APPROACH TO DETERMINE TRANSPORT DELAYS AT UNSIGNALIZED INTERSECTIONS

Olha Bieletska[1], Yevhen Liubyi[1], Serhii Ocheretenko[1], Dmitriy Muzylyov[2], Vitalii Ivanov[3,*], Ivan Pavlenko[4]

[1]Department of Transport Systems and Logistics, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine
[2]Department of Transport Technologies and Logistics Department, State Biotechnological University, Kharkiv, Ukraine
[3]Department of Manufacturing Engineering, Machines and Tools, Sumy State University, Sumy, Ukraine
[4]Department of Computational Mechanics named after Volodymyr Martsynkovskyy, Sumy State University, Sumy, Ukraine

*E-mail of the corresponding author: ivanov@tmvi.sumdu.edu.ua

Olha Bieletska 0000-0002-6256-8705,
Serhii Ocheretenko 0000-0001-5132-5647,
Vitalii Ivanov 0000-0003-0595-2660,
Yevhen Liubyi 0000-0003-0681-0920,
Dmitriy Muzylyov 0000-0002-8540-6987,
Ivan Pavlenko 0000-0002-6136-1040

Resume

This study proposes an approach to determine transport delays at unsignalized intersections, according to the theory of stationary Poisson flow and considering the priority of vehicle traffic in competing directions. The accuracy of the proposed approach was estimated by comparing the average values of delays of vehicles performing a left turn from a minor road and their actual values obtained as a result of processing data from field studies. The results of the accuracy evaluation at unsignalized intersections of non-equivalent roads indicate the obtained results' reliability, because the calculation error does not exceed 10%, as well as the possibility of using the developed approach in the process of transport planning and unsignalized intersections modelling.

Article info

Received 26 February 2023
Accepted 24 May 2023
Online 19 June 2023

Keywords:

transport systems
sustainable transportation
traffic control
traffic flow
sustainable cities
queuing system
field studies

Available online: https://doi.org/10.26552/com.C.2023.052

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

In recent years, a constantly rising level of motorization has caused vehicle congestion in Ukrainian cities' road networks, especially their centers. The central parts of cities are characterized by a high density of the road network, which provides a convenient approach to various places of attraction, disperses traffic and pedestrian flows in space and creates an extensive network of urban passenger traffic routes. However, the higher the density of the road network, the more often traffic and pedestrian flows cross and the non-optimal regulation negatively affects the economy. Negative effects in the last decades include a significant increase in road accidents, increased environmental pollution and more frequent traffic congestion. To reduce the impact of a rising level of motorization, it is necessary to develop the effective measures to improve the road safety in cities [1-4] avoiding risks [5-6].

The impact of transport on the environment is primarily determined by the downtime and delays. If the transport speed is high enough, the environmental impact is slight, particularly noise pollution. If the matter concerns the more frequent impact of traffic flows, we get more serious consequences, up to socio-economic issues - especially for cities. A delay indicates excess time consumed by a vehicle, compared to the control value. It is one of the most widely used criteria for assessing the quality of traffic management at intersections and is used in analyzing road investment [1].

It should also be understood that in most cases, transport delays are local and private problems that can be observed and investigated not only in terms of planning the development of an overall master plan of the territory but in the small areas, as well. Therefore, to reduce the vehicle delays on the road network, it is necessary to determine a rational traffic light cycle at regulated intersections and pay special attention to reducing vehicle delays at unsignalized intersections. There are controversial issues at such intersections that cause accidents with actual damages. Thus, the problem under consideration is technical and socio-economic, as mentioned above. However, considering the situations where a delay is temporary and, at the same time, the geometry and peculiarities of functioning transport delay areas are diversified, it is necessary to identify the possibilities of the technique for eliminating delays. This issue requires development of mathematical models for determining the transport delays at unsignalized intersections under different conditions.

2 Literature review

Determining the transport delays at intersections aims to estimate and develop effective measures to increase the road traffic efficiency. Methods for estimating the transport delays at unsignalized intersections can be divided into two groups: based on empirical studies and various analytical models. The methods of the first group allow to solve problems for selected local objects, but they are specified by sufficiently high accuracy. The advantages of the second group methods are operational versatility and flexibility, while the disadvantage is lower estimation accuracy. The analysis results of the most widely used approaches to determine delays at unsignalized intersections are presented below.

The basis for calculating the transport delays at unsignalized intersections in the post-Soviet space (e.g., Ukraine, Moldova, Georgia, etc.) are the results of Kremenets's studies, [7-8]. He considered that when crossing an unsignalized intersection with indicated main and minor roads, time losses occurred in the secondary direction with the lack of driver priority in traffic. The study [7] noted that the components of time losses, even with constant intensities at intersections, vary over wide ranges and differ for each vehicle. Considering the impact of many random factors, time losses are estimated by the average delay of one vehicle and are calculated with some assumptions. In general, the expression for determining the average delay can be written as follows [7]:

$$t_{\Delta H} = t_{\Delta H1} + t_{\Delta H2} + t_{\Delta H3}\,, \quad (1)$$

where:
$t_{\Delta H1}$ is the average waiting time for an acceptable interval, s,
$t_{\Delta H2}$ is the average delay associated with staying in a line of vehicles formed on the minor road, s,
$t_{\Delta H3}$ is the average delay related to braking the vehicle before the intersection, s

The following $t_{\Delta H1}$ is taken as equal to the ratio of the total duration of unacceptable intervals to the number of acceptable ones, [8]. It depends on the number of vehicles in a line before the main road. It can be determined using the fundamentals of the queuing theory, provided that the secondary direction of the traffic can be represented as a service line with an exponential distribution of arrival time requirements and service time. In turn, $t_{\Delta H3}$ is defined as the difference between the time required for braking before the intersection and the further vehicle acceleration and its passing time under free conditions.

With constant deceleration and acceleration while changing the speed and with an exponential distribution of the probability of time intervals occurrence between cars on the main road, the average delay of a vehicle in this direction of the minor road can be defined as [8]:

$$t_{\Delta H} = \frac{e^{N_{mn} t_{bd}} - N_{mn} t_{bd} - 1}{N_{mn} - N_{mr}(e^{\lambda t_{bd}} - N_{mn} t_{bd} - 1)} + \\ + \frac{V_v}{7.2}\left(\frac{1}{a_d} + \frac{1}{a_a}\right), \quad (2)$$

where:
N_{nm} is the main road intensity in both directions, veh./s,
N_{mr} is the average intensity per one lane of the minor road in the relevant direction, veh./s, t_{bd} is a boundary interval, s,
a_d, a_a is deceleration and acceleration of the vehicle, m/s^2,
V_v is the vehicle speed under free conditions, m/s

The average vehicle delay at an unsignalized intersection is defined as the average value of delays for all directions of the minor road [8]:

$$t_{\Delta Hn} = \frac{\sum_1^n t_{\Delta H} N_j}{\sum_1^n N_j}\,, \quad (3)$$

where:
N_j is the traffic intensity on the j-th direction of the minor road, veh./s,
n is the number of directions on the minor road.

By analogy with the Kremenets' model, the authors of [9] have developed a model of the total transport delay for all possible directions at an X-shaped unsignalized intersection that can be calculated as:

$$T = \sum_{i=1}^{n} t_{wi} + n(t_{ul} d_l + t_{ur} d_r + t_{us} d_s) + nC\,, \quad (4)$$

where:
t_{wi} is the time spent for the i-th vehicle waiting in a line, s,
n is the vehicles number per time unit, veh.,
t_{ul}, t_{ur}, t_{us} is the average time for performing a left turn, right turn, moving straight, respectively, s,
d_l, d_r, d_s is the share of vehicles moving left, right and straight, respectively,
C is the time for braking and acceleration, s

It should be noted that the presented model for calculating the total transport delays is more applicable for the economic assessment of traffic management efficiency than the average delay, which mainly specifies the service quality of a particular vehicle [9].

The authors of [10] proposed determining the vehicle delays at an unsignalized intersection based on the traffic flow field studies. The authors have developed a software package that allows to calculate the total delay time, average delay time, the length of a vehicle line and the number of vehicles that arrived. It should be noted that the article's content does not clarify the models, methods and algorithms incorporated in the software shell for calculating transport delays at unsignalized intersections.

The foreign theory (primarily the United States, Australia, and Eastern European countries) of transport regulation focuses on estimating delays and lengths of queues. Transport delays and the vehicle queue length are the main indicators introducing the concept of level of service (LOS) and used in assessing the adequacy of road lane length before the intersection, fuel consumption and exhaust emissions. Today's delay models used for intersections are generally described from deterministic and stochastic points of view to reflect both the constancy and randomness of traffic flow properties [11].

Tanner's approach is one of the first attempts to calculate delays at unsignalized intersections for vehicles moving in a secondary direction [12]. His approach is based on the following issues: vehicles arrive at the intersection randomly; the main traffic flow creates an alternating updating process with the time spent on crossing the intersection by a group (bunch) of vehicles, while the time intervals between the groups (bunches) of vehicles are distributed exponentially; the vehicles of secondary direction cross the main road at regular intervals during the presented interval, which is limited by the arrival time of the next group (bunch) of vehicles.

In turn, Kimber et al. [13-14] proposed an approach to estimate delays at an unsignalized intersection and predicted the length. Authors have analyzed the correlation between the delay and traffic flow intensity for minor roads.

In the paper [15], Troutbeck proposed to consider the following parameters in the model for determining vehicle delays at unsignalized intersections: an average delay with a little secondary flow; a degree of the secondary flow saturation; an indicator that quantifies the effect of minor flow queuing.

For intersections with the traffic priority, Heidemann [16] presented a formula for calculating transport delays on a secondary road as a saturation function.

For example, in the two-way stop-controlled intersections, the authors of [17] divided the total transport delay into queuing and service delays. In this case, the queue delay is determined by the time from the arrival of the vehicle at the end of the queue to its approach to the stop line. In turn, a service delay is a time between the vehicle's arrival at the stop line and its departure.

Considering the results of driver behavior observations, Horowitz [18] improved the queue-waiting model for all-way stop-controlled intersections. The authors of [19] developed a probabilistic model of delays representing the driver's behavior when deciding on manoeuvring that applies to describing a right turn at a T-junction.

In the study [20], three existing models of delays at unsignalized intersections were compared: the HCM 94 model, the Akcelik-Troutbeck model and the SIDRA 5 model. The differences in the calculation results are presented in the paper and these models are improved based on the simulation results. The total delay at unsignalized junction with relative priority under [21] has four components: delay to deceleration (braking); queue delay; delay in waiting for the possibility to turn (waiting time for a break in the main flow); acceleration delay (running-away).

The authors of [22] propose models for estimating queuing delays and service delays at the two-way stop-controlled intersections, where the service delay is calculated as a function of the degree of competing flows. In turn, the average value of the service delay and its variance are used as input parameters for the delay estimation.

Kaysi and Alam [23] used a simple simulation model to study the traffic service quality at unsignalized intersections with priorities. The developed simulation model reflected drivers' behavior and the traffic flow interaction process. The authors concluded that the basic models considering the peculiarities of driver's behavior (driver learning and impatience, aggressive driver attitudes) and the interaction of traffic flows differ from the simple perception of critical gaps at unsignalized intersections.

In most cases, to clarify drivers' behavior characteristics on highways, it is necessary to conduct time-consuming real-field investigations (video surveillance, survey) with subsequent processing, verification and calibration of obtained results. The question of studying drivers' behavior at both signalized and unsignalized intersections has been given numerous research papers. The main issues that are considered in these scientific publications are the following: studies of an acceptable critical interval for various maneuvers implementation at intersections [24-25]; cross-roads capacity studies [26]; studying reasons for making false decisions when crossing intersections [27], etc. It should be understood that there are many examples when drivers of conflicting flows at unsignalized intersections cooperate. An example of such cooperation is the provision by main road drivers of ways right for the secondary road drivers in various congestion (critical) situations. Such cooperation is a positive from the viewpoint of secondary flows since delays at intersections are reduced for them. On the other hand, even a slight speed decrease in driving in main directions reduces intersection throughput. The best way to define truth in this matter may be using software complexes of traffic modelling.

Based on the simulation modelling results by AWSIM, the authors of [28] developed empirical models for estimating delays and queue lengths at all-way-stop-controlled intersections. A better correlation than exponential form models characterizes the proposed generalized form of the delay model. In the paper [29], Luttinen studied the relationship between the delay and a traffic on minor roads.

Cvitanic et al. [30] developed a new model for estimating the total delay at unsignalized intersections using the queuing theory. Brilon in [31] tried to test methods for calculating delays based on the queuing theory. The author developed a technique using Markov chains to obtain numerically accurate results. Stochastic modelling and empirically obtained data were used to assess the accuracy of obtained approximating models. The author has developed equations that can be used to calculate the value of delays at unsignalized intersections under the free traffic conditions.

Chandra et al. [32] developed a service delay model and conducted a microscopic analysis of delay in mixed traffic. The study revealed a significant impact of the share of heavy vehicles in the conflicting flow on the value of service delay.

The Transportation Research Board presented a procedure for estimating transport delays at unsignalized intersections in HCM [33]. In this case, delays are estimated separately for each secondary direction flow and left-turning flows of the main direction. According to this study, a delay is the time from when a vehicle stops at the end of the queue to when the vehicle leaves the stop line. A similar approach is used in the Malaysian HCM [33].

$$D = \frac{3600}{C_{m,x}} + 900T\left[\frac{V_x}{C_{m,x}} - 1 + \sqrt{\left(\frac{V_x}{C_{m,x}} - 1\right)^2 + \frac{\left(\frac{3600}{C_{m,x}}\right)\left(\frac{V_x}{C_{m,x}}\right)}{450T}}\right] + 5, \quad (5)$$

where: D total delay, s/veh.,
V_x - flow speed for traffic direction x, veh./h,
$C_{m,x}$ - throughput of direction x, veh./h,
T - period of analysis, h (T = 0.25 for a 15-min period).

In turn, the average delay for the secondary direction is estimated as a traffic capacity function and a saturation degree, where the capacity is expressed as a function of the degree of the conflicting flow.

The author of [34] proposed a new approach to determine delays at unsignalized intersections that allows one to estimate the change in the average delay depending on the previous queue and variable throughput. The advantage of this approach is the possibility of obtaining sufficiently accurate results for an extended period, for example, a day.

Another group includes approaches to determine delays at unsignalized intersections based on applying micro-modelling and regression dependencies. Particular attention should be paid to Caliendo's work [35]; the presented models of the delay time, downtime and peak queue were developed using AIMSUN and can be used for decision-making by transport infrastructure designers and road operators.

One of the recent studies should be emphasized [36], where modelling the transport delays at unsignalized intersections, using an artificial neural network was carried out using Malaysia as an example. Obtained results showed that the neural network, could predict the delay at unsignalized intersections more accurately than the approaches presented in the Malaysian HCM and HCM 2010. The accuracy of the developed models was estimated based on the field study results at three intersections with different configurations.

In addition to traffic flows, the transport delays amount within a coverage area of unsignalized intersections is impacted by pedestrian crossing presence. Pedestrian flows create additional obstacles to traffic and can be accident reasons since it is extremely difficult consider the pedestrians' behavior by drivers driving through the unsignalized intersections. The study of accounting challenges for pedestrians and drivers' behavior within unsignalized intersections is described in many scientific publications. Turner et al. [37] evaluated various engineering measures that could be used to improve pedestrian safety within unsignalized intersections and formulated recommendations on the feasibility of using them at various kinds of unsignalized intersections. In the investigation [38], a large volume of real-field observations of transport and pedestrian flow interaction, within unsignalized intersections, were carried out. The obtained results are more aimed at accounting for pedestrian behavior for delays in mixed traffic conditions. Moreno et al. [39] designed a model predicting the pedestrian behavior at an unsignalized intersection at different locations around it. The results show that the model can provide crossing intentions within a 3-second time window. In addition to the above, a separate component of traffic participants can be considered categories of persons with special needs, which include blind, elderly, children and people with limited mobility, which significantly affect the traffic conditions and efficiency at unsignalized intersections. For such person categories, engineering structures are developed and information tools are introduced based on smart technologies that increase the driving safety on street and road networks. Information to these persons about the current traffic functioning can be obtained through the corresponding applications in smartphones, as well as smart bracelets [40-41].

It should be noted that most of the analyzed studies were performed in countries where the traffic management at unsignalized intersections, their geometric parameters, drivers' behavior and traffic rules' abidance are significantly different from Ukrainian realities. Almost all the considered approaches for determining the transport delays refer to unsignalized intersections of two types: two-way stop-controlled and all-way stop-controlled, that indicates development of models for determining delays at unsignalized intersections, with an organization that differs from the worldwide traffic, for example, unsignalized intersections of equivalent roads are often found on the territory of Ukraine. The priority in developing a new approach should be given to analytical modelling, allowing one to obtain universal models, which will be possible at unsignalized intersections of any type. The developed approach will be based on the principles of the simplest flow, which will allow for taking into account the priority of vehicles passing in conflicting directions.

3 Purpose and objectives of the study

A general scientific challenge addressed in this study is improving the road traffic efficiency in urban areas. Herewith, the study object is traffic flows through unsignalized intersections. This problem cannot be considered as well-studied, confirmed by numerous research and design works analyzed in this field. In such cases, various approaches are used to determine the transport delays - from analytical models to applying specialized software, for example, VISSIM or others [42-43]. It should be understood that the software tools for modelling the transport flows allow specialists to obtain an important data set for analyzing and predicting traffic, including the transport delays. However, information completeness received ensures applying only the commercial versions of such a software, which is not always accessible to Ukrainian transportation planning and modelling experts because their costs are high. The main focus of the paper is on designing analytical models for determining transport delays at unsignalized intersections.The main focus of the paper is on designing analytical models for determining transport delays at unsignalized intersections The main model advantage is the possibility to accurately assess received calculations based on empirical results of traffic observations at these road infrastructure objects.

That is why the main focus of the paper is to create the main paper aims to create mathematical models for calculating transport delays at various types of unsignalized intersections: with equivalent and unequal traffic directions. Therefore, the priority study objectives are the following:

- Theoretical aspects are designing analytical models of average transport delays at unsignalized intersections with different priorities;
- Experimental studies conduct and process the traffic flow video surveillance results at unsignalized intersections. The proposed approach assesses the accuracy of results of calculating the transport delays according to developed analytical models based on data obtained during the empirical observations.

It should also be noted that the proposed models are being created for the first time.

4 Study materials on vehicle delays at unsignalized intersections development of analytical models of vehicle delays at unsignalized intersections

4.1 Unsignalized intersection with equivalent directions

Suppose that λ_1, λ_2 are the intensities of vehicles approaching an unsignalized intersection from competing directions, s^{-1}, Δ_1, Δ_2 - time to pass the intersection by vehicles moving in competing directions time to pass the intersection by vehicles moving in competing directions, s Then congestion of the directions will be determined as:

- for direction 1

$$\rho_1 = \lambda_1 \Delta_1 , \tag{6}$$

- for direction 2

$$\rho_2 = \lambda_2 \Delta_2 . \tag{7}$$

In turn, the average duration of the loaded period for each direction is determined as follows:

- for direction 1

$$P_1 = \frac{\Delta_1}{1 - \rho_1} , \tag{8}$$

- for direction 2

$$P_2 = \frac{\Delta_2}{1 - \rho_2} . \tag{9}$$

In this case, the total congestion of both directions of the equivalent unsignalized intersection will be determined as the sum of Equations (6) and (7)

$$\rho = \rho_1 + \rho_2 \tag{10}$$

and the total intensity of vehicles approaching to an unsignalized intersection of equivalent directions is:

$$\lambda = \lambda_1 + \lambda_2 . \tag{11}$$

Using Equations (10) and (11), will make it possible to determine the average passing time of the dynamic dimensions of a vehicle across an equivalent unsignalized intersection in Equation (12) and the average duration of the loaded period when vehicles cross a two-way intersection in Equation (13):

$$\Delta = \frac{\rho}{\lambda} , \tag{12}$$

$$P = \frac{\Delta}{1-\rho}. \tag{13}$$

If the total intensity of vehicles approaching to an unsignalized intersection of equivalent directions is known, it becomes possible to determine the average free time If the total intensity of vehicles approaching to an unsignalized intersection of equivalent directions is known, it becomes possible to determine the average free time:

$$T_0 = \frac{1}{\lambda}. \tag{14}$$

The average passing time of vehicles from each of the equivalent directions of an unsignalized intersection is determined based on the values of the average duration of the loaded period for vehicles crossing the intersection:

- for direction 1

$$T_1 = \frac{P_1}{P_1 + P_2} P, \tag{15}$$

- for direction 2

$$T_2 = \frac{P2}{P_1 + P_2} P. \tag{16}$$

Here is used an assumption of the stationary flow of vehicles approaching to an unsignalized intersection. It follows that a vehicle arriving at an unsignalized intersection can get into three probable states:
{0} - free intersection;
{1} - the intersection is loaded with vehicles moving from the first direction;
{2} - the intersection is loaded with vehicles moving from the second direction.

Taking into account this fact, the stationary probability of an arriving vehicle getting into the corresponding state will be determined as:

$$p_i = \frac{T_i}{T_0 + T_1 + T_2}. \tag{17}$$

Given the assumption stated in the work, as well as taking into account the equation for calculating the average waiting time of Zilbertal [44], the conditional average delay time of vehicles of the i-th direction got into the delay state can be defined from Equation (18):

$$T_i^O = \frac{B_i}{2T_i}, i = 1.2, \tag{18}$$

where:
B_i is the second moment of the loaded period of passing the i-th direction of an unsignalized intersection (the mathematical expectation of a squared random variable).

Within the limits of this work, the second moment of the loaded period of passing in each direction is calculated as:

- for direction 1

$$B_1 = \frac{\Delta_1^2}{(1-\rho_1)^3}, \tag{19}$$

- for direction 2

$$B_2 = \frac{\Delta_2^2}{(1-\rho_2)^3}. \tag{20}$$

The average vehicle delay for each equivalent direction of an unsignalized intersection is calculated based on Equations (17) and (18):

- for direction 1
-

$$W_1 = p_2 T_2^O = p_2 \frac{B_2}{2T_2} = \frac{B_2}{2(T_0 + T_1 + T_2)} = = \frac{\frac{\Delta_2^2}{(1-\rho_2)^3}}{2(T_0 + T_1 + T_2)}, \tag{21}$$

- for direction 2

$$W_2 = p_1 T_1^O = p_1 \frac{B_1}{2T_1} = \frac{B_1}{2(T_0 + T_1 + T_2)} = = \frac{\frac{\Delta_1^2}{(1-\rho_1)^3}}{2(T_0 + T_1 + T_2)}. \tag{22}$$

In turn, the average vehicle delay at an unsignalized intersection of equivalent directions can be calculated as:

$$W = \frac{\lambda_1 W_1 + \lambda_2 W_2}{\lambda_1 + \lambda_2}. \tag{23}$$

4.2 Unsignalized intersection with non-equivalent directions (relative priority)

The first direction has a relative priority compared to the second direction (allowing them to complete the movement of a vehicle arriving at the intersection from the second direction).

The approach to determining the vehicle delays at an unsignalized intersection with non-equivalent directions and the assumption that the flow of vehicles approaching the intersection is stationary is identical as for the case 4.1. The main difference is the consideration of vehicles manoeuvring at unsignalized intersections with relative priority. So, the average delay for vehicles of the main (first) direction is calculated as follows:

$$W_1 = \frac{\lambda_1 \Delta_1^2}{2(1-\rho_1)}. \tag{24}$$

The average delay of the secondary (second) direction vehicles is calculated as a matter of necessity for the mandatory passing of vehicles moving along the main (first) direction:

$$W_2 = \frac{\lambda_1 \Delta_1^2 + \lambda_2 \Delta_2^2}{2(1-\rho_1)(1-\rho_1-\rho_2)}. \tag{25}$$

Additionally, the average vehicle delay at an unsignalized intersection with non-equivalent directions is calculated similarly to Equation (23).

5 The field study results of transport delays at unsignalized intersections

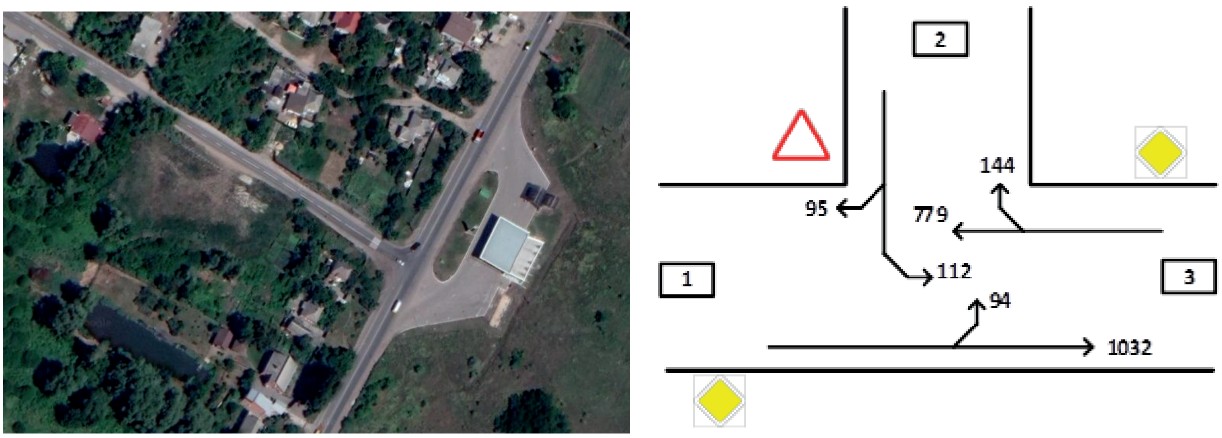
The developed approach for determining delays at unsignalized intersections was tested on the example of two T-junctions with a relative priority (unsignalized intersection with non-equivalent directions), where the delay was determined for vehicles performing a left turn from a minor road. To obtain the initial data (traffic intensity in directions, passing the time of the dynamic dimensions, the actual time of vehicle delay) for calculating vehicle delays, video monitoring of traffic flows was carried out at unsignalized intersections in Kharkiv: Les Serdyuk St. -Novo-Solonetskaya St. and Saltovskoye Shosse St. - 7th Gvardeyska Army St.

Video monitoring was organized in such a way as to have the possibility to record vehicle movement in all directions. Current traffic monitoring was carried out in the morning peak period (7.30 - 8.30 a.m.) on weekdays (from Monday up to and including Friday). As a result of processing the field study materials of traffic at selected intersections, the average values of traffic intensity for the morning peak period on weekdays have been defined. The results are shown in Figure 1.

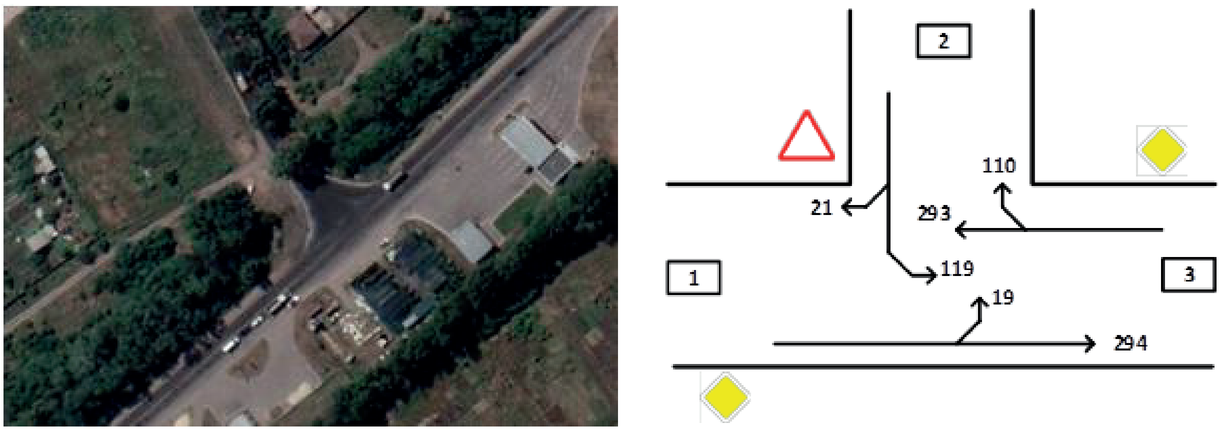
Based on the results of traffic studies at selected intersections, the average values of the actual vehicle delay, when performing the left turn from a minor road, are determined: it is 37.9 s for the intersection of Les Serdyuk St. -Novo-Solonetskaya St., it is 27.3 s for the intersection of Saltovskoye Shosse St. - 7th Gvardeyska Army St.

Based on the obtained values of the traffic flow intensity and passing time of vehicle dynamic dimensions, the delay values for vehicles performing the left turn from a minor road are calculated using Equations (6) - (20), (24), (25) (direction 2-3, Figure 1). Thus, the estimated delay values for vehicles performing a left turn from a minor road are 34.2 s for the intersection of Les Serdyuk St. -Novo-Solonetskaya St. and 24.8 s for the intersection of Saltovskoye Shosse St. - 7th Gvardeyska Army St.

Estimating accuracy of calculation for average values of transport delays, defined with designed analytical models is carried out by their comparison to empirical delay values of vehicles performing a maneuver to turn left from the secondary road. For both unsignalized intersections selected as objects of experimental studies,



a



b

***Figure 1** The cartogram of vehicle traffic intensity: a - the intersection of Les Serdyuk St. -Novo-Solonetskaya St. b - the intersection of Saltovskoye Shosse St. - 7th Gvardeyska Army St.*

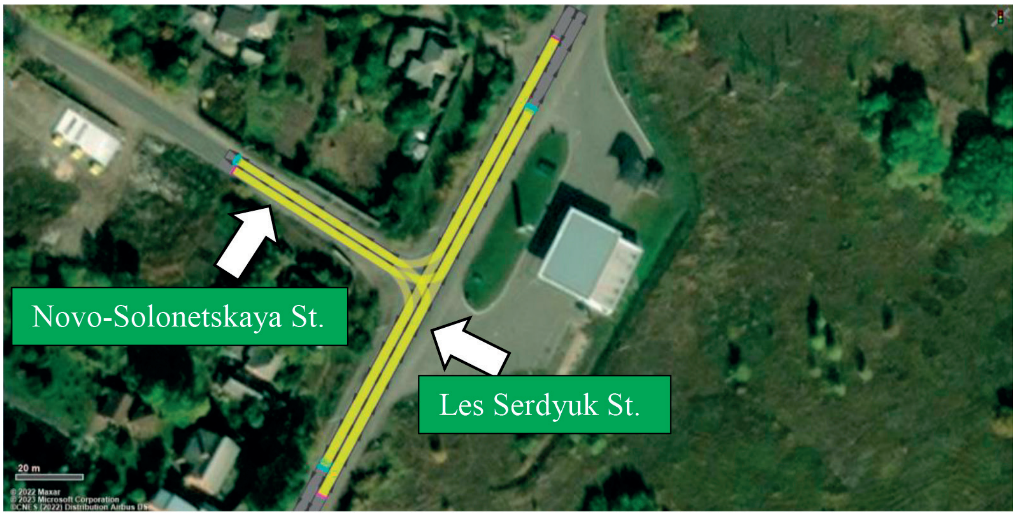


Figure 2 *Visualization of Vehicle Routes at Les Serdyuk St. Intersection - Novo-Solonetskaya St. using VISSIM*

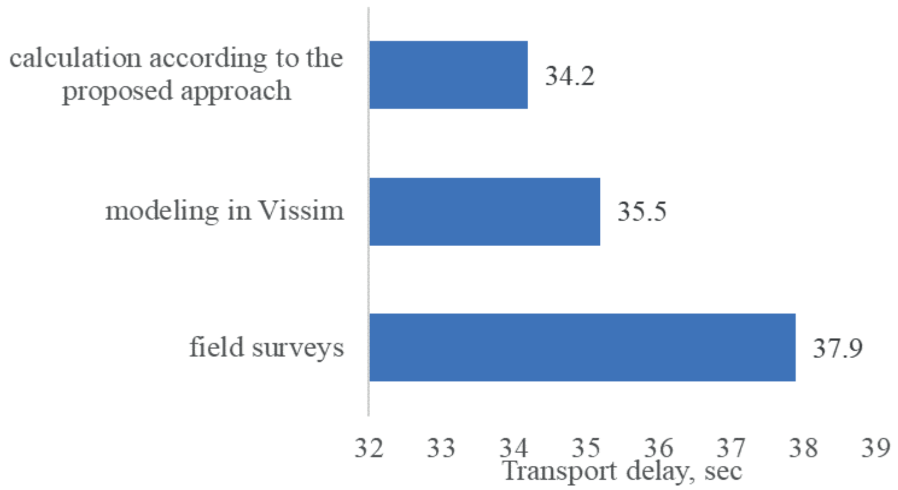


Figure 3 *Results comparison of calculating vehicle delays turning left from the minor road to the main traffic direction at unsignalized intersections Les Serdyuk St. - Novo-Solonetskaya St.*

the average relative deviation does not exceed 10%: for the intersection Les Serdyuk St. -Novo-Solonetskaya St. - 9.8%; for the intersection Saltovskoye Shosse St. - 7th Gvardeyska Army St. - 9.2%. The obtained results indicate a relatively high accuracy of modelling the transport delays at unsignalized intersections using designed analytical models and the possibilities of their application in practice.

6 Discussing the study results of transport delays at unsignalized intersections

Currently, the main way to represent the traffic flow is through traffic simulation on streets and highways. In this study, VISSIM was used to evaluate the proposed analytical models for determining delays at unsignalized intersections and to assess the effect of increasing the traffic intensity on main and minor roads on its value. For the unsignalized intersection Les Serdyuk St. - Novo-Solonetskaya St., a simulated traffic model was designed according to the following data (Figure 2):

- traffic flow intensity - average weekdays peak values are considered (Figure 1);
- traffic composition: on the main road (Les Serdyuk St.) - cars 94%, trucks (lorries) 5%, buses 1%; by minor road (Novo-Solonetskaya St.) - cars 98%, trucks (lorries) 2%;
- permitted speed - up to 50 km/h;
- overall vehicle dimensions - cars: length up to 5 m; width up to 2.1 m; trucks: length up to 11 m; width up to 2.5 m; buses: length up to 12 m, width up to 2.5 m.

According to the simulation results, the average delay values of vehicles turning left from the minor road to the main road and general delays at the intersection were set. The results confirm the preliminary conclusion on a sufficiently high accuracy of delay calculation based on the proposed analytical models (Figure 3). It should also be noted that the deviation of the results

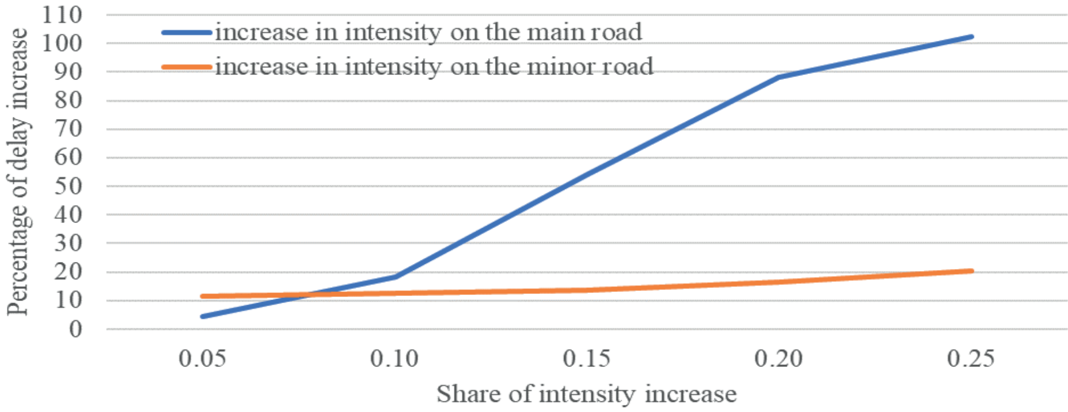


Figure 4 *Effect characterization of traffic intensity change on average vehicle delays turning left from Novo-Solonetskaya St. to Les Serdyuk St.*

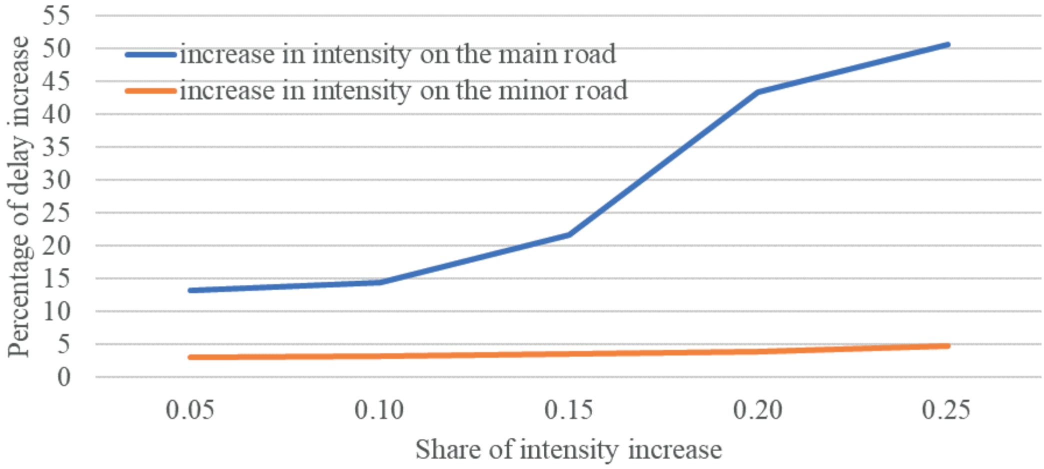


Figure 5 *Effect characterization of traffic intensity change on values of total vehicle delays at unsignalized intersections Les Serdyuk St. - Novo-Solonetskaya St.*

in calculating delay average values of vehicles turning left from the minor road to the main traffic direction obtained using Vissim (35.2 s) from their empirical value (37.9 s) is about 7%. This percentage characterizes the obtained transport model as suitable for the initial assessment of traffic terms at unsignalized intersections and for providing a simulation experiment.

A good opportunity is having a simulation model at one's disposal. It helps to study the nature of impact of the amount traffic intensity changing in different directions on delay values at selected unsignalized intersections. This study analyzed the effect in traffic volumes changes (increase in intensity from 5% to 25%) separately on the main and secondary roads on vehicle delays turning left from the minor road to the main one (Figure 4) and total delays (Figure 5).

The obtained data indicate a significant impact on delay values in traffic intensity in the main direction (main road). This influence is especially noticeable with an increase in intensity on the main road by more than 10-15%. With a further increase in intensity, the appearance of congestion is observed.

It should be noted that factors affecting the transport delay value quantity at unsignalized intersections and which researchers are actively using are the next: intersection geometry, traffic intensity, dynamic vehicle characteristics, traffic composition (most often represented through freight transport share), pedestrian traffic intensity (if pedestrian crossings are within the intersection), as well as drivers' behavior. Analytical models, based on the proposed approach for determining delays at unsignalized intersections, consider most of the above factors. They can be used to preliminary assess the traffic conditions at unsignalized intersections.

It should be added that when calculating delays from designed analytical models, empirical data on passage time of intersection vehicles were used (averages: the main road is 2 s; the minor road is 8 s), characterizing the specific intersections and specific time periods during which it was recorded, which may affect calculation accuracy of the transport delays under other conditions and other unsignalized intersections. To improve the calculation accuracy of transport delays according to designed analytical models, it is necessary to consider the stochastic characteristics of parameters for process variables during appropriate maneuvers implementation (mergers, crossing) at unsignalized intersections. With this parameter, a critical time interval can be chosen between cars (critical gap), which can be determined by several approaches [24, 45-49].

Given the traffic management similarity at unsignalized intersections and exits from adjacent areas to city highways, it is advisable to consider the possibility of adapting designed analytical models for determining the transport delays at entrances (exits) from such urban road network elements.

7 Conclusions

The analysis results of current methods for estimating transport delays at unsignalized intersections indicate the limited capabilities of models based on empirical data and a relatively low accuracy of calculations using analytical models.

The developed approach to determine delays at unsignalized intersections is based on the principles of a queuing system, considering the priority of traffic in competing directions.

The findings of evaluating the accuracy of calculating the delays of vehicles performing a left turn from a minor road using developed analytical models, at selected unsignalized intersections, indicate their reliability and objectivity (divergence is not higher than 10 %), as well as the possibility of their use for preliminary assessment of traffic conditions at unsignalized intersections. The traffic simulation results in Vissim confirm the high accuracy of the delay calculation using the proposed approach.

Improvement of the proposed analytical models is possible by considering probabilistic components in them, when drivers perform appropriate maneuvers on main and minor roads at acceptable limit intervals (critical gap).

It is necessary to conduct additional real-field traffic observations to obtain a complete and accurate assessment of actual vehicle delays at selected intersections. It allows for obtaining a larger data array, determining the trip times of dynamic vehicle dimensions of different types while fulfilling various maneuvers in all the possible traffic directions.

Acknowledgment

The research was partially carried out within the project “Digital twin framework for cellular manufacturing systems: design and simulation” of The NAWA Ulam Programme (grant number BPN/ULM/2022/1/00045). The research was partially supported by the International Association for Technological Development and Innovations.

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.

References

[1] TAPIO LUTTINEN, R. *Capacity and level of service at Finnish unsignalized intersections*. Finnra Reports 1/2004, Helsinki: Finnish Road Administration, Traffic Engineering, 2004. ISBN 951-803-180-0, ISSN 1457-9871.
[2] AHMED, A., SADULLAH, A. F. M., YAHYA, A. S. Analysis of the effect of directional traffic volume and mix on road traffic crashes at three-legged unsignalized intersections. *Transportation Engineering* [online]. 2021, **3**, 100052. ISSN 2666-691X. Available from: https://doi.org/10.1016/j.treng.2021.100052
[3] ZHANG, X., YAN, X. Predicting collision cases at unsignalized intersections using EEG metrics and driving simulator platform. *Accident Analysis and Prevention* [online]. 2023, **180**, 106910. ISSN 0001-4575. Available from: https://doi.org/10.1016/j.aap.2022.106910
[4] JENA, S., PATRO, S., DUTTA, M., BHUYAN, P. K. Assessment of service quality at unsignalized intersections using traffic simulation and computational intelligence. *Transportation Letters. The International Journal of Transportation Research* [online]. 2022, **14**(4), p. 365-377. ISSN 1942-7867, eISSN 1942-7875. Available from: https://doi.org/10.1080/19427867.2020.1868179
[5] POHUDINA, O., MORIKOVA, A., HAIDABRUS, B., KIYKO, S., DRUZHININ, E. Comparison of metoheuristic search methods for the task of choosing a rational set of measures to risks' respond. In: *Integrated computer technologies in mechanical engineering - 2020. ICTM 2020* [online]. NECHYPORUK, M., PAVLIKOV, V., KRITSKIY, D. (eds.). Lecture Notes in Networks and Systems. Vol. 188. Cham: Springer, 2021. ISBN 978-3-030-66716-0, eISBN 978-3-030-66717-7, p. 657-666. Available from: https://doi.org/10.1007/978-3-030-66717-7_56
[6] KIYKO, S. G., DRUZHININ, E. A., KOBA, S. A., HAIDABRUS, B. V. A mathematical background for information technology of project's processes integration taking into account risk factors. *Metallurgical and Mining Industry*. 2014, **6**(3), p. 66-70. ISSN 2076-0507.
[7] KREMENETS, Y., PECHERSKIY, M. *Technical means of road traffic control*/*Tekhnicheskie sredstva regulirovaniya dorozhnogo dvizheniya* (in Russian). Moskow: Transport, 1981.

[8] KREMENETS, Y., PECHERSKIY, M., AFANASEV, M. *Technical means of road traffic management/ Tekhnicheskie sredstva organizatsii dorozhnogo dvizheniya* (in Russian). Moskow: Akademkniga, 2005. ISBN 5-94628-111-9.

[9] KUNITSYA, O., ZAKABLUK, O. Determination of the real traffic delay at unsignalized intersections in one level/ Viznachennya diysnoi transportnoi zatrimki na neregulovanikh perekhrestyakh v odnomu rivni (in Ukrainian). *Bulletin of Kharkov National Automobile and Highway University/Visti Avtomobilno-Dorozhnogo Universitetu*. 2009, **2**(9), p. 46-51. ISNN 1990-7796.

[10] UDZHUKHU, A., LABUTIN, A. Application of methods for calculation of traffic delays in practice/Primenenie metodik rascheta transportnykh zaderzhek na praktike (in Ukrainian). *Bulletin of the Donetsk Academy of Automobile Transport / Vestnik Donetskoy Akademii Avtomobilnogo Transporta*. 2018, **3**, p. 34-40. ISSN 2219-8180, eISSN 2518-7899.

[11] LEVASHEV, A., MIKHAYLOV, A., GOLOVNYKH, I. *Designing regulated intersections/Proektirovanie reguliruemykh peresecheniy* (in Russian). Irkutsk: IrGTU, 2007. ISBN 978-5-8038-0458-1.

[12] TANNER, J. A Theoretical analysis of delays at an uncontrolled intersection. *Biometrika* [online]. 1962, **49**(1/2), p. 163-170. eISSN 1464-3510. Available from: https://doi:10.1093/biomet/49.1-2.163

[13] KIMBER, R., HOLLIS, E., MARLOW, M. Flow/delay relationships for major/minor priority junctions. *Traffic Engineering and Control*. 1977, **18**(11), p. 516-519. ISSN 0041-0683.

[14] KIMBER, R., HOLLIS, E. *Traffic queues and delays at road junctions*. Wokingham, Berkshire United Kingdom; Transport and Road Research Laboratory, 1979. ISSN 0266-7045.

[15] TROUTBECK, R. J. Average delay at an unsignalized intersection with two major streams each having a dichotomized headway distribution. *Transportation Science* [online]. 1986, **20**(4), p. 272-286. ISSN 0041-1655, eISSN 1526-5447. Available from: https://doi: 10.1287/trsc.20.4.272. 1986

[16] HEIDEMANN, D. Queue length and waiting-time distributions at priority intersections. *Transportation Research Part B: Methodological* [online]. 1991, **25**(4), p. 163-174. ISSN 0191-2615, eISSN 1879-2367. Available from: https://doi.org/10.1016/0191-2615(91)90001-Y

[17] KYTE, M., CLEMON, C., MAHFOOD, N., LALL, B. K., KHIST, C. J. Capacity and delay characteristics of two-way stop-controlled intersections. *Transportation Research Record* [online]. 1991, **1320**, p. 160-167. ISSN 0361-1981. Available from: https://onlinepubs.trb.org/Onlinepubs/trr/1991/1320/1320-020.pdf

[18] HOROWITZ, A. J. Revised queueing model of delay at all-way stop-controlled intersections. *Transportation Research Record* [online]. 1993, **1398**, p. 49-53. ISSN 0361-1981. Available from: https://onlinepubs.trb.org/Onlinepubs/trr/1993/1398/1398-007.pdf

[19] MADANAT, S. M., CASSIDY, M. J., WANG, M. H. Probabilistic delay model at stop-controlled intersection. *Journal of Transportation Engineering* [online]. 1994, **120**(1), p. 21-36. ISSN 0733-947X, eISSN 1943-5436. Available from: https://doi.org/10.1061/(ASCE)0733-947X(1994)120:1(21)

[20] AKCELIK, R., CHRISTENSEN, B., CHUNG, E. A comparison of three delay models for sign-controlled intersections. In: 3rd International Symposium on Highway Capacity: proceedings. Vol. 1. 1998. ISBN 8774919059, p. 35-56.

[21] NIELSEN, O. A., FREDERIKSEN, R. D., SIMONSEN, N. Stochastic user equilibrium traffic assignment with turn-delays in intersections. *International Transactions in Operational Research* [online]. 1998, **5**(6), p. 555-568. eISSN 1475-3995. Available from: https://doi.org/10.1111/j.1475-3995.1998.tb00137.x

[22] AL-OMARI, B., BENEKOHAL, R. F. Hybrid delay models for unsaturated two-way stop-controlled intersections. *Journal of Transportation Engineering* [online]. 1999, **125**(4), p. 291-296. ISSN 0733-947X, eISSN 1943-5436. Available from: https://doi.org/10.1061/(ASCE)0733-947X(1999)125:4(291)

[23] KAYSI, I., ALAM, G. Driver behavior and traffic stream interactions at unsignalized intersections. *Journal of Transportation Engineering* [online]. 2000, **126**(6), p. 498-505. ISSN 0733-947X, eISSN 1943-5436. Available from: https://doi.org/10.1061/(ASCE)0733-947X(2000)126:6(498)

[24] LIUBYI, Y., BIELETSKA, O. Experimental research of traffic delays at the adjacent territory exit. *Advances in Mechanical Engineering and Transport* [online]. 2021, **1**(16), p. 106-116. ISSN 2313-5425. Available from: https://doi.org/10.36910/automash.v1i16.513

[25] MUSTAFAYEV H., GETSOVICH, E. Experimental investigation of the driver's behavior at uncontrolled intersections in cross traffic flows. *Automobile Transport* [online]. 2018, **48**, p. 98-102. ISSN 2219-8342, eISSN 2309-981X. Available from: https://doi.org/10.30977/AT.2219-8342.2018.42.0.98

[26] ADVANI, M., GUPTA, N. J., VELMURUGAN, S., MADHU, E., CHANDRA, S. Defining and analyzing forceful gap behavior at unsignalized intersections. *Transportation Research Record: Journal of the Transportation Research Board* [online]. 2020, **2674**(8), p. 420-428. ISSN 0361-1981, eISSN 2169-4052. Available from: https://doi.org/10.1177/0361198120925258

[27] ARAMITA, B. A., MAIMUNAH, S., PURWANTO, E., TOHOM, F. Evaluation of driver behavior when crossing unsignalized intersection from minor road to major road. *RSF Conference Series: Engineering and Technology*

[online]. 2022, **2**(2), p. 109-118. ISSN 2809-6878, eISSN 2809-6843. Available from: https://doi.org/10.31098/cset.v2i2.564

[28] TIAN, Z. Z., KYTE, M., VANDEHEY, M., KITTELSON, W., ROBINSON, B. Simulation-based study of traffic operation characteristics at all-way-stop-controlled intersections. *Transportation Research Record: Journal of the Transportation Research Board* [online]. 2001, **1776**(1), p. 75-81. ISSN 0361-1981, eISSN 2169-4052. Available from: https://doi.org/10.3141/1776-10

[29] LUTTINEN, R. T. Movement capacity at two-way stop-controlled intersections. *Transportation Research Record: Journal of the Transportation Research Board* [online]. 2004, **1883**(1), p. 198-202. ISSN 0361-1981, eISSN 2169-4052. Available from: https://doi.org/10.3141/1883-23

[30] CVITANIC, D., BRESKI, D., VIDJAK, B. Review, testing and validation of capacity and delay models at unsignalized intersections. *Promet - Traffic and Transportation* [online]. 2007, **19**(2), p. 71-82. ISSN 0353-5320, eISSN 1848-4069. Available from: https://traffic.fpz.hr/index.php/PROMTT/article/view/937

[31] BRILON, W. Delay at unsignalized intersections. *Transportation Research Record: Journal of the Transportation Research Board* [online]. 2008, **2071**(1), p. 98-108. ISSN 0361-1981, eISSN 2169-4052. Available from: https://doi.org/10.3141/2071-12

[32] CHANDRA, S., AGRAWAL, A., RAJAMMA, A. Microscopic analysis of service delay at uncontrolled intersections in mixed traffic conditions. *Journal of Transportation Engineering* [online]. 2009, **135**(6), p. 323-329. ISSN 0733-947X, eISSN 1943-5436. Available from: https://doi.org/10.1061/(ASCE)0733-947X(2009)135:6(323)

[33] TRB Transportation Research Board of the National Academies. *HCM2010 - Highway Capacity Manual. Vol. 3: Interrupted flow*. USA: National Academy of Sciences, 2010. ISBN 0-309-06681-6.

[34] BRILON, W. Average delay at unsignalized intersections for periods with variable traffic demand. *Transportation Research Record: Journal of the Transportation Research Board* [online]. 2015, **2483**(1), p. 57-65. ISSN 0361-1981, eISSN 2169-4052. Available from: https://doi.org/10.3141/2483-07

[35] CALIENDO, C. Delay time model at unsignalized intersections. *Journal of Transportation Engineering* [online]. 2014, **140**(9), p. 1-13. ISSN 0733-947X, eISSN 1943-5436. Available from: https://doi.org/10.1061/(ASCE)TE.1943-5436.0000696

[36] MOHAMMAD, M. A., PUAN, O. B. Traffic delay estimation using artificial neural network (ANN) at unsignalized intersections. In: 3rd International Conference on Civil, Structural and Transportation Engineering ICCSTE'18: proceedings [online]. 2018. Paper 106. Available from: https://doi.org/10.11159/iccste18.106

[37] TURNER, S., FITZPATRICK, K., BREWER, M., PARK, E. S. Motorist yielding to pedestrians at unsignalized intersections: findings from a national study on improving pedestrian safety. *Transportation Research Record* [online]. 2006, **1982**(1), p. 1-12. ISSN 0361-1981, eISSN 2169-4052. Available from: https://doi.org/10.1177/0361198106198200102

[38] TOWHIDUL, I., SHISHIR KUMAR, S. A., S M RAHAT, R., SUDIPTA, B. Road crossing behavior of pedestrians at unsignalized intersection under mixed traffic condition. In: 2nd International Conference on Research and Innovation in Civil Engineering ICRICE-2020: proceedings. 2020. Paper ID 123. Available from: http://surl.li/gracy

[39] MORENO, E., DENNY, P., WARD, E., HORGAN, J., EISING, C., JONES, E., GLAVIN, M., PARSI, A., MULLINS, D., DEEGAN, B. Pedestrian crossing intention forecasting at unsignalized intersections using naturalistic trajectories. *Sensors* [online]. 2023, **23**(5):2773. eISSN 1424-8220. Available from: https://doi.org/10.3390/s23052773

[40] PERISA, M., CVITIC, I., PERAKOVIC, D., HUSNJAK, S. Beacon technology for real-time informing the traffic network users about the environment. *Transport* [online]. 2019, **34**(3), p. 373-382. ISSN 1648-4142, eISSN 1648-3480. Available from: https://doi.org/10.3846/transport.2019.10402

[41] PERAKOVIC, D., PERISA, M., SENTE, R. E., ZORIC, P., BUCAK, B., IGNJATIC, A., MISIC, V., VULETIC, M., BIJELICA, N., BRLETIC, L., PAPAC, A. Smart wristband system for improving quality of life for users in traffic environment. smart technology trends in industrial and business management. In: *Smart Technology Trends in Industrial and Business Management. EAI/Springer Innovations in Communication and Computing* [online]. CAGANOVA, D., BALOG, M., KNAPCIKOVA, L., SOVIAR, J., MEZARCIOZ, S. (eds.). Cham: Springer, 2019. ISBN 978-3-319-76997-4, eISBN 978-3-319-76998-1, p. 429-450. Available from: https://doi.org/10.1007/978-3-319-76998-1_32

[42] BARI, C. S., GUNJAL, T. V., DHAMANIYA, A. A simulation approach for evaluating congestion and its mitigation measures on urban arterials operating with mixed traffic conditions. *Communications - Scientific letters of the University of Zilina* [online]. 2022, **24**(3), p. D126-D140. ISSN 1335-4205, eISSN 2585-7878. Available from: https://doi.org/10.26552/com.C.2022.3.D126-D140

[43] KALASOVA, A., CERNICKY, L., KUBIKOVA, S. Microscopic Simulation of coordinated route in the city of Zilina. *Communications - Scientific letters of the University of Zilina* [online]. 2014, **16**(2), p. 46-50. ISSN 1335-4205, eISSN 2585-7878. Available from: https://doi.org/10.26552/com.C.2014.2.46-50

[44] ZILBERTAL, A. *Tram economy / Tramvaynoe khozyaystvo* (in Russian). Moscow: Gostransizdat, 1932.
[45] KOCIANOVA, A. The capacity limits of roundabouts. *Communications - Scientific letters of the University of Zilina* [online]. 2014, **16**(4), p. 81-86. ISSN 1335-4205, eISSN 2585-7878. Available from: https://doi.org/10.26552/com.C.2014.4.81-86
[46] KOCIANOVA, A., PITLOVA, E. Critical gaps at unsignalized intersections with bending right-of-way. *Communications - Scientific letters of the University of Zilina* [online]. 2018, **20**(4), p. 69-75. ISSN 1335-4205, eISSN 2585-7878. Available from: https://doi.org/10.26552/com.C.2018.4.69-75
[47] CELKO, J., KOVAC, M., HUSZAROVA, K. Influence of selected vehicle manoeuvres on reduction of the urban roads capacity. *Communications - Scientific letters of the University of Zilina* [online]. 2019, **21**(4), p. 81-89. ISSN 1335-4205, eISSN 2585-7878. Available from: https://doi.org/10.26552/com.C.2019.4.81-89
[48] BHATT, K., SHAH, J. Reckoning level of risk and severity (LORS) based on the gap acceptance at a three-legged uncontrolled intersection of a rural highway. *Communications - Scientific letters of the University of Zilina* [online]. 2023, **25**(1), p. F1-14. ISSN 1335-4205, eISSN 2585-7878. Available from: https://doi.org/10.26552/com.C.2023.013
[49] BAGHERI, M., BARTIN, B., OZBAY, K. Simulation of vehicles' gap acceptance decision at unsignalized intersections using SUMO. *Procedia Computer Science* [online]. 2022, **201**, p. 321-329. ISSN 1877-0509. Available from: https://doi.org/10.1016/j.procs.2022.03.043