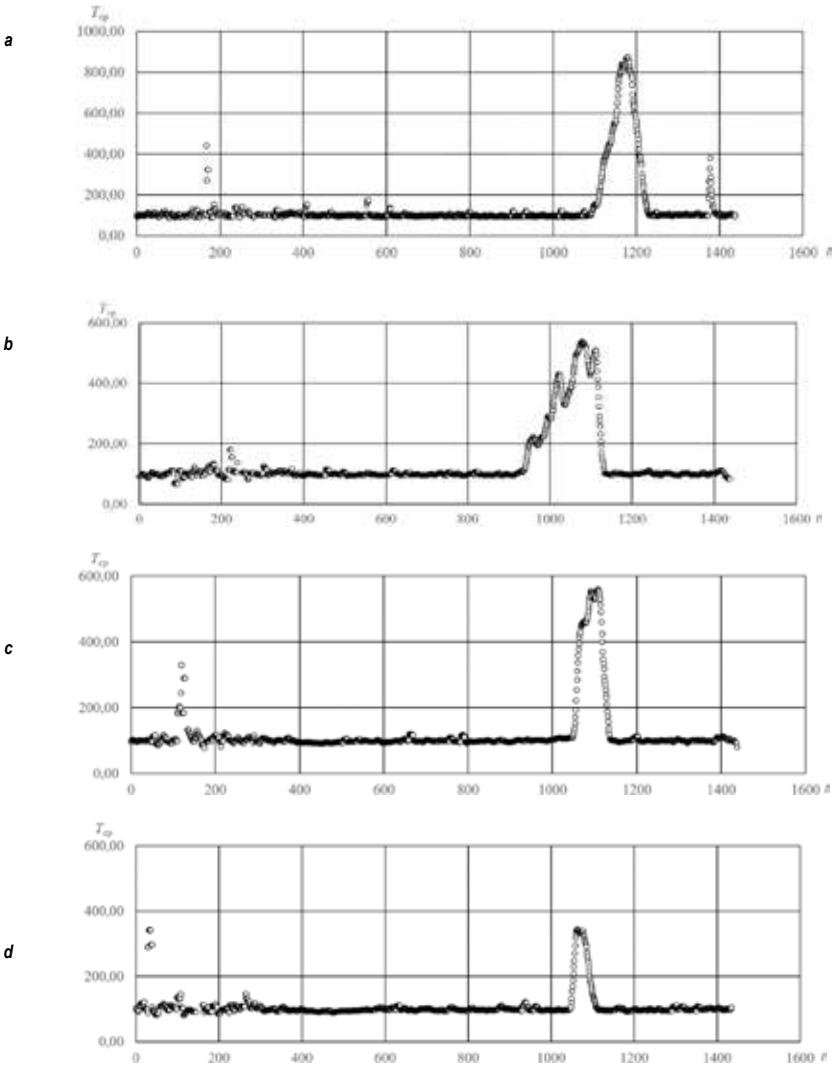
• Standard deviation has increased by 9,86 times.

• Variation coefficient has changed by 2,97 times.

• Asymmetry indicator has evolved from 0,29 to –0,30.

• Kurtosis indicator has changed from 0,23 to –1,11.

Thus, all indicators of distribution of random duration of movement of cars in the presence of a traffic jam have changed significantly compared to the same indicators in the absence of a traffic jam. It can be assumed that some of these indicators may turn out to be effective indicators,



Pic. 6. Averaged durations <<Eqn288.eps>> (s) of movement of cars depending on the moment of time t (min) of the appearance of cars at the beginning of the section on May 9, 2021 (a), May 3 (b), May 16 (c) and May 27 (d) 2022 [developed by the authors].

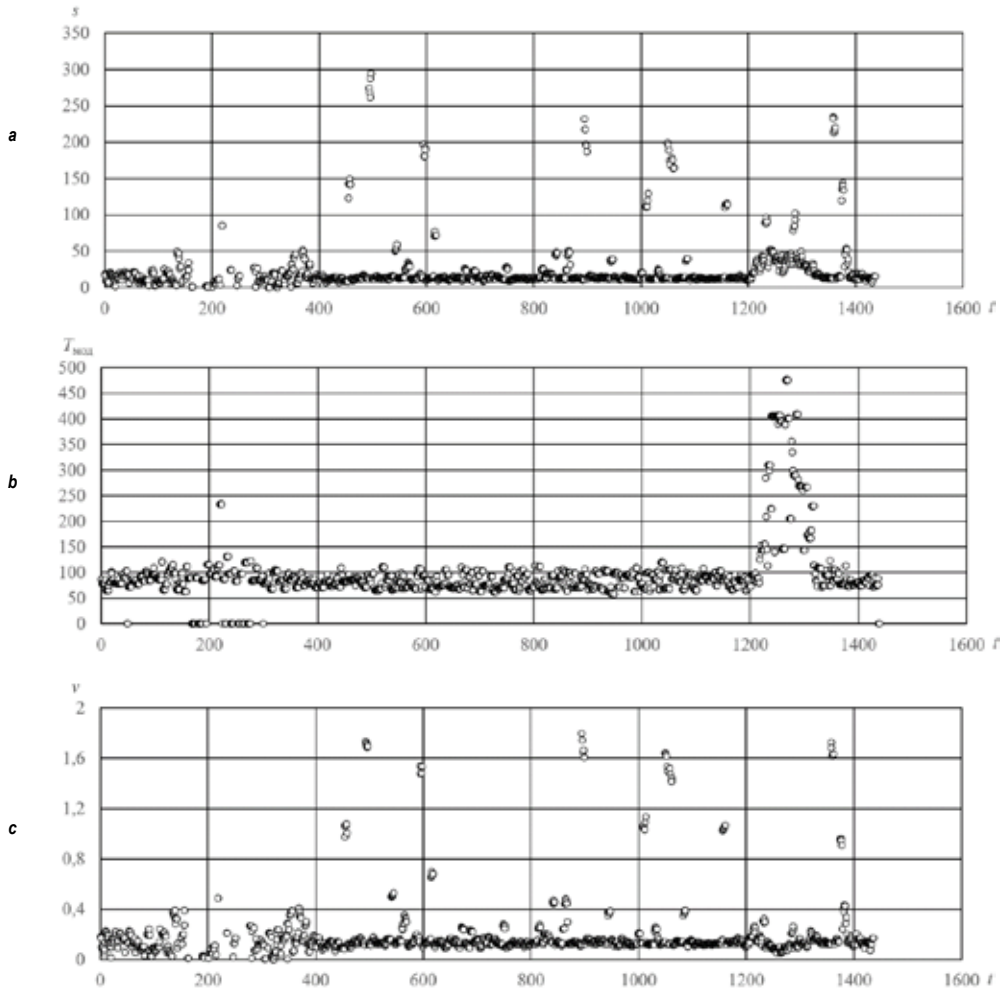
the observation of which will make it possible to predict formation, development, and elimination of traffic congestion on urban street-and-road networks, intercity routes and highways.

Pic. 6 shows the average duration T_{av} of movement of cars along the studied section of the road during the day, depending on time of their appearance t at the initial boundary. Averaging was carried out over ten-minute time intervals with a successive shift of these intervals by one minute («sliding» averaging interval). The formation of congestion was recorded on May 9, 2021 (Pic. 6, *a*), May 3 (Pic. 6, *b*), May 16 (Pic. 6, *c*) and May 27, 2022 (Pic. 6, *d*).

According to the data presented, the onset of traffic jams (from 15:00 to 20:00 local time) and their duration (from 1 hour 15 minutes to 3 hours 20 minutes) are different. As before (Pic. 5, *b*), formation of a traffic jam is detected by a rapid increase in the average duration T_{av} of movement of cars between the control lines. The elimination of traffic congestion can also be recorded by return of duration of movement of cars to the established average value characteristic of this section of the road.

Pics. 7 and 8 show the statistical characteristics of distribution of a random variable of duration T_i of movement of cars between the control lines: standard deviation, mode, coefficient of variation, asymmetry indicator and kurtosis according to the data obtained for May 9, 2022.

These functions were determined, as before, using averaging over ten-minute time intervals with a sequential shift of these intervals by one minute («sliding» interval).



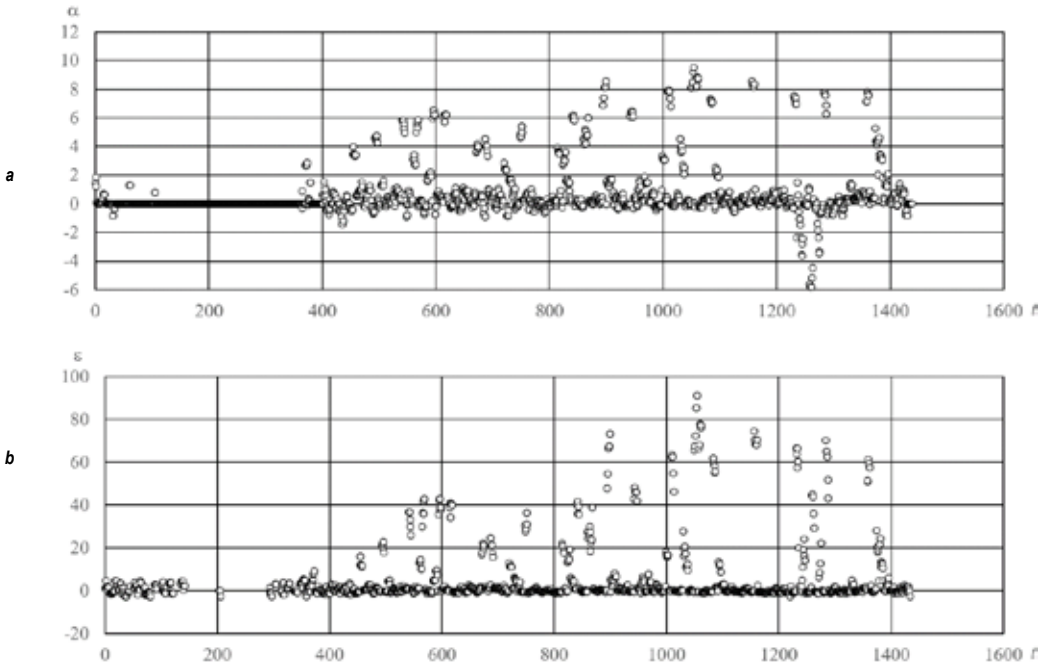
Pic. 7. Statistical characteristics of distribution of the random variable T_i of duration of movement of cars between the control lines: standard deviation (a), mode (b), coefficient of variation (c); data for May 9, 2022 [developed by the authors].

The presented results show that it is advisable to fix the beginning of formation and the end of the traffic congestion precisely by the average value T_{av} of duration of movement of cars, since the dependences of the standard deviation, mode, coefficient of variation, asymmetry index and kurtosis on the observation time t differ in a significant scatter of values and do not allow uniquely identify traffic congestion.parison of Pics. 4 and 5, *b* also shows that the identification of the beginning of formation of a traffic jam should be performed using the average value T_{av} of duration of movement of cars, since the observed duration of movement T_i of each particular car depends on its operational characteristics, experience, driving skills and individual characteristics of drivers, and the dependence of T_i on time is characterised by high oscillation (Pic. 4).

CONCLUSIONS

The processing of data obtained with the help of hardware-software complexes for photo and video recording of traffic violations makes it possible to obtain important and reliable information about the state of the traffic flow in real time. The study has revealed that the dependencies on duration of movement of cars in the flow between two control lines differ significantly in free movement of road transport and in case of a traffic jam. The proposed approach to identifying a traffic congestion can be useful for preventing and promptly identifying the conditions for formation of traffic jams when cars move along street-and-road networks.

The study performed can serve as a scientific and methodological basis for developing a forecast mathematical, computational or simulation model of emergence, evolution and



Pic. 8. Statistical characteristics of distribution of the random variable T_i of duration of movement of cars between the control lines: asymmetry indicator (a) and kurtosis (b); data for May 9, 2022 [developed by the authors].

ending of traffic congestion considering core factors (growing number of cars, road traffic accidents, decrease in transit capacity of roads, intersections without traffic lights, entrances and pedestrian crossings, traffic lights with numerous phases, road maintenance and repair works, psychological features of drivers, and other factors). This model can allow further developing recommendations for a prompt response of transport management organisations, science-based forecasting and long-term planning tools, substantiating and making managerial decisions on preventive measures to eliminate the conditions for emergence of traffic congestion.

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Information about the authors:

Boyarshinov, Mikhail G., *D.Sc. (Eng), Professor at the Department of Vehicles and Technological Machines of Perm National Research Polytechnic University, Honorary Employee of the Higher Professional Education of the Russian Federation,Perm, Russia, mgboyarshinov@pstu.ru.*

Vavilin, Alexander S., *Ph.D. student at the Department of Vehicles and Technological Machines of Perm National Research Polytechnic University, Perm, Russia, vavilin@tbdd.ru.*

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From the editors. The article, as the editors hope, can serve as a starting point for further discussion of the topic from various points of view. The reviewers noted the originality of the field observations with the use of photo and video recording tools, the use of methods of statistical analysis of the characteristics of the speed modes of the traffic flow in-between intersections to assess the probability of congestion, whilst in their opinion the recognition of the average duration of movement on the section (or average speed) as an indicator of the formation of congestion is generally recognised, and, therefore, the analysis of other characteristics of the distribution of a random value of the time of movement might be used rather for our purposes, i. e., to assess reliability of transportation, safety, etc. The authors recognising the significance of these areas of scientific research, would like to consider the creation of a basis for the formation of a predictive model of traffic congestion to further develop tools for justification and management decision-making on preventive measures to eliminate conditions for traffic congestion. In this regard, it is important to continue the discussion in the journal.