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STRAIGHT LANE SATURATION FLOW AND ITS RATE IN SERBIAN CITIES

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Abstract: Saturation flow is the base rate in the procedure for optimizing traffic signal operation and determining the measure for effectiveness of intersection operation. Different approaches and structures of analytical value models indicate the complexity of the problem of determining the saturation flow value in real conditions. This paper presents the synthesis of the results and conclusions of studying the saturation flow rate phenomenon at signalised intersections in Serbia in the last thirty years, by applying various survey techniques. The surveys relate to straight lane saturation flow value, in the survey conditions mostly resembling the idealised conditions in which saturation flow can be generated. The obtained results indicate that there is a significant trend of changes in the base saturation flow value compared with those first referred in 1963 by Webster and Cobbe, change in the significance of impact factor on saturation flow value, and the necessity to determine them on the local level.

Keywords: saturation flow rate, straight lane, signalised intersection, queue discharge, headway.

1. Introduction

Saturation flow is a very important road traffic performance measure of the maximum rate of flow; it is used in junction design and control applications (Webster, Cobbe 1966; Branston, Van Zuylen 1978; Branston 1979; Bhattacharya, P. G., Bhattacharya, A. K. 1982; Hussain 1990; Stanić 1981, 1988, 1991, 1994; Turner, Harahap 1993; Akçelik 1998; Stanić, Osoba 1998; Osoba *et al.* 1999; Bester, Varndell 2002; Agbolosu-Amison *et al.* 2004; Bonneson *et al.* 2005; Kidwai, Karim 2005; Rahman *et al.* 2005, etc.). Saturation flow is a performance measure of junction operation. Saturation flow rate in practice depends on several impact groups:

- lane type;
- number and type of conflicts in the signal plan (signal plan structure);
- regularity of intersection geometric layout;
- traffic composition;
- discipline, aggressivity and skilfulness of drivers; i.e. their ability to use green phase duration;
- type of vehicle approach to an intersection;
- size of settlement or town/city;
- vehicle fleet characteristic (vehicle types, average age...);
- nonstandard factors (weather conditions, carriageway markings conditions, pedestrian discipline…).

The notion of saturation flow was introduced for the first time in the basic definition of the signalised intersection approach capacity (Webster, Cobbe 1966). Saturation flow rate was defined as the maximum number of vehicles that can pass through an intersection during green phase. In the source model, the saturation flow rate was put into the context of intersection geometric layout, i.e. it was thought that its value mainly depends on the lane (or approach) width and flow structure.

The methodology of its experimental determination (at specially shaped polygon in then-Road Research Laboratory (RRL Crowthorne, England)) is based on the distribution of saturation duration throughout the green phase to smaller time intervals, with the duration of six seconds (A Method of Measuring Saturation… 1963). Saturation flow value is determined on the basis of the average vehicle flow values during the observed time intervals. The condition which has to be fulfilled is that the queue discharge process within individual interval is realized in saturation conditions.

The first research experiences outside England show that there are differences between saturation flow values originally referred by Webster and those obtained

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in local conditions, what after that became the subject of interest of numerous researchers.

Table 1 provides an overview of the most important sources and researchers who referred the data on the straight lane saturation flow.

From 30 results presented in Table 1 it is noticeable that saturation flow rate from the original 1850 pcu/hr (Webster, Cobbe 1966) increased to somewhat more than 2184 pcu/hr (Kimber *et al.* 1986). This is an increase of about 18%, which cannot be neglected. Kimber *et al.* (1986) referred the straight lane saturation flow value of 2293 pcu/hr, what is an increase of about 25%.

The increase in saturation flow rate is noticeable also in the results obtained in Belgrade by (Stanić 1991) and later also by Čelar (2007), from 2120 pcu/hr to 2150 pcu/hr. Compared with the value referred by Webster these values are higher by approximately 15%, what is not negligible also.

Table 1. Overview of saturation flow rate by different sources

Source /researcher /country	Reference year	Saturation flow (pcu/hr)
Webster, Cobbe – England	1963÷1966	1675÷1850
HCM – USA	1965	1500÷2000
Davies – England	1966	1325
Azmus	1970	1585÷1600
Miller – Australia	1968	1710
Depolo – Belgrade, Serbia	1971÷1975	1140÷1698
Kapeli	1975	1714
Reilly, Dommasch, Jagannath – USA	1975	900÷1750
Branston, Van Zilen	1978	1750
Teply – Canada	1978	1150÷1750
Branston - England	1979	1757÷1767
TRB – USA	1980	1800
Akçelik – Australia	1980÷1990	1270÷1850
Kremenec, Pečerski	1981	1338÷1890
Kimber, Semmens – England	1982	1741÷2184
Bhattacharya *et. al.* – India	1982	1232
Vini, Pretty – Canada	1982	1800
RIST – Germany	1982	1800÷2000
Sibata, Jamamoto	1984	2200
HCM – USA	1985	1800
Kimber, Semmens – England	1986	1573÷2293
De Anrade	1988	1660
HEL – Greece	1990	1972
Stanić (Belgrade, Serbia)	1991	1600÷2120
HCM – USA	1994	1900
Kehittämiskeskus – Finland	1996	1750
HCM – USA	2000	2000
HBS Germany	2001	2000
DANCAP – Denmark	2002	2000
Čelar – Belgrade, Serbia	2008	1765÷2150

In Serbia saturation flow rate was surveyed in Belgrade in the early 1970s at a limited number of intersections (Depolo 1975). Later, in the 1980s, saturation flow rates were surveyed in the central zone of Belgrade and in 10 greater cities of then-Yugoslavia (Stanić 1991). In these surveys the source RRL (Road Research Laboratory) methodology was applied, with a certain number of smaller corrections relating to the specification of the conditions under which saturation occurs. The subsequent, more voluminous, surveys were conducted at the signalised intersections in Belgrade, in the period 2006–2007, by applying the technique of direct determination of headway value during queue discharge (Čelar 2007).

Turner and Harahap (1993) specified the results of saturation flow rate measurements in several non-western countries – Table 2.

Table 2. Overview of saturating flow rate in non-western countries

Source /researcher /country	Reference year	Saturation flow (pcu/hr)
Shoukry, Huzayyin – Egypt	1986	1617
Hussain, Malaysia	1990	1945
Coeymans, Meely – Chile	unpublished *	1603
Bhattacharya, Bhattacharya – India	1982	1232
De Andrade – Brazil	1988	1660

* cited according to Turner and Harahap (1993)

Saturation flow rates provided in Table 2 are significantly lower than the results presented in Table 1. It can be assumed that this is a consequence of multiplication of individual impacts of a greater number of nonstandard factors on saturation flow value.

The surveys and measurements of the saturation flow rate worldwide and in Serbia have opened many questions in the field of traffic engineering: is saturation flow a constant or a variable and what does this depend on, does it have an absolute maximum rate, what are the conditions to fulfil the saturation circumstances on an intersection approach, what is the relation between measurements at a polygon (in planned and controlled conditions) and the measurements at intersections, are there more types of saturation flow, in real conditions is it affected by the way in which the signal plan has been designed, does green phase duration affect saturation flow value, etc.

2. Saturation Flow Calculation Procedures

Straight lane saturation flow rate (adopted from some model or obtained by measurements at an intersection) is the basis for calculation of traffic signal operation and capacities of intersection approaches. The structure of analytical procedures used to determine the saturation flow rate directly depends on the way of defining the, so called, base saturation flow value and the total number of factors of its reduction, with the associated degree of impact on the base value.

The general difference between the analytical procedures indicates the existence of different approaches to the problem, starting with the definition of the unique base saturation flow value for all lane types (Highway Capacity Manual 2000) and definition of more base saturation flow values (in terms of lane width, lane use, signal plan type, headway value, green phase duration...).

The way in which the base saturation flow value has been defined, later on, directly influences the applied number of influential factors and definition of the degree of influence on the base value.

From the overview provided in Table 3 it can be noticed that there are differences in the saturation flow calculation procedures – on the one hand they relate to the way of defining the base value and its uniformity for all cases, and on the other hand to the number of reduction factors ranging from 2 to 11. Such a range also points to the existence of significant differences in the very approach to define the base saturation flow value and influential factors.

In general, the approach to the base saturation flow rates according to lane type (Akçelik, Finnish model and Stanić) is justified, and the surveys conducted by Stanić indicated that there are differences in the base saturation flow rate between the straight lanes and the turn lanes – turn lane saturation flow never achieves the straight lane saturation flow rate (Stanić 1991).

Within the context of analysing the saturation flow calculation procedure the question arises whether it is necessary to form a more complex model to determine saturation flow rate (from the aspect of greater number of influential factors), as an approximation of the situation really occurring at an intersection; and secondly, to what extent such procedure is appropriate to be applied from the aspect of the model end users? Does a smaller number of reduction factors present in the procedure affect the accurate estimate of saturation flow value in the specific cases?

The practice indicates the tendency to form procedurally more simple procedures which theoretically interpret the greatest number of standard cases and provide a simple way to obtain the output with relatively high degree of reliability.

However, the overview provided in Table 3 indicates that there is no unique attitude to the essence of the saturation flow – in a way all procedures are universal and local at the same time. In such circumstances, the surveys on the level of separate entities (countries and cities) are gaining in significance – the best approach always is to check the saturation flow rate in local circumstances for local conditions, along with intersection appearance, driver behaviour, fleet structure and age, etc.

3. Some More Important Results of Saturation Flow Survey in Serbia

Based on the surveys carried out in about ten cities/towns of the ex-Yugoslavia, in the procedure of analytical determination of saturation flow value Stanić (1991) proposes three types of saturation flow: ideal, operative (base) and actually realized. The ideal saturation flow represents the basic, starting rate having unique value of 2290 pcu/hr obtained on the basis of maximum vehicle flow averages in six-second intervals during green phase.

The ideal saturation flow is a theoretical value, in essence, connected with the most favourable conditions in the traffic flow and environment (almost homogenous flow consisting only of vehicles; disciplined, trained, skilled and aggressive drivers; straight lane; geometrically accurately shaped intersection; modern carriageway without any gradient; favourable weather conditions; no disturbances caused by pedestrians or other vehicles and alike.

Taking into account that ideal conditions at an intersection are difficult to achieve in reality, an operative-base saturation flow value has been defined as the base

Table 3. Saturation flow calculation procedures – basic data

Procedure	Number of base saturation flow value	Way of defining base values	Number of reduction factors
Webster – 1963	1*	Defined in terms of intersection approach width	7
HCM – 2000	1	Unique, uniform value for all cases	11
HBS – 2001	3	Defined on the basis of average headway value for different lengths of green phase duration	2 (5)**
Akçelik – 1980	9	Defined in the function of traffic lane use and type of intersection environment	4
DANCAP – 2002	4	Defined in the function of average headway value for various types of movement at intersection	2
Finnish model – 1996	6	Defined in terms of traffic lane use	5
Stanić – 1991	3	Defined in terms of signal plan type and traffic lane use	4

* defined in terms of geometric layout
** 2 quantificationally most influential ones out of the offered 5 are used in the model

value with which calculation is initiated, and for which it has been determined to rely on two dominant factors: traffic lane use and the signal plan type where saturation flow is generated in.

The relations between the saturation flow rate to signal plan type in the research was made by quantifying the mutual flow interactions to different types of conflicts at an intersection.

The straight lane base saturation flow values obtained by this research range from 1600 veh/hr, for the signal plan in which the straight direction is serviced concurrently with the opposing left turn (two-stage signal plan), to 2120 veh/hr, for the cases in which the straight flow is realized without any conflicts by non-priority flows.

Reduction of above defined straight lane base saturation flow value is predominantly influenced by two factors: traffic flow structure and the size of the city where intersection is located in. The investigations showed that different saturation flow values are obtained when the experiment with identical conditions is conducted in the cities having different sizes.

This statement can be explained with the difference in the driver's behaviour during the queue discharge process and its dependence upon the average length and time duration of individual trip made in the systems having different sizes.

More recent surveys of the straight lane saturation flow value at intersections in Belgrade (Čelar 2007) were carried out by applying the technique of direct determination of saturation flow value based on individual headway values during queue discharge process.

The measurements were carried out by manual technique using a specific measuring device capable automatically to monitor the time bases and records of the data recorded. The surveys were conducted for the straight lane at eight intersections. The following three conclusions were derived from the analysis of the obtained results:

- queue discharge process represents individual characteristic of an intersection, dependable on the specific traffic conditions, environment conditions and the applied management parameters; the results and conclusions of the surveys conducted at one intersection, regardless of the sample size, cannot be generalized to the level of the entire network;
- behaviour of the first four vehicles in the queue, i.e. the achieved headways, differ from other vehicles in the queue; the obtained saturation flow value for this group of vehicles is lower by 10÷15% compared with the remaining queue;
- by observing the diagram of the queue discharge at intersections, it is noticed that there are three zones of saturation flow value, as follows (see Fig.):
  – the first zone, with rapid increase in saturation flow value, in the diagram defined up to the position of the fifth vehicle in the queue, resulted as a consequence of start-up lost times and commencement of the continual queue discharge process,

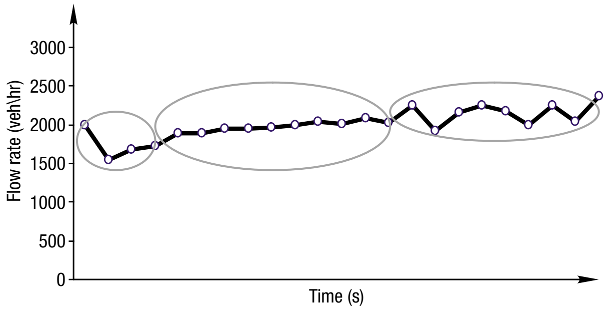

Fig. Saturation flow value – change during green phase

  – the second zone, with relatively stable or mildly increasing saturation flow value, and
  – the third zone, with constant saturation flow value variations, presented until the end of the green phase.

Čelar's studies of some attributes of driver behaviour throughout green phase duration (Table 4) show that some drivers use also, so called, clearance intervals (say, all-red interval) in the signal plan – such drivers' indiscipline is 'useful' for saturation flow rate, but it is outside the usual rules prescribed for the drivers.

From the analysis of the results obtained at the observed intersections it may be concluded that amber light duration (standard time duration 3.0 s) is used within the limits from 40 to over 100%.

In addition, it was established that the registered saturation flow rate does not depend on the way amber light is used. If we observe dependence of amber light use and the relation of the number of saturated cycles in the total sample (a kind of saturation degree during measurement period), the rule is noticed that higher saturation degree ensures higher degree of amber light utilisation.

However, that this is a necessary, but not sufficient condition is shown by certain deviations (example recorded at Ušće intersection – 93% saturation cycles). Relation between the number of saturated cycles and the cycles in which use of amber light had been registered was used as another indicator. It was determined that simultaneous high values of both observed indicators (close to zero) result in high degree of amber light utilization.

In other words, for intersection approaches with high degree of saturation (exceeding 85%) and frequent amber light use (also exceeding 85%), in average amber light is used 2.7 seconds or 90% of its total time duration intended for movement – Table 4.

The values of start-up lost time – Table 5, obtained by the surveys, are ranging in average from 0.7 to 1 second. The analysis determined that there is no correlation between the value of start-up lost time and the achieved saturation flow value within the observed green phase, and also that there is no dependence between the obtained values and other influential factors (observation periods, intersection location and the prevailing conditions at intersections).

Table 4. Straight lane saturation flow and other data – measurement results by registering the headway

Intersection name	Average time of amber light use (s)	Saturation flow (veh/hr)	Length of green light (s)	Relation of number of measurements/ saturation cycles/cycle in which passing through 'amber light' was registered
Rudo	3.36	2195	22	40/39/39
Karađarđev trg	2.45	1967	17	70/58/55
Hajat	2.29	2209	38	35/30/27
Južni bulevar	2.10	1818	31	27/12/10
Cvijićeva	1.88	1856	42	36/15/14
Ušće	1.50	2169	38	30/28/22
Palmotićeva	1.25	2011	32	27/16/14
London	1.21	1791	34	28/14/8

Table 5. Straight lane saturation flow and start-up lost time by locations

Intersection name	Average value of start-up lost time (s)	Achieved saturation flow value (veh/hr)	Location of intersection within the system	Survey period	Prevailing conditions during survey
Ušće	0.73	2169	Fringes	Peak	Saturated
London	1.18	1791	Centre	Off-peak	Partially saturated
Palmotićeva	0.73	2011	Fringes	Off-peak	Saturated
Tošin bunar	0.31	2000	Outskirts	Peak	Partially saturated
Južni bulevar	0.88	1818	Outskirts	Off-peak	Partially saturated
Dž. Vašingtona	0.29	2000	Fringes	Off-peak	Partially saturated

General comparison of the results for the straight lane saturation flow value in the studies of Čelar (2007) and Stanić (1991) shows that the obtained results are similar (Table 1), however, it can be concluded that the saturation flow rate obtained in 2007 is somewhat higher than those referred earlier. The probable reason for this is different circumstances under which queue is discharged at intersections: changes in driver behaviour, differences in management methods, traffic signal operation, traffic regime at intersections, fleet structure and characteristics, etc. This shows that the circumstances in which saturation flow is studied are changing as time passes.

It is interesting that Čelar (2007) did not register maximum saturation flow values referred by Stanić (1991) at the same intersection – centre of Belgrade, London intersection.

At this intersection maximum saturation flow values are registered in the traffic regime without any turnings and without marked and reserved 'yellow lanes' for public transport vehicles (Stanić 1991). In the meantime at this intersection 'yellow lanes' came into use, what reduces saturation flow rate both in the non-reserved lane, what was registered by Čelar (2007).

However, possible cause for saturation flow rate reduction is the influence of smaller width of traffic lane (2.85 m) reserved for public transport vehicles and use of high curbs – because of these measures queue discharge process is very much influenced by lateral disturbances (public transport vehicles), resulting in the decreased saturation flow value.

4. Conclusions

The increase in the straight lane saturation flow rate is noticeable in the results obtained by the studies conducted by (Stanić, 1991) and later by Čelar (2007), from 2120 pcu/hr to 2150 pcu/hr. Compared with the value referred by Webster (Webster, Cobbe 1966) these values are higher by 15%, what is not negligible. The maximum saturation flow value registered by Stanić (1991) of 2120 pcu/hr increased to 2209 pcu/hr (Čelar 2007). This is a small increase, not significant by the quantity itself.

The surveys confirmed that in the conditions when all intersections are equipped with traffic signals, constructed with similar and unified curve radii, gradients and lane widths, any influence of geometric layout on the saturation flow rate is out of the question.

Putting saturation flow rate by (Stanić 1991) into the context of signal plan type it is recorded as not completely confirmed by the surveys conducted by (Čelar 2007), but not rejected either.

The analysis of the use of the green phase by the drivers shows that occurrence of higher values of the effective green time at an intersection (higher percentage of utilisation of amber light), is not associated with the actually realized saturation flow values, but exclusively with the conditions in which the queue is discharged. Presence of higher percentage of saturated and oversaturated states at an intersection directly affects the increase in the effective green time and/or traffic lane capacity.

Saturation flow rate measurement technique based on the headway value of adjacent vehicles in the flow, Čelar (2007), in combination with simple software supported survey technique, justified the expectations and enabled the researcher to obtain all necessary data which describes the queue discharge process on intersection approach. At the same time, this technique is easy to implement and requires no special technical conditions for its implementation.

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