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Impact of Saturation Flow Changes on Performance of Traffic Lanes at Signalised Intersections

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Abstract

The paper presents analysis of saturation flow variability in traffic signal cycles during periods of congestion on the basis of empirical measurements. The purpose of this study was to investigate the impact of adverse weather conditions on the capacity of entry lanes. The empirical research was conducted in period 2007 – 2009 in three Polish cities. Investigated were lane groups with through traffic and geometrical characteristics corresponding to basic conditions in calculation methods and focused on detailed analyses of departure headways between vehicles, especially during the middle interval of the green signal of variable length, depending on drivers' behaviour. It was shown that saturation flow in traffic signal cycles at individual intersections is a random variable which can be described by gamma or normal distribution. Measurements' results show noticeable impact of different weather conditions on the saturation flow. The last part shows regression analyses which were conducted to accommodate numerous saturation flow determinants. The paper presents practical, aggregated models for prediction of basic saturation flow together with a proposed scale of efficiency of driver's behaviour, which is largely determined by traffic conditions. Simulation research enabled the authors to determine capacity variability and its impact on traffic performance (delay and vehicle queues).

Keywords: saturation flow variations; empirical research; capacity; traffic signals; reliabilty;

1. Introduction

The high level of vehicle ownership coupled with a limited road network means that even in stages of early conceptual geometrical and traffic control design, potential traffic congestion must be taken into account. At high level of saturation of an intersection entry lanes even the modern traffic controller works as a simple fixed-time traffic controller, i.e. base on signal settings with a maximum duration of the green signals.

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In urban areas signalised intersections usually determine the efficiency of urban road network. One can notice that rainfalls or snowfalls during peak hours often add to traffic problems of urban arteries already operating at their peak capacity. This tends to be attributed to a higher-than-usual use of cars at periods of adverse weather conditions. Despite the fact that the issue of traffic congestion is far from new for researchers, work on capturing and describing factors which gravely affect variability of saturation flows and a more detailed assessment of traffic performance in states of congestion has been embarked upon only recently ([Brilon 2008, Mahmassani 2010]).

Adverse traffic performance are particularly noticeable in the rain, snow or fog when congestion measured in terms of delay and length of queues is significantly higher than normal. Current capacity analyses methods do not take into account the variability of saturation flows at periods of adverse weather conditions, variations in roadway surface wetness (except for the Canadian method) and overlook other factors affecting saturation flows, e.g. lane location within a group of lanes, area of intersection, time of day and traffic congestion.

Variability of saturation flows is directly translated into variability of capacity, which is the basic characteristic used in designing of geometry and traffic lane assignment at intersections and in estimating measures of traffic performance. Lack of data on the variability of the capacity of a single lane or a group of lanes leads to hard-to-explain congestion on entry lanes to signalised intersections. The current range of congestion variability at intersections and streets inspired the authors to embark on a quest for such more accurate capacity estimation methods that would incorporate factors leading to periodic decline of congestion's, which, in turn, would lend themselves to potential response measures by means of traffic engineering methods. This paper outlines the results of research into variability of saturation flows in through traffic lanes and empirical prediction models of basic saturation flow, as well as graphs illustrating the adverse impact of weather conditions on the capacity and reliability of lane operation.

2. Description of empirical research

Field measurements involved recording time headways between the rear bumpers of subsequent vehicles leaving entry on stop line during the display of the following signals: red/amber, green and amber - in lanes assigned for through traffic. Additionally, departures of vehicles on red signal were recorded. In these measurements recorded were also types of vehicles; passenger cars, vans, trucks and buses and trucks with trailers. In the course of observations use was made of special microprocessor push button metering devices operated by observers (Fig. 1). Additionally, in the course of the red signal, the number of vehicles remaining in the lane after the termination of the green signal (residual queue) was recorded. Recorded results were used to build a database for analyses of the basic value of saturation flow.

Figure 1. Sample research site and metering devises RP5 and RP6

Empirical research was carried out on selected signalised intersections, carrying through traffic in single and multiple lane groups (2, 3 lanes) during morning and afternoon peaks. The measurements were conducted for each lane (research site) separately in various weather conditions.

Research sites were located mainly in Krakow. To differentiate between cities on account of their size, additional small-scale research into traffic in selected research sites in Warsaw and Rzeszow was also conducted over a number of days.

2.1. Assumptions relating to research sites

For empirical measurements, research sites were selected in a manner ensuring that the geometrical and traffic characteristics of entries under analysis correspond to basic ideal conditions employed to determine the basic values of saturation flow according to [Poland 2004, Canada 2008, HCM 2000]. The research was confined to isolated urban intersections. Below are given the major assumptions:

– in the course of the green signal, there should be full traffic saturation, which is translated into the existence of residual queues remaining in the course of a measurement period of at least 40 signal cycles,
– traffic is not held up and the area of the intersection is not blocked, which means that the queue from the upstream intersection does not have any impact on the vehicles leaving the entry under analysis,
– the queue of turning movement stays in the additional separate turning lane and does not block through traffic,
– the number of lanes feeding traffic is the same on the entry to the intersection as on the upstream section,
– the number of lanes at exit is equal to number of lanes at entry,
– small vertical grade at the entry ($i \pm 1{,}5\%$), typical lane widths (approx. 3.5 m), good technical condition of the surface including of tramway tracks, potentially large radius of curvature and small intersection angle ($R>100$, $\gamma<10^{o}$). These factors do not affect either drivers' behaviour or traffic dynamics,
– stops located in a bus bay, outside the carriageway or in a lane dedicated to public transport.

2.2. Database

In the wake of field research conducted in 2007–2009 at 11 entries to intersections in Krakow and 6 entries to intersections in Warsaw and Rzeszow carrying through traffic in 1, 2 and 3 lanes, a database has been built containing departure headways between vehicles and lengths of residual queues. On balance, 38 275 signal cycles were recorded with a total research duration of 1 155 hours.

2.3. Factors potentially influencing saturation flow incorporated into the research

Measurements of headways were conducted in conditions similar to ideal basic conditions [Poland 2004] and therefore the authors avoided impacts of certain factors e.g. lane width (other than 3.5m), entry grade, existence of bus stops without bus bays, existence of a short entry lanes. Both the objective of the analyses and the degree of detail (cycle by cycle) demanded need for an analysis of other relevant factors partially presented in foreign literature [Sadek 2004, Tarko 2005, Webster 1966]. Factors which were distinguished were subsequently defined as qualitative and quantitative variables. These variables were divided into two groups depending on type of identified variability, i.e. into deterministic and random variables.

Measurements were conducted during morning and afternoon peaks for each lane (research site) separately for the following groups of weather conditions:

a) sunny,
b) cloudy, dry road surface,
c) long and short duration of rainfall (Long duration of rainfall is a rainfall of variable intensity, usually continuous with possible short rain-free spells, lasting a better part of the day, the whole day or several days in a row. Short duration of rainfall means a sudden rainfall of variable intensity, on a day with predominantly sunny or cloudy skies and dry roadway surface).
d) snowfall, wet and snowy roadway surface,
e) cloudy, wet surface,
f) cloudy, foggy, dry road surface.

The analyses included other independent variables, defining, e.g. drivers' behaviour, impact of queue length, size of an intersection area, location of a lane in a group of lanes, impact of traffic composition, type of lighting, share of the green signal in cycles.

3. Method of analysis

The analysis approach is based on the departure headways between pairs of passenger cars. Authors eliminated departure headways between pairs of vehicles other than between passenger cars (heavy and delivery vehicles), but the impact of these vehicles on headways for pairs of passenger cars was not eliminated entirely. A significant impact on headways between pairs of passenger cars was ascertained wherever the percentage of heavy vehicles in the traffic in a lane was high. Despite the fact that the analyses were solely carried out for pairs of passenger cars, their speeds and headways depended on how heavy vehicles preceding pairs of passenger cars moved. During the initial interval of the green signal, in determining the value of lost time t_{st} in each cycle, the authors considered solely passenger cars, and elimination of one of the departure headways (whenever one of the vehicles in the pair was not a passenger car) in this interval, entailed elimination of the entire cycle from the analysis.

The intensity of departure during the middle interval of the green signal, in a signal cycle was computed from the $3600/t_{n,s}$ quotient, where $t_{n,s}$ stands for average departure headway between pairs of passenger cars during a state of saturation. It can be seen from Fig. 2 that average departure headway between vehicles varies in line with weather conditions. In consideration of differences between the values (which values were usually higher) of departure headways during the initial interval and the last interval of the green signal, it was resolved that the method should accommodate a variable number of eliminated f and k headways between vehicles (Fig. 3) depending on the existing weather conditions. The beginning and end of the middle interval was determined on the basis of comparative analysis of adjacent departure headways of subsequent vehicles passing the stop line. In the analyses use was made of the t-Student parametric test at relevance level of $\alpha = 0{,}05$ and of an assessment of the shape of the moving average for subsequent departure headways in various weather conditions (last interval).

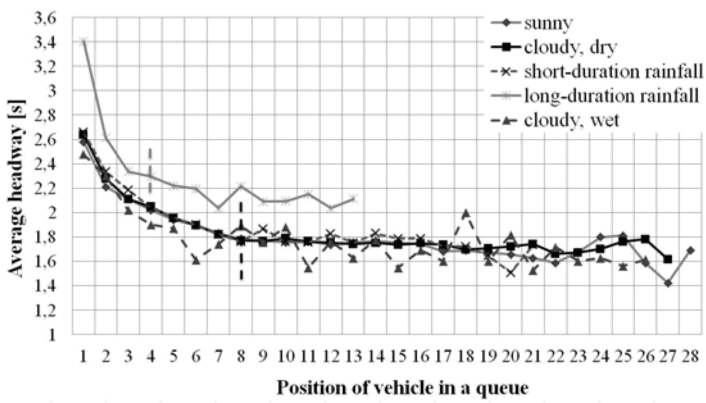

Figure 2. Departure headways between of subsequent vehicles departing during the green signal in various weather conditions during the afternoon peak at a one-lane entry. Size of data 30 to 1 249 vehicles. For cloudy sky, wet road surface size of data 7-12 vehicles.

Table 1. Ranges of middle intervals of green signal during states of saturation

Weather conditions	One-lane research site	Two-lane research site	
		Inner lane (left)	Outer lane (right)
Sunny	From 8 to 23 vehicles	From 8 to 28 vehicles	From 3 to 19 vehicles
Cloudy, dry	From 7 to 25 vehicles	From 8 to 32 vehicles	From 6 to 13 vehicles
Cloudy, wet	From 4 to 26 vehicles	From 3 to 23 vehicles	From 3 to 21 vehicles
Rainfall, short-duration	From 6 to 19 vehicles	From 5 to 26 vehicles	From 3 to 20 vehicles
Rainfall, long-duration	From 4 to 12 vehicles	From 4 to 7 vehicles	From 4 to 14 vehicles
Cloudy, foggy, dry	–	From 5 to 22 vehicles	From 3 to 12 vehicles

Analyses of traffic lanes (one-lane research site and an inside lane in a two-lane research site, table 1) indicate that the more adverse the weather conditions, the shorter the middle interval. The ranges for the outside lane differ from the ranges for the inside lane. The differences arise, amongst others, from the “hidden” impact of heavy vehicles when there is a noticeable vehicles impact (U_c for the inner and outer lanes stands at 1.6% and 17.3% respectively). Heavy vehicles effect not merely the vehicles immediately following them, but likewise the flow of subsequent vehicles (elimination of pairs of vehicles other than passenger cars failed to fully remove this impact).

To recapitulate, drivers need less time (less lost time) to reach a steady level of departure headways between vehicles during the middle interval of the green signal phase under adverse weather conditions, than in sunny or cloudy weather with dry road surface (Fig. 2, table 1). In favourable weather conditions, with good visibility more drivers will be involved to attain high intensity of departures during the middle interval than in adverse weather conditions (lower intensity of departure during the middle interval).

Increased departure headways between vehicles during rainfalls can also lead to the shortening of the green signal whenever a wrong, excessively short time unit extension of the green signal is input into the control algorithm. Such a situation took place itself at an intersection under analysis (Fig. 2). The curve for long duration rainfall ends at the 13th vehicle, despite a noticeably longer queue on the entry.

Below defined and illustrated is a method of calculation of a lost time in the initial interval (Fig. 3) by *f* of the initial vehicles ($t_{st,j}$), average saturation headway during the middle interval ($t_{n,s}$) and the stopped delay ($t_{z,j}$) in a single *j*- traffic signal cycle - arrived at on the assumption, that traffic is moving during the red/amber, green and amber signals. This research approach permitted recording the full headway duration between the beginning of the red/amber signal and the passage of the rear of the first vehicle, in a scenario when the vehicle made a too-early start.

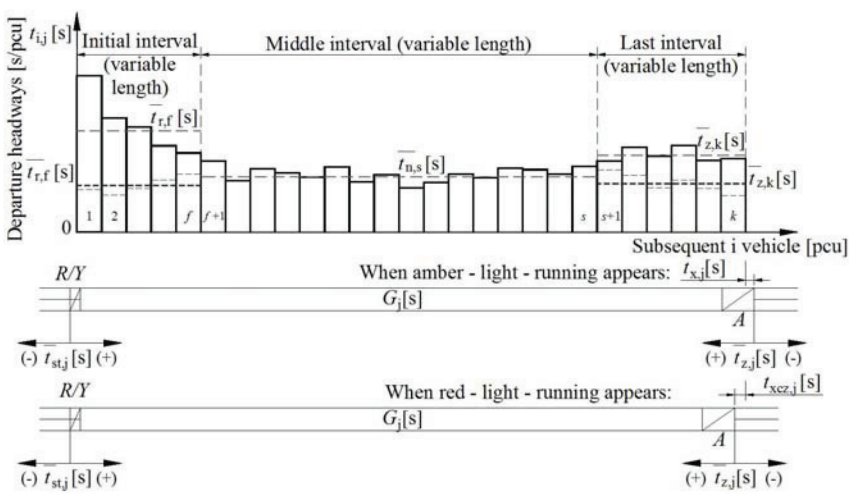

Figure 3. Model of departure process during green signal of *j* cycle

$$\overline{t_{r,f}} = \frac{\sum_{i=1}^{f}(t_{i,j})}{f} \text{ [s]}; \qquad \overline{t_{n,s}} = \frac{\sum_{i=f+1}^{s}(t_{i,j})}{s-f} \text{ [s]}; \qquad \overline{t_{z,k}} = \frac{\sum_{i=s+1}^{k}(t_{i,j})}{k-s} \text{ [s]} \qquad (1, 2, 3)$$

where: $\overline{t_{r,f}}$ – average length of time between the first f vehicles during the initial interval, $\overline{t_{n,s}}$ – average saturation headway in the middle interval determined for $(s - f)$ vehicles, $\overline{t_{z,k}}$ – average length of time between last $(k - s)$ vehicles, in j cycle,

$$\overline{t_{st,j}} = \overline{t_{r,f}} - \overline{t_{n,s}} \text{ [s]}; \qquad \overline{t_{z,j}} = \overline{t_{z,k}} - \overline{t_{n,s}} + t_{x,j} \text{ [s]}; \qquad \overline{t_{z,j}} = \overline{t_{z,k}} - \overline{t_{n,s}} - t_{xcz,j} \text{ [s]} \qquad (4, 5 ,6)$$

where: $\overline{t_{st,j}}$ – average lost time during the initial interval by the first f passenger cars, in j-traffic signal cycle , $\overline{t_{z,j}}$ – average time lost to stop when vehicles do not enter during the red signal (5) and when vehicles enter during the red light $t_{xcz,j}$ (6)

4. Statistical analysis of saturation flow

4.1. Analysis of variability distribution of base saturation flow S_w

In capacity calculation methods [Poland 2004, HCM 2000] it is commonly assumed that the base value of saturation flow is fixed. The only exception is the Canadian method [Canada 2008], in which a few different (fixed) values of basic saturation flow S_0 are given for different cities and activities in the vicinity of streets. The analysis of variability of saturation flow presented in the paper will be based on variability of departure intensity during the middle interval of the green signal of traffic signal cycles under base conditions outlined in section 2.1. Theoretical distributions were fitted to empirical data with the use of the Kolmogorov-Smirnov test at a level of relevance of α = 0.05. The following theoretical distributions were considered: normal, log-normal, Gumbel, gamma and Weibull. For aggregated data from a few cities (Krakow, Warsaw, Rzeszow) the Weibull distribution revealing noticeable left-sided asymmetry has occurred the best (parameters: $\alpha_W = 2160$, $\beta_W = 8.74$). The shape of the distribution for the aggregated data depends on sizes of samples recorded in various weather conditions (Fig. 4). For the aggregated data, the ratio of the number of cycles with rainfall to the total number of cycles corresponds to the average ratio of days with rainfall to all the days in year 2009 in cities of Krakow, Rzeszow and Warsaw. Consequently, the aggregated distribution S_w depends on the location and weather conditions during the year under analysis.

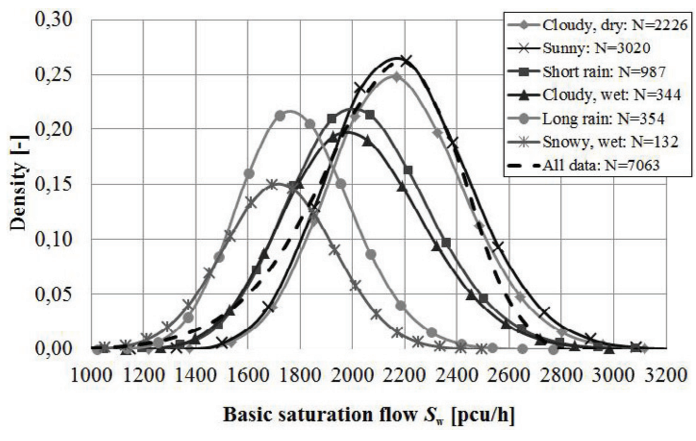

Figure 4. Density function S_w [E/h] for aggregated data from 8 one-lane sites in Krakow, Rzeszow and Warsaw broken down by group of weather conditions (N – sample size)

Figure 4 indicates that the more favourable weather conditions are for departures, the higher the modal values of base values of the saturation flow in adjusted theoretical distributions. In the case of the most adverse weather conditions, i.e. snowfalls, normal distribution was ascertained, and in the case of the remaining weather conditions the gamma distribution proved most appropriate. One can distinguish three distinct groups of weather and surface conditions which essentially differentiate the base saturation flow S_w values. These are; dry road surface in sunny or cloudy weather, wet road surface in short duration rainfall or cloudy weather and wet road surface with long duration of rainfall or snowfall. The differences in modal values of saturation flow S_w between these groups range between 150 and 250 E/h. The spread of base saturation flow in traffic signal cycles for different types of weather conditions is similar, as it stands at ± 600E/h.

4.2. Regression analysis of variability of saturation flow S_w

The method of analysis was selected on the basis of the number and character of dependent and independent variables (quantitative and qualitative variables). The authors searched for a simple method for which model assumptions would be met. Moreover, a method whose result, apart from a quantitative description of the impact of individual independent variables on the dependent variable will yield model equations usable in practical predictions of basic saturation flow S_w. After analyses, it was determined that the linear model of multiple regression should be selected.

By eliminating of heavy vehicles, prediction models of base saturation flow S_w, expressed in passenger cars per hour were developed, incorporating however, as previously stated, partial impact of the movement of heavy vehicles. By analysing regression models S_w obtained separately for each site on multi-lane entries, it was observed that with a share U_c of heavy vehicles standing at below 10%, the „hidden" impact of heavy vehicles was not statistically relevant ($p > \alpha$) in modelling S_w. It was also shown that when the share of heavy vehicles stood at below 10%, identified was also an additional, statistically relevant, impact arising from the location of the lane on the entry. The division employed to reflect the „hidden" share of heavy vehicles does not capture all potential scenarios, as it stems from the limited range of empirical measurements conducted. Table 2 shows the application of the above division in regressive equations of models of prediction of base saturation flow S_w for through traffic.

Symbols used in table 2:
V_d and Q_m – demand flow and queue at the beginning of the green signal,
S_r 0_1, *L_r 0_1*, *Sn_w 0_1* – short-duration rainfall, long-duration rainfall and snowfall (wet),
Sm 0_1, *Med 0_1* – area of intersection: small (<1200m^2] , medium (1200 m^2 ÷ 2400m^2] and large (>2400m^2],
Left 0_1 – left lane (inner lane), *Aft 0_1* – afternoon peak, U_c – share of heavy vehicles, *N* – sample size.

Table 2. List of aggregated equations of multiple regression of estimators of base saturation flow for morning and afternoon peaks data in Krakow, Warsaw and Rzeszow

Models division	Measurement site	Multiple regression equations	Variable characteristics					
			Var.	$\overline{x}_i$	min	max	σ	ν
I	One lane $\overline{U}_c \le 10\%$	$\mathbf{S_w = 1689 + 82 \cdot (t_{st}) + 5 \cdot (Q_m) - 175 \cdot (L\_r\ \ 0\_1) - 243 \cdot (Sm\ 0\_1) \pm 160}$ ($N = 2834$) $R = 0.78$ $R^2 = 0.61$	S_w [pcu/h] observe	1907	887	2679	255.19	0.13
			t_{st} [s]	1.97	-3.9	8.3	1.82	0.93
			Q_m [pcu/cycle]	24	5	65	10.62	0.45
II	**a)** Left and right lane when $\overline{U}_{c,Left} \le 10\%$ $\overline{U}_{c,Right} \le 10\%$	$\mathbf{S_w = 1249 + 91 \cdot (t_{st}) + 20 \cdot (Q_m) - 138 \cdot (L\_r\ \ 0\_1) + 85 \cdot (Left\ 0\_1) \pm 150}$ ($N = 522$) $R = 0.71$ $R^2 = 0.50$	S_w [pcu/h] observe	1899	1354	2459	213.12	0.11
			t_{st} [s]	0.78	-1.7	5.0	1.04	1.33
			Q_m [pcu/cycle]	27	13	50	4.74	0.17
	b) Left and right lane when $\overline{U}_{c,Left} \le 10\%$ $\overline{U}_{c,Right} > 10\%$	$\mathbf{S_w = 1810 + 68 \cdot (t_{st}) + 2 \cdot (V_d) - 502 \cdot (U_c) - 113 \cdot (L\_r\ \ 0\_1) - 213 \cdot (Sn\_w\ \ 0\_1) \pm 176}$ ($N = 1819$) $R = 0.67$ $R^2 = 0.45$	S_w [pcu/h] observe	1912	1060	2580	238.76	0.12
			t_{st} [s]	1.43	-5.0	7.7	1.86	1.29
			V_d [pcu/cycle]	28	0	83	14.19	0.50
			U_c [-]	0.047	0	0.46	0.08	1.73
III	Left, middle and right lane when $\overline{U}_{c,Left} \le 10\%$ $\overline{U}_{c,Middle} \le 10\%$ $\overline{U}_{c,Right} \le 10\%$	$\mathbf{S_w = 1577 + 83 \cdot (t_{st}) + 9 \cdot (V_d) - 196 \cdot (L\_r\ \ 0\_1) - 73 \cdot (S\_r\ \ 0\_1) - 84 \cdot (Med\ 0\_1) + 165 \cdot (Aft\ 0\_1) \pm 166}$ ($N = 6042$) $R = 0.72$ $R^2 = 0.52$	S_w [pcu/h] observe	1964	1014	2842	240.60	0.12
			t_{st} [s]	1.62	-5.9	8.0	1.75	1.08
			V_d [pcu/cycle]	19	0	47	4.18	0.22

Below, short characteristics of selected investigated variables and variables statistically relevant from the equations featured in table 2 are presented.

Lost time during the initial interval t_{st}: this descriptive variable appearing in regression equations to describe time lost during the initial interval t_{st} used for the project, hardly lends itself to interpretation or use for calculation of base saturation flow S_w. For practical purposes, the authors introduced a rating scale of driving skills relying on lost time t_{st} (Fig. 5). The construction of a scale consisting of five efficiency bands originates in differences in drivers' behaviour in different weather conditions. Favourable weather conditions favour high intensity of departure flow during the middle interval of the green signal, which translates itself into a longer time needed after the beginning of green signal to achieve high intensity of flow departures ($t_{n,s}$) and, consequently, longer times t_{st}, generated by a larger number of vehicles f included in the initial interval of the green signal (table 1).

Weather conditions: Unfavourable weather conditions, including short and long duration rainfall, snowfall and fog markedly reduce visibility, which, in turn, contributes to a reduction in base saturation flow S_w.

The negative consequences of rainfalls or snowfalls can include poorer visibility (intensity of precipitation), a state of roadway wetness, activated windscreen wipers, lower atmospheric pressure etc.. They all contribute to the development of unfavourable road conditions, under which the majority of drivers will move less efficiently scoring "very low to average" on the driving skills scale (Fig. 5).

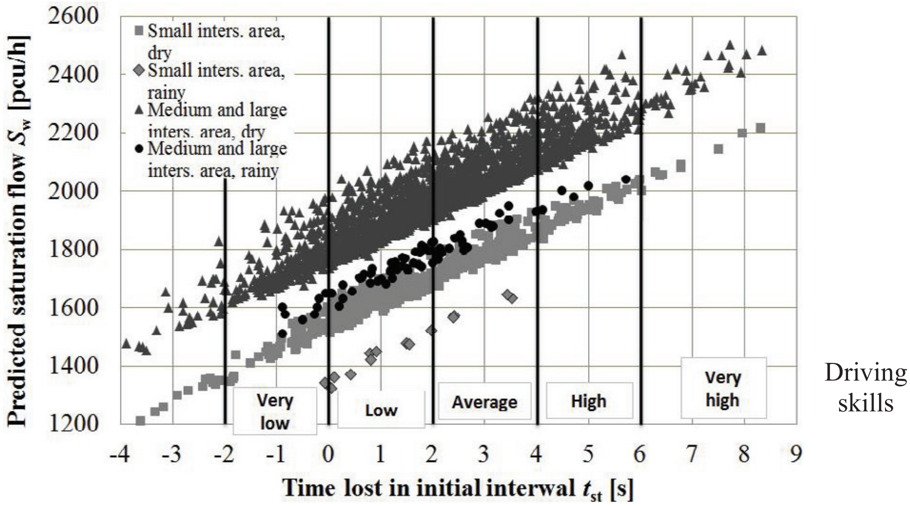

Figure 5. Graphic illustration of model I containing a proposed scale of driving skills

Apart from weather conditions and lost time during the initial part t_{st}, the following factors have impact on the basic value of saturation flow S_w:

1) *Queues of vehicles at the beginning of the green signal* Q_m *and demand flow in cycle* V_d: It was noted that the impact of a queue at the beginning of the green signal Q_m is related only to one lane entry and to the inside lane in a two-lane group with a small share of heavy vehicles (≤ 10%). In the remaining cases, the analysis ascertained stronger impact of demand flow V_d. The queue of vehicles Q_m is a measure of the lane saturation of the intersection entry. The higher the saturation of an entry, the faster the drivers leave the intersection, which, in turn, contributes to an increase in the base saturation flow S_w. Similar results were yielded in [Ahn 1987].

2) *Share of heavy vehicles in traffic flow:* The existence of heavy vehicles during the middle interval of the green signal will have an adverse impact on subsequent passenger cars leaving the queue, despite the elimination of departure headways for vehicles other than passenger cars from analyses, has an adverse impact on saturation flow in cases of a higher share of heavy vehicles in the traffic lane (Fig. 6). The authors also considered the impact of the share of vans, which however proved to be statistically irrelevant. More analysis of saturation flow rate fluctuation is needed.

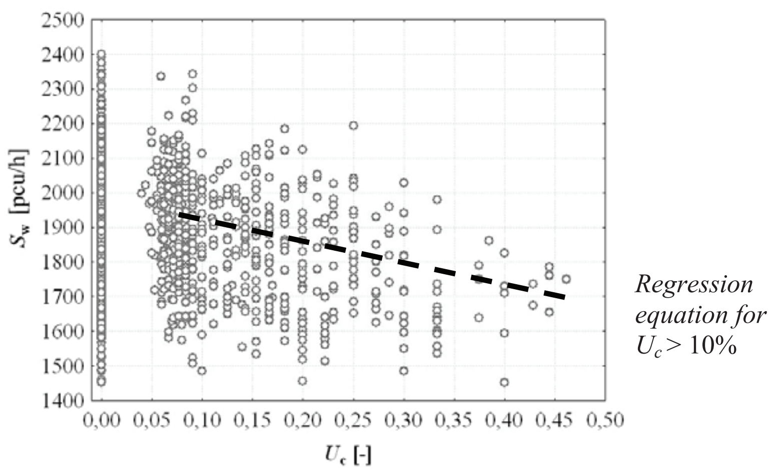

Figure 6. Dependence of predicted value of base saturation flow S_w on the share of heavy vehicles in traffic signal cycles (based on model IIb)

3) *Intersection's area size:* Three intersection's area sizes were taken for analysis: small <1200 m^2, medium: 1200–2400 m^2 and large: >2400 m^2). This showed that the factor significantly affects the base saturation flow S_w [E/h]. Small intersections, located mainly in the vicinity of housing estates and shopping centres (intense activity in the intersection's vicinity), have the lowest initial base saturation flows. Regression analyses were also used to investigate the impact of other variables, including length of the passage through the intersection, width of entry and exit, type of cross-section as well as location and type of development.

4) *Share of the green signal in the cycle (G/T):* The impact of adaptive steering characterised by significant differences in variable *G/T* (variability coefficient $\nu \geq 10\%$) causes that with higher values of *G/T,* the initial value of saturation flow S_w diminishes. The variable is not featured in models I, IIa, IIb and III, as it is strongly correlated with variables Q_m and V_d and explains the differences in S_w less accurately. The appearance of variable Q_m in models I and IIa indirectly stems from the *G/T* proportion. When the quantitative variable *G/T* registers low against a similar level of demand flow, queues of vehicles at the entry to the intersection will be greater, which inspires drivers to depart from the intersection faster. It was noted that the appearance of variable V_d in models results from insignificant differences in variable *G/T* in adaptive steering or fixed timed steering.

5. Impact of variability of saturation flow on traffic performance

In the previous chapters, the authors presented the impacts of unfavourable weather conditions on the base value of saturation flow. The results of measurements also laid ground for conducting of simulation research into the impact of weather conditions on capacity values and measures of traffic conditions. With a view to conducting further analysis, a simulation micro-model incorporating the variability of service and generation of traffic was built**.**

The simulation model was honed to accommodate parameters of a selected theoretical distribution for any vehicle position in a queue. The evaluation of the fit of theoretical distributions to empirical data carried out by means of the Kolmogorov–Smirnov test (Statistica program) showed that the most accurate theoretical distribution describing the variability of departure headways between vehicles in a queue with relevance of α = 0.05 was a log normal distribution ($d_{K\text{-}S} < d_{kryt,\alpha} = 1.36$). This distribution was used for modelling departures of vehicles in a cycle. The model allows the realisation of several kinds of demand flow variations in time according to: a) empirical profiles, b) theoretical parabolic profiles, both symmetric and non-symmetric, with different ratios of maximum intensity to average intensity in the course of analysis, c) theoretical sinusoidal profiles with a predetermined number of intervals and amplitude of change, 4) any other predetermined profile.

The capacity of entries to a signalized intersection is a variable dependent on random and deterministic factors. Variability of capacity variability originates mostly in variability of saturation flow and control parameters, including the length of the green signal as well as weather conditions. Fig. 7 shows results yielded by a simulation model. Fitted theoretical distributions of capacity are gamma and Weibull distributions.

Figure 7 indicates that weather conditions may lead to changes in the entry capacity, including its significant reduction. Capacity density functions for short green signals (G = 18 s) indicate lower variability in values than the same for longer green signals. It was determined that during periods of rainfall, capacity values are, on the average, 15.8% and 18.4% smaller - respectively for $\lambda = G/T = 0.3$ and T = 60 s (G = 18 s) and λ = 0.3 and T = 120 s (G = 36 s). Smaller differences in capacity values are occur in shorter green signals, as a result of reduced intensity departures in the initial interval. Differences increase as the duration of the green signal increases.

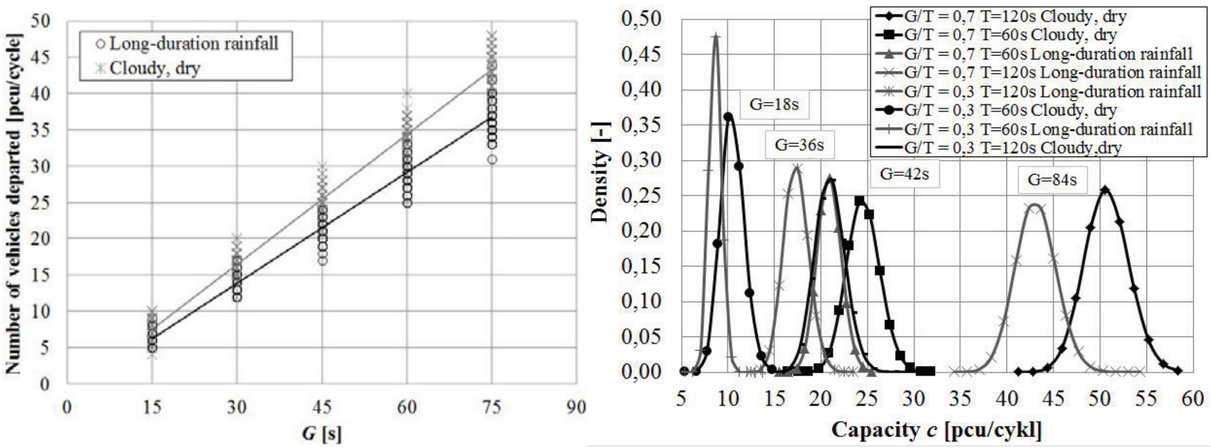

Figure 7. Relation between capacity and length of green signal and functions of capacity density c for $\lambda = G/T = 0.3$ and $\lambda = 0.7$ and $T = 60$ s and 120 s in different weather conditions

In order to investigate the impact of capacity variability on selected measures of traffic conditions, the authors conducted simulation research at a predetermined intensity of the demand flow and variable saturation flow S_w and variable control parameters. It was assumed that the value of demand flow depends on the assumption that for saturation flow S_w=1800 [P/h] the demand flow will be close to the lane capacity ($X = V_d/c \approx 1.0$). Five average values of saturation flows were determined S_w: 1400 [E/h], 1600 [E/h], 1800 [E/h], 2000 [E/h], 2200 [E/h]. The assumed values S_w stem from an empirically established range of variability of saturation flow (Fig. 4 and Fig 5, table 2) and illustrate the impact of weather conditions. In the graphs below, the relationships between selected measures of traffic performance (average delay and average residual queues) and a lane's saturation flow can be seen.

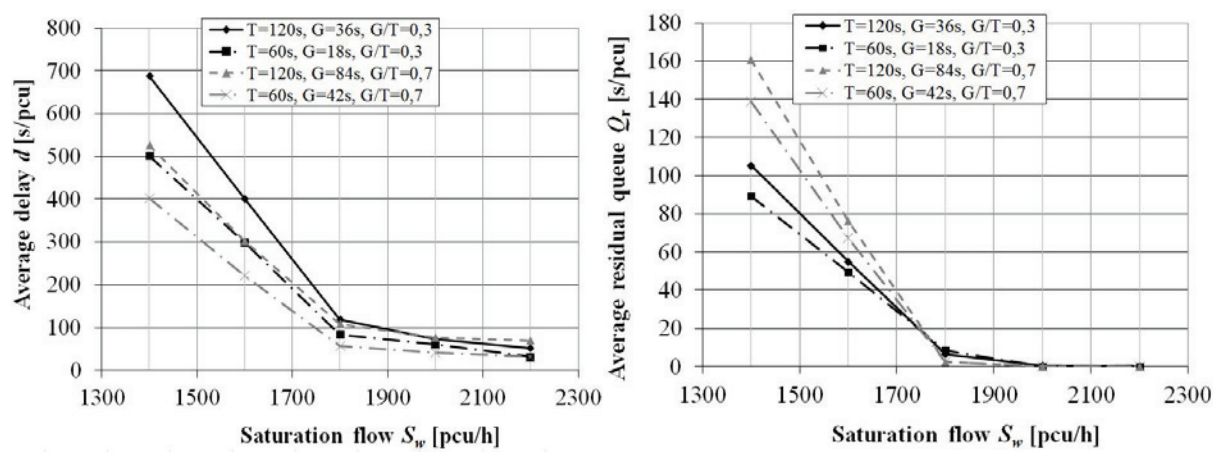

Figure 8. Relationship between average lost time and residual queues and saturation flow for $\lambda = 0.3$ and 0.7, $T = 60$ s and 120 s

The graphs (Fig. 8) show that in respect of traffic lanes operating at traffic volumes close to capacity, one can expect good traffic performance on days without rainfall (higher saturation flow) and unsatisfactory traffic performance in adverse weather conditions (long duration rainfall or snowfall, fog) for any given demand flow. Longer queues arising with a greater share λ of the green signal in the signal cycle stem from the way if investigations. For the same degree of saturation X to reveal itself against a higher value of λ, the demand flow must reveal markedly higher intensity, which leads to longer queues, which in the conditions of higher lane overloading increase also during the green signal. The graphs (Fig. 8) indicate that in respect delay, both the length of the cycle and of the green signal exert a comparable impact on average vehicular delay, whilst in relation to residual queues, a larger impact of the green signal's share in cycle, rather than the length of the cycle can be seen.

Conclusions

1) Variability of the value of saturation flow S_w in traffic signal cycles, in selected types of weather conditions (sunny, cloudy on dry and wet roadway surface, short and long duration rainfalls, snowfalls) is best described by gamma and Weibull distributions. The aggregated distribution S_w for data on all days of the year will depend on the number of days with unfavourable weather conditions in the year under analysis.

2) The relative decline in average saturation flow in relation to rain-free weather conditions stands at; 8.5%-12.3% in long duration rainfalls, ~3.6% in short duration rainfalls and approximately (based on less data) ~10,0% in snowfalls (wet roadway surface) and ~11.4% in cloudy or foggy weather with a dry roadway surface.

3) Growing demand flow (V_d) and queue of vehicles (Q_m) result in an increase in the initial values of S_w, due to more dynamic driving behaviour.

4) In multi-lane approaches to intersections, the impact of the lane's location itself affects the behaviour of drivers using the various lanes and variations in the share of heavy vehicles in these lanes are not without an impact either. (variable U_c),

5) The total area of the intersection is a factor affecting the initial value of S_w (similarly as in [Canada 2008, HCM 2000, Webster 1966]). This single factor captures also the indirect impact of an intersection's location and activities in the vicinity.

6) Assuming different levels of drivers' skills in various weather conditions and total areas of intersections, the designer can flexibly select the base value of saturation flow S_w to ensure adequate driver comfort. In view of the fact that models I, IIa, IIb and III feature a relevant random factor, it is recommended that, for design purposes, low and average levels of drivers' efficiency be assumed, which, in turn, should ensure higher reliability of an intersection's operation.

7) Given today's technology, which permits the use of sensors responsive to wet roadway surface or precipitation, it is possible to implement dedicated signal programmes allowing for adjustment of time losses during the initial period t_{st}, thereby ensuring adequate saturation flow S_w.

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