INCREASING URBAN INTERSECTION CAPACITY: THEORETICAL AND PRACTICAL APPROACHES

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Abstract

This article addresses the issues of efficient traffic management and increasing the throughput capacity of urban streets. Particular attention is given to the interaction between traffic intensity, vehicle flow density, and traffic signal cycle duration at signal-controlled intersections. The possibilities of enhancing roadway capacity through coordinated signal control systems are examined using mathematical expressions, graphical nomograms, and empirical data. Furthermore, the article explores vehicle movement patterns, queue discharge intervals, and their dependence on traffic flow composition. The study provides both theoretical and practical foundations for urban transport system design and planning.

Keywords: traffic flow, signal cycle, capacity, traffic intensity, intersection control, urban transport, vehicle flow density, street design.

The rapid growth of the population, the increasing number of motorized vehicles, and the acceleration of urbanization processes have made the efficient organization of traffic flow on urban streets a pressing issue. In large cities in particular, the high density of traffic flows has led to streets operating at or near their maximum capacity. This situation results in increased congestion, reduced traffic speed, and heightened environmental pollution.

Therefore, improving the throughput capacity of streets using scientifically grounded methods has become one of the primary directions in modern transportation engineering. In this regard, the proper and optimal management of traffic flow at signal-controlled intersections plays a crucial role. Accurate consideration of signal cycle durations, traffic intensity, flow composition, and queue discharge intervals can significantly enhance the efficiency of traffic operations.

At intersections with relatively low traffic intensity, traffic can be organized using an uncontrolled (non-regulated) method. In such cases, the efficiency of the intersection is ensured by providing a sufficient number of travel lanes.

When traffic intensity increases, successful traffic organization can be achieved by installing traffic lights. In this case, the capacity of the street is primarily determined by the capacity of the section where the traffic light is installed (the location with the stop line).

The maximum number of vehicles that can pass through a single lane during one cycle of the traffic light's designated permissive signal depends on how fully this signal is utilized. That is, to achieve the highest traffic density during the green light phase, there must be a sufficient number of vehicles queued in line.

The capacity of the travel lane for this case is calculated as follows:

$$t_{zel} = \bar{\delta}t_1 + \bar{\delta}t\ (\overline{m} - 1) \quad (1)$$

$$m = (t_{zel} - \delta t_1 + \delta t)/\delta t \quad (2)$$

$$P = 3600(t_{zel} - \delta t_1 + \bar{\delta}t)/(T_s\bar{\delta}t) \quad (3)$$

Where:

t_{zel} - green light duration, seconds;

δt - headway (departure interval);

δt - time interval from the moment the green light turns on until the first vehicle leaves the intersection, seconds;

δt - average time interval between vehicles passing the stop line, seconds;

m - number of vehicles passing through a single lane during one cycle;

P - capacity of the lane controlled by the traffic light, vehicles per hour;

Ts - duration of the traffic light cycle, seconds.

As the basis for this calculation, the patterns of variation in the intervals between departing vehicles and changes in the duration of the traffic light cycle along the street length under traffic light control are used.

When designing streets, the duration of *Ts* for all traffic light-controlled intersections is determined by considering the composition of vehicles, traffic intensity, and the type of traffic organization, according to the following formula:

$$T_{s.min} \frac{3600(\sum_{i=1}^{n} = \delta t_1 - \sum_{i=1}^{n} \overline{\delta t} + \sum_{i=1}^{n} t_{ji})}{3600 - \delta t \sum_{i=1}^{n} N_i} \quad (4)$$

Where:

t_{ji} - duration of the intermediate stage in phase i, seconds;

Ni - design traffic intensity in this phase (the highest observed traffic intensity in this phase), vehicles/hour.

The value of *Ts* may vary at different intersections. In such cases, a coordinated traffic control system is used to improve traffic conditions on the street. This approach does not increase the capacity of the street, but it reduces time losses caused by vehicles waiting in queues at traffic lights.

In coordinated traffic control, the calculated duration of *Ts* is assumed to be constant from the beginning to the end of the street and is the same at all intersections. In this case, the largest previously determined value of *Ts* among the intersections is used for all.

If the operation of the traffic lights is uncoordinated and each intersection operates independently with its own *Ts* duration, the capacity at different points along the street will vary. In such cases, the overall capacity of the street is considered to be equal to the capacity of the intersection with the lowest throughput.

The intervals δt1and δt depend on the sequence number of the vehicles in the queue.

For the first vehicle, the interval δt1represents the time required to accelerate from a stationary position and reach the stop line. This movement occurs under acceleration conditions.

The second vehicle also starts under similar acceleration conditions. The value of the δt2 interval at the stop line depends on how far behind the second vehicle lags during its start compared to the first vehicle. Subsequent vehicles also begin moving slightly later relative to the vehicles ahead of them. However, due to steady or rapid acceleration, this delay gradually decreases for each following vehicle and has less impact on the δt interval.

During the queue dispersion phase, a minimum interval between vehicles is achieved. Such an interval typically occurs when vehicles are moving at relatively low speeds.

As the queue disperses, vehicle speed increases, and once a portion of the queue is cleared, the traffic flow density begins to decrease. Based on research findings, it can be concluded that,

Table 1

Average Values of Intervals During Queue Dispersion

"Share of trucks in the traffic flow, %"	0–20	20–50	More than 50
δt_1, s	3,1	3,5	3,9
δt, s	2,2	3,0	3,5

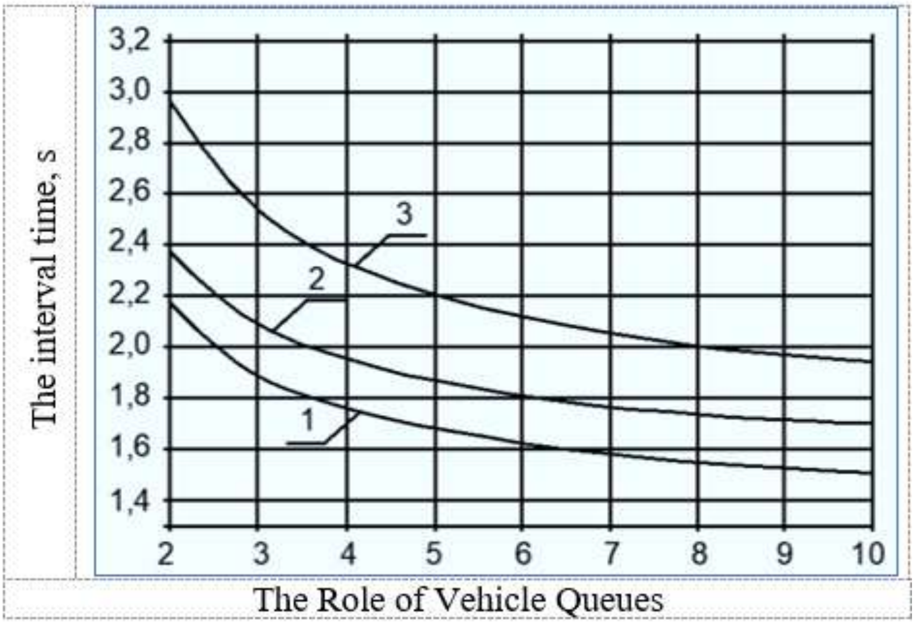

Figure 1. Intervals between vehicles leaving the queue at the stop line depending on the composition of the traffic flow: 1 – 0.4% trucks, 2 – 6.6% trucks, 3 – 11% trucks.

When 7–8 vehicles leave the queue, the traffic flow density begins to decrease (see Figure 1). Based on this, it can be concluded that allowing more vehicles from the queue to pass reduces the effectiveness of the green phase of the traffic signal cycle. The interval between vehicles during queue dispersion depends on the composition of the traffic flow: the heavier the vehicle, the greater the distance drivers tend to maintain from the vehicle in front (the leader).

Additionally, the leading vehicle also affects the δt interval. For example, if a truck is following a passenger car, the value of the δt interval is 0.5–1.0 seconds shorter than when a passenger car follows a truck. In calculations, it is acceptable to use the average values of intervals observed during queue dispersion.

The capacity of a traffic lane controlled by a traffic signal can be considered as the sum of the δti intervals.

Figure 2 illustrates a nomogram showing the relationships between the green phase duration t_{zel}, the number of vehicles passing during one cycle Ps, and the capacity of the traffic lane Pp. This nomogram provides valuable insights for determining the capacity of multi-lane streets during the street network design phase in urban areas.

It is important to note that the diagram refers to the **maximum capacity** of the traffic lane - i.e., the maximum number of vehicles passing through the stop line under conditions of maximum traffic flow density.

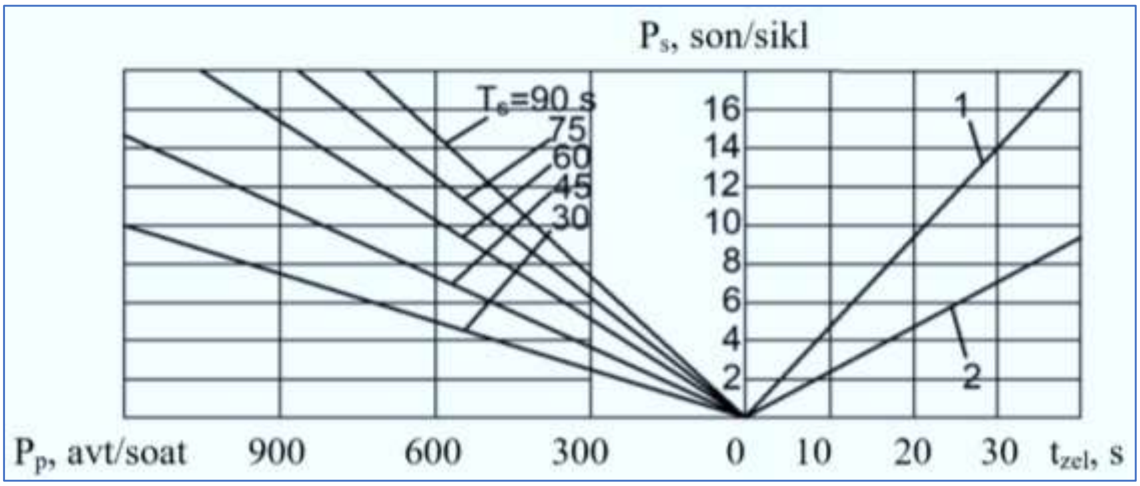

Figure 2. Capacity of the signal-controlled traffic section at various traffic signal cycle durations (Ts) and different traffic compositions: 1 – 100% passenger cars; 2 – 100% trucks.

The level of service of streets to transport can be improved by coordinating the operation of traffic signals. The street capacity changes little in this case, but it can be increased by reducing the number of vehicles queued at the stop line.

In this control method, a platoon of vehicles must be able to move continuously through the remaining part of the street after leaving the first intersection without stopping. The larger the size of such platoons, the higher the likelihood that they will pass through subsequent traffic signals without stopping.

The dispersion of these platoons occurs because vehicles travel at different speeds. Within the 600 - 800 m section before the traffic signal where platoons form, the traffic flow becomes randomized, and vehicles are dispersed. On streets with such traffic organization, when selecting design solutions for intersections and assessing their capacity, it is necessary to know the number of vehicles arriving at the segment per unit time.

This problem is solved based on the rules of traffic flow theory.

In practical calculations, the relationship shown in Figure 3 is taken into account, where the coefficient *K* quantitatively represents the number of vehicles passing at time t:

$$K = \frac{N_1 * t_i}{3600}$$

Here,

N1 - the traffic intensity (flow rate) on one traffic lane, vehicles per hour;

ti - the duration of the i - signal phase in the traffic signal cycle, seconds.

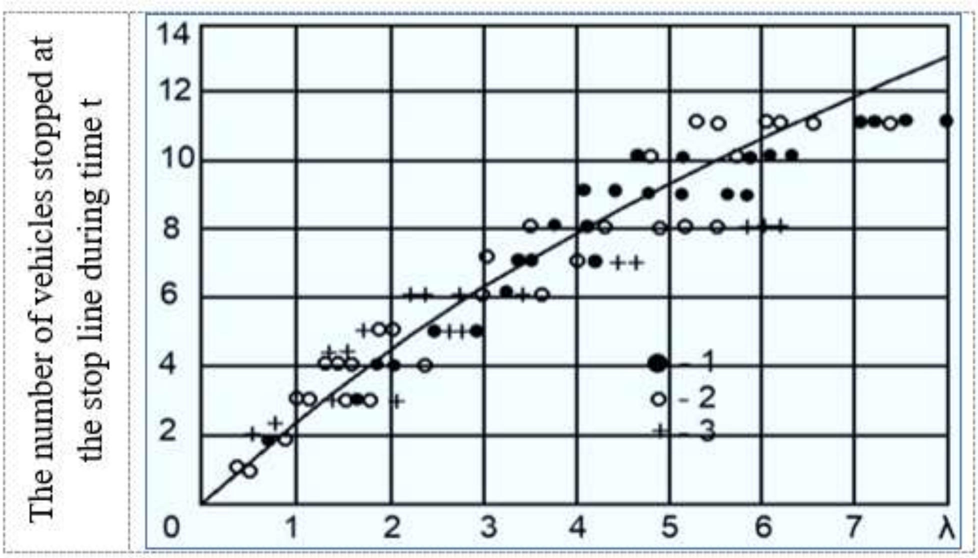

Figure 3. s: 1 – 35; 2 – 60; 3 – 75;

To determine the number of vehicles passing through the stop-line without stopping, the following conditions are accepted: *ti - tzel*, and

$$K = \frac{N_1 * t_i}{3600} \quad (6)$$

To find the maximum queue length before the traffic light, the time *ti* is assumed equal to the duration of the red (prohibitory) signal in that direction. Taking this into account, formula (5) takes the following form:

$$K = N_1(T_s - t_{zel})3600 \quad (7)$$

Knowing the number of vehicles standing in the queue before the traffic light is necessary for calculating the elements of the intersection and planning its design solutions, especially for calculating the length of additional lanes serving turning traffic at the intersection.

Efficient organization of traffic flow on city streets and increasing their capacity is one of the most pressing issues in modern urban planning. The scientific foundations and practical recommendations presented in this article are of great importance in the design of urban street networks and the optimization of existing systems.

The conducted analysis shows that the efficiency of traffic movement at intersections largely depends on the properly organized traffic light control system. At intersections with high traffic intensity, the duration of the traffic light cycle should be determined considering the composition of the traffic flow, vehicle types, and characteristics of queue dispersion. This ensures balanced and continuous traffic flow.

The relationship between the departure intervals of queues, traffic flow density, the proportion of heavy vehicles, and drivers' psychophysiological characteristics has been identified, and taking these factors into account can enable uninterrupted traffic movement. In particular, ensuring that vehicle flows move in "platoons" (groups) and implementing coordinated traffic signal control systems that allow these platoons to move continuously along the entire route significantly increases efficiency.

Based on these scientific findings, the following recommendations can be made:

1. When determining the duration of the traffic signal cycle at each intersection, it is necessary to rely on statistical analysis of the structural changes in the vehicle flow and the departure interval of the queue. This allows for managing the intersection according to its individual characteristics.
2. Synchronizing traffic signals across the city by implementing coordinated control systems can harmonize vehicle flow and increase overall traffic speed.
3. It is recommended to develop dynamic control strategies based on the proportion of heavy vehicles in the traffic flow. For example, during periods of high truck traffic, adjusting the green light duration can optimize flow capacity.
4. To improve the efficiency of traffic signal control, the introduction of Intelligent Transportation Systems (ITS) that collect real-time data is essential for modernizing urban transport infrastructure.
5. When designing intersections, it is necessary to use theoretical model-based calculations to determine the maximum queue length and the length of auxiliary lanes serving turning traffic. This helps reduce congestion at problematic points.

In conclusion, merely installing traffic signals is not sufficient for effective traffic management on urban streets. A thorough study of the traffic characteristics of each intersection and optimization based on statistical and theoretical models can improve the overall efficiency of the transport system. These approaches play a crucial role in ensuring comfortable traffic movement for city residents, reducing fuel consumption, and enhancing environmental safety.

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