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Modelling Signalised Intersections Reliability of Functioning

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Abstract. The article addresses a fundamental aspect of traffic, i.e. the operation of traffic signals at intersections, in reference to the reliability theory. In many cases, when intersections carry substantial amounts of traffic, selecting control parameters to produce satisfactory traffic conditions is quite difficult. Design methods do not cover all possible situations which are the result of intersection geometry and location within the city. Neither do they account for reduced capacity in bad weather. Inefficient signal-controlled intersections have a strong influence on motorists, causing frustration and fatigue and eventually leading to risky behaviour in road traffic. Sustained congestion in urban areas has a negative effect on the residents and how they function in the urban environment. As a consequence, big city dwellers who drive grow accustomed to poor traffic conditions and are ready to accept some time lost at peak times. When designing traffic signals, the methods should relate to the size of the city and levels of traffic overload that are acceptable to motorists, rather than identify inferior levels of free flow only. This particular field of study is suited for the reliability theory as presented in the article. When analysing the reliability of groups of traffic lanes, we must be clear about boundary traffic conditions where the reliability state transitions into the unreliability state. The state of reliability is when an intersection operates seamlessly and traffic volume Q is below capacity C (periods in between peak times or at night-time). The article will show the division of the reliability state into levels. This helps to define the boundaries based on boundary values of selected measures of those traffic conditions that are of particular importance to us when managing junction traffic. Once these values are identified and geometry and weather factors are included, traffic signals can be designed more efficiently and urban traffic will improve as a result.

1. Introduction

When signal-controlled intersections become congested it is usually due to substantial traffic streams which are close to capacity or above it and feature variable traffic volumes, both weekly and seasonally. To define the level of service at intersection entries (table 1) road traffic engineers estimate capacity and delays using available formulas [1] whose mathematical notations build on empirical analyses of traffic or traffic simulations. Similar methods are used to determine other measures of traffic including queue lengths, number of stops and other indirect measures such as emissions [2], traffic noise, etc.
Capacity and traffic conditions are calculated and checked by designers. This is part of the design which they develop by following specific control parameters and set procedures [3]. Delay is calculated for a known level of traffic. Next, the level of service is defined which provides a qualitative measure of traffic conditions. If identified as poor (e.g. LOS IV), traffic conditions will cause delays that are not acceptable to most drivers in the period of analysis. This could be an hour or peak-hour quarter of an hour.

Table 1. Level of service criteria in the Polish method [1]

Quantitative measure	Qualitative measure	
Delay d [s/P]*	Level of service LOS	Traffic conditions
≤ 20	I	very good
20.1 ÷ 45.0	II	good
45.1 ÷ 80.0	III	average
> 80	IV	bad

*s/P – seconds/vehicle,

When designing intersection geometry and traffic organisation on the approaches, it is extremely important to be clear about anticipated traffic conditions. The objective is to achieve an LOS above IV on the analysed groups of lanes. If set at IV, the level of service means the design is unacceptable and must be corrected. These briefly presented analyses are usually conducted relative to an hour of peak time for a selected day of the week. No such analyses are conducted to understand intersection performance relative to a day or longer periods such as weeks, months or years. This particular field of study is best suited for the reliability approach [4, 5, 6]

2. Measures of overload

While delays are most often used to describe the LOS, other measures of traffic can also be determined such as those that identify traffic overload as it emerges. A simple measure of intersection performance which combines demand flow with lane capacity is the degree of overload X, defined as:

$$X = \frac{Q_d}{C} \text{ [-]} \tag{1}$$

where:

Q_d – volume of incoming traffic stream within an hour to a group of lanes [P/h] (P/h – vehicles per hour),
C – capacity of a group of lanes [P/h].

The degree of overload is one of the basic parameters used for estimating delays, queue length and number of stops [1]. A high degree of overload X means that queues remain K_p when the green signal ends G. Depending on the level of demand flow and its varying volume in relation to capacity, queues may build up for X as low as $X \geq 0.7$ [7]. A lane is defined as overloaded when queues persist over the duration of several signalisation cycles T or more. Figure 1 shows an example of an overloaded lane with very long queues and a repetitive pattern of heavy traffic over the next days. When lane demand flow significantly exceeds capacity over longer periods of time, traffic measures, including the length of queues persisting, become a function of overload duration until the degree of overload X has not gone down.

By combining into the quotient the length of residual queue K_p and capacity C in a cycle by cycle analysis, we can answer the following question: how many signal cycles before we can clear the intersection? Quotient K_p/C> 1 means that the queue which continues over the next green signal will not be dissipated.

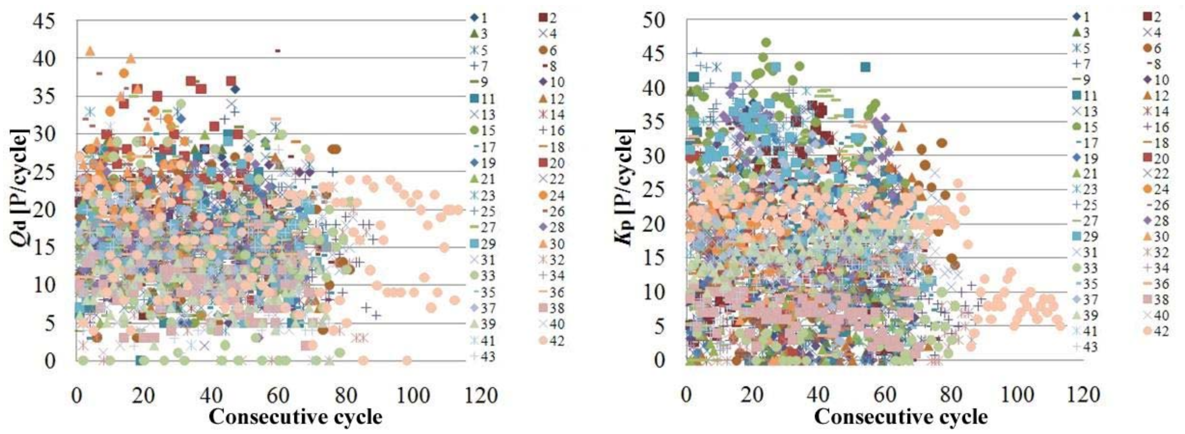

Figure 1. Spread of average demand flow Q_d [P/cycle] and average residual queues K_p [P/cycle] from 43 working days for a single lane approach at a selected signalised intersection in Krakow

To recap: the time for load X to increase until it reaches overload (end of lane performance reliability), duration of overload and queue dissipation time depend on:

- the shape of the profile and variability of demand flow (figure 2) over the period of analysis (random segment). For a 15 minute period of analysis the variability of demand flow within an hour can be described with rate k_{15} [8], peak rate w_s and other rates [7];
- degree of overload X within the analysed peak hour and queue length (random segment);
- control parameters G and T (deterministic segment) and saturation intensity variability S (deterministic and random segment) [9]. During states of overload accommodative signalisation is operated using maximal programmes (just as fixed-time signalisation);
- other random factors.

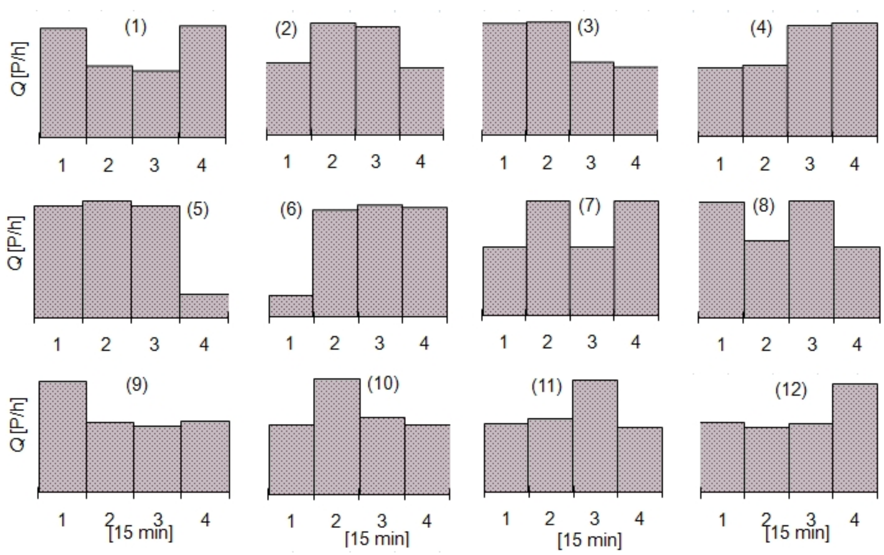

Figure 2. Theoretical profiles of demand flow variability in 15 minute intervals for traffic peak hour according to [7, 8]

3. Assessing the reliability of performance of lane groups with signalisation

The reliability of a traffic lane should only be assessed over longer periods such as a week, month or a year. The longer the time horizon, the more general and less reliable the analyses. As regards intersections, reliability can be studied over a day by analysing traffic and how it changes in the consecutive hours, quarters or shorter time intervals [10]. Some results are likely to be the same for specific days of the week or subsequent days of the week [11, 12]. There are two approaches to analysing lane group reliability:

A) The assessment is conducted by experts (road authorities, designers) who can assess the performance of lane groups, approaches or intersections based on how long periods of overload are at peak hours. The acceptable boundary time until an overload occurs (over which the lane in question performs reliably) can be determined based on:
- length of residual and maximum queues and their duration on the lanes,
- time lost (average, maximum, 85th percentile)

B) Traffic on a lane is assessed by the driver while they wait in a queue to exit the intersection. As they approach an intersection, the driver wants to know the queue status and the time until they can exit the intersection. Some drivers prefer to know the number of cycles to elapse before they can leave the intersection.

3.1. Expert assessment

Experts, i.e. traffic engineers who assess or design signalisation can make their assessment based on three criteria:

1) Efficiency of service;

The expert will base their subjective opinion on the observed critical length of residual queue which identifies the duration of the overload or estimated number of cycles to elapse before the driver will be able to clear the intersection;

2) How the queues will affect the capacity of other links on the approach;

The assessment will be based on an analysis of queue lengths and the length of the critical maximum queue which is a result of the lengths of additional traffic lanes or the distance between intersections;

3) The effects of traffic congestion on intersection coverage;

Traffic overloads which have similar durations will impact the areas surrounding the intersection at varying degrees of nuisance. The expert's assessment of the reliability of lane groups, entries or intersections will differ depending on the location, i.e. a residential area, industrial zone or a hypermarket.

Because expert opinions vary greatly and represent different views on the quality of performance, overload acceptance should be defined at several levels. These will depend on *a priori* assumptions of boundary values of traffic measures [10]. The assessment of signalised intersection performance quality described in the article is based on the length of residual queue K_p. Experts believe that it is the time of reliable traffic lane performance that is critical. It starts when acceptable queues are forming until they reach their critical lengths leading to an unacceptable overload ($t_{N,i}$, $t_{N,i+1}$, $t_{N,k}$ – figure 3) which persists over a certain period ($t_{zaw,i}$, $t_{zaw,i+1}$, $t_{zaw,k}$). The critical length of a residual queue is closely related to the process of queue formation. The nature of that process depends on the size and variability of demand flow over time and control parameters. The overload itself does not necessarily mean that the intersection is not reliable. Experts should also assess overload duration ($t_{zaw,i}$, $t_{zaw,i+1}$, $t_{zaw,k}$ – Fig.3)[13].

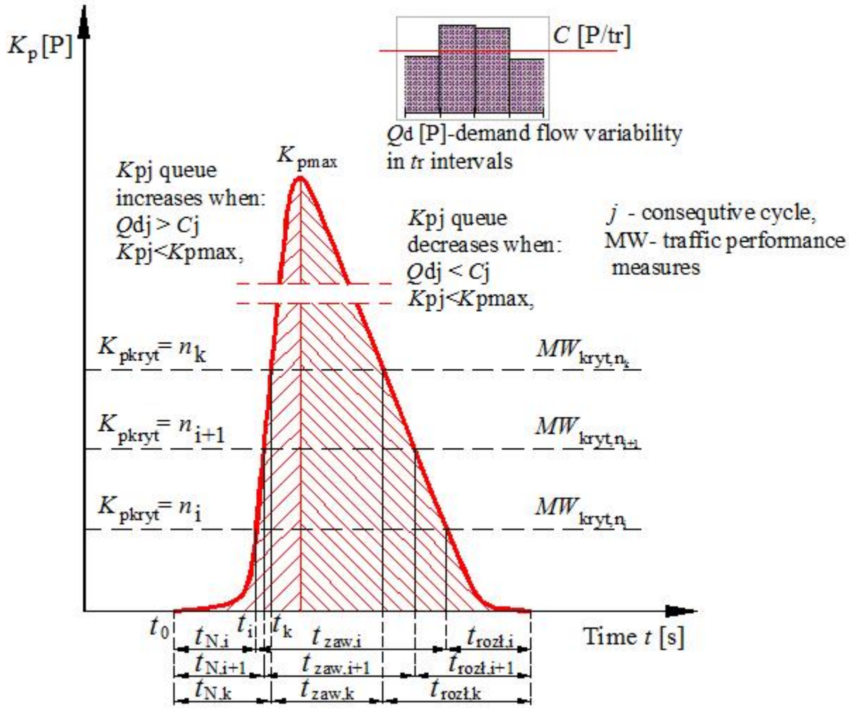

Figure 3. Process of residue queue formation and dissipation for a selected profile of variable peak-hour demand flow

3.2. Driver assessment

The time spent in a queue at an intersection approach may be estimated in a number of ways, e.g. by assessing queue length and/or how quickly vehicles move in that queue. Waiting time in a queue depends on a number of factors, i.e.:

A) Parameters and type of control and lane capacity;

The length of green time *G* and cycle *T* in the initial and final period of overload, when demand flow increases and decreases relative to capacity, can be fixed (fixed-time signalisation) or variable over time until it reaches maximum values of G and T (accommodative signalisation). When traffic reaches saturation, the reliability of lane groups should be assessed with the G/T quotient because it has a direct effect on queue formation. In [14] it was demonstrated that the intensity of saturation and, by the same token, lane capacity is a deterministic and random variable and depends on the weather;

B) Type, geometry and location of intersections;

The capacity of traffic lanes may be affected by signalised intersections themselves, a process which is both predictable and unpredictable. There may be situations where the capacity of a lane (i.e. the reliability of performance) will be diminished due to [14]:

- the intersection being blocked regularly or irregularly by vehicles waiting at the intersection centre (so called backflows from the next intersection),
- inner accumulation areas are not big enough for the demand and control parameters,
- poor technical condition of roadway,
- the intersections are not spread out enough,
- a lot of slow traffic, i.e. driving school vehicles, heavy goods vehicles.

Urban intersections will typically have the same users commuting regularly at similar times of day. Frequent drivers are able to foresee that the roads will be busy on specific sections such as signalised intersections and adjust their routes in advance as traffic conditions change [15, 16]. Random capacity reductions (e.g. the effects of rainfall or snowfall) further deteriorate traffic on entries and extend overload duration making any predictions more difficult for drivers.

C) The number of vehicles queuing in front of the vehicle in question;

Waiting time assessment may differ from driver to driver. Drivers may first consider the number of vehicles queuing or the length of the queue, if there are no traffic lights in sight. Drivers analyse traffic, the speeds of vehicles in the queue and changing control parameters. The time until they can clear the intersection may be viewed as the number of cycles that drivers will have to wait through. It is likely that the lower the G/T relation, the more frustrated and disheartened the driver;

D) The time (moment) to reach the queue in peak traffic;

Waiting time will depend on the moment at which the driver reached the end of the queue. The queue may have just started to form (more and more vehicles arriving), reached its maximum (traffic volume just starting to decrease or stabilising) or started to decrease (fewer vehicles arriving). Depending on when (actual moment) the driver reaches the queue during peak time, the length of the queue and the time to exit will differ (figure 3).

Each driver may be assigned their individual acceptable waiting time which, once exceeded, will cause the driver to believe that the traffic signals are unreliable. When drivers assess the reliability of a traffic lane, they will focus on the estimated time that will elapse between joining the queue until they can exit the intersection. With no visible signals or the intersection, drivers will make their assessment based on the speed of the vehicles queueing. Any estimates of the waiting time can only be rough and change once the driver is able to see the intersection and change of traffic lights. What this means is that the length of the acceptable waiting time changes making empirical studies very difficult. Driver opinions on the performance of intersections will vary (when confronted with their expectations) in big and small towns or in built-up areas and outside them [14, 17]. The reliability of lane groups as seen by drivers can also be studied using surveys [10].

4. Reliability tests and modelling

The critical points of traffic lane reliability research are those moments when the rate of service transitions from acceptance to lack of acceptance. The reliability of a traffic lane can be studied at time of traffic saturation which is usually at peak hours with the traffic lane operating at capacity. The traffic acceptance boundary can be defined using a selected measure of overload (residual queue K_p, maximum queue K_m, quotient K_p/C, rate of overload X, etc.). Once selected the measure should be easy to interpret in physical terms. As an example, when analyses are based on the critical value of residual queue, once it is exceeded in the subsequent cycles overload will be unacceptable. Figure 3 shows a schematic division of overload relative to the *a priori* assumed critical value of residual queue K_{pkr}. The classes of the quality of service can also be presented using other measures of traffic *MW* with the values resulting from the agreed critical values of residual queues K_{pkr}.

The cut-off point for traffic acceptance transitioning into lack of acceptance differs from driver to driver and depends on a number of factors such as queue waiting time, length of queue and other random factors which change dynamically and are difficult to predict [18, 19]. Time t_p from the moment an acceptable queue begins until it becomes unacceptable is of key importance, if related to the time within which we expect to reach our destination. As a result, time t_p is the time between the normal operation of a traffic lane until the emergence of unacceptable traffic conditions and can be a measure of traffic conditions (variable over time t).

Because of the nature of reliability studies (day after day), fieldwork is very difficult and costly. As a result, to ensure that the reliability analysis is reliable and that it is based on large samples and varying input parameters (traffic data), the recommended method is to use traffic simulations.

5. Conclusions

With roads and streets having to accommodate more traffic (rates of motorisation) and intersection approaches and entire intersections becoming increasingly more congested, the effect on road safety is clear [20, 21]. Overloaded lane groups on signalised intersection approaches deteriorate traffic conditions. Long queues of vehicles on intersection approaches usually involve long waiting times and overloaded groups of lanes. Overload is most frequent at peak hours on weekdays and/or during the weekend (tourist traffic). The article has presented a new approach to studying traffic during overload using the reliability theory and known parameters typical for the process of arrivals and service, when arrival flow is close to and greater than the capacity in the subsequent signal cycles.

The analyses suggest the following general conclusions:

- If introduced, *a priori* assumed service quality classes K_{pkr} for signalised intersection traffic lanes will help road authorities to manage overloads and assess traffic and will help designers to design and control traffic lanes during overload and meet driver expectations.
- The definition of the critical length of residual queues K_{pkr} (service quality classes) helps to model the duration of congestion t_{zaw} (figure 2). By using the technical capabilities available today (induction loops, video detection, automatic weather stations), it is possible to predict dynamically when K_{pkr} will occur or forecast and limit the duration of congestion t_{zaw} in real time.
- Zones of restricted traffic in major cities suggest that high quality classes of reliability make sense for the area's routes and signalised intersections (e.g. historic city centres). As regards other parts of the city where traffic is not restricted, traffic lights can be designed to lower quality classes depending on the particular street.

References

[1] J. Chodur, M. Tracz, S. Gaca, S. Gondek, M. Kieć, K. Ostrowski, "Manual for capacity analyses of at-grade intersections," *General Directorate of National Roads and Motorways,* Warsaw 2004.

[2] Zhu, F. Lo, H.K. Lin, H.Z. (2013) Delay and emissions modelling for signalised intersections. *Transportmetrica B: Transport Dynamics*, 1 (2), 111-135.

[3] S. Gaca, W. Suchorzewski, M. Tracz, „Traffic engineering," *WKiŁ*, Warsaw 2008.

[4] Rao, S. S. (1992) Reliability based design. *Purdue University*, USA.

[5] Lo, H.K. (2006) A reliability framework for traffic signal control. *Intelligent Transportation Systems,IEEE Transactions on, 7(2)*, pp. 250-260.

[6] Lam, W.H.K. Zhang, N. Lo, H.K. (2007) A reliability-based user equilibrium model for traffic assignment. *Critical Infrastructure*, 151-171.

[7] J. Chodur, "Functioning of road intersections in conditions of traffic variability," (in Polish), *Cracow University of Technology*, Cracow 2007.

[8] J. Chodur, K. Ostrowski, "Assessment of traffic conditions at signalized intersections," *Archives ofTransport*, Warsaw 2006.

[9] J. Chodur, K. Ostrowski, M. Tracz, "Impact of saturation flow changes on performance of traffic lanes at signalized intersections," *Procedia - Social and Behavioral Sciences, Elsevier,* vol. 11, pp. 600 – 611, Stockholm 2011.

[10] K. Ostrowski, "Attempt to apply the theory of reliability to assessment of signalised lane operation," *Proc. of European Safety and Reliability Conference ESREL, Safety and Reliability, Methodology and applications, CRC Press/Balkena, Taylor and Francis Group,* pp. 335-341, Wroclaw 2014.

[11] Smith, M. Hazelton, M.L. Lo, H.K. Cantarella, G.E. Watling, D.P. (2014) The long term behaviour of day-to-day traffic assignment models. *Transportmetrica A: Transport Science* 10 (7), 647-660.
[12] Shao, H. Lam, W. Sumalee, A. Chen, A. Hazelton, M. (2014) Estimation of mean and covariance of peak hour origin–destination demands from day-to-day traffic counts. *Transportation Research Part B: Methodological Volume 68*, pp. 52-75.
[13] K. Ostrowski, M. Tracz, "Availability and reliability of a signalised lane, "*Proc. of the 6th International Symposium on Transportation Network Reliability*, Nara 2015.
[14] J. Chodur, K. Ostrowski, M. Tracz, "Variability of Capacity and Traffic Performance at Urban and Rural Signalised Intersections," *Transportation Research Procedia*, vol. 15. Elsevier B.V. pp 87−99, Berlin 2016.
[15] Siu, B.WY. Lo, H.K. (2014) Punctuality-based route and departure time choice. *Transportmetrica A: Transport Science* 10 (7), 585-621.
[16] Siu, B.WY. Lo, H.K. (2013) Punctuality-based departure time scheduling under stochastic bottleneck capacity: formulation and equilibrium. *Transportmetrica B: Transport Dynamics*, 1 (3), 195-225.
[17] M. Budzynski, D. Ryś, W. Kustra, "Selected problems of transport in port towns - tri-city as an example, *Polish Maritime Research,* vol. 24, special issue: 1, pp 16-24, 2017.
[18] Lo, H.K. Sumalee, A. (2013) Transport Dynamics: Its time has come!. *Transportmetrica B: Transport Dynamics*, 1(1), 102.
[19] Szeto, W.Y. Lo, H.K. (2006) Dynamic traffic assignment: properties and extensions. *Transportmetrica* 2 (1), 31-52.
[20] W. Kustra, K. Jamroz, M. Budzynski, „Safety PL - a support tool for Road Safety Impact Assessment," *Transport Research Arena Tra2016, Book Series: Transportation Research Procedia,* vol. 14, pp. 3456-3465, 2016.
[21] K. Jamroz, M. Budzynski, W. Kustra, „Tools for road infrastructure safety management - Polish experiences," *17th Meeting Of The Euro Working Group On Transportation, Ewgt2014, Book Series: Transportation Research Procedia,* vol. 3, pp. 730-739, 2014.