The object of the study is the vehicle driving mode and the results of trip on the road network of a large city under various speed limit conditions. The problem of quantitative assessment of the impact of speed limits on the average speed on the route, as well as on the indicators of driving mode unevenness, was solved. The values of such traffic parameters as average speed, average speed deviation, acceleration noise, speed gradient, energy gradient at different values of the posted speed limit (PSL) were obtained. Graphs of changes in the average speed and indicators of the unevenness of the speed regime were constructed and mathematical models of the dependence of the average speed on urban routes on the adopted speed limit were proposed. The results showed an increase in the average speed on the route by an average of 2.4 km/h with an increase in PSL by 10 km/h. At the same time, the dependence of the average speed on the PSL is non-linear and shows a decrease in the impact of the speed limit factor at higher PSL values (from 3.5 km/h for a PSL of 50 km/h to 1.24 km/h for a PSL of 80 km/h). Increasing the PSL does not affect the specific time in motion and leads to an increase in the specific idle time. With an increase in PSL, the acceleration noise and energy gradient increase. The increase in average speed is explained by the ability to increase speed in low-loaded sections of the route, but with an increase in PSL, the ability to realize the increased speed decreases, and the traffic mode itself becomes more uneven.

The research was carried out using the "driving laboratory" method on three different routes under the same initial conditions for speed limits from 50 to 80 km/h. The driving mode of the car was recorded in the form of GPS tracks. The results can be used to assess the impact of PSL changes on the technical and economic performance of urban road transport. The results will also be useful in conducting an information campaign and promoting a culture of compliance with the speed limits established in cities among drivers

Keywords: speed limit, average speed, speed mode, acceleration noise, speed gradient, GPS track

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IDENTIFYING THE IMPACT OF POSTED SPEED LIMITS ON VEHICLE TRAVEL MODE ON URBAN ROUTES

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1. Introduction

One of the main components of a smart city concept is the effective management of the speed of vehicles on the road network. Such a system must satisfy the population's need for mobility at the required level of comfort of travel. At the same time, high road safety standards must also be ensured. Ensuring high average speeds of vehicles between travel points is also necessary to maintain the required level of productivity and reduce the cost of transporting goods and passengers. Thus, the contradiction is inherent in the very concept of speed management, since setting higher speed limits to save travel time inevitably leads to an increased risk of accidents. Therefore, the main tool for managing vehicle speeds in urban conditions remains limiting speeds to values that ensure a minimally acceptable risk to human life and health.

Personal vehicles today remain the basis for ensuring the mobility of the urban population, and the infrastructure of road transport is a city-forming factor in modern megacities. The problem of speed limit management in cities, in addition to being purely technical, also has a social aspect. Reducing speed limits or additional restrictions on certain road sections can be negatively perceived by drivers, even if they do not have a significant impact on average speed and average travel time. At the same time, exceeding the established speed limit in the city is perceived by some drivers as a means of saving travel time.

The main goal of road users is the desire to reach their destination in a shorter time, so most drivers try to drive at the highest speed that traffic conditions allow on a given section of road. The speed mode during the trip, as well as its stability, is directly perceived by the driver and can serve as a subjective criterion for assessing the quality of traffic organization. The criteria of average speed and average travel time already require comparison with human expectations or comparison with alternative modes of transport. But it is the average speed that reflects the main positive effect for the user, which is saving their travel time.

Failure to comply with the established speed limit when traveling on the road network of cities is one of the most pressing problems of traffic management, the solution of which constantly consumes significant resources. In an effort to reduce travel time by speeding, drivers usually do not think about the risk of accidents, as this danger is not immediately apparent. The problem of compliance with the posted speed limit is mainly solved by police methods through the punishment of violators. Information campaigns and propaganda promoting compliance with speed limits, when used, are mainly aimed at intimidating drivers with the risks of getting into an accident. This approach does not deprive speeders of their main motive, which is to save time on travel. An analysis of traffic patterns and travel results under different speed limit conditions will allow for an objective assessment of the effects of speeding. Therefore, the success of urban speed limit policies largely depends on drivers' motivation to comply with speed limits, as automated speed enforcement measures cannot cover the entire urban road network.

Thus, studies devoted to establishing a relationship between the speed limit set in the city and the actual speed mode during driving and the results of the trip are relevant. This is especially true for experimental studies on real city routes, which would allow for an objective assessment of the impact of the posted speed limit (PSL) on average speed, comfort, and safety characteristics of traffic in urban conditions. In addition, average technical speed is included in many mathematical models used to calculate the productivity of motor transport. Therefore, the results of observations of vehicles on real urban routes will also allow assessing the economic effect of changing the speed limit.

2. Literature review and problem statement

Publications that study the speed modes of vehicles in urban conditions usually describe the dependence of traffic speed on certain types of roads (highways, collectors, low-speed city streets) on various factors. The type of terrain (central part of the city or periphery), geometric parameters of the road, the intensity of traffic flow, the presence of parking and others are considered as influencing factors. In general, it was found that for expressways, the volume of traffic flow, as well as the presence of horizontal curves, has the greatest impact on the average speed [1]. For other roads, average speeds largely depend on the presence of regulated intersections and pedestrian crossings [2]. However, these studies do not specifically examine the factor of speed limits.

The largest number of studies on the problem of optimizing speed limits in cities is related to road safety issues [3, 4]. Separate papers consider the relationship of this factor with emissions of harmful substances [5] and fuel consumption [6]. These papers note the negative impact of increasing speed limits on the likelihood and severity of accidents, fuel consumption and emissions, but do not investigate how such changes affect the average speed, time indicators and unevenness of the speed limit.

In general, it can be noted that less attention is paid to the study of the impact of speed limits on road traffic efficiency, the reason for which may be the underestimation of the importance of these factors in comparison with road safety and environmental safety factors.

The average technical speed and the operating speed are often considered as criteria for the quality of traffic management. The paper [7] notes that the condition of ensuring an acceptable average speed for road users is one of the main criteria of mobility in assessing the quality of traffic management in urban areas. In [8], the analysis of studies of the effect of speed for individual trips on average speed and travel time is carried out and their low correlation is noted. But in these works, the effect of the speed limit factor on the average speed was not studied. In [9], the floating car method was used to study travel time and the degree of speed unevenness in urban conditions. However, the studies were conducted only for individual urban highways and without taking into account the speed limit factor.

In [10], based on the results of the analysis of data on the mode of taxi traffic, it was shown that the average speed on the city's road network varied from 25 to 45 km/h depending on the type of territory, time of day and traffic capacity. In the article [11], speed parameters and its unevenness on the road network of the metropolis are studied by the method of modeling. However, these studies also did not take into account the influence of speed limits. The reason for this may be the insufficient number of sections with different speed limits, which makes such studies impractical.

In the paper [12], the average parameters of speed and travel time were studied for specific routes on the city's road network using the method of floating cars using GPS data. However, this work also did not investigate the speed limit factor. In [13] there is a significant influence of the type of territory through which the route passes on the average speed and travel time. Significant differences in speed and travel time values for central and peripheral areas of cities were observed regardless of the type of models used and the type of transport (public transport or private car) [14]. Therefore, the level of traffic congestion can be considered one of the key factors affecting the speed and time indicators of vehicle movement on the route. The study [15] also notes the effect of peak periods on average speed and travel time, as delays associated with traffic jams significantly increase travel time. For different cities, the peculiarities of land use will also affect these indicators. The results of the research [13–15] are of practical interest and can be the basis for forecasting the indicators of the functioning of the city road networks a whole. At the same time, they are less suitable for the purposes of propaganda and encouraging road users to comply with the established speed mode. Also, these studies did not analyze PSL as a separate factor and its impact on the average speed and time in motion.

Studies [16] note a positive correlation between average speed and PSL for urban conditions, with this factor having a greater impact on residential streets than on main roads. Study [17] notes that increasing the speed limit from 65 to 70 mph led to an increase in average speed by 1.7 mph. However, the authors of these studies analyzed the impact of speed limits only for a narrow range of PSL, which does not allow for the construction of an adequate mathematical model. In addition, in works [16, 17], the impact of PSL on average speed is assessed for individual sections or elements of the road network. This does not allow for an assessment of the final effect for road users who focus on the results of their trip and the degree of comfort when using the city's road network as a whole.

Works [18, 19] investigate the impact of speed limits on traffic flows in urban road networks, but they do not consider the impact of PSL on the traffic mode and trip results for an individual car in a traffic flow.

Work [20] investigates the impact of reducing speed limits on various traffic factors, including average speed and travel time. The TrafikPlan model is used to analyze speed limit modes of 60, 50, and 40 km/h on city roads. As a result, the average speed decreased from 42.6 km/h to 31 km/h. However, in this work, the modeling of speed limit changes was performed only for high-speed city highways.

In [21], it was shown that lowering the speed limit has almost no effect on the average speed in conditions of heavy traffic. At the same time, in conditions of free traffic, the effect of speed limits is very significant. However, this study is not empirical, but was conducted using simulation modeling.

Some empirical studies challenge the common assumption that reducing speed limits in cities significantly affects average vehicle speed and travel time. Study [22] notes that in various areas with speed limits ranging from 20 to 40 km/h, there is no significant reduction in average speed. Study [23] showed that delays at intersections and road congestion have a greater impact on travel time in urban conditions than speed limits. These studies show how driver behavior can dilute the impact of PSL and complicate the derivation of a mathematical model of the dependence of average speed on PSL. One way to overcome these difficulties may be to use a driving laboratory technique, where the driver adheres to specified PSL values.

A wide range of models is known that describe the speed of traffic flow in free-flow conditions, where the speed limits installed on street sections are considered as one of the initial parameters [24]. But these models are only the basis for predicting the value of the average speed in real conditions of the functioning of the city's road network when it is computer modeled, as shown in the paper. Macromodeling of the functioning of the city's road network allows to assess the state of traffic flow and traffic conditions, including at different PSL values. But to simulate the results of an individual trip along the selected route, it will be necessary to use micromodeling tools on the scale of the road network of the whole city and the corresponding ultra-large computing powers. In such conditions, field studies seem more appropriate. But models obtained on the basis of full-scale experimental studies, in which the speed limit factor would be considered separately, were not widely used, primarily due to the difficulty of creating a sufficient range of speed limits on real sections of the city's road network. This problem can be solved by conditionally reproducing different speed limit values only for the car that acted as a driving laboratory.

Although the indicators of time spent traveling on the road network are closer to the target function of the trip from the road user's point of view, speed change analysis is a more universal tool for reflecting changes in traffic conditions on the route. It is known that the efficiency and safety of road traffic, as well as fuel consumption and emissions into the atmosphere, depend on the stability of the speed mode, which can be characterized by the magnitude of the speed spread and accelerations while driving. Back in the middle of the last century, criteria such as acceleration noise, speed gradient, and energy gradient were proposed to characterize the quality of traffic management. A number of more recent studies have shown that these criteria can be used to assess the level of comfort and safety of road traffic [25, 26]. However, these studies do not examine changes in energy criteria depending on speed limits for individual routes in the urban road network.

Some studies note that the speed of an individual vehicle is influenced by the driver's psycho-emotional state, which, in turn, depends on the time of day and the purpose of the trip [27, 28]. However, it can be assumed that the driver's state will affect the absolute values of speed and travel time at different times of the day, but will not have a significant impact on the nature of the change in the indicators studied in the article from the PSL value.

Throughout the known history of observations, a wide range of methods has been used to record the parameters of vehicle movement on the road network of cities, ranging from cards and questionnaires to machine vision systems. With the development of modern traffic monitoring technologies and navigation systems, some of these methods have become obsolete. Some methods can be implemented at a new technical level at significantly lower cost. The widespread introduction of satellite geolocation systems in both commercial and private transport makes it possible to record the speeds of individual vehicles in real time. An example of this capability is the INRIX Global Roadmap service (https://inrix.com/scorecard-city), which analyzes the time spent traveling on the street networks of the world's largest cities.

However, assessing the PSL impact on the average speed of a vehicle on typical commuting routes requires special research, an example of which is this work. At the same time, recording the movement of a floating vehicle can be effectively implemented in the form of GPS tracks. In addition, data on changes in instantaneous speed during movement allow for additional calculation of indicators of speed regime unevenness under various speed restriction conditions.

Summarizing the analysis of the literature, it can be noted that studies conducted using simulation modeling considered the PSL impact on the state of the transport flow as a whole, but did not consider the results of the trip of an individual vehicle. The reason is that such a formulation of the problem requires the use of micromodels, and micromodeling at the level of a city road network requires enormous computing resources and a long time to develop a model. The works that considered the results of field studies focused on individual types of road network sections and analyzed paired PSL values. Thus, the problem of quantitative assessment of the PSL impact on the average speed and indicators of speed mode unevenness in real traffic conditions remains unresolved.

3. The aim and objectives of the study

The aim of the study is to determine the impact of the speed limits when driving on the city's road network on the average speed, indicators of unevenness and driving comfort. This will make it possible to predict the impact of speed management measures in cities on the efficiency of traffic management. The results of the study will also be useful in conducting an information campaign to encourage road users to comply with the established speed limits.

To achieve the aim, the following objectives were set:

– to investigate the speed mode of the car on the selected routes under different speed limit conditions, to build appropriate graphs and analyze them;

– by approximating experimental data, to determine the dependence of the average speed on the value of the posted speed limit;

– to calculate the indicators of unevenness of the driving mode and analyze their dependence on the speed limit.

4. Materials and methods

The object of the study is the driving mode and the results of a car's trip on the road network of a large city under various speed limit conditions. The main hypothesis of the study is that an increase in PSL on the city's road network in the range from 50 to 80 km/h will lead to a slight increase in average speed and a significant increase in the indicators of unevenness of the speed limit.

The assumptions made in the study are that the effect of PSL on average speed and driving unevenness indicators can be established by observing the vehicle operating mode along typical routes of a work trip, and these results will reflect general patterns for the city's road network as a whole.

The simplifications adopted in the study concern the consideration of artificially accepted values of the speed limit during the experiment as a PSL factor, which is an equivalent reflection of the value of the total speed limit in the city.

Experimental studies were carried out in the city of Kharkiv (Ukraine) with a population of more than 1.5 million inhabitants, located in eastern Ukraine. The city's road network has a radial-circular transport layout, which is typical for many large cities in Eastern Europe. The research was carried out by the method of a driving laboratory, which was a passenger car moving in real traffic along a predetermined route.

Three alternative routes with the same start and end points were chosen in the city (Fig. 1). The starting point of the routes was one of the most remote residential areas of the city, located at the intersection of the ring road and one of the radial main streets of the city. The end point of the routes was Kharkiv National Automobile and Highway University, located in the city center. The study of three alternative routes was aimed at reducing the impact of the characteristics of individual sections of the city's street and road network on the results of the experiment. The characteristics of each route are given in Table 1.

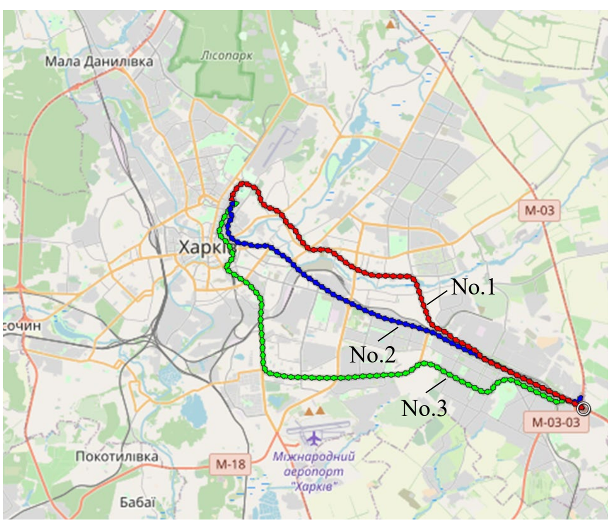

Fig. 1. Location of experimental routes on the city map

Table 1

Main characteristics of experimental routes

Route designation	No. 1: Red	No. 2: Blue	No. 3: Green
Route length, km	18.89	17.69	22.43
Ratio L_m/L	0.59	0.66	0.48
Number of traffic lights	25	31	27

According to the construction regulations of Ukraine, the roads of large cities are divided into "main streets", which have at least 2–4 lanes in one direction, and "local streets", which have at least 1–2 lanes. Since the speed limit largely depends on the type of road, Table 1 shows the ratio of the total length of the main streets L_m on each route to the total length of the route L. Table 1 also shows data on the number of traffic lights on each route.

Trips on selected routes were carried out in four modes of maximum speed limit: 50, 60, 70, and 80 km/h. While driving, the driver adhered to the accepted speed limit mode, guided by the readings of the car's standard speedometer. In addition to the speed mode, the driver complied with all traffic rules while driving in traffic. To exclude the influence of the time of day at this stage of the study, all trips were made on weekdays at the same time in the morning. The start of the trip was approximately 10:30 a.m.

If during the trip on any of the routes there were traffic delays or traffic jams due to force majeure, such as accidents, road works, traffic light failure, the results of this trip were not taken into account. Also, to reduce the influence of random factors on the results of the study, 4 trips were performed on each of the routes in each of the speed limit modes. Thus, the total volume of the experiment was 48 trips.

The method of obtaining and processing data on the driving mode of a car is described in the paper [29]. To record the tracks, the Pioneer7014 car GPS navigator (China) and the Navitel software (Ukraine) were used. The data was saved as a GPS track file in *.gpx format. To extract data about the car's driving mode from the GPS track file, the GPS Track Editor program (developed by MapSphere) was used. MS Excel was used for further calculations and graphing.

5. Results of the study of the impact of changes in posted speed limits on driving conditions on urban routes

5. 1. Research on speed mode

Fixing the driving of the car in the form of a GPS track after its processing allows to explore the driving mode of the car throughout the entire route. A very convenient tool for this is two-dimensional motion graphs, which can be constructed in different coordinates. Fig. 2 shows the motion graphs of the vehicle based on the results of four randomly selected trips along the blue route and the coordinates "distance – time."

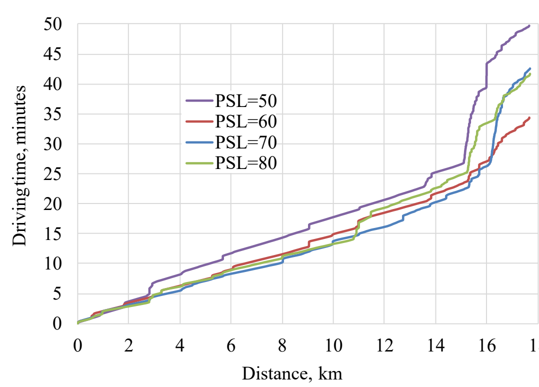

Fig. 2. Car movement graphs in "distance – time" coordinates

The graph of the car's movement in the "distance – speed" coordinates allows to see the change in the instantaneous speed of the car during the entire route. In Fig. 3–5, such graphs are plotted for the red route.

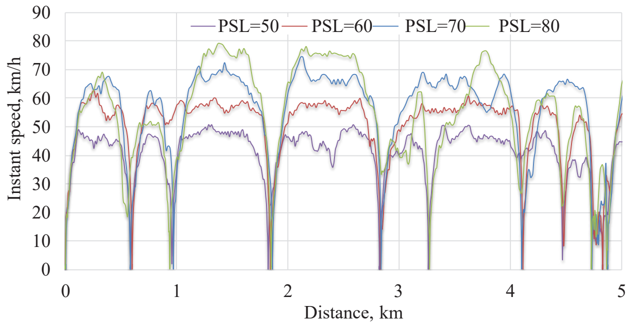

Fig. 3. Graph of movement in "distance — speed" coordinates on the initial section of the route

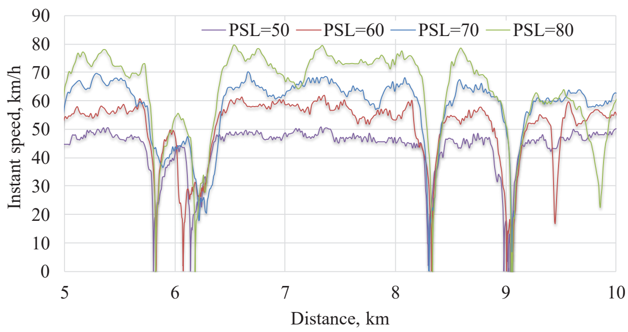

Fig. 4. Graph of movement in "distance — speed" coordinates on the middle section of the route

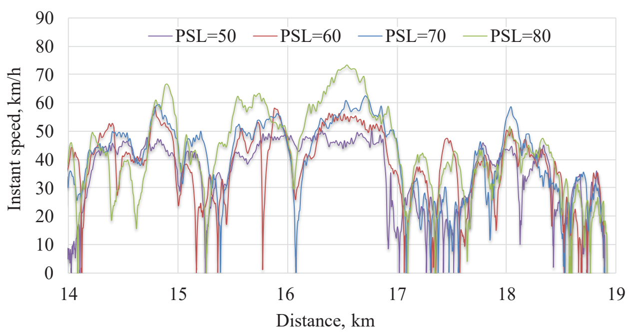

Fig. 5. Graph of movement in "distance — speed" coordinates on the last section of the route

In Fig. 5, it is possible to see that after about the 14th kilometer of the route, there is a change in the instantaneous speed graph. The frequency of stops increases with an overall decrease in speed. This is due to an increase in traffic density as the vehicle approaches the city center, where there is a higher level of congestion on the road network.

A visual representation of the prevailing speed modes when driving with different PSL is given by a diagram of the density of the distribution of total travel time over speed intervals. The corresponding graph for the red route is shown in Fig. 6. The speed scale on the graph is graduated with an interval of 2 km/h.

It can be seen that the travel time distribution diagrams for PSL values of 50 and 60 km/h do not have pronounced peaks. The travel time distribution diagrams for 70 and 80 km/h modes have pronounced maxima for the corresponding instantaneous speed intervals.

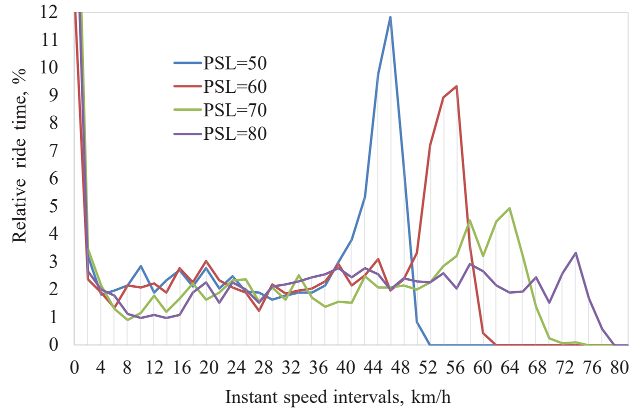

Fig. 6. Diagram of the distribution of travel time by instantaneous speed intervals

5. 2. Determining the dependence of the average speed on the value of the posted speed limit

The average speed values were calculated for each trip using the formula

$$V_m = \frac{60 \cdot L}{t_r}, \tag{1}$$

where L – the route length, km; t_r – the travel time of the car along the route, min.

In total, the results of 48 trips were taken into account: 4 trips on the route in each of the PSL modes. Table 2 shows the results of calculating the average speeds for each trip on each of the three experimental routes.

In Fig. 7, the position of the points on the coordinate plane corresponds to the average speeds for each experimental trip. The results for different routes are labeled with different markers, allowing to visually assess the dispersion of the average speed values for each route in each PSL mode. Solid lines combine the average values of average speeds along each route. Thanks to this, it is possible to notice a positive correlation between the PSL and the average speed both for the results of all trips and for individual routes. However, there are differences in the nature of these addictions. If for the red route, the average speed growth is almost linear, then on green and blue routes there is a decrease in average speed as PSL increases.

Table 2

Summary results of experimental studies

PSL, km/h	Routes			Routes			Routes		
	No. 1	No. 2	No. 3	No. 1	No. 2	No. 3	No. 1	No. 2	No. 3
	Average speed for a single ride, km/h			Average speed for each PSL mode, km/h			Standard deviation, km/h		
50	24.6	22.6	21.7	26.1	22.3	23.9	1.32	0.96	1.77
	26.9	21.2	24.9						
	25.3	23.4	23.3						
	27.4	21.8	25.7						
60	29.4	25.9	28.2	29.8	26	28.9	1.43	1.10	2.39
	28.8	26.0	31.0						
	30.4	27.3	25.8						
	27.0	24.6	30.5						
70	31.6	28.3	31.6	31.5	26.8	32.2	2.34	1.92	2.26
	28.8	24.0	33.5						
	34.5	27.8	34.4						
	31.2	26.9	29.3						
80	35.2	30.2	31.4	34.2	27.3	32.8	2.30	2.17	2.33
	36.8	25.0	34.6						
	31.5	26.7	35.0						
	33.3	27.1	30.3						

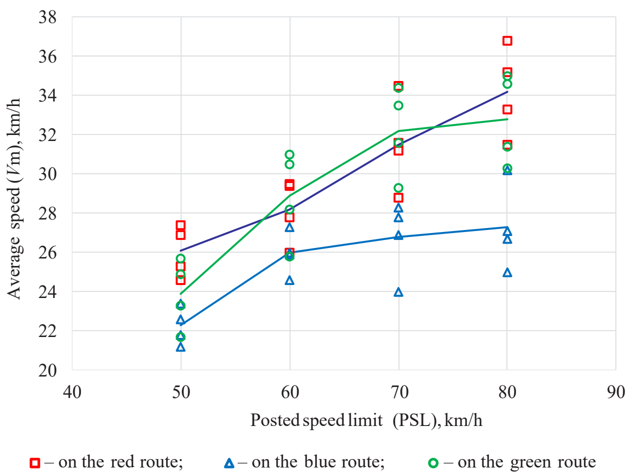

Fig. 7. Distribution of average speed values for all experimental trips

Fig. 8 shows the results of approximation of average speed values by theoretical dependencies. The dependence of the change in average speed on the PSL can be approximated by a linear relationship at the value of the Pearson criterion of 0.66

$$V_a = 0.24 \cdot PSL + 12.46. \quad (2)$$

Such a mathematical model is more convenient for practical application, but it does not take into account the detected tendency to decrease the magnitude of the increase in average speed with increasing PSL. This factor can be taken into account by approximating the experimental points with a second-degree polynomial

$$V_a = -0.006 \cdot PSL^2 + 1.01 \cdot PSL - 11.63. \quad (3)$$

In this case, the accuracy of the Pearson approximation increases to 0.69.

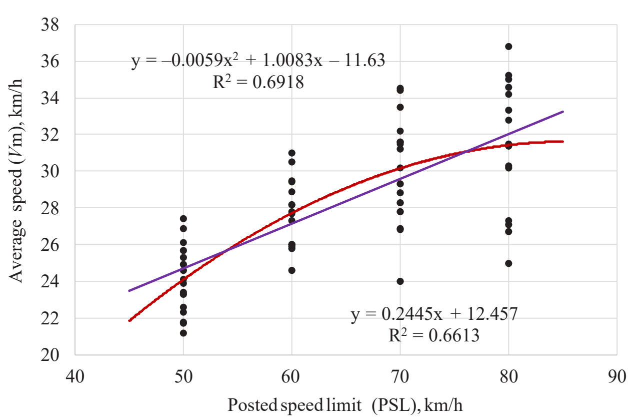

Fig. 8. Approximation of experimental values of average speed by theoretical equations

The change in the scattering of the experimental meanings of the average speed can be estimated according to the graphs of the dependence of the standard deviation from PSL (Fig. 9).

As is seen in Fig. 9, the general tendency to increase the standard deviation of the average speed as the PSL increases is observed both as a whole and for each route separately. As a result of approximation of experimental data, the expression

$$\sigma_V = 0.033 \cdot PSL - 0.277, \quad (4)$$

where σ_V – the standard deviation of the average speed on the route, km/h. The accuracy of the approximation is 0.53.

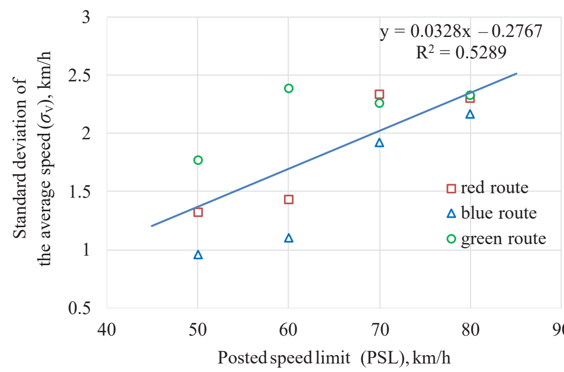

Fig. 9. Dependence of the standard deviation of the average speed along three routes on the PSL

5. 3. Estimation of motion unevenness indicators

In addition to the average speed on the route, which characterizes the total time spent on overcoming a given distance, other indicators can be used as a characteristic of the efficiency of traffic management, as indicated above. Some of them, among other things, will characterize the level of comfort, convenience and safety of using the road.

The speed utilization coefficient is the ratio of the average speed on the route to the PSL

$$K_V = \frac{V_a}{PSL}. \quad (5)$$

It shows how much the maximum permitted speed was realized during the trip.

In addition to the total specific travel time, the road user assesses the stability of the driving mode. To take this factor into account, the values of the specific running time T_r and the specific idle time T_s were calculated for each trip:

$$T_r = \frac{\sum \tau_r}{L}, \quad (6)$$

$$T_s = \frac{\sum \tau_s}{L}, \quad (7)$$

where $\Sigma\tau_r$ – the sum of the time intervals when the vehicle was in motion, min; $\Sigma\tau_s$ – the sum of idle speed intervals, min (idle intervals were considered periods when the instantaneous speed of the car was less than 5 km/h).

The presence of an array of data on the vehicle's instantaneous speeds allows the vehicle acceleration to be calculated, which makes it possible to obtain the values of energy criteria based on the results of each trip.

The acceleration noise, which is the standard deviation of the acceleration of a vehicle on a route, was calculated as

$$\sigma_j = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} \left(j_i^2 \cdot \Delta\tau \right)}, \quad (8)$$

where j_i – the instantaneous speed of the vehicle, m/s²; Δr – the acceleration fixation intervals, s; n – the number of measurement intervals.

The speed gradient for each trip was calculated as the ratio of acceleration noise to average speed

$$G_V = \sigma_j / V_a. \quad (9)$$

A more universal criterion for evaluating speed stability for city conditions is the energy gradient

$$G_e = \frac{\sqrt{\frac{1}{n}\cdot\sum_{i=1}^{n}\left(j_i \cdot V_i - \overline{j_i \cdot V_i}\right)^2}}{V_a}, \qquad (10)$$

where V_i – the instantaneous speed of the vehicle, m/s; $\overline{j_i \cdot V_i}$ – the average value of the product of speed and acceleration, m^2/s^3.

These parameters were calculated for each trip, then averaged for each route and PSL mode. The results of the calculations are given in Table 3.

Table 3

Average values of the nervousness of the driving mode for different PSL values

Criterion	PSL, km/h			
	50	60	70	80
Speed utilization coefficient	0.48	0.47	0.43	0.39
Running time, min/km	1.49	1.46	1.39	1.59
Idle time, min/km	0.46	0.48	0.52	0.76
Acceleration noise, m/s^2	0.59	0.72	0.75	0.81
Speed gradient, s^{-1}	0.088	0.091	0.086	0.087
Energy gradient, m/s^2	0.62	0.68	0.8	0.89

Fig. 10 shows graphs of changes in speed utilization coefficient, acceleration noise, and energy gradient depending on the PSL. The points on the graph correspond to the average values of indicators for trips on all routes at a given PSL.

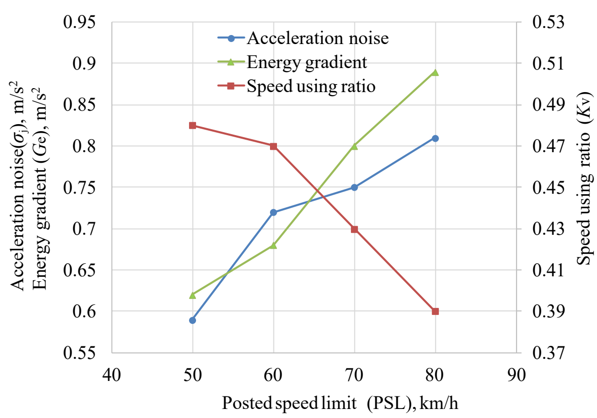

Fig. 10. Dependence of the nervousness indicators of the driving mode on the PSL

As can be seen from Fig. 9, the acceleration noise and energy gradient indicators show almost linear growth with increasing PSL. It can also be seen that when the PSL increases, there is a decrease in the speed utilization coefficient.

6. Discussion of the results of the study of the impact of speed limits on driving conditions on urban routes

The problem of quantifying the impact of the speed limit on driving conditions on urban routes was posed in this paper. This problem was solved by studying the change in instantaneous speed along the length of the routes, which resulted in the dependence of the average speed, standard deviation of the average speed, acceleration noise, and energy gradient on the PSL value. The mechanism of achieving the result was the conduct of field studies on typical routes of the road network of the city of Kharkiv using the "driving laboratory" method. Using the chosen methodology, the speed and distance of the car were recorded in second intervals, which makes it possible to build graphs of the car's movement in the "time – distance" and "distance – speed" coordinates for each individual trip. This makes it possible to visually assess the vehicle's driving mode both along the entire route and on its individual sections.

In Fig. 2, it is possible to see a change in the nature of the graphs as is possible to approach the central part of the city, the border of which for all the routes considered is located approximately around the 15th kilometer. This is explained by a change in the increasing level of congestion on the road network. Obviously, the tangent of the angle of inclination of a line connecting a certain point in the graph with the origin represents the average speed for overcoming a given distance. Thus, it can be assumed that the differences in the average speed based on the results of each trip under the same PSL conditions are primarily due to random factors of traffic conditions on sections of streets in the central part of the city.

Fig. 4, 5 show the initial and middle sections of the route, along which the car moves mainly along main streets with more lanes and relatively low traffic congestion. This makes it possible to fully realize the maximum permitted speed for a given trip in some areas, which is also confirmed by the diagrams in Fig. 6. At the same time, the speed mode is generally more stable. Slowing down and stopping are observed only in traffic light control zones. On the final section of the route (Fig. 5), as is possible to approach the city center, the traffic flow and the level of congestion increase. The speed mode becomes less stable with frequent stops. The average speed for a given segment has little to do with the PSL for a given trip, but is more determined by the state of the traffic flow.

Fig. 6 shows that high PSL values (80 km/h and 70 km/h) could be realized in relatively short periods of time during ride in the respective modes. This was mainly observed on the initial and middle sections of the route, when traffic was carried out mainly on main streets in conditions of low traffic congestion. When driving in the PSL modes of 60 km/h and 50 km/h, the maximum permitted speed can be realized for a longer period of time. Since the stability of the speed mode depends on the frequency and magnitude of fluctuations in the instantaneous speed of the vehicle, driving modes with a lower PSL value should be more stable. It can also be noted that in all PSL modes, the longest periods of time are spent in idle periods or driving at close to zero speed, which is generally typical for driving in a large city.

From Fig. 7 it can be seen that both for the average results of the entire set of trips and for individual routes, there is a tendency to increase the average speed as the PSL increases, which was generally the predictable result. More useful for practice is the possibility of quantifying changes in the value of the average speed, which allows to make formulas (2), (3). Unlike the known models, these dependencies were obtained not for individual types of city streets, but for the entire set of sections of the city's road network. Therefore, they allow to predict how a change in the speed limit will affect the average speed on typical business travel routes in cities with a similar transport planning structure. Thus, formula (2) predicts an increase in average speed by 2.4 km/h with a 10 km/h increase in the PSL.

Formula (3) takes into account the nonlinear nature of the dependence of average speed on PSL, which is to reduce the impact of the speed limit on the average speed of the ride at high PSL values. The model shows an increase in average speed by 3.5 km/h when the PSL increases from 50 to 60 km/h. Whereas, when the PSL increases from 70 to 80 km/h, the increase in average speed is only 1.24 km/h. This nonlinearity can be explained by the fact that, in addition to PSL, the instantaneous speed of a car during a ride depends on the parameters of the traffic flow. As can be seen in Fig. 3– 5, high PSL values can be realized by a driver only on long stretches of streets between traffic lights, mainly in the initial and middle sections of the route. That is, where traffic on main streets is carried out in conditions of low traffic density (on average 10–50 veh/km). Whereas on the final section, as is possible to approach the central business part of the city, traffic is denser (on average 100–150 veh/km). In such conditions, regardless of the PSL value, the driver is forced to move at the speed of the flow. Therefore, as the PSL increases, there are fewer and fewer opportunities to realize high speed, as evidenced, in particular, by the decrease in the speed utilization rate in Fig. 9. Therefore, further increases in PSL will have almost no effect on the average speed.

It can be assumed that the absolute value of the average speed obtained will be influenced by the specifics of a particular route, including the relative length of main streets, the number of regulated interchanges, etc. The combined influence of such factors can explain the lower average speed on the blue route. At the same time, these features of a particular route should not significantly affect the amount of increase in average speed, which will allow using formula (3) to predict its relative change with an increase or decrease in speed limits.

Although average speed is an important characteristic of the quality of the city's road network, for an individual road user, the indicators of traffic uniformity are more important. During a ride, the driving mode of a vehicle on different sections of the road network can vary from moving at a speed close to the PSL to idling or moving in a start-stop mode. Long delays at traffic lights or in traffic jams lead, in addition to increasing the total travel time, to a negative assessment by the road user of the quality of traffic management in the city.

As can be seen in Table 4, the running time is insensitive to PSL, while the idle time shows an increase with increasing PSL. This is due to the fact that downtime on a particular route is associated with traffic lights, bottlenecks, and traffic complications in dense traffic. Obviously, these factors do not depend on PSL, while in free traffic conditions with higher PSL, the car will cover the same sections in less time. For the same reason, no changes in the speed gradient were detected, as this indicator is also sensitive to long stops.

In some studies [15, 28, 30], it is proposed to use the travel time reliability (TTR) indicator as a criterion for the quality of traffic management on the road network of cities. Although this factor was not separately investigated in the study, it can be assumed that with an increase in PSL, the TTR value will decrease, since the increase in the standard deviation of average speeds shown in Fig. 10 makes the outcome of the trip less predictable.

The level of traffic management can also be assessed by the degree of irregularity, which is characterized by the frequency and magnitude of vehicle accelerations during a ride. It is known that frequent accelerations while driving (both positive and negative) lead to increased driver fatigue, reduce safety, increase fuel consumption and emissions of harmful substances [26]. Thus, the increase in acceleration noise and energy gradient shown in Fig. 10 indicate a deterioration in driving conditions with increasing PSL.

Considering the limitations of this study, first of all, it is necessary to make several clarifications regarding the research methodology used.

The speed limit on the city streets along the experimental routes was 50 km/h, as set by the traffic rules. This speed limit applies to all Ukrainian cities and towns. At the same time, the permissible speed limit for which a driver is not punished in Ukraine is 20 km/h. During the period of the study, an automatic speed camera was installed on only one section of the blue route. The almost complete absence of control over compliance with speed limits leads to the fact that on sections of main streets with low traffic congestion, the average speed of traffic flow significantly exceeds the limits set by the rules. This is the case in almost all major Ukrainian cities. The combination of these factors created unique conditions for the implementation of the chosen research methodology.

Another feature of the described methodology is that the parameters of car driving mode were analyzed along individual routes that correspond to a road user's daily work trip from the area of residence to the city center. This approach allows to analyze traffic performance parameters from the perspective of a typical road user who is primarily interested in the overall duration and comfort of the trip to the destination. Depending on this, it assesses the level of traffic management in the city as satisfactory or unsatisfactory. For commercial vehicles, the travel time along a particular route may be more important than the driving conditions on individual sections of the route.

Most of the studies described in the scientific literature that analyze the relationship between average speed and PSL were obtained by measuring speeds on separate road sections with different speed limits. This study examined the impact of speed limits on the same routes. In traditional floating car studies, a car is driven at the speed of the traffic flow. The peculiarity of this study was that the speed limit conditions were realized by the driver's behavior when choosing a speed. At the same time, the state of the main traffic flow remained unchanged. Because of this, the term posted speed limit (PSL) is used in this paper in a not quite traditional sense, but its use can be considered appropriate as the most common.

The above study results were obtained for a large Ukrainian city with a typical type of transport planning for the road network and a level of traffic management that can generally be considered typical for large cities in Eastern Europe. For regions and cities with a fundamentally different concept of road network planning, the degree of PSL impact on average speed and traffic performance may differ, although the general trend should remain.

The studies were conducted on weekdays during the time period from 9:00 to 11:00, which generally does not include peak periods. It can be assumed that increased road congestion during peak periods of the day can lead not only to a decrease in average speed, but also show a decrease in the PSL impact on average speed and travel time on routes. Therefore, this issue requires separate research.

The results obtained in this paper can be useful in conducting a rational and informed policy of speed management on urban roads as part of the implementation of the smart city concept. Despite the fact that the speed limit in settlements of 50 km/h is a global standard, there are countries that have 60 km/h limits. The same applies to speeding tolerance values, which can vary significantly. This is particularly true in Ukraine, where a 20 km/h tolerance is actually in effect, which is one of the highest in Europe. Such studies can help governments in such countries make informed decisions about reducing speed limits or adjusting the value of speeding tolerance.

The results of the study show that travel time savings are usually insignificant compared to the increased risk of getting into an accident. Therefore, they can be used to encourage drivers to refrain from speeding in the city.

The main limitation of this paper stems from the peculiarities of the research methodology itself. It lies in the fact that PSLs were applied only to the "driving laboratory car" and did not affect the traffic parameters of the general traffic flow. Also, the recorded speed of other vehicles could not be recorded during the experiment. Therefore, the results obtained relate to the impact of PSL on the average speed and driving mode of an individual vehicle on its route, and do not reveal the impact of PSL on the parameters of traffic flow on sections of the city's road network.

Among the shortcomings of the study is the use of a limited sample of routes for experimental trips, which can be eliminated in the future by expanding the number and functional purpose of routes in further research. Another disadvantage is that the study does not take into account the possible influence of the driver's personality on the vehicle's driving mode during experimental trips. In the future, this can be eliminated by involving several vehicles in the experiment.

7. Conclusions

1. The analysis of traffic graphs showed an increase in the number of stops and a decrease in instantaneous speeds as the car approached the central part of the city. This result can be explained by the fact that up to that point, traffic had been moving mainly along main streets with relatively low traffic congestion. This made it possible to fully realize the maximum permitted speed for a ride when driving between traffic lights. As to get closer to the city center, the level of traffic congestion increases and the speed limit becomes less stable with frequent stops. PSL values of 70 and 80 km/h could be realized for short periods of time in the initial and middle sections of the route. PSL values of 50 and 60 km/h could be realized over a longer period of time. With all PSL modes, the longest periods of time are spent in idle or near-zero speeds.

2. Both the average results for the entire set of trips and for individual routes show an increase in average speed as the PSL value increases. For typical routes of work trips from a remote residential area to the city center, the formula obtained in this paper predicts an increase in average speed by 2.4 km/h for every 10 km/h of PSL. At the same time, there is a decrease in the average speed increase with an increase in the PSL. The model predicts an increase in average speed for every 10 km/h of PSL from 3.5 km/h for PSL = 50 km/h to 1.24 km/h for PSL = 80 km/h.

3. As the PSL increases from 50 to 80 km/h, the acceleration noise shows an almost linear increase of 37%. The energy gradient increases by 43%. This result is explained by the fact that the driving mode at higher PSL values is characterized by greater irregularity.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal nature, authorship or other nature, which could affect the research and its results presented in this article.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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