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A study of vehicle speed distribution influenced by urban traffic conditions

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Abstract: The most common approach in forecasting vehicle speed is to estimate the average value of this variable on a short segment or at some cross-section on the road. Since many factors influence the speed variable, determining the speed distribution law remains actual. Given that the numerous studies confirm the normally distributed free-flow speed on intercity roads and a minority of urban speed studies, the mentioned task is especially relevant for urban transport planning which often requires consideration of traffic conditions far from the free-flow ones because of traffic signalling and other factors, which complicate driving and decrease the speed compared to the desired one. This paper explores the speed influenced by two types of places frequent in urban areas – signalized intersections and narrow carriageway sections. The data for the study were collected in Kharkiv, the second-largest city in Ukraine. During the study, it was determined that the narrow carriageway decreases the speed in a way that speed values can be described by the gamma distribution, while the influence of signalized intersections results in the possibility of using both exponential and gamma distribution to represent the speed variable. To measure the speed during the surveys, a novel methodology that considers the waiting for the green signal was applied. The research results showed that the urban traffic environment decreases the mean of the speed variable, increases its standard deviation and changes the normally distributed free-flow speed to the gamma-distributed.

1 Introduction

Vehicle speed is among the most significant performance measures in traffic management because it represents travel and transportation conditions as well as quality of service for drivers [1,2]. At the same time, even up-to-date transport modelling software makes calculations using the average vehicle speed despite the obvious fact that the speed is a random variable having its own distribution and influenced by many factors which are hard to predict [3-5] (driving styles, weather, time of day, personal reaction on traffic conditions, vehicle loading etc.). The appropriateness of this speed representation during modelling sometimes creates doubts, especially when assessing vehicle speed in the case of dense traffic. Accordingly, the issue of defining speed distribution is especially relevant for urban transport flow modelling since very often, corresponding flows are not free because of the following:

- first of all, the complications of traffic conditions in terms of speed appear at the influence zones of single-grade intersections, especially signalized ones, which are numerous in any city and create most restrictions on vehicle movement;
- the second most frequent complications occur at the narrow carriageway sections.

The complications arising at the listed places force drivers to slow down or stop, and this certainly affects the speed distribution parameters. Thus, the purpose of this paper is to study the vehicle speed variable in urban areas and establish its distribution in places with complicated traffic conditions, namely, at (i) narrow carriageways and (ii) zones before the stop-line of signalized intersections [6].

The first step in this study should be the hypothesizing of the type of speed distribution for these conditions. The places of the first type usually only decrease the speed. To adequately measure the speed affected by corresponding complications, it should be done outside the influence zones of intersections, pedestrian crossings, public transport stops, etc. As for vehicle speed measurements before the stop line, it is worth noting that vehicle full stops are possible at all signalized intersections. This causes methodological problems because in this case, it is inappropriate to measure the speed as the ratio of the distance l travelled to the travel time t – while waiting for the green, both l and t are equal to 0. Such a situation points to the need to develop a new methodology to measure the speed before the stop-line, which will allow for taking into account possible vehicle accelerations, decelerations, and full stops.

2 Literature review

Most of the present developments in the research of vehicle speed variable consists of observations of the free transport flow on intercity roads. In this case, the only speed limit is that prescribed by traffic rules, and most surveys on the mentioned roads aim to collect data on the speed, define the general speed trend, and assign rational speed range to ensure safety for drivers [7,8]. The similarity of approaches to study the speed led to the similarity of results, which testify that vehicle speed in free-flow conditions on interurban roads is normally distributed [8-10]. The general shortcoming of most of the analysed papers is the lack of statistical assessment of the correspondence between the empirical and theoretical normal distribution, but the plots shown in the papers fully indicate the similarity with the Gaussian density curve.

At the same time, there is a shortage of works devoted to vehicle speed distribution under conditions that decrease the speed compared to those that could be in the free flow. One of these works presents the results of the speed study that took place at 18 crash hotspot intersections on rural roads in Uttar Pradesh state, India [11]. The traffic was complicated by a lack of lane discipline. The authors of this study were able to fit normal, lognormal, logistic, gamma, Weibull, Burr, and extreme value (EV) distributions to the speed values for different traffic compositions.

The conditions which usually decrease the speed often occur in urban areas because of the dense traffic. For example, the paper by Dhamaniya and Chandra [12] examines vehicle speed on major urban roads in three Indian capital cities (New Delhi, Jaipur, Chandigarh) and shows the speed distribution plot which looks like normal distribution but has the left-shifted mode. These facts testify that the complication of traffic conditions as well as the urban environment change the trend in speed values specific to the free flow. Similar results are also presented in the paper by Rao A. and Rao K. [13] for the ring road in Delhi, India.

Urban traffic flows were also studied in the papers by Shi et al. [14] and Mondal & Gupta [15]. In the former paper, the gamma and Burr distribution were fitted best to the speed values recorded in Xi'an, China. Both distribution density curves have a left-shifted peak. In the latter paper, gamma, beta, Burr, and extreme value distributions appeared to be most suitable to represent the speed of vehicles at 16 signalized intersections in Delhi, Kolkata, Bhubaneswar, and Jaipur, India. The authors of this paper claim that the main reason for the deviation of the speed distribution from the normal is traffic heterogeneity. This explanation cannot be considered sufficient since many more factors influence the speed in urban conditions [15,16].

One more reason that makes drivers decrease their speed is the traffic lane (or carriageway) width insufficient for comfortable driving. This issue is purely studied in the literature, and only a few papers demonstrate that lane width influences vehicle speed, traffic accident frequency, driving behaviour, and movement trajectory [17,18].

The summary of the reviewed literature is presented in Table 1.

Table 1 The results of vehicle speed studies in different traffic conditions

Authors	Place of study	Speed distribution type
Hashim [8], Vadeby and Forsman [10]	intercity roads	normal
RSA [9]	rural roads	normal
Shuo et al. [18]	driving simulator	normal
Sarkar and Kumar [11]	intersections on rural roads	normal, lognormal, logistic, gamma, Weibull, Burr, EV
Rao A. and Rao K. [13]	urban arterial (ring road)	normal
Dhamaniya and Chandra [12]	urban arterials	normal (left-shifted mode)
Shi et al. [14]	urban roads	lognormal, gamma, Burr
Mondal and Gupta [15]	urban signalised intersections	lognormal, gamma, beta, Burr, EV

This table clearly shows the trend for the shift of the speed modal values to the left with the complication of traffic conditions particularly that specific to urban environment. Also, it should be noted that we have not found a clear explanation for this trend in available literature including those devoted to the concept of a fundamental diagram of traffic flow [19,20].

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The existence of different traffic conditions that complicate driving and decrease speed raises the task of developing the methodology for speed research considering the revealed trends in the speed values and the specificity of the mentioned conditions. The need for this methodology is premised upon the fact that most of the existing researches contain the measurements of the "instantaneous" speed on the road section chosen according to different manuals, most of which recommend avoiding influence zones of signalized and non-signalized intersections, pedestrian crossings, and other objects causing vehicle acceleration or deceleration. It is clear that these recommendations cannot be implemented in cities, especially in their downtowns with numerous signalized intersections.

Apart from that, the mentioned measurements were made using radars, LiDARs, microwave, acoustic, magnetic, and infrared sensors, pneumatic road tubes, inductive loops, video recording, etc. [1,21]. All these devices measure the speed over some time (like radars) or at some distance (like pneumatic road tubes). This way of measurement is not applicable for the places before signalized intersections in urban areas, because vehicle speed at these places can be equal to 0 for some time due to waiting for the green. So, it requires searching for how to consider this time during the speed survey.

Also, the important thing here is that in urban transport system modelling, the "travel speed" or "journey speed" is significantly more valuable than the instantaneous speed. During the calculation of travel or journey speed, it is necessary to consider that *l* and *t* are determined not by a measuring device, but by the road users. They are also dependent on traffic management measures, city logistics, traffic conditions, and the personal perception of drivers. These issues are of little attention in the existing studies on speed distribution.

Summarising the analysed literature, it can be concluded that there is a need for both developing a new methodology to measure the speed in urban networks concerning possible vehicle speed decrease or full stop as well as to properly apply a goodness-of-fit test when fitting the distribution to the recorded speed values.

3 Methodology

3.1 Hypotheses about speed distribution affected by urban traffic conditions

A prerequisite for hypothesising the type of vehicle speed distribution under urban traffic conditions is the probable change in the free-flow speed distribution curve conditioned by the decrease in average speed.

Since the speed variable is non-negative, the minimum speed value is 0. If a mean speed is $v \gg 0$, which is typical for the free flow, the left tail of the normal distribution $[-\infty;0)$ has a very low probability $F_0 \approx 0$. The question here is what change will be in the free-flow speed distribution curve in case of a considerable average speed decrease?

If the normal distribution is suggested for representing the vehicle speed, a decrease in the mean should cause a heavy negative tail, Figure 1. This tale is impossible due to the speed domain ($v \geq 0$). At that, the right tail remains valid, and it looks like the exponential distribution curve. Therefore, it is reasonable to suppose that the result of the average speed decrease will be the change of the normal distribution curve to an exponential one. A gamma distribution can be considered an intermediate point in this process because:

- gamma distribution with the shape parameter $g = 1$ is exponential distribution;
- gamma distribution approaches normal distribution when the shape parameter $g \to \infty$.

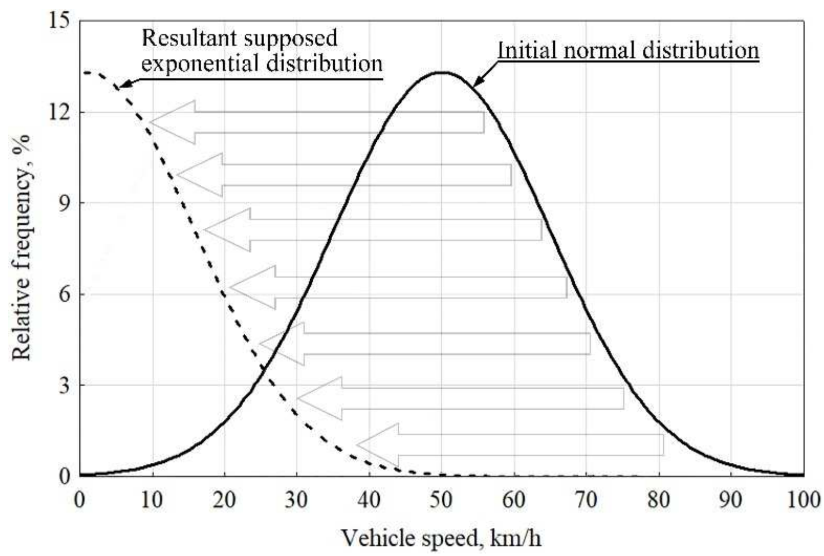

Figure 1 Supposed result of the decrease in the mean of the normally distributed speed

According to these prerequisites, the complication of traffic conditions should cause a decrease in average speed and, consequently, decrease the gamma distribution shape parameter bringing it closer to 1, i.e., to the exponential distribution. The reverse statement is also true.

Since the carriageway narrowing does not cause extremely complicated traffic conditions because it rarely forces drivers to stop a vehicle, the hypothesis about gamma-distributed vehicle speed at the narrow carriageway looks grounded.

Traffic conditions before the stop line are more complicated compared to those at a narrow carriageway, because a certain share of drivers must stop and wait for the green. It allows for further testing of the hypothesis in the conditions which should lead to an additional decrease in the gamma distribution shape parameter *g*.

Since *g* is the squared ratio of the average speed $\overline{v}$ to the standard deviation σ, i.e., $g = \left(\overline{v} / \sigma\right)^2$, to estimate it for different traffic conditions, it is necessary to estimate the main moments of the speed variable.

Compared to the narrow carriageway, the signalized intersection will make a certain share of speed values very close to 0 because of situations when vehicles arrive at the intersection on red, stop at the stop-line, and wait for the green. At the same time, the conditions for driving through the intersection on the green are complicated only by other road users, so the speed survey will also show rather high speeds. This should lead to a significant increase in the speed standard deviation compared to the situation of the narrow carriageway. So, there are no reasons to expect considerable changes in the average speed since the range of the speed extends due to the shift of both bounds. These considerations allow supposing that during the survey of vehicle speed before the stop-line, it is reasonable to expect a decrease in the gamma distribution shape parameter compared to that one for the narrow carriageway because of an increase in the standard deviation of sampled speeds.

3.2 Approach to measure the speed

It can be certainly stated that the use of instantaneous speed to evaluate traffic conditions had arisen as the simplest solution obtained by researchers in the effort to characterize a specific road section – there is no need to specify the distance at which the speed is measured, it is only necessary to implement recommendations of the most manuals mentioned in the literature review.

Such conditions cannot be met at the influence zones of signalized intersections. When calculating the vehicle speed before the stop-line of a signalized intersection, both the distance *l* travelled and the travel time *t* can be equal to 0 due to the situations when certain vehicles wait for the green. To address this issue, it is necessary to develop a special methodology for speed measurement.

To calculate speed using the ratio of *l* to *t*, it is necessary to specify a distance and measure the passing time, or specify a time span and then measure the distance passed. Specifying a constant time span for measuring the vehicle position in the zone before the stop-line is not suitable because of the wide range of speed values – any constant time span will lead to either omission of a part of the vehicles during measurement or multiple estimations of the position of the same vehicle. Specifying a road segment of a constant length will also result in unclear situations caused by the random distance between the places where vehicles stop at the stop line. To solve these problems, we came to the conclusion that it is reasonable to take the vehicle dimension as the distance for which the passing time is measured.

The proposed methodology for speed measurement is as follows:

- a researcher assigns the road cross-section for the speed measurement;
- during the observation of traffic flow, it is necessary to record two points of time - when the assigned cross-section is crossed by the front and rear points of each vehicle;
- it is necessary to record a vehicle's length - the distance between the mentioned points;
- in the absence of special tools, the best way to make such measurements is to make a video record of traffic and process it.

To measure the speed, the cross-section before the stop-line should be assigned in a way that when waiting for the green, the body of the front vehicle in a queue should be within the cross-section. Then the waiting time will be taken into account in speed calculation, which is obligatory to assess the impact of signalized intersection.

To avoid uncertainties with the mode of estimated speed distribution, the speed survey should focus on vehicles of similar technical parameters. For this reason, during the survey, it is reasonable to cover the vehicles permitted for movement in city centres, most of which are cars. Considering the common lengths of the cars, it is reasonable to assign the cross-section at 1.5 m before the stop-line. The final aim of the listed measurements at a desired cross-section is to determine the average speed with which a car passes a distance equal to a car's length. From here on, this average speed will be referred to simply as 'speed'.

The feature and the advantage of the proposed methodology is the opportunity to assign the road cross-section for the speed measurements, which is not available in any existing approach and allows for avoiding difficulties with the situations when vehicles wait before the intersection as well as ensuring the comparability of the speed values measured in all considered urban traffic conditions. That is why this methodology was preferred for speed studies presented below.

4 Results and discussion

4.1 Vehicle speed at a narrow carriageway

The speed influenced by the narrow carriageway was studied in Kharkiv, Ukraine. This study is presented in detail in the paper by Horbachov et al. [22]. The main points which had conditioned the choice of the narrow section for speed observation were as follows:

- the considered section of Yaroslava Mudroho St. (Figure 2) is free of public transport;
- the section is outside the zones influenced by intersections that allow drivers to go faster before and after the narrowing;
- during the observation, the section had one traffic lane in each direction because of car parking in the right lanes, and there was the heavy snowfall that significantly narrowed the carriageway (up to 5.45 m for oncoming traffic flows) and caused the “bottleneck”. These conditions made it possible to study the drivers’ response to the carriageway narrowing and excluded their habituation to the lane width.

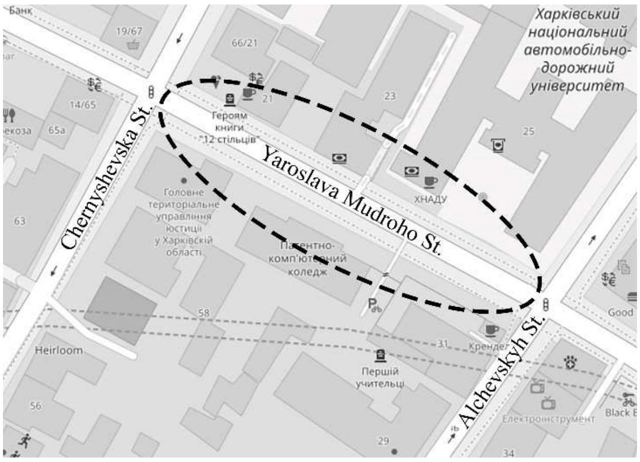

Figure 2 The segment of Yaroslava Mudroho St. (Kharkiv, Ukraine) selected for the study of speed influenced by the narrow carriageway

The traffic on the considered street section was filmed from 8:30 a.m. to 10:16 a.m. and then processed. Here, it is appropriate to show the final result of the speed survey with the statistical estimation of fitting the theoretical distributions – gamma and normal – to the empirical one. The video processing results are presented in Table 2. The results of fitting the distributions are shown in Figure 3.

Table 2 Speed statistics at the narrow carriageway section of Yaroslava Mudroho St. in Kharkiv (retrieved from [22])

No. of observations	-	216
Speed ($m \cdot s^{-1}$)	min	1.32
	max	12.50
	ave	5.99
	std. dev.	2.32
Gamma distribution parameters	scale	0.899
	shape	6.666

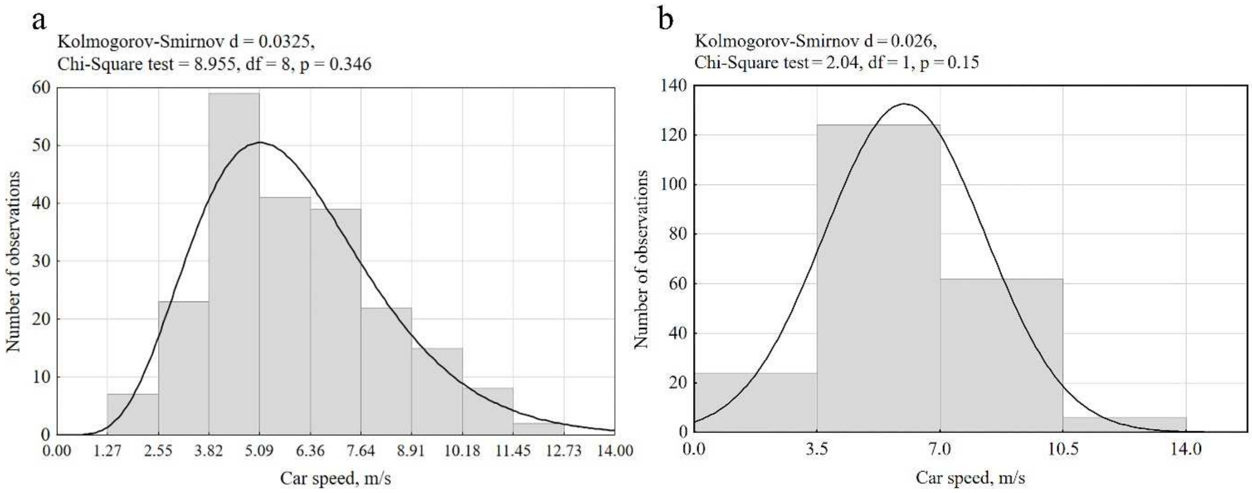

Figure 3 The distributions fitted to the values of speed influenced by the narrow carriageway: (a) Gamma; (b) Normal (retrieved from [22])

The Kolmogorov-Smirnov and χ^2 test indicated a positive result in fitting the gamma distribution to the speed values recorded at the narrow carriageway section (Figure 3a). The normal distribution was fitted to the recorded speed values at the minimum sufficient number of bins (Figure 3b), which makes this result not so convincing but supports the connection between gamma and normal distribution considered at the beginning of subsection 3.2. These findings confirm the tangible impact of the traffic lane (carriageway) width on the vehicle speed variable [22].

The results obtained in the paper [22] correspond to the hypothesis of gamma-distributed vehicle speed variable but give insufficient data to anticipate the speed distribution type under more complicated urban traffic conditions.

4.2 *Vehicle speed influenced by traffic signalling*

The study of vehicle speed influenced by traffic signalling also requires choosing an intersection for observation. The key factor in making this choice is the possibility of video recording in conditions specified in subsection 3.3 - the camera should record the traffic passing through the cross-section 1.5 m before the stop-line. The opportunity to meet these conditions was found at the intersection of Yaroslava Mudroho Str. and Alchevskyh Str., namely, at the approach from Chernyshevska St. (Kharkiv, Ukraine), Figure 4a.

a b

Figure 4 The approaches to the intersections selected for the speed study: (a) the section of Yaroslava Mudroho; (b) the section of Peremohy Avenue

The cycle time at the intersection is 60 s, and the green time for the traffic direction under observation (in Figure 4a - from right to left) is 20 s. The observation was carried out on 21 Nov. 2018 for three hours, from 8:15 a.m. to 11:15 a.m. The recorded video was processed according to the methodology proposed in subsection 3.3. The processing results are presented in Table 3.

Table 3 Speed statistics for the zone before the stop-line at the approach to Alchevskyh Str. in Kharkiv

No. of observations	-	403
Speed ($m \cdot s^{-1}$)	min	0.07
	max	19.12
	ave	5.30
	std. dev.	4.94
Gamma distribution parameters	scale	4.602
	shape	1.152

This table shows that at the given signalized intersection, the speed has decreased compared to the speed at the narrow carriageway observed before. The standard deviation has increased more than twice which can be explained by a noticeable extension of the speed range. Major changes in the main moments of the speed variable have led to a significant change in the gamma distribution parameters - the scale parameter has grown significantly along with the significant decrease in the shape parameter that has approached 1.

The gamma distribution was fitted to the recorded speed values, Figure 5a, and the goodness of fit was evaluated using the Kolmogorov-Smirnov criterion. The evaluation allowed for the conclusion that the hypothesis of the possibility of describing the speed influenced by traffic signalling with the gamma distribution cannot be rejected because of achieving the acceptable 15-percent significance level of the used criterion. The Pearson criterion was not applicable in this case. This result can be considered preliminarily positive taking into account the significance level of the Kolmogorov-Smirnov criterion (less than 20%) and interpreted as a one-time non-rejection of the hypothesis that should not be considered as confirmation.

The proximity of the gamma distribution shape parameter to 1 makes it reasonable to test the hypothesis of the exponential distribution of the speed variable, Figure 5b. In this case, the significance level of the Kolmogorov-Smirnov criterion has decreased to less than 15%.

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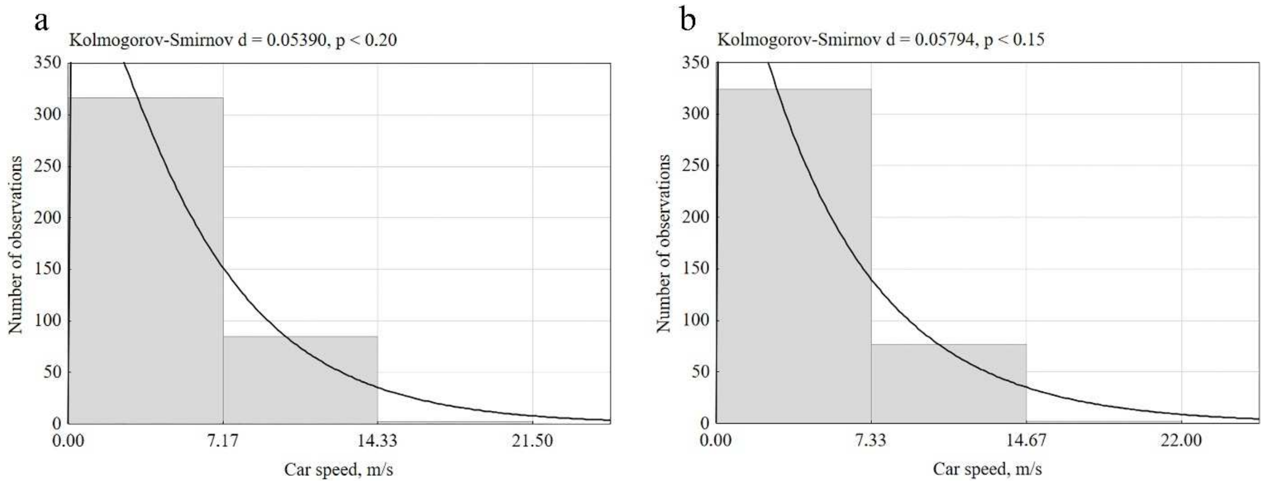

Figure 5 The distributions fitted to the values of speed influenced by traffic signalling at the approach to Alchevskyh Str. in Kharkiv: (a) Gamma; (b) Exponential

Consequently, it appeared reasonable to continue the research under conditions even more complicated in terms of speed. This research allowed for further testing of the hypothesis of the suitability of the use of gamma distribution to describe vehicle speed under various urban traffic conditions and define the relationship between traffic conditions and the gamma distribution shape parameter.

Traffic conditions complicated more than the above-described can occur before the stop-line at the approach to a signalized intersection where both a green time and its share in the cycle are even less. This complication can be observed at the secondary approach to a signalized intersection with a long cycle time. The conditions of this type are specific to the approach of Peremohy Avenue to Klochkivska St. in Kharkiv. At this approach, there exist two lanes and the left-turn phase, Figure 4b. The intersection has a large area and good road surface that allows driving in almost free conditions after the start from the stop-line. Therefore, these conditions can be considered similar to the conditions in the previous observation of the car speed before the stop-line. At the same time, the cycle time and the green time for the selected approach, which are 90 s and 16 s correspondingly, differ significantly from those in the previous case – 60 s and 20 s respectively. The green time for the selected traffic direction is not extremely short and equals 16 s which is 20% less than at the previous intersection. But the green share in the cycle time has decreased almost twice – from 33.3% to 17.8%. It justifies the observations at the intersection of Peremohy Ave and Klochkivska St, as it will extend the speed range that characterizes urban traffic conditions. The observation at this intersection was carried out for one hour on the weekday - Friday, 10 January 2020 - using video recording of the traffic passing the cross-section before the intersection stop-line. As a result of video processing, 260 values of car speed in more complicated traffic conditions were obtained, Table 4.

Table 4 Speed statistics for the zone before the stop-line at the approach to Klochkivska Str. in Kharkiv

No. of observations	-	260
Speed ($m \cdot s^{-1}$)	min	0.03
	max	11.50
	ave	2.423
	std. dev.	3.005
Gamma distribution parameters	scale	3.719
	shape	0.651

The data in Table 4 are consistent with the hypothesis that a decrease in average speed leads to an increase in speed standard deviation, which decreases the gamma distribution shape parameter. Compared to the previous observation, the average speed has decreased from 5.30 $m \cdot s^{-1}$ to 2.42 $m \cdot s^{-1}$, i.e. 2.2 times, and the standard deviation has decreased from 4.94 $m \cdot s^{-1}$ to 3.00 $m \cdot s^{-1}$, i.e. 1.45 times. At the same time, the ratio of the average speed to the standard deviation has resulted in the gamma distribution shape parameter taking a value that is very close to 1.

The results of fitting the distribution with this parameter have convincingly indicated the suitability of gamma distribution to describe the car speed, Figure 6a. The scale and the shape parameter have taken the values 3.011 and 1.005, respectively. At these parameters, the mean of the fitted gamma distribution approximately equals the standard deviation, and both moments are close to the value of the scale parameter. The gamma distribution shape parameter close to 1 indicates the possibility of describing the observed car speed distribution by the exponential one that was confirmed by the appropriate tests, Figure 6b. These results fully confirm the hypothesis of the gamma-distributed vehicle speed in urban traffic conditions.

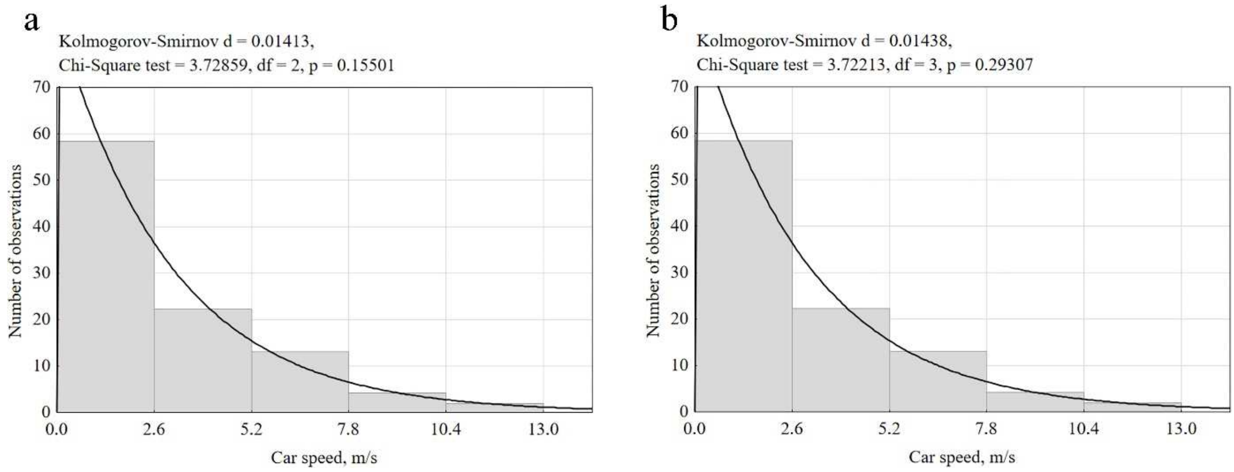

Figure 6 The distributions fitted to the values of speed influenced by traffic signalling at the approach to Klochkivska St. in Kharkiv: (a) Gamma; (b) Exponential

It is necessary to point out that in up-to-date literature, there is a lack of results similar to those presented above. Also, there are no convincing explanations for the revealed changes in the speed distribution type caused by an urban environment.

The way that can help to explain these changes is the study of the speed in the conditions that make driving even more complicated in terms of speed. These conditions can be found on the network links with limited overtaking opportunities and only one lane available for movement. A speed study of this type will deepen the knowledge about speed distribution in urban areas and allow for better clarification of the regularities reflected by the fundamental diagrams of traffic flow.

5 Conclusions

The research on the speed in places which are usual for urban areas and complicate traffic conditions in terms of speed – narrow carriageways and the zones before the stop-lines of signalized intersections – has discovered the change of normally distributed free-flow speed to exponentially distributed. The gamma distribution was considered the intermediate point in this change because of its relationships with the mentioned distributions.

To research the vehicle speed influenced by signalized intersections, the speed measurement methodology was proposed. According to the methodology, to obtain the speed value, the length of the moving vehicle should be taken as the distance for which the passing time is measured. This methodology ensures sufficient measurement accuracy, avoids restrictions on the choice of the place for observation without losing comparability of results, as well as provides a researcher with the possibility to verify them.

During the research, it was found that the gamma distribution shape parameter decreases with the complication of traffic conditions. It was confirmed by the following: at a narrow carriageway, which does not cause the most complicated traffic conditions, gamma distribution was suitable to describe the car speed; at a signalized intersection, which causes a noticeable complication of traffic conditions, exponential distribution appeared to be suitable to represent the speed variable. The reason for this change in speed distribution type is a steady decrease in average speed and an increase in speed standard deviation with the complication of traffic conditions.

The results obtained in this paper are sufficient to conclude that (i) gamma distribution is suitable to represent the vehicle speed variable influenced by urban traffic conditions and (ii) the discovered background for the changes of speed distribution type is fully appropriate for dealing with real-world issues related to the traffic management performance, city logistics, and urban transport planning.

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Conflict of interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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