signalized intersection; saturation flow; intersection passing speed

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THE SATURATION FLOW VOLUME AS A FUNCTION OF THE INTERSECTION PASSING SPEED

Summary. Different methods of calculating the saturation flow volume were examined. It was found that none of them considers the speed of vehicles passing through the intersection (intersection passing speed). For this reason we examined the effect including intersection passing speed has on the accuracy of assessing traffic conditions at intersections by including this parameter in tests run on VISSIM software. Our tests showed that accurately assessing the saturation flow volume depends on including intersection passing speed and the size of the intersection.

ИНТЕНСИВНОСТЬ ПОТОКА НАСЫЩЕНИЯ КАК ФУНКЦИЯ СКОРОСТИ ПРОЕЗДА ПЕРЕКРЕСТКА

Аннотация. Рассмотрены методы расчета интенсивности потока насыщения и установлено, что они не учитывают скорости проезда перекрестка. Исходя из этого, предложено использовать скорость проезда перекрестка как обобщенный параметр условий движения на перекрестке, для чего в среде VISSIM проведены соответствующие исследования. Установлено, что интенсивность потока насыщения зависит от скорости проезда перекрестка и его длины.

1. INTRODUCTION

Using inaccurate data to program traffic lights leads to congestion, increased traffic delays, unnecessary fuel consumption, pollution and more accidents. For signalized intersections to function efficiently the main control parameters must be properly calculated. One way to improve signal plan creation is to use the correct traffic flow parameters and to create or adjust design procedures. Specifically, it is important to recalculate the signal plans at intersections where conditions or traffic flows have changed.

2. LITERATURE REVIEW

The most important parameter used in designing signalized intersections and analyzing their functioning is saturation flow – the flow of vehicles, which start to move across the stop-line when the light turns green [1]. Saturation flow shows how traffic flow is affected by interruptions made by traffic lights [2]. For an accurate calculation of the saturation flow's intensity, it should be calculated on the spot as there are many different factors that influence it (lay-out of the intersection, traffic patterns and traffic light control and coordination, etc.). There are different procedures which can be use to measure the saturation flow rate, but they are all time consuming [2-5]. For this reason, when designing or improving a signal plan a basic saturation flow volume is generally use and adjusted to reflect local conditions. The basic saturation flow exists under the following conditions: a 3.6m wide lane, a 0% grade on the approach to the intersection, dry pavement, the absence of obstacles created by curbside parking or public transportation stops, the absence of interference from other vehicle traffic, bicycle or pedestrian flows and the absence of trucks and busses in the flow [2-3].

2.1. An Analysis of saturation flow volume estimation procedures

The Ukrainian procedure for estimating saturation flow volume is quite simple. The volume of the basic saturation flow is determined by considering roadway width. It is then adjusted to accommodate the longitudinal grade, turning radiuses and how vehicles are distributed among the available directions (straight, left or right) using the appropriate adjusting coefficients. Other factors that define traffic conditions (presence of pedestrians, curbside parking, lighting, type and condition of pavement etc.) are added using an additional coefficient [5].

The Canadian procedure for estimating saturation flow volume starts from a baseline saturation flow volume which is specific for each area (province). It fluctuates from 1665 passenger car units (pcu) per hour (h) (Fredericton) to 2100 pcu/h (Calgary). For intersections whose geometric parameters are less than ideal, the saturation flow volume can be obtained using appropriate adjustment factors [2].

Adjustment factors reflect the impact of the intersection's geometric parameters (lane width, longitudinal grade, turning radius, length of additional lanes before and after the intersection for queuing and discharging), traffic conditions (public transportation stops, curbside parking, pedestrians) and control conditions (length of green light and the composition of its phases).

The adjusted saturation flow volume is estimated using the formula [2]:

$$S = S_0 f\left(F_{к}\right), \tag{1}$$

where S_0 is the volume of the basic saturation flow; and $f\left(F_{к}\right)$ is the adjustment of the saturation flow volume, whose variables consist of the relevant adjustment factors.

Additionally, the Canadian procedure considers the impact of weather conditions, the condition of the pavement and geography separately [2].

The American procedure for estimating saturation flow volume uses 1900 pcu/h for one lane as the basic saturation flow volume [3]. The actual saturation flow volume is then adjusted for local conditions using the following formula:

$$S = S_0 N f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}, \tag{2}$$

where S_0 is the basic saturation flow volume; N is the number of lanes in the lane group; and $f_w \ldots f_{Rpb}$ are the adjustment coefficients related to lane width, flow structure, approach grade, curbside parking, hindrance of public transport stops, area type, lane utilization, right and left turns, pedestrian movement for left turns and pedestrian and bicycle movement for right turn.

All the listed procedures start with the basic saturation flow volume and adjusted values obtained from all the procedures vary between 1700-2100 pcu/h which corresponds to a 1.7-2.1 second interval between vehicles. The fact that such intervals exist during peak volume is confirmed by Keroglu, Kaluzhskyy and Lobanov's research [6, 7]. The saturation flow volume of 1800-2560 pcu/h was corroborated by Akcelik and Besley's field investigations [8].

2.2. Analysis of research

The saturation flow is, in essence, traffic flow which exists when a roadway (lane) operates under capacity conditions. It is known that traffic flow volume can reach up to 2400 pcu/h with headways of 1.5 sec. But in practice such volume is rarely reached because it requires considerable emotional tension. The theoretical lane capacity is estimated by taking into account the average flow speed (v) and the safe following distance (gap) between cars (L) [6]:

$$N = \frac{1000 \cdot v}{L}. \tag{3}$$

An increase in lane capacity due to an increase in speed during uniform motion is also confirmed by data compiled by Silyanov [9]. It is an interesting approach that uses prior information about the movement at the intersection [10].

Factors which have an impact on the saturation flow volume also have an effect on changes in traffic flow speed [11]. It was found however, that none of the examined procedures for estimating saturation flow volume consider intersection-passing speed (the speed of vehicles passing through the intersection).

There are many recent studies conducted to clarify the calculation of the saturation flow volume estimation but most of them focus on a more precise definition of adjustment factors in existing procedures [12, 13] or investigating the impact the composition of traffic flow has on saturation flow volume [14-16]. These studies do not consider intersection-passing speed as a factor that affects saturation flow volume.

It is known that intersection-passing speed decreases when the pavement is in disrepair. Nonetheless, no current method can consider pavement condition because the degree of disrepair in each instance varies and can differ from one side of the road to the other. Specifically, Fornalchyk and Hilevych [17] show that intersection-passing speed at intersections with poor quality pavement is 3 times slower than at intersections with good quality pavement; additionally poor quality pavement reduces intersection capacity and creates congestion.

Dolhushyn [18] shows that drivers reduce their speed to 20-30 km/h while crossing tramlines at intersections where the asphalt is in poor condition. The volume of the saturation flow goes down by 15% in comparison with intersections, which have rubber-cord surface at tram crossings instead of asphalt.

Romanov [19] affirms that the maximum number of cars in one lane, which can pass through an intersection on a green light during one cycle, depends on intersection passing speed and the interval between vehicles.

Thus, despite what we have already stated, it is reasonable to carry out an investigation of the impact intersection passing speed has on the saturation flow volume. In this scenario, speed should be seen as a value influenced by the geometric and planning characteristics of the intersection, traffic conditions, the condition of the pavement, the composition of the traffic flow and the technical condition of the vehicles etc.

3. REVIEW OF PRELIMINARY RESULTS

In 2011-2012 the authors carried out preliminary investigations on how intersection passing speed influences saturation flow volume using simulations in the VISSIM computer program [1]. Five intersection speed limitation patterns were identified (where speed limit means the speed at which a vehicle should travel to ensure road safety); the speed may be limited only in the intersection (fig. 1, *a*). Intersection only speed restriction can be caused by changes in road surface, poor condition of the pavement and reducing speed to increase turning safety among others. Speed can also be limited both in and beyond the intersection, for example, when the type of pavement changes or when roadway conditions worsen starting at the intersection (fig. 1, *b*). Speed can also be limited only beyond the intersection (fig. 1, *c*) or only before it (fig. 1, *d*). A constant reduction in speed (fig. 1, *e*) arises not only when the road surface is in poor condition but also from low dynamic properties of vehicles and their state of repair. The baseline situation is when the speed of traffic, from the approach to the intersection through and beyond it, is limited only by Traffic laws, (fig. 1, *f*). Intersections were understood to mean the 20-meter area after the stop line.

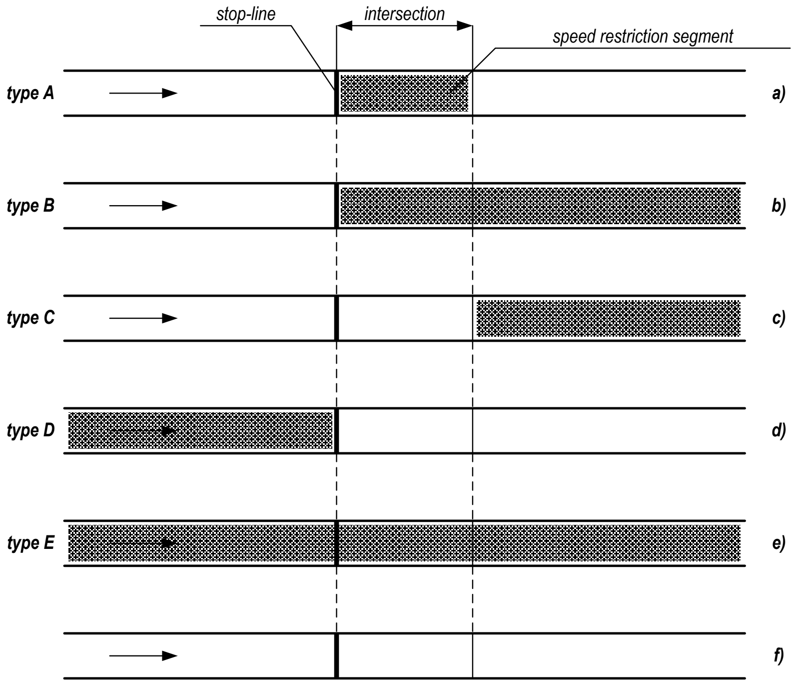

Fig. 1. Possible cases of speed limitation
Рис. 1. Возможные случаи ограничения скорости движения

It was determined that the intersection passing speed impacts the saturation flow volume during all examined types of speed limitation patterns (fig. 2). The saturation flow volume reduces to 1250-1400 pcu/h when cars pass through the intersection at 15 km/h. An increase in the speed limit leads to an increase in the saturation flow volume; it reaches 2134 pcu/h if there are no speed limitations. This value is similar to the baseline volume of saturation flow and to the effective lane capacity.

We use power function to give an analytic description of how the intensity of the flow is determined by the intersection passing speed (tab. 1). The obtained dependencies describe the experimental data well; they are also confirmed with a close correlation coefficient. As speed is the only parameter that is entered into the equation, we can consider the saturation flow volume a function of the intersection passing speed.

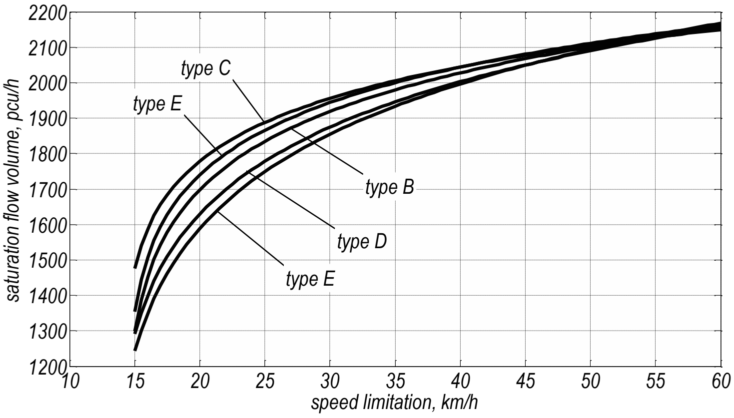

Fig. 2. The dependencies of the saturation flow volume under different types of speed limitation patterns
Рис. 2. Зависимости интенсивности потока насыщения при разных типах ограничения скорости

Table 1

The correlation of the saturation flow volumes and speed limitations

Type of speed limitation	Equation	Correlation coefficient
A	$S = -140800 \cdot v^{-1,892} + 2193$	0,9977
B	$S = -154000 \cdot v^{-1,900} + 2187$	0,9933
C	$S = -87720 \cdot v^{-1,776} + 2185$	0,9924
D	$S = -33570 \cdot v^{-1,297} + 2300$	0,9978
E	$S = -32030 \cdot v^{-1,224} + 2338$	0,9951

As follows from fig. 2, all lines between the intersection passing speeds of 45 and 60 km/h virtually coincide. But the type of limitation affects the saturation flow volume at lower speeds (15-30 km/h). It plays the biggest role in type E, when speed is limited along the entire length of the road. The saturation flow volume is the highest under low speed for type C when vehicle speed is reduced after the intersection. This can be explained in the following way: the first vehicles accelerate while entering the intersection, and reach a speed that is too high for the restricted segment requiring them to brake after passing through the intersection. When compared to other types of speed restriction patterns, this scenario allows the queue to disperse faster and therefore to increase the saturation flow volume.

Figure 2 also shows that the saturation flow volume in scenario B (speed reduced in the intersection and beyond) is somewhat lower than in scenario A (when speed is reduced only in the intersection); this points to the fact that lengthening the area of speed restriction reduces saturation flow volume (scenario B can be understood as an extreme type of scenario A). Moreover, the length of the speed restriction area was fixed in this study, but in practice it can change from dozens of centimeters (when potholes are present) to dozens of meters. For this reason additional research was carried out on saturation flow volume, which included the impact of both factors: (intersection passing speed and length of restriction segment) simultaneously.

4. DESCRIPTION OF THE SIMULATION MODEL

VISSIM, used for the microscopic simulation of vehicle movement, was used to analyze saturation flow volume. VISSIM gave an animated display of vehicle movement and estimated various parameters such as: distribution of travel time and delays, length of congestion and characteristics of each vehicle etc. [20].

As saturation flow is created when vehicles start moving on a green light and its volume is calculated at the stop-line cross section of one lane, then it is necessary to create a one lane model which includes the stop-line and the area of speed restriction to investigate the saturation flow volume.

For creating the model in the VISSIM environment a single lane segment link 800 meters long was built using the input traffic flow of 2500 vehicles/h, which considerably exceeds the lane capacity. The traffic composition and desired speed for each vehicle type are given in the table 2.

Table 2

Parameters of the input flow

Vehicle type	Percentage in the flow, %	Desired speed, km/h
passenger car	75	60
truck	15	50
bus	10	45

The traffic light was set 300 m from the start of the segment link; its cycle duration was 50 sec. with green light duration of 25 sec. These traffic light parameters allow a queue of at least 10-15 vehicles at the moment the light switches to green. These vehicles have enough time to pass through the intersection during this signal.

In the model, the 5 to 50 meters beyond the stop-line (traffic light) is the actual intersection. When the intersection is 5 m long it imitates, for example, uneven pavement or potholes or small radiuses for right-turn flows. The intersection was simulated as a reduced speed area. Additionally, the speed limitation was changed from 10 km/h to 55 km/h at a 5 km/h interval (the speed limitation of 45 km/h has an effect on passenger cars and trucks, 50 km/h and 55 km/h only have an effect on passenger cars). There is no speed limitation area in the baseline scenario.

VISSIM does not record saturation flow volume. For this reason we recorded the moment the green light came on, the moment the vehicles crossed into the intersection over the stop-line and details of each vehicle. This data was then processed using methods based on the field investigations of the saturation flow volume used in Kremenets's study [5]:

1) to record vehicles which cross the stop-line after the light turns green;
2) to record the moment of the last vehicle which crosses the stop-line;
3) to adjust the mixed traffic flow that crossed the stop-line to the flow of passenger cars (using the passenger car unit equivalents for signalized intersections proposed by Levashev [4]);
4) repeat the measurements 20 times;
5) to calculate the saturation flow volume using the formula:

$$S = \frac{3600}{n} \cdot \left(\frac{m_1}{t_1} + \frac{m_2}{t_2} + \ldots + \frac{m_n}{t_n} \right), \tag{4}$$

where: n is the number of experiments ($n = 20$); m_i is the amount of passenger car units that have crossed the stop-line; and t_i is the difference between the moment the last vehicle crosses the stop-line and the moment the light switches to green for this group of vehicles.

5. PROCESSING AND ANALYZING RESEARCH RESULTS

After the preliminary processing of the simulation results we obtained the saturation flow volumes as they related to speed limitations and length of the speed restriction area (tab. 3). A speed restriction of 60 km/h corresponds to the baseline scenario, when the intersection passing speed is limited only by Traffic laws.

Table 3

Results of the saturation flow volume research, veh/h

		Length of the speed restriction segment, m									
		5	10	15	20	25	30	35	40	45	50
Value of the speed limitation, km/h	10	1098	1125	1026	1009	965	962	970	957	965	960
	15	1488	1433	1396	1336	1357	1353	1329	1317	1286	1286
	20	1787	1677	1715	1686	1695	1666	1660	1628	1629	1648
	25	1958	1942	1937	1914	1957	1926	1915	1924	1920	1912
	30	2014	2043	2016	1981	2013	2010	2000	2014	2010	2012
	35	2094	2051	1953	1945	2052	2064	2075	2038	2068	2056
	40	2130	2128	2087	2104	2117	2129	2036	2120	2130	2121
	45	2159	2141	2106	2122	2121	2171	2146	2151	2151	2152
	50	2158	2137	2126	2123	2166	2167	2087	2119	2152	2159
	55	2158	2165	2122	2122	2064	2168	2151	2183	2164	2150
	60	2103	2103	2103	2103	2103	2103	2103	2103	2103	2103

It is obvious that while the impact of speed on the saturation flow volume is nonlinear the impact of the length of the restriction segment on the saturation flow volume is linear. At the same time the impact of speed is substantial, but the length of the restriction area is rather slight and is best seen at low speeds. Given this, to account for the simultaneous effect of both factors the following relationship was founded:

$$S(v,L) = -17200 \cdot v^{-1,08} - 0,8635 \cdot L + 2417, \tag{5}$$

where: v is the intersection passing speed in km/h; and L is the length of the intersection or the speed limitation segment in m.

The coefficients of this model were selected through regression analysis using the MATLAB environment and the Surface Fitting Toolbox. The surface is shown in fig. 3.

To test the accuracy of our model we calculated the errors between experimental data $S_{i,j}^{exper}$, which were obtained after simulation in VISSIM, and calculated data $S_{i,j}^{calc}$, which were obtained using dependence (5), using the formula

$$err = S_{i,j}^{exper} - S_{i,j}^{calc}. \tag{6}$$

It is clear (fig. 4) that errors are evenly distributed in the neighborhood of zero and that its values do not exceed 200 pcu/h (10% of the calculated data); this confirms the accuracy of the model. For the proposed model we also calculated the adjusted R-square ($adjR^2 = 0,9671$). This figure also confirmed the accuracy of our model.

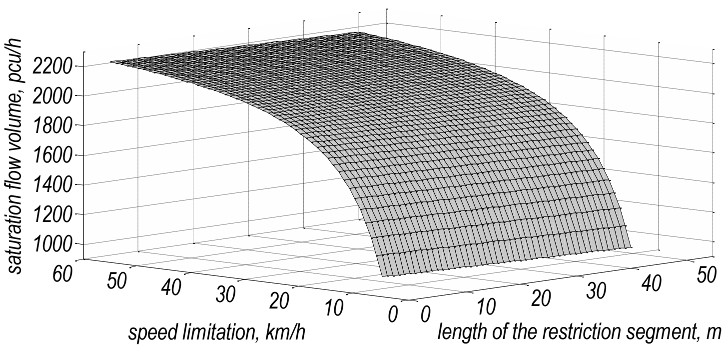

Fig. 3. Dependence of the saturation flow volume on speed limitation and length of the restriction segment

Рис. 3. Зависимость интенсивности потока насыщения от ограничения скорости и длины участка ограничения

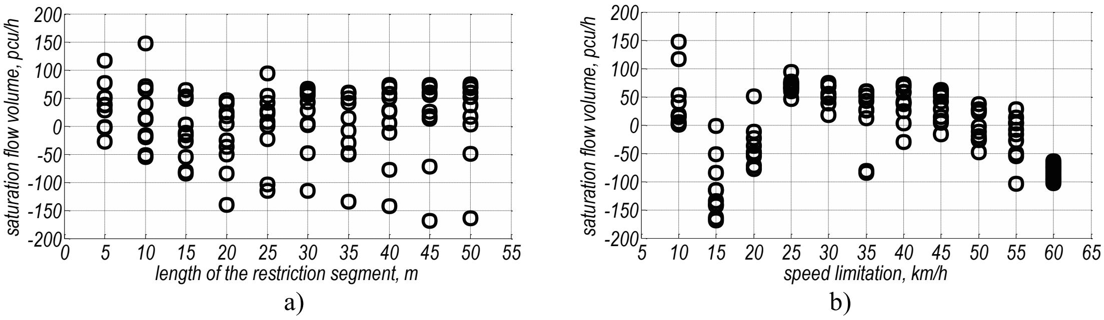

Fig. 4. Errors between experimental and theoretical data on the saturation flow volume in 'segment length – saturation flow volume' (a) and 'speed limitation – saturation flow volume' (b) coordinates
Рис. 4. Отклонения (ошибки) экспериментальных и расчётных значений интенсивности потока насыщения в координатах «длина участка – интенсивность потока насыщения» (a) и «ограничение скорости – интенсивность потока насыщения» (b)

6. CONCLUSIONS

After analyzing given procedures for estimating saturation flow, it was determined that none of them consider intersection passing speed despite the fact that it is one of the parameters that determine lane capacity and that it is influenced by the same factors which influence saturation flow volume.

It was determined that intersection-passing speed has an impact on the saturation flow volume. As speed is the only parameter, it shows that the saturation flow volume can be considered as a function of the intersection passing speed. Taking into consideration the fact that the speed restriction area can vary greatly we used VISSIM to study the simultaneous impact of these two factors. We found that the length of the speed restriction segment has practically no impact on the saturation flow volume when speed remains constant. It indicates that one small pavement defect (pothole, pavement waviness etc.) causes drivers to reduce their speed, which leads to decreased saturation flow volume and, as a result, a reduction in intersection capacity.

Dependence was proposed to describe the changes both these factors have on saturation flow volume; the impact of speed is exponential while the length of the speed restriction area is linear. The proposed dependence is adequate and can be used in further studies. This dependence can be used only for existing intersections, not when designing new ones. Nonetheless when compared to other methods of calculating saturation flow volume this model is superior because it requires only two parameters be estimated while considering the indirect impact of such factors such as geometric and planning conditions, traffic and control conditions, traffic composition, state of pavement etc.

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