

The problem of determining traffic and pedestrians delay in the city road-street network unregulated intersection area

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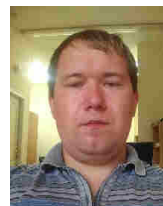
Abstract. The motorization level increase in the city of Kyiv, taking place since the late 1990s up to 2008, caused the increase of the traffic flows intensity in the city and overwork of the city road-street network (RSN). The city streets and roads intersections became the places of traffic and pedestrian flows network concentration. In the City of Kyiv over a half of all intersections of streets and roads are unregulated. Therefore, in the aforementioned conditions (continued motorization level increase, limited number of parking spaces, public transport lanes allocation), as well as increasing demand for individual vehicles (Segway, gyro scooters, bicycles), the problem of unregulated crossings operation assessment is relevant. Proper traffic organization, taking into account all traffic participants, is the factor of the whole system efficient operation.

While analyzing the regulatory framework of Ukraine for the design and operation of urban transport infrastructure, there are several problem areas: the lack of sufficient description of the requirements for the unregulated crossings design; the absence of a comprehensive assessment of the intersection including all traffic participants (cars, pedestrians, cyclists and public transportation); the absence of regulatory transportation capacity.

The article proposes to introduce the common structure of indicators of unregulated intersection work efficiency of traffic network. Such indicators have been used for more than 50 years by American, European and other countries' designers to solve urgent urban construction and transport problems. This direction uses the level of service (LOS) Concept that aims to maximize the comfort of the transportation infrastructure



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elements – roadway, sidewalk, pedestrian crossing etc. The main indicators in this concept are the traffic and pedestrians delay control in the unregulated intersection area; this article deals with the method of its determination. Thus the method of full-scale traffic and pedestrians delay measurements is provided. Multimodal intersection level of service (MMLOS) is determined using the automotive and pedestrian components.

Keywords: road-street network (RSN), unregulated intersection, level of service, pedestrian crossing delay, traffic delay.

OBJECT AND SUBJECT OF RESEARCH

The object of the research is a simple (unregulated) intersection on the city road network. The subject of the research is the principles and methods of functional-planning

solutions of simple (unregulated) intersections in the city road-street network.

The *unregulated intersection* of the city streets and roads is any RSN crossing or adjacent, which does not have traffic lights.

The *simple intersection* of city streets and roads is referred to as RSN crossing or adjacent, which do not have straight structures and elements (islets, road marking, etc.) that organize traffic.

PROBLEM FORMULATION

The purpose of this study is to develop and reason the methodology for evaluating the operation of unregulated intersection on the city's road-street network.

It requires the research and development of a scientific base for complex solutions of unregulated crossings when choosing them depending on the urban conditions. For this purpose it is necessary to collect and structure the road network output data – traffic intensity, flow composition, intersection geometry etc. The main objective of the study is to establish the boundaries of the effective functioning of unregulated crossings, depending on the urban planning conditions using the specified evaluation criteria – traffic delays, queuing length and lines capacity levels.

STUDIES AND PUBLICATIONS ANALYSIS

The theme of increasing the unregulated crossings efficiency in the city has been traced back to the 1960s. In Western Europe, the USA and the former USSR, cross-sectional studies have been conducted, based on which two approaches can be outlined:

- an approach based on Probability Theory, whose founder is E.M. Lobanov [1, 2]. Also in this direction worked such scholars as Buga P.G., Shelkov Yu. D. [3], Romanov A.G. [4], (USSR); B. Grinschilds [5], T. Metson [6], (USA); as well as contemporary scholars Chikalina Y.M. [7, 8], Simul M.G. [9] (Russian Federation), O.O. Lobashov [10], Gorbachov P.F. [11], Shirin V.V. [12] (Ukraine);

- an approach based on queuing theory with the introduction of a level of service (LOS) criterion. This trend has developed primarily in the USA and the Western Europe. The scholars D. Drew [13], I.E. Baerwald, A.V. Trofimov [14], A.Y. Mikhailov [15, 16], Kyte, M., Z. Tian, Z. Mir, Z. Hameedmansoor, W. Kittelson, M. Vandehey, B. Robinson, W. Brilon, L. Bondzio, N. Wu [17] worked in this area.

THE CITY ROAD-STREET NETWORK UNREGULATED INTERSECTION INDICATORS STRUCTURE

Prior to choosing the basic unregulated intersection model, it is necessary to classify the object of study according to the set of criteria characterizing the intersection operation conditions. The RSN unregulated crossings operation conditions in Kyiv can be divided into planning and transport ones, which in turn are divided into the following subtypes:

Planning conditions include the city functional-planning area and the intersection geometry.

Transport conditions – the category of intersecting streets; transport flows priority; transport flow composition.

Based on the current State Building Standards [18, 19] there are no clear criteria for the unregulated intersections operation in the city [32]. In the previous DBN B.2.3-5:2001 edition [18] the following transport conditions restrictions (the traffic and pedestrians intensity) were specified in the area of unregulated intersection as 700 units per hour of total transport flow and 150 persons per hour for one pedestrian crossing in the intersection zone. There was also a restriction on the category of streets – an unregulated traffic and pedestrian traffic scheme was allowed on city streets and local roads (residential streets). There were no planning restrictions regarding the intersection geometry. There is no regulation on the use of unregulated crossings at the level of the City Master Plan [20, 33].

The intersection was designed in accordance with the city roads and streets design rules. In contemporary urban conditions, the

traffic intensity and its individual types (bicycle, gyro, Segway) increase, pedestrian mobility augment and growing demand for such services of the current standards are not sufficient for a comprehensive urban development assessment of the unregulated crossroads design solution.

Several parameters have been used to evaluate the work of the city RSN unregulated intersection. These parameters are described the US Highway Capacity Manual [21, 22] and its German analogue [23]. These include delay level d , delay of pedestrians d_p , 95th grade queue length Q_{95} , emissions level M , intersection safety G , and road transport costs D .

Table 1. The unregulated crossroads operation indicators interrelation

RSN Element	LOS Criteria	Different Assessments Availability		
		Air quality	Noise level	Transport costs
Unregulated crossing	Operation delay	Yes	No	Yes
	Queue length	Yes	Yes	Yes
	Line capacity factor	Yes	No	Yes

For an unregulated intersection, the main efficiency indicator is *traffic delay* and *pedestrians delay* at the junction. These two parameters determine the Level of Service (LOS). The LOS Concept is used from Queuing Theory [14]. In the number of publications the LOS Indicator is defined as "quality characteristics that reflect such aggregate factors as speed, travel time, free makeover, driving safety and convenience" [14, 15].

METHODS OF DETERMINING TRANSPORT TRAFFIC DELAY: THEORY AND PRACTICE

The methodology for determining the traffic delay according to HCM-2010 [22] is a

13-step algorithm. The HCM use boundary conditions for the unregulated intersections are the absence of influence of closely spaced crossings, except for those unregulated intersections that are located 0,467 km (0,25 miles) from the regulated intersection. The necessary model preconditions are:

1. The number of lanes and their width at each intersection approach;
2. Traffic flow percentage rate;
3. Intensity of traffic of input and output traffic flows and intensity of pedestrians crossings at each unregulated crossroads during rush hour;
4. Geometric characteristics of intersection:
 - 4.1. Channelization form of traffic flows;
 - 4.2. The presence of the left turn line or the cumulative line, marked or having islets;
 - 4.3. Intersection zone surface curves;
 - 4.4. Subordinate street approaches;
 - 4.5. Presence of road traffic lights;
 - 4.6. Rate of drivers yielding pedestrian movement and pedestrian "jam traffic";
 - 4.7. The analyzed period length (15 min per rush hour).

Hereford, all movement directions in the unregulated intersection area can be divided into the ranks in relation to the right turn traffic (for X-shaped crossings) (Fig.1):

Rank 1(i): 2 (2-1), 3 (2-3), 5 (1-2), 6 (1-4), 15 (3-3 ped.), 16 (4-4 ped.)

Rank 2(j): 1 (2-4), 4 (1-3), 4U (1-1), 1U (2-2), 9 (3-1), 12 (4-2), 13 (2-2 ped.), 14 (1-1 ped.)

Rank 3(k): 8 (3-4), 11 (4-3)

Rank 4(l): 7 (3-2), 10 (4-1)

For T-sections, these categories are divided as follows (Fig.2):

Rank 1(i): 2 (2-1), 3 (2-3), 5 (1-2), 15 (3-3 ped.)

Rank 2(j): 4 (1-3), 4U (1-1), 1U (2-2), 9 (3-1), 13 (2-2 ped.), 14 (1-1 ped.)

Rank 3(k): 7 (3-2)

There are 13 HCM-2010 steps [22]:

Step 1. Determine movement priorities

Step 2. Determine flow intensity rates.

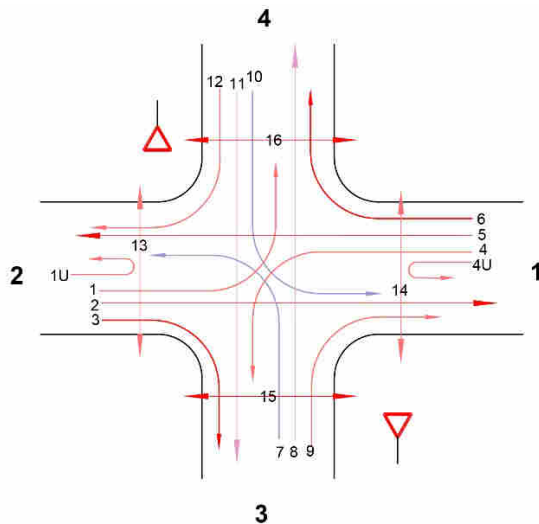


Fig.1. Priority of pedestrian and transportation flows at the unregulated T-shaped crossing

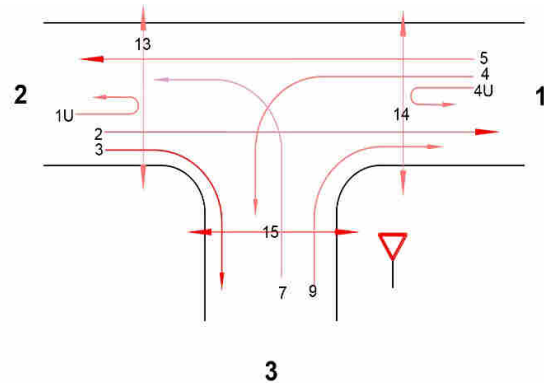


Fig.2. Priority of pedestrian and transportation flows at the unregulated X-shaped crossings

Step 3. Determine conflicting flow rates.

Step 4. Determine critical movement intervals and casual intervals

Step 5. Potential capacity calculation.

5a) Potential capacity accounting neighboring regulated crossings.

5b) Potential capacity under road traffic lights.

Step 6. Determine Rank 1 movement capacity.

Step 7. Determine Rank 2 movement capacity.

Step 8. Determine Rank 3 movement capacity.

8a) One direction highway crossing.

8b) One direction highway crossing.

Step 9. Determine Rank 4 movement capacity.

Step 10. Determine common lane (right turn and turns).

Step 11. Determine movement directions delay.

Step 12. Determine intersection approach delay.

Step 13. Determine 95th grade queue lengths.

For the model verification let us use the calculation of indicators at the intersection of Vishniakivska street and L. Rudenko street in Darnytskyi district (Kyiv) (Fig.3, 4). Open air

examinations were conducted on June 25, 2019 (6:15-6:40 pm).

Initial data were collected in terms of traffic and pedestrian traffic intensity by the method [24] developed by the KNUCA MB Department. According to this method, the values of the traffic intensity are reduced to the average daily using the coefficients of non-uniformity [25]. Some parameters of the traffic flow, such as composition and time intensity, can be determined by [10, 26 – 27]. The transition from daily average to hourly intensity can be made by the formula:

$$N_{hrs} = 0,08 \overline{N_{day}}, \quad (1)$$

where N_{hrs} – hour traffic intensity, veh/h;

N_{day} – average daily traffic intensity, veh/day.

The theoretical calculation of intersection operation according to [22] is performed in MS Excel. The whole algorithm of the problem is not specified in detail, but in Tables 2 and 3 were given the results of calculating delays of all movements d , s/veh. Under traffic delays we understand a traffic speed decrease compare to normative one, permitted by the Traffic Rules of Ukraine [28].

Analysis of field surveys is carried out according to the method described in [29].

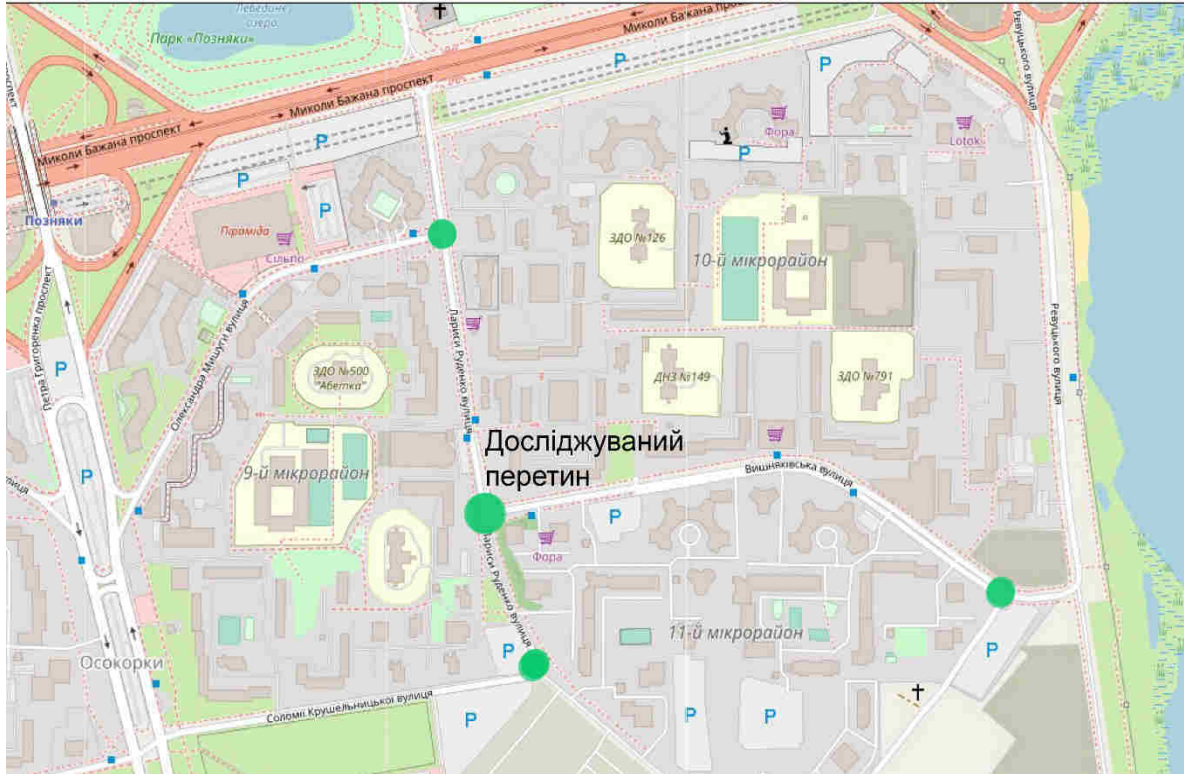


Fig.3. Intersection location in the road-street network



Fig.4. Intersection scheme

In order to show the traffic situation, a 15 min video recording (five 3-min videos) was made (Fig.5). The manual data processing protocol is presented in Table 4.

The whole video is split into 1 min segments. The periods of detailed fixation of the vehicle number make 15 seconds. Each 15-second segment shows the number of cars waiting in a queue $n_{i,ч}$ and every 1 min video shows the number of cars that stopped $n_{зуп.}$, or drove nonstop $n_{б.зуп.}$

The processing of the delay determination results includes the following steps:

The HCM-2010 traffic delay [22] is determined by equation:

$$d = \frac{3600}{P_i} + 900T \times \left[\frac{N_i}{P_i} - 1 + \sqrt{\left(\frac{N_i}{P_i} - 1 \right)^2 + \frac{3600 N_i}{P_i^2}} \right] + 5 \quad (2)$$

де d – average traffic delay, s/veh;

N_i – movement intensity, veh/h;

P_i – movement capacity, veh/h;

T – observation time ($T = 0,25$ for 15-min period).

Table 2. Determination of traffic delay and level of service directions, Rank 2-4

Movement	T	V_x , veh/h	$C_{m,x}$, veh/h	d, s/veh	LOS
1	-	-	-	-	-
4	0,25	252	1122	9,13	A
4U	-	-	-	-	-
1U	-	-	-	-	-
9	0,25	277	638	14,89	B
12	0,25	-	-	-	-
7	0,25	182	173	135,99	F
8	-	-	-	-	-
11	-	-	-	-	-
7	-	-	-	-	-
10	-	-	-	-	-

Table 3. Determination of traffic delay and level of service directions, Rank 1

Movement	N, lane	$d_{M,LT}$, s/veh	$V_{i,1}$, veh/h	$V_{i,2}$, veh/h	$S_{i,1}$, veh/h	$S_{i,2}$, veh/h	$P_{0,j}$	$P^{*0,j}$	d, s/veh	LOS
2	2	0	113	0	2000	2000	0	-0,0600	0,00	A
3	2	0	113	0	2000	2000	0	-0,0600	0,00	A
5	2	9,13	194	0	2000	2000	0,7758	0,7517	1,13	A



Fig.5. Video fixation of the traffic situation at the intersection of Vishniakivska str. and L. Rudenko str. (25.06.2019, 18:15:17)

Table 4. Traffic delay determination of direction 4 (1-3) by the method of field studies

Time		n _{i.ч.} , veh in period I, s				Movement, veh	
Hour	Minute	0 - 15	15 - 30	30 - 45	45 - 60	n _{зуп.}	n _{б.зуп.}
18	15	0	2	1	1	0	5
18	16	1	0	1	1	0	3
18	17	1	0	1	0	0	2
18	20	0	2	0	1	2	1
18	21	1	0	1	2	3	2
18	22	1	0	0	0	0	1
18	26	1	2	1	1	1	4
18	27	1	0	1	1	0	3
18	28	0	0	0	0	0	0
18	32	1	2	0	1	0	4
18	33	0	1	0	1	1	1
18	34	1	0	0	0	0	1
18	38	0	1	1	1	0	3
18	39	1	0	1	1	2	1
18	40	1	1	0	0	0	2
Σ		10	11	8	11	9	33

Movement capacity is determined by equation:

$$P_i = k_{\Sigma} N_{\text{гол}} \frac{e^{-\frac{N_{\text{гол}} t_c}{3600}}}{1 - e^{-\frac{N_{\text{гол}} t_f}{3600}}} \quad (3)$$

де P_i – potential movement capacity of i line, veh/h;

$N_{\text{гол}}$ – highway movement intensity, veh/h;

t_c – critical movement interval, s;

t_f – movement interval i , s;

k_{Σ} – adjustment factor for steps 5 – 8 [22].

1. Determination of total delays in one direction:

$$AT = \sum_i^{i=15} n_{i.ч.} I \quad (4)$$

where AT – total delays in the traffic direction, veh·s;

$n_{i.ч.}$ – the total number of cars in a queue, veh;

I – fixation interval ($I=15$ s).

2. One car stop average delay

$$t_{\text{зуп.}} = \frac{AT}{\sum n_{\text{зуп.}}} \quad (5)$$

where $\sum n_{\text{зуп.}}$ – the total number of cars that stopped at the intersection during the observation period

3. Nominal delay of each car passing through the intersection is given by the formula:

$$t_{\text{ум.}} = \frac{AT}{n_{\text{зуп.}} + n_{\text{б.з.}}} \quad (6)$$

where $n_{\text{б.зуп.}}$ – the total number of cars passing non-stop through the intersection.

Calculate the appropriate parameters for direction 4:

1. $AT = (10 + 11 + 8 + 11) \cdot 15 = 600$ авт · с

2. $t_{\text{зуп.}} = \frac{600}{9} = 66,7$ с ;

3. $t_{\text{ум.}} = \frac{600}{9 + 33} = 14,3$ с

We do the same calculations for directions 7 (3-2) and 9 (3-1). The results of theoretical and practical calculations are summarized in Table 5 to compare.

Table 5. Delay level comparison results

Directions	Traffic delay for [3,4]	Practical calculation according to [14]	Error, %
4 (1-3)	9,13	14,3	+36,0
7 (3-2)	135,99	24,6	-81,9
9 (3-1)	14,89	15	+0,73

As we can see, in two cases the results of theoretical calculations and experimental data differ significantly (over 10% error). There are several factors that can affect this:

- Data collection accuracy;
- Data analysis accuracy;
- Data collection quality;
- The need for calculation methods adjustment.

**METHODS OF DETERMINING
PEDESTRIANS CROSSING DELAY
ON UNREGULATED INTERSECTION:
THEORY AND PRACTICE**

The pedestrian crossing delay method according to HCM-2010 is a 6-step algorithm that allows us to determine the level of service on an unregulated pedestrian crossing.

Step 1. Determine two-way crossings.

Step 2. Determine critical intervals.

Step 3. Probability of delayed pedestrian crossings.

Step 4. Calculate average waiting interval delay.

Step 5. Estimate delay reduction due to yielding vehicles.

Step 6. Calculate average pedestrian delay and determine LOS (pLOS).

The pLOS Assessment Model, which was first tested in HCM 5th edition [22], offers three versions of unregulated pedestrian crossing:

A. Unmarked crosswalk, no median safety islet;

B. Unmarked crosswalk, median safety islet;

C. Marked crosswalk with visible equipment and median safety islet.

HCM recommends the following data to determine pLOS:

- Number of lanes on a major street;
- Traffic intensity on a major street, veh/h;
- Crosswalk length without median islet (option A), m;
- Crosswalk length with median islet (option B and C), m;
- Pedestrian crossing speed, m/s;
- No pedestrian “jam traffic”.

As an example, let us take the calculation of indicators at the intersection of Vishniakivska street and L. Rudenko street (see Fig.4), Tables 6 – 8. On-site examinations were conducted on June 25, 2019, 6:15-6:40 pm.

Table 6. Traffic delay and pLOS, crosswalk 1-1

	d_{gd}		$d_{gd,\Sigma}$	pLOS
Scen. A	13,15		13,15	E
Scen. B	1,01	1,17	2,18	B
Scen. C	1,01	1,17	2,18	B

Table 7. Traffic delay and pLOS, crosswalk 2-2

	d_{gd}		$d_{gd,\Sigma}$	pLOS
Scen. A	13,27		13,27	D
Scen. B	0,96	1,20	2,16	A
Scen. C	0,96	1,20	2,16	A

Since HCM-2010 has no procedure for determining the unregulated pedestrian crossing capacity, it is necessary to further distinguish two approaches in the crossing determination – namely the determination of the traffic lane capacity in the area of the unregulated crossing and the capacity of the pedestrian lane across the traffic lane.

In general, within the framework of urban transportation planning, the general tasks of pedestrian crossing design are to calculate their capacity and to select the location in the street.

In the former USSR, pedestrian crossing subject was studied by such scholars as Buga P.G, Shelkov Y.D., Lobanov E.M., Romanov A.G., as well as contemporary Russian researchers Chikalin E.M., Simul M.G. etc. In 1977, an act was adopted [30] that addressed issues related to improving the pedestrian crossing arrangement. The one lane pedestrian crossing capacity is determined by the formula:

$$N_{n.1} = \frac{e^{-\left(1,5 + \frac{\Delta t_{zp} M}{3600}\right)}}{1 - e^{-\frac{\delta t M}{3600}}} \quad (6)$$

where M – major street total traffic intensity, veh/h;

$\lambda = M/3600$ – M traffic intensity mathematical expectancy, veh/s;

Δt_{zp} – critical interval in major street, s;

δt – traffic interval in subordinate street, s

The crosswalk capacity is determined by the formula:

$$N_n = \frac{b_n}{b_{n.1} N_{n.1} K_p} \quad (7)$$

where b_n – crosswalk width, m;

$b_{n.1}$ – crosswalk lane width, m (0,75 – 1,0 m);

K_p – adjustment factor of traffic road lights.

Scholars Bug PG, Shelkov Y.D. offered a formula for estimating traffic delays in a pedestrian crossing area [7, 8]:

$$d_{ped} = 0,00147 \frac{N_n N_{mp}}{v^2} \quad (8)$$

where N_p та N_{mp} – respectively the intensity of pedestrian (ped/h) and automobile traffic (veh/h); v – speed of movement, km/h.

In Ukraine, the issues of pedestrian crossing in the area of unregulated intersection are regulated by a number of DBN and DSTU, among them [18, 19] and the new DBN [31].

Table 8. Calculation of pedestrian crossing delay (1-1) by the method of field studies

Time		ni _{п.п.} ped in period I, s				Movement, ped	
Hour	Minute	0 - 15	15 - 30	30 - 45	0 - 15	п _{зуп.}	п _{б.зуп.}
18	15	0	0	0	0	0	1
18	16	0	2	0	0	2	0
18	17	0	1	0	0	1	2
18	20	0	0	1	0	1	1
18	21	0	0	0	0	0	2
18	22	0	0	0	0	0	4
18	26	1	0	0	0	1	0
18	27	0	0	0	0	0	0
18	28	0	0	0	0	0	0
18	32	0	0	0	1	1	3
18	33	0	2	0	0	2	3
18	34	0	0	0	0	0	0
18	38	0	0	0	0	0	2
18	39	0	0	0	0	0	2
18	40	0	0	0	0	0	5
Σ		1	5	1	1	8	25

As we can see (Table 9), the results of theoretical calculations and experimental data differ significantly in the two cases (over 10% error). There are several factors that can affect this:

- Data collection accuracy;
- Data analysis accuracy;
- Data collection quality;
- The need for calculation methods adjustment.

Table 9. Calculation of crossing delay

Dir.	Crossing delay for [22]	Practical calculation according to [29]	Error, %
1-1	13,15	3,63	-72.2
2-2	13,27	8,95	-33.5

CONCLUSION

Nowadays the problem of providing capacity of both the RSN as a whole and its separate nodes – streets and their crossroads – is urgent for the city of Kyiv. Therefore, first, unregulated crossroads make up about 70% of the total number of RSN nodes in Kyiv, as the study of their work and determining the criteria for their effective functioning is an important part of the complex task of improving the whole RSN efficiency.

Second, in the current regulatory framework of Ukraine for the RSN design and operation there is no method of applying RSN design solutions of unregulated intersections. There is no assessment of its impact on the entire network operation, nor even individual criteria for such assessment.

Third, in the Ukrainian regulatory framework there is no assessment of individual transport, pedestrians, cyclists and public transportation for their mutual (comprehensive) impact on the intersection operation.

Based on the analysis of foreign literature and the regulatory framework, three indicators of the city RSN unregulated intersection operation were identified – traffic delay, queue length and load factor in the movement directions. Traffic delay is used in the United

States and Germany as a key indicator of the efficiency of unregulated crossings.

However, when determining the movement delays by the "manual" method, there is a certain problem of inconsistency between the theoretical data (according to calculations [22]) and the data determined by the method [29].

Based on this, we can make some recommendations:

- Further scientific and theoretical research with the introduction of correction factors of reduction in formulas (2-3) is needed;
- Computer video processing method application to show the road situation in order to determine the traffic and pedestrians delays.

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Проблематика определения задержки движения транспорта и пешеходов в зоне нерегулируемого пересечения на городской улично-дорожной сети

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Аннотация. Рост уровня автомобилизации в городе Киеве, которое состоялось с конца 1990-х гг. до 2008 года, способствовало увеличению интенсивности транспортных потоков в городе и перегрузке городской улично-дорожной сети (УДС). Местом концентрации транспортных и пешеходных потоков на сети является пересечения городских улиц и дорог. На УДС города Киева больше половины всех пересечений улиц и дорог приходится на нерегулируемые. Поэтому, в вышеупомянутых условиях (продолжающегося роста уровня автомобилизации, недостаточном количестве парковочных мест, решений по выделению полос для движения общественного транспорта), а также рост спроса на индивидуальные транспортные средства (сегвей, гироскутер, велосипед) вопросы оценки работы нерегулируемых пересечений является актуальным. Правильная организация дорожного движения с учетом всех участников движения является фактором эффективной работы всей системы.

Анализируя нормативную базу Украины по проектированию и эксплуатации объектов городской транспортной инфраструктуры можно выделить несколько проблемных направлений: отсутствие достаточного описания требований проектирования нерегулируемых пересечений; отсутствие комплексной оценки работы пересечения с учетом всех участников дорожного движения (автомобили, пешеходы, велосипедисты и общественный транспорт); отсутствие нормативных транспортных нагрузок. Основными показателями в этой концепции является задержка движения транспорта и пешеходов в зоне нерегулируемого пересечения, методика определения которых рассмотрена в данной статье. Предложена методика натуральных измерений задержки движения транспорта и пешеходов.

Ключевые слова: улично-дорожная сеть, нерегулируемое пересечение, уровень обслуживания, задержка движения транспорта, задержка движения пешеходов.