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THE AVERAGE VEHICLE SPEED IN A DENSE TRAFFIC FLOW WITH TWO SLOW-MOVING VEHICLES ON A ROAD SECTION WITH LIMITED MANOEUVRING OPPORTUNITIES

The wide range of vehicle speed studies indicates considerable attention to speed as the parameter of traffic flow that affects traffic safety and comfort, the environment, and the quality of life. This parameter is also one of the most important in transport modelling, where the speed distribution law, its percentiles, and the mode and mean are used. Most of the literature presents the results of speed surveys on sections of interurban roads and urban arterial streets, where traffic flow is mostly free. It is common for these studies to consider normal distribution typical for vehicle free-flow speeds, as well as the possibility of using the percentiles of this distribution, its mode and mean value in practice. However, this is not the case with the results of studying the speed in urban traffic conditions complicated by dense traffic and limited manoeuvring opportunities. In such conditions, a much smaller number of studies have been conducted. They do not demonstrate a consensus on the possibility of using speed distribution, which could be considered reference one, but at the same time, they are consistent in indicating a tendency to the decrease in average speed and the shift of the distribution mode to the left compared to the case of free-flowing traffic. This paper presents the initial steps in studying speed in complicated urban traffic conditions characterised by a strong influence of vehicles on each other, which can be observed on road sections with a single traffic lane and without a possibility of overtaking. In this research, the formula for calculating the average speed of a vehicle platoon with one slow-moving vehicle is used to derive the analogous formula for the case of two slow-moving vehicles, which limit the speed of the others. These formulas allow for deepening the knowledge of the limiting effect of dense flow on vehicle speed and the first moment of speed distribution, as well as coming closer to obtaining a relationship to calculate average traffic flow speed with any number of slow-moving vehicles.

Keywords: traffic speed, average speed, traffic flow, flow density, traffic lane, traffic conditions, analytical modelling, transport system.

INTRODUCTION

Vehicle speed has a special place among the urban traffic flow (TF) parameters, and the corresponding attention of international institutions confirms the importance of studying it. To date, urban and rural traffic speed has been studied in many countries in the following context: The World Health Organisation presented the speed study in the Global Status Report on road safety [1]; The United Nations Economic Commission for Europe showed the importance of managing speed and its impact on travel comfort and safety within the Workshop on speed management in urban areas [2]; The Directorate-General for Mobility and Transport of the European Commission prepared a thematic report on road safety and the problem of speeding in the European Union [3]; The Organisation for Economic Co-operation and Development and The European Conference of Ministers of Transport reported on the impact of speeding on the severity of road traffic accidents, the environment and quality of life [4].

As evident from the mentioned sources, speed is an object of studies related to traffic safety and comfort, environmental impact and quality of life. In addition, speed is the basic parameter in traffic simulation software, activity travel scheduling in transport behaviour studies, theoretical analysis of TFs, and traffic management [5]. Such applications often require knowledge of the average speed, the distribution of this random variable, and its percentiles [5, 6]. Most studies on obtaining these characteristics have been conducted in rural areas [7-9], while the studies on speed in urban areas are significantly fewer. Urban traffic conditions are substantially more complicated regarding manoeuvrability and speed [10], with many factors affecting the speed variable. This creates certain difficulties in establishing a speed distribution that could be considered a reference for the elements of urban street networks like intersections, narrow carriageways and places with limited manoeuvring opportunities, including those due to heavy traffic. All of the above indicates the relevance of continuing research on speed variable in urban environment.

LITERATURE REVIEW AND PROBLEM STATEMENT

The distribution of speed variable is the research object in numerous works, many of which refer to free flow [5, 11]. These works often present experimental research resulting in histograms of vehicle speed distribution for the road sections outside cities without assessing the conformity between empirical and theoretical distribution [12]. The works of this type are made to: assess the current TF parameters flow on a particular road section; determine speed trends, the 50th and 85th percentile of speed, a pace speed, an advisory speed, the speed limits for certain areas; assess the effectiveness of traffic control devices; monitor the effectiveness of speed enforcement programmes; estimate the impact of the carriageway geometry (horizontal and vertical alignment) on speed; determine the proper location of road signs and markings; establish proper sight distances; assess the impact of speed on road safety; determine the reasons of speeding offences; determine the validity of complaints related to speeding; study the actual or potential effect of the input from the public and officials, etc [6, 9, 12-15].

On rural roads, most vehicles usually have pretty high speeds (much higher than 0) because there is inherently the only speed limit set by road signs or local traffic rules. The influence of other natural or design constraints that complicate traffic is usually eliminated by the choice of road section and period for the survey. For example, manual [7] points to the need to select a road section that would allow recording typical vehicle speeds in free-flow conditions [8] and avoid the effects of vehicles slowing down or accelerating due to traffic signals, intersections, industrial and parking areas, active pedestrian crossings, small radii of horizontal curves, etc. This manual and the handbook [9] indicate that the survey period should not cover or overlap with rush hours, weekends and holidays, public or unique events (festivals, carnivals, concerts, etc.), or adverse weather conditions.

The surveys in free-flow conditions are conducted using radars, lidars, stopwatches, pneumatic tubes, inductive loops, magnetic, microwave, acoustic, ultrasonic, infrared, and laser sensors, as well as sensors that combine several of the listed technologies [7, 9, 16, 17]. Such surveys often provide researchers with data on instantaneous speed in a free flow [17], and the thing these surveys have in common is that they consider the normal distribution typical for the mentioned speed [5, 17, 18]. The results of both local and national scales support this statement. Thus, the statistical release published by the UK Department for Transport [19]. This release assesses vehicle compliance with posted speed limits in free-flowing conditions and presents speed histograms very similar to the histograms of the normal distribution [19].

The US studies also confirm the relevance of using the normal distribution to represent free-flow speed on rural roads – in the report [6], this distribution is mentioned as typical for speed in free-flow conditions with reference to the results of in-depth studies conducted in the 1970s, 1985 and 1990. This can be considered a recognition of the continuous use of the normal distribution as a reference for free-flow speed.

References to the normal distribution of speed in free-flow conditions are present in studies aimed at establishing reasonable posted speed limits. The report [6] states that the 85th percentile of the normally distributed speed is the traditional value to set the speed limit. The reference to the 85th percentile is also mentioned in the European Commission report [20], which examined the impact of the directive on the use of speed limitation devices for specific motor vehicle categories in the European Union (EU) on speed profiles, road safety, fuel consumption, and emissions. This report acknowledges the assumption of a normal distribution of free-flow speed [20].

The similarity of the survey conditions in the works analysed above can be considered the reason for the results' similarity. Even though the goodness-of-fit is rarely assessed statistically, there is no doubt that the empirical histograms can be approximated with the normal distribution.

Although the distribution of vehicle speeds when driving in free traffic flow outside cities can be considered established, the issue of determining a similar distribution and its moments for urban traffic remains open. Urban traffic conditions are more complicated in terms of speed [7] because the speed is influenced here by dense flows, at-grade unsignalized and signalised intersections, narrow carriageways at certain road sections, etc. The purposes of speed studies in urban conditions, in addition to those listed in the first paragraph of this section, also include defining appropriate traffic signal settings and sight distances at the approaches to intersections [9, 13]. Urban studies are impossible in conditions that meet the same requirements for the sites as in the case of rural studies, and this is especially true for street sections in the downtown areas with dense buildings, short road network links, and narrow carriageways.

Urban traffic conditions limit the space and time for manoeuvring [10] and the ability to make certain manoeuvres. The complications of this type affect drivers' choice of speed, and usually, the more complicated the traffic conditions are, the lower the speed. At the same time, the individual driving style of each driver contributes to the speed randomness, which requires additional attention when determining speed distribution.

The number of vehicle speed studies in urban areas is significantly lower, and a certain share of these studies present results consistent with non-urban ones. An example is the paper [21] devoted to studying the motorcycle flow parameters at four locations in the central part of Hanoi, Vietnam. A similar result was obtained in the thesis [11], which also confirmed the possibility of describing the speed of motorcycles passing an intersection in Đống Đa central district in Hanoi with the normal distribution. However, the normal distribution of the speed of two-wheelers can be explained by their small dimensions, low requirements for road space and high manoeuvrability [11, 22].

Results similar to those obtained in Hanoi are presented in the study of vehicle speed in the free flow at 60 sites on 14 urban arterials in three Taiwan cities – Taipei, Taoyuan and Taichung [23]. Here, speed measurements were made for three vehicle types – motorcycles, small vehicles, and large vehicles. The difference between the results obtained and those analysed in the previous paragraph is that the normal distribution was used to describe the free speed of not only motorcycles but also other vehicle types [23]. This is also supported by the paper [24], which presents survey data from the Zhongxiao arterial road in Taipei.

Paper [25] explores the speed on 17 four- and six-lane roads in the Indian metropolitan areas of New Delhi, Jaipur, and Chandigarh – the authors note that the normal distribution is suitable for describing the speed of separate vehicle types, but at the same time, indicate the non-normality of the combined distribution of the speeds of all vehicles in the TF and the possibility of several modes in the empirical distribution depending on the TF composition. At the same time, the presented density curves allow for noticing a certain shift of the mode of the empirical distributions to the left relative to the mode of the theoretical normal distribution [25]. This can be considered a consequence of complicated traffic conditions in cities.

The tendency of shifting the speed distribution mode to the left is also traced in Ukrainian studies. For example, paper [26] studies the speed distribution on two arterials and two local roads in Kharkiv, Ukraine. As a result, the normal, lognormal, chi-square, and gamma distributions were fitted to speed values from all four locations, emphasising better fitting results for the three latter distributions [26].

A further leftward shift in the mode of speed distribution is presented in the paper [27], which considers speed distribution during the assessment of exhaust emissions from road transport. The authors of that paper took the SETS software [28] settings for the city of Florence, Italy, to simulate eight speed distributions for different complicated traffic conditions up to those close to congestion. The curves of all eight distributions resemble the curves of the gamma distribution with a shape parameter which gradually approaches 1, i.e., they indicate that the speed distribution approaches exponential distribution.

The distributions with a significant right skewness are used in a speed study from Budapest, Hungary [5]. Here, in the influence zones of intersections on the Hamzsabegi Road and Szent Gellert Road, the vehicle speed was studied in various traffic conditions, which determine the TF behaviour. The conditions studied were as follows: accelerated flow, decelerated flow, congestion, free flow, under-saturated flow, and over-saturated congestion (when the traffic volume exceeds the capacity for a long period of time). Only the speed in the under-saturated flow turned out to be describable by a normal distribution. In the other traffic conditions, distributions most suitable for describing the vehicle speed appeared to be as follows: for an accelerated flow – beta distribution; for a decelerated flow – chi-square distribution; for a free flow – lognormal distribution; for a congestion – gamma distribution; for over-saturated congestion – exponential distribution [5]. The obtained results indicate a significant impact of urban traffic conditions and traffic flow parameters, particularly volume and density, on vehicle speed distribution. Paper [5] is one of the few that shows and statistically confirms the possibility of using the exponential distribution to describe vehicle speeds in the most complicated traffic conditions.

A definite left shift in the speed distribution plot for urban traffic conditions can be seen in studies [8, 29], which present the results of observations of the speed before the stop line of two signalised intersections in Kharkiv, Ukraine. In both cases, the exponential distribution was suitable for describing the speed. This is another confirmation that under traffic conditions complicated in terms of speed, the distribution of the speed variable has a significantly left-shifted mode. At the same time, work [8] indicates that vehicle speed is also influenced by the carriageway narrowing in addition to signalised intersections. This influence is not so strong because the gamma distribution best describes the vehicle speed, which is confirmed by the empirical data collected in Kharkiv.

Confirmation of the fact that carriageway narrowing complicates traffic and affects vehicle speed distribution can also be found in other works. For example, in the paper [30], a study of the impact of the roadway geometry and TF parameters on the accident frequency in the state of Washington, USA, found that road sections with a lane width of less than 3.5 m have a lower accident rate due to lower speeds compared to sections with a ‘standard’ lane width. Similar conclusions were drawn in a study of the same impacts conducted in Canada`s Metro Vancouver Regional District [31].

These results can be complemented by an active experiment on a driving simulator at Tongji University, China, which, among other things, studied the effect of carriageway width on traffic speed [32]. The simulator reproduced one-way traffic in a three-lane tunnel and allowed for testing driving scenarios with lane widths of 2.85 m, 3.00 m, 3.25 m, 3.5 m, and 3.75 m. The experiment results showed a clear trend for speed to decrease as the lane width decreases. The authors explain these results by the fact that drivers feel safer and freer when driving in wider lanes [32]. It should be added that a year earlier than this experiment, the speed was surveyed on eight underground roads in Shanghai [33] to define the relationship between recorded speeds and lane widths, number of lanes, slope grade, and speed limits. The results regarding the relationship between speed and lane width were similar [33].

The analysis of existing speed studies indicates a noticeable influence of urban areas with dense traffic and limited manoeuvring opportunities on the speed variable distribution, which becomes right-skewed compared to the situation of free flow and shows a decrease in the mode and mean. This testifies to the expediency of developing theoretical prerequisites for explaining these changes in the speed distribution, and an initial step in this process is to analytically represent the average speed, which is the first moment of the speed variable.

AIM AND TASKS

Literature review shows that a reduction in road space available to drivers generally reduces traffic speed. In urban traffic conditions, there are many reasons for the decrease in the quantity of space per flowing vehicle, but the most common and understandable are a significant increase in traffic density and the restriction of manoeuvring opportunities caused by traffic management and other road users, or the combined effect of these circumstances. These complications of traffic conditions make it possible to formalise the flow of traffic because they cause significant mutual influence of vehicles, which is not typical for a free flow. The role of this influence in the formation of both the speed distribution and the average speed should be studied in the conditions that, on the one hand, should be characteristic of the urban street network and, on the other hand, should create opportunities for an analytical description of the speeds that drivers choose or are forced to choose. The conditions that meet both requirements regularly appear in urban networks when traffic flows along the following network elements:

– network sections with a temporary or permanent narrowing of the carriageway to one lane at a traffic volume equal to or exceeding the lane capacity;
– sections with traffic restrictions that cause the same consequences and volume-to-capacity ratio;
– two-lane two-way roadways with prohibited overtaking;
– single-lane one-way roads;
– two-lane one-way roads in situations where one lane is occupied by parked vehicles;
– three-lane one-way roads in situations where both the left and right lanes are occupied by parked vehicles;
– tunnels with one lane in each direction;
– sections where there has been a traffic accident which caused partial carriageway blocking;
– all network sections during bad weather, etc.

In everyday life, situations from the above list occur quite often in total, but on the listed sections, there is not always a strong relationship between drivers' behaviours in the TF. At low traffic volume, there may well be free-flow conditions, so a strong interaction between vehicles occurs only when a queue of vehicles is formed at the entrance to a section with one lane available for traffic and no possibility of passing and overtaking. When a queue forms, vehicles cannot move at a speed higher than the speed of the vehicle ahead. In contrast to free flow, this creates opportunities for finding an analytical formula for calculating the average traffic speed, which is very important because it ensures the generality of the research results obtained in this way. At the same time, the fact that drivers choose different speeds under the same traffic conditions can be considered an axiom in an analytical study.

If a queue enters a traffic lane where passing and overtaking are impossible, the obvious consequence is a dense traffic flow in which vehicles form the platoons. Each platoon can split gradually into groups due to the different speeds chosen by drivers. These groups will be led by slow-moving vehicles (SV), limiting the speed of the others – those who would like to travel at a higher speed in the free flow. This creates the conditions for formalising the traffic flow process and deriving the formula for average speed based on the speed of each vehicle in the group within the platoon. For this formalisation, it is also important that those vehicles that travel in the platoon and are not restricted by the SVs should have enough clear road ahead to attain the desired speed. This means that the average speed of the platoon will be a characteristic of a part of the street section somewhat ahead of the point where the platoon was formed. This part, in particular, may be at the exit from the section. At the same time, for macromodelling purposes, the average speed can be considered the space mean speed for the whole section.

In the absence of specific measures to control traffic flows in time and space in urban conditions, the formation of vehicle platoons can be considered a random process. This is important for the correct statement of the task of determining the average traffic speed on a single-lane road section with no passing and overtaking opportunities because, in this case, we can assume a random order of vehicles and, consequently, the equal probability of each vehicle to take any position in the platoon.

It is reasonable to start searching for a general formula for calculating the average traffic speed on a lane without overtaking opportunities by studying the simplest hypothetical cases. These include the consideration of a moving platoon in which all vehicles tend to drive at the same maximum permitted speed, except for one or two SVs that limit the speed of the others. The case with one SV was studied in the paper [34]. The materials of the paper [34] will be used to derive the formula of the average speed for the case of two SVs in a platoon, which is the purpose of the current paper.

RESEARCH RESULTS

To find an analytical formula to calculate the average vehicle speed in a TF with two SVs that limit the speed of others on a lane with no passing and overtaking opportunities, it is expedient to formalise this problem as follows:

– let N vehicles moving in a dense flow randomly enter a lane where overtaking are not possible;

– let the order numbers of vehicle positions in the platoon start from 0. Under the equal probability of taking any position in the platoon, each vehicle can take the position $[0; N-1]$ with probability $1/N$;

– let all but two drivers want to drive at the maximum permitted speed $V_{\max}$;

– let the driver of the first slow-moving vehicle (SV1) travels at speed V_s, $0 < V_s < V_{\max}$, and the driver of the second slow-moving vehicle (SV2) travels at speed V_2, $V_2 > V_s$;

– let $\Delta_s = (V_{\max} - V_s)$ be the deviation of SV1's speed from the maximum permitted speed;

– let $\Delta_2 = (V_2 - V_s)$ be the deviation of SV2's speed from SV1's speed.

It is necessary to determine what will be the average vehicle speed at the exit from the lane.

From the mathematical point of view, the simplest case in determining the average vehicle speed on a lane where passing and overtaking are impossible is the presence of one SV in the platoon, Fig. 1. This case is studied in detail in paper [34], where the average vehicle speed at the exit from the lane is initially represented as

$$\bar{V}_x = \frac{x \cdot V_{\max} + (N - x) \cdot V_s}{N} \tag{1}$$

where x is the position of the single SV (SV with speed V_s) in the TF.

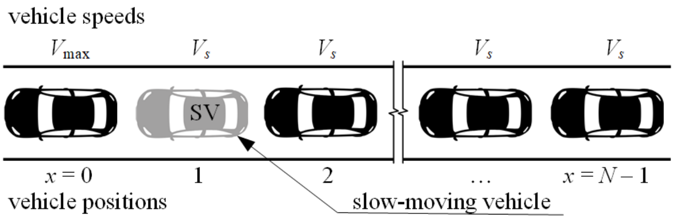

Figure 1 – The representation of the platoon with one slow-moving vehicle [34]

If there is a single SV which travels at speed V_s in the platoon, then, taking into account the equal probability for each vehicle to take any position in the platoon, the desired $\bar{V}$ is defined as follows [34]:

$$\bar{V} = \frac{1}{N}\sum_{x=0}^{N-1}\bar{V}_x = \frac{1}{N^2}\sum_{x=0}^{N-1}\left(x \cdot V_{\max} + (N - x) \cdot V_s\right), \tag{2}$$

where $\bar{V}_x$ is the average speed of vehicles in the TF when a single SV takes the position x. Speed $\bar{V}_x$ is possible with probability $1/N$, $x \in [0; N-1]$;

$[x \cdot V_{\max} + (N - x) \cdot V_s]$ is the sum of the speeds of all vehicles in the TF in the case when the only SV (which travels at speed V_s) takes position x in the flow [34].

The use of the introduced designation for Δ_s, as well as the collection of the like terms in the course of removal of brackets with consideration of the identities for the sum of a simple arithmetic progression [35], allowed for obtaining a formula for calculating the average vehicle speed in the TF with one SV on a lane where passing and overtaking are impossible [34]:

$$\bar{V} = V_s + \frac{N-1}{2N}\Delta_s . \tag{3}$$

A more complicated case in terms of analytical representation of the average speed $\bar{V}$ at the exit from a lane with no passing and overtaking opportunities is the consideration of the TF with two SVs, i.e., vehicles that travel at a speed lower than the maximum speed permitted in certain conditions. Given that $V_2 > V_s$,

$$\Delta_s > \Delta_2 ;\ \Delta_s, \Delta_2 > 0 .$$

The complication with respect to the case of a single SV consists of the following. Since overtaking is prohibited, the speed of $(N-2)$ vehicles whose drivers want to travel at speed $V_{\max}$ will depend on which SV they follow. If they follow the first SV, they will exit the road section at speed V_s. If they follow the second SV only, they will exit at speed V_2, and the cars ahead of both SVs will exit at speed $V_{\max}$.

If the slowest vehicle (SV1) travelling at speed V_s took the position x in the flow, and this position is ahead of the second SV (SV2), Fig. 2, then the average vehicle speed at the exit from the lane will be the same as in the simplest case with one SV in the flow. The probability of this event is $1/N$. To calculate the average speed in this situation, Eq. (1) can be used.

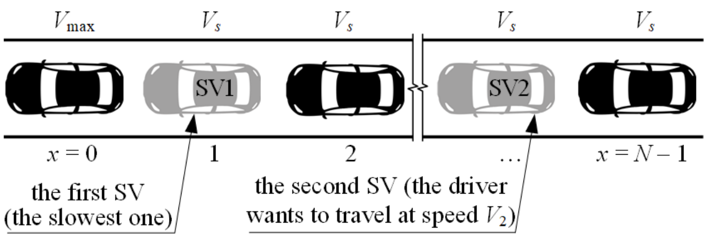

Figure 2 – The representation of the platoon with two SVs when the slowest one is ahead of the other one

With the same probability $1/N$, the second SV travelling at speed V_2 can take the position x ahead of the first SV (which is the slowest). Then, all the vehicles ahead of SV2 will travel at the maximum (permitted) speed $V_{\max}$, SV2 will travel at speed V_2, and the vehicles which follow SV2 will travel either at speed V_2 if there is no SV1 ahead of them or at speed V_s otherwise, Fig. 3.

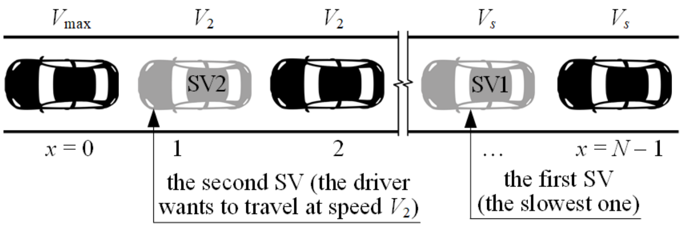

Figure 3 – The representation of the platoon with two SVs when the faster one is ahead of the slowest one

Thus, the case of one SV studied in [34] and represented by Eq. (1)-(3) can be applied to $(N-x-1)$ vehicles after position x in the flow, but with a maximum speed equal to V_2. Then, their average speed $\bar{V}_x$, where x denotes the position in the flow taken by the second SV, can be determined from the equation written based on Eq. (3) and the number of vehicles in the flow after the position x:

$$\bar{V}_x = V_s + \frac{N - x - 2}{2(N - x - 1)}\Delta_2 . \tag{4}$$

The probability of the event that one of the two SVs takes position x in the flow is equal to $2/N$, and the probability of taking the position x by each of the two SVs is equal to $1/N$. Therefore, for the average speed of the whole platoon, it is possible to write

$$\bar{V}_x = \frac{1}{2}\bar{V}_{x1} + \frac{1}{2}\bar{V}_{x2} , \tag{5}$$

where $\bar{V}_{x1}$ is the average traffic speed when the first SV takes the position x in the flow;

$\bar{V}_{x2}$ is the average traffic speed when the second SV takes the position x in the flow.

It should be noted that the mandatory presence of one SV behind the other SV, regardless of the speed of these vehicles, means that the vehicle that moves ahead has not N, but only $(N-1)$ alternatives for positioning in the flow.

By analogy with Eq. (2), based on Eq. (5) and new designations, it is possible to write the equation for the unconditional average speed of the whole platoon when all possible alternatives for positioning two SVs among N vehicles are considered:

$$\bar{V} = \frac{1}{2}\bar{V}_1 + \frac{1}{2}\bar{V}_2 . \tag{6}$$

where $\bar{V}_1$ is the average traffic speed for all $x \in [0; N-2]$ if the first SV takes position x in the flow;

$\bar{V}_2$ is the average traffic speed for all $x \in [0; N-2]$ if the second SV takes position x in the flow.

For each position x of the first SV, it is necessary to determine the total number of situations when it can be in this position. This number is known and equal to.

$$\frac{N!}{N} = (N-1)!, \ (0, 1, 2, \dots N-2), \tag{7}$$

that is the number of permutations of the remaining cars regardless of the value of x. And if the first SV is in the first position ($x = 0$), the number of permutations corresponds to Eq. (7).

As for the next positions, it should be kept in mind that in the situation under consideration, i.e., when the first SV (the slowest one) is ahead of the second SV in the flow, only fast vehicles can be ahead of the first SV. To consider this fact while examining the positions $x > 0$ of the first SV when it is ahead of the second SV, it is necessary to subtract from Eq. (7) the number of situations when the second SV is ahead of the first SV.

Then, when the first SV is in the second position ($x = 1$), the second SV can be ahead of it only in the first position and as many times as there are permutations of the rest, only fast vehicles (willing to drive at a higher speed). The number of these permutations is equal to the factorial of the number of fast vehicles, i.e., $(N-2)!$. This means that the number of situations when the first SV is in the second position ($x = 1$) and ahead of the second SV is equal to $[(N-1)! - (N-2)!]$.

If the first SV is in the third position ($x = 2$), then the second SV can be ahead of it either in the first or in the second position, again, in each case as many times as there are permutations of fast vehicles for which it does not matter whether they are ahead of or behind the first SV. In any case, the number of permutations of the fast vehicles is equal to $(N-2)!$. Then, the total number of situations in which the first SV is in the third position ($x = 2$) and ahead of the second SV is equal to $(N-1)! - (N-2)! - (N-2)! =$ $= (N-1)! - 2(N-2)!$.

Similarly to the already considered situations, if the first SV is in the fourth position ($x=3$), then the second SV can be in the first, second and third positions ahead of it, again, in each case as many times as there are permutations of fast vehicles, i.e., $(N-2)!$. Then the total number of situations in which the first SV is in the fourth position ($x=3$) and ahead of the second SV equals to $[(N-1)!-3(N-2)!]$.

A similar situation occurs for each position of the first SV when it is ahead of the second SV, and in general, the relationship for the number of situations that arise for each position of the first SV can be written as follows:

$$(N-1)!-x(N-2)!=(N-2)!\cdot(N-1-x)\,. \tag{8}$$

Eq. (8) makes it possible to write down the relationship for the average traffic speed when the first SV is in the position ahead of the second SV:

$$\bar{V}_1=\frac{\sum\limits_{x=0}^{N-2}(N-2)!\cdot(N-1-x)\cdot\dfrac{\left(x\cdot[V_s+\Delta_s]+[N-x]\cdot V_s\right)}{N}}{\sum\limits_{x=0}^{N-2}(N-2)!\cdot(N-1-x)} \tag{9}$$

where $(N-2)!\cdot(N-1-x)$ is the number of situations when the first SV in the flow consisting of N vehicles occurs ahead of the second SV and takes position x;

$\dfrac{(x\cdot[V_s+\Delta_s]+[N-x]\cdot V_s)}{N}$ is the speed of the TF in which the first SV travels in the position x ahead of the second SV.

After factoring out the multipliers independent of x, removing the square brackets and obviously cancelling similar terms, Eq. (9) is simplified to

$$\bar{V}_1=\frac{\sum\limits_{x=0}^{N-2}(N-1-x)\cdot(N\cdot V_s+x\cdot\Delta_s)}{N\cdot\sum\limits_{x=0}^{N-2}(N-1-x)}\,. \tag{10}$$

Separating the two parts in the numerator by the sum terms $N\cdot V_s+x\cdot\Delta_s$ results in

$$\bar{V}_1=\frac{N\cdot V_s\cdot\sum\limits_{x=0}^{N-2}(N-1-x)}{N\cdot\sum\limits_{x=0}^{N-2}(N-1-x)}+\frac{\Delta_s\cdot\sum\limits_{x=0}^{N-2}(N-1-x)\cdot x}{N\cdot\sum\limits_{x=0}^{N-2}(N-1-x)},$$

and after that, a simpler relationship for $\bar{V}_1$ becomes available:

$$\bar{V}_1=V_s+\frac{\Delta_s}{N}\cdot\frac{\sum\limits_{x=0}^{N-2}(N-1-x)\cdot x}{\sum\limits_{x=0}^{N-2}(N-1-x)}\,. \tag{11}$$

To simplify further transformations, it is reasonable to introduce the temporary variable $M=N-1$ instead of $(N-1)$, and this results in the following equation:

$$\bar{V}_1 = V_s + \frac{\Delta_s}{N} \cdot \frac{\sum_{x=0}^{M-1} (M - x) \cdot x}{\sum_{x=0}^{M-1} (M - x)} = V_s + \frac{\Delta_s}{N} \cdot \left[\frac{M \sum_{x=0}^{M-1} x - \sum_{i=0}^{M-1} x^2}{\sum_{x=0}^{M-1} M - \sum_{x=0}^{M-1} x} \right].$$

Now, it is necessary to simplify the expression in square brackets using the well-known identities for the sum of arithmetic progression [35]:

$$\frac{M \sum_{x=0}^{M-1} x - \sum_{x=0}^{M-1} x^2}{\sum_{x=0}^{M-1} M - \sum_{x=0}^{M-1} x} = \frac{\frac{M^2(M-1)}{2} - \frac{M(M-1)}{2} \cdot \frac{2M-1}{3}}{M^2 - \frac{M(M-1)}{2}},$$

and then

$$\frac{\frac{M^2(M-1)}{2} - \frac{M(M-1)}{2} \frac{2M-1}{3}}{M^2 - \frac{M^2}{2} + \frac{M}{2}} = \frac{\frac{M(M-1)}{2}\left[M - \frac{2M-1}{3}\right]}{\frac{M(M+1)}{2}} = \frac{(M-1)\left[M - \frac{2M-1}{3}\right]}{M+1}.$$

After these transformations, the initial number of vehicles in the TF $N = M + 1$ can be returned to the obtained fraction instead of the temporary variable M :

$$\frac{(N-2) - \left[N - 1 - \frac{2N-2-1}{3}\right]}{N} = \frac{(N-2) \cdot \frac{1}{3} N}{N} = \frac{N-2}{3}.$$

Taking into account the obtained result, Eq. (11), which represents the average traffic speed when the first SV (the slowest one) takes a position ahead of the second SV, transforms to the following final formula:

$$\bar{V}_1 = V_s + \frac{\Delta_s}{N} \cdot \frac{N-2}{3}. \tag{12}$$

The second summand in Eq. (6) should be considered in more detail based on (i) new designations introduced at the beginning of this section, (ii) awareness that each term under the summation sign is the sum of the speeds of all vehicles in the flow (like in Eq. (2)), (iii) considerations from the two paragraphs before Eq. (4).

When two SVs travel in the flow (platoon) and the faster one is ahead of the slower one, each determines the speed for the following vehicles. This forms not two but three groups of vehicles in the flow, and the summand under the summation sign should reflect this situation. Therefore, the second term of the x-th summand should no longer reflect the speed of all vehicles following the very first SV, as in the case of a single SV in the TF (see the terms of the summand $\bar{V}_x$ in Eq. (2)), but their average speed, which differs depending on the position of the first SV in the tail of the flow and behind the second SV travelling at speed $V_2 > V_s$. Then, the sum of the speeds of all vehicles in the flow, provided that the second SV is in position x and the first SV follows it at some other position remaining in the flow, can be derived through the number of vehicles following the second SV and their average speed determined from Eq. (4):

$$x \cdot (V_s + \Delta_s) + (V_s + \Delta_2) + (N - x - 1) \cdot \bar{V}_x.$$

Here, the first term represents the sum of the speeds of the vehicles which travel at the maximum permitted speed ahead of the second (faster) SV, the second term is the second SV's speed, and the third term is the sum of the average speeds of the vehicles following the second SV, which depends on the position of the first (slowest) SV.

Since the proportions between the number of vehicles in the groups under the location of the SV in position x do not depend on which of the SV is located in that position, the number of situations when the second SV can be ahead of the first SV will also be represented by Eq. (8). Given that multiplier $(N-2)!$ is independent of x and the transformations made in Eq. (9) and Eq. (10), Eq. (8) can be simplified and introduced to the formula for $\bar{V}_2$:

$$\bar{V}_2 = \frac{\sum_{x=0}^{N-2}(N-1-x)\cdot\frac{\left(x\cdot(V_s+\Delta_s)+(V_s+\Delta_2)+(N-x-1)\cdot\bar{V}_x\right)}{N}}{\sum_{x=0}^{N-2}(N-1-x)}. \quad (13)$$

The substitution of Eq. (4) into Eq. (13) results in the following:

$$\bar{V}_2 = \frac{\sum_{x=0}^{N-2}(N-1-x)\cdot\frac{\left(x(V_s+\Delta_s)+(V_s+\Delta_2)+(N-x-1)\left[V_s+\frac{N-x-2}{2(N-x-1)}\Delta_2\right]\right)}{N}}{\sum_{x=0}^{N-2}(N-1-x)},$$

$$\bar{V}_2 = \frac{\sum_{x=0}^{N-2}(N-1-x)\cdot\left(x[V_s+\Delta_s]+(V_s+\Delta_2)+(N-x-1)\cdot V_s+\frac{N-x-2}{2}\Delta_2\right)}{N\cdot\sum_{x=0}^{N-2}(N-1-x)},$$

$$\bar{V}_2 = \frac{\sum_{x=0}^{N-2}(N-1-x)\cdot\left(x\cdot\Delta_s+N\cdot V_s+\Delta_2+\frac{N-x-2}{2}\Delta_2\right)}{N\cdot\sum_{x=0}^{N-2}(N-1-x)}.$$

Removal of the brackets in the numerator results in three terms, and the first two of them correspond to the expression to the right of the equal sign in Eq. (10), which was transformed into Eq. (11). This allows for collecting the like terms taking into account Eq. (11):

$$\bar{V}_2 = \bar{V}_1 + \frac{\Delta_2\sum_{x=0}^{N-2}(N-1-x)+\sum_{x=0}^{N-2}(N-1-x)\cdot\frac{N-x-2}{2}\Delta_2}{N\cdot\sum_{x=0}^{N-2}(N-1-x)},$$

$$\bar{V}_2 = \bar{V}_1 + \frac{\Delta_2}{N} + \frac{\Delta_2}{2N}\frac{\sum_{x=0}^{N-2}(N-1-x)\cdot(N-x-2)}{\sum_{x=0}^{N-2}(N-1-x)}. \quad (14)$$

The introduction of the temporary variable $M = N-1$ into the fraction at multiplier $\frac{\Delta_2}{2N}$ in Eq. (14) results in the following:

$$\frac{\sum_{x=0}^{M-1}(M-x)\cdot(M-x-1)}{\sum_{x=0}^{M-1}(M-x)}=\frac{\sum_{x=0}^{M-1}\left(M^2-2\cdot x\cdot M+x^2-M+x\right)}{\frac{M(M+1)}{2}},$$

$$\frac{M^3-2M\sum_{x=0}^{M-1}x-M^2+\sum_{x=0}^{M-1}x^2+\sum_{x=0}^{M-1}x}{\frac{M(M+1)}{2}},$$

$$\frac{M^3-M^2(M-1)-M^2+\frac{M(M-1)}{2}\frac{2M-1}{3}+\frac{M(M-1)}{2}}{\frac{M(M+1)}{2}},$$

$$\frac{M^3-M^3+M^2-M^2+\frac{M(M-1)}{2}\frac{2M-1}{3}+\frac{M(M-1)}{2}}{\frac{M(M+1)}{2}},$$

$$\frac{M(M-1)\frac{2M-1}{3}+M(M-1)}{M(M+1)},$$

$$\frac{(M-1)\left[\frac{2M-1}{3}+1\right]}{M+1}.$$

Back substitution of the initial number of vehicles in the TF $N=M+1$ instead of the temporary variable M leads to the final form of the fraction in Eq. (14):

$$\frac{(N-2)\left[\frac{2N-2-1+3}{3}\right]}{N}=\frac{2}{3}(N-2).$$

With this in mind, Eq. (14) takes the final form

$$\bar{V}_2=\bar{V}_1+\frac{\Delta_2}{N}\left[1+\frac{N-2}{3}\right]. \qquad (15)$$

Now it is possible to substitute Eq. (12) for the traffic speed in situation when the first (slower) SV is ahead of the second SV and Eq. (15) for the traffic speed in situation when the second (faster) SV is ahead of the first SV in Eq. (6) and obtain the final relationship for the desired speed of a dense traffic with two SVs at the exit of a road section with one lane available for traffic without passing and overtaking opportunities:

$$\bar{V}=V_s+\frac{\Delta_s}{N}\cdot\frac{N-2}{3}+\frac{\Delta_2}{2N}\cdot\left[1+\frac{N-2}{3}\right]$$

or

$$\bar{V}=V_s+\frac{\Delta_s}{N}\cdot\frac{N-2}{3}+\frac{\Delta_2}{2N}\cdot\frac{N+1}{3}. \qquad (16)$$

Eq. (16) makes it possible to trace the impact of both SVs' speeds and the total number of vehicles in the TF on the average speed in considered traffic conditions.

DISCUSSION

The preliminary analysis of Eq. (16) indicates that, ceteris paribus, the impact of the second SV's speed represented by the third term in the equation on the average speed $\bar{V}$ decreases nonlinearly with the increase in N, Fig. 4. On the contrary, the influence of the second term, which corresponds to the contribution of the first (slowest) SV, increases nonlinearly with the increase in N.

This result is logical since the second SV's speed, being closer to $V_{\max}$, has less impact on the average speed of the platoon than the speed of the first SV, the slowest one. These impacts can be characterised as follows: as $N \to \infty$, the average platoon speed does not exceed the V_s by more than $(\Delta_s/3 + \Delta_2/6)$. It is also worth noting that the coefficients at the terms in Eq. (16) are the reciprocal triangular numbers (1, 1/3, 1/6) [36-38].

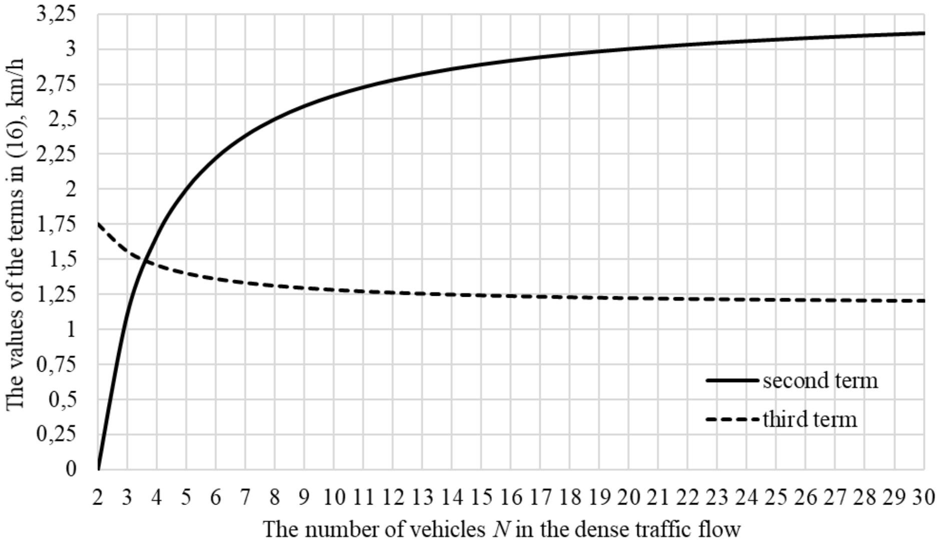

Figure 4 – Illustration of the impact of the terms in Eq. (16) on the average vehicle speed in a dense traffic flow with two SVs for different total number of vehicles in the flow: example for $\Delta_s = 10$ km/h and $\Delta_2 = 7$ km/h

This may be used to characterise a significant decrease in the contribution of the second SV to the average speed $\bar{V}$ compared to the contribution of the first SV. A graphical interpretation of this decreasing impact is shown in Fig. 5.

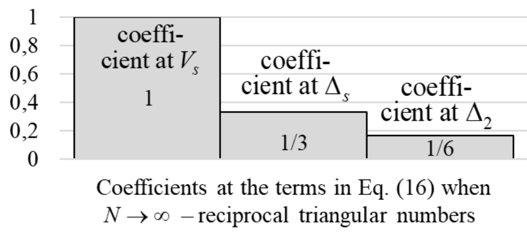

Figure 5 – Graphical interpretation of the decreasing impact of the second SV on the average platoon speed compared to the impact of the first SV

Under the minimum number of vehicles in the platoon, i.e., at $N = 2$, the average platoon speed will not exceed V_s by more than a quarter of Δ_2.

The discovered properties of the average traffic speed on a road section with one lane available for traffic without overtaking opportunities induce further research to derive the formulas for the cases with a larger number of SVs in a platoon.

CONCLUSIONS

The existing studies of vehicle speed as a random variable suggest that using a normal distribution to describe vehicle speed on rural roads is generally recognised. As for the distribution that would be suitable for describing vehicle speeds in urban areas, no consensus has been reached. One part of the research results points to the possibility of using the already mentioned normal distribution, and the other part points to several distributions with right skewness, i.e., with a left-shifted mode. The latter include the lognormal, gamma, beta, chi-square distribution, etc. These distributions were fitted to the speeds recorded in the influence zones of unsignalized and signalised intersections, in dense traffic, and on narrow lanes. In general, traffic conditions at the listed places restrict the space available for driving as well as manoeuvring opportunities, making driving complicated in terms of speed.

The analysis of all these studies makes it possible to identify the transformation of the histogram of the speed distribution from one that can be described by a normal distribution to one that an exponential distribution can describe, and this occurs with a change in traffic conditions from the free flow on rural roads to complicated conditions in urban areas. This indicates quite a clear general trend of decreasing vehicle speed as traffic conditions become more complicated. Still, there is no theoretical background for explaining this trend and the transformation of the associated speed distribution. To develop this background, it is reasonable to study the flow of vehicles in conditions opposite to free flow, i.e., when there is a strong interaction between road users.

In this paper, we have studied a dense traffic flow in which vehicles travel in a platoon along a road section with one lane available for traffic without the overtaking possibility. As a result, formulas for calculating the average speed in traffic flow for the simplest cases – when the platoon contains only one or two SVs, which make other drivers drive at a speed lower than they want to – were obtained.

The obtained results are the initial steps to determine the first moment of the speed distribution and create the preconditions for developing the study presented in this paper by considering more complex cases with a larger number of SVs. Ultimately, this should allow us to obtain a general relationship for calculating the average vehicle speed in the TF with any number of SVs. This relationship will be a basis for deepening knowledge about the limiting effects of a dense flow with SVs on vehicle speeds that would be normally distributed under free-flowing conditions and have a higher average value.

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Горбачов П.Ф., Свічинський С.В. **Середня швидкість щільного транспортного потоку з двома повільними автомобілями на ділянці дороги з обмеженими можливостями маневрування**

Існуючий спектр досліджень швидкості руху транспортних засобів вказує на велику увагу до даного параметру транспортного потоку як такого, що впливає на безпеку і комфорт руху, навколишнє середовище і якість життя. Даний параметр також є одним із найважливіших у транспортному моделюванні, де знаходять застосування закон розподілу випадкової величини швидкості, його перцентилі, а також модальне та середнє значення цієї величини. Більша частина літератури презентує підсумки обстежень швидкості на ділянках позаміських доріг і магістральних вулиць міст, де рух є здебільшого вільним. Загальним для цих досліджень є визнання нормального розподілу як типового для швидкості транспортних засобів у вільному потоці, а також можливості практичного використання перцентилів даного розподілу, його моди і математичного сподівання . Цього не можна сказати про результати вивчення швидкості у міських умовах руху, ускладнених щільними транспортними потоками і обмеженими можливостями маневрування. У таких умовах проведено суттєво меншу кількість досліджень. Вони не демонструють консенсусу щодо можливості застосування якогось одного референтного розподілу швидкості, але в той же час об’єднані тим, що вказують на тенденцію зміщення моди розподілу вліво у порівнянні з ситуацією вільного руху і зменшення середнього значення швидкості. Дана стаття презентує початкові кроки дослідження швидкості в складних міських умовах, коли наявний сильний вплив транспортних засобів один на одного, який можна спостерігати на ділянках доріг з однією доступною для руху смугою без можливості виконання маневрів обгону або випередження. У даному дослідженні з використанням формули для розрахунку середнього значення швидкості пачки автомобілів з одним повільним автомобілем виведена формула для розрахунку середньої швидкості пачки у ситуації з двома повільними автомобілями, які обмежують швидкість інших. Дані формули дозволяють поглибити знання про обмежуючі впливи щільного потоку на швидкості транспортних засобів та перший момент їх розподілу, а також наблизитись до отримання залежності для розрахунку середньої швидкості транспортного потоку при будь-якій кількості повільних автомобілів у ньому.

Ключові слова: швидкість руху, середня швидкість, транспортний потік, щільність потоку, смуга руху, умови руху, аналітичне моделювання, транспортна система.

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