

Generalising cases of insensitive queuing city traffic management systems and their impact on the delivery of goods by air and road

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Abstract. It is established that the urban traffic management system, as well as the aviation traffic management system, has a significant impact on the multimodal delivery of goods in the road-air transport, which requires the creation of tools for theoretical substantiation and practical implementation. The authors' method of determination the occurrence of vehicles queues in cities using mathematical modelling tools for three scenarios of crossing intersections was developed. The conceptual scheme for calculating the occurrence of the queue of vehicles was proposed. It was noted that vehicles in the queue often arrive randomly, the duration of service is constant, and the probability that before the queue disappears for the first time a certain number of cars cross the intersection has a Borel-Tanner distribution. The given mathematical modelling should become a part of tools for the implementation of the integrated intelligent information system of cities as a cluster of the city traffic management system.

Keywords: queuing system, transport flows theory, urban logistics, traffic.

1 Introduction

One of the important features of the transport flow is its randomness, which ensures the uneven movement of vehicles over a long period of time.

An insensitive queuing system is a system with alternating periods of service and inactivity of the service device.

The uneven movement of vehicles characterizes the random nature of the movement of the population by any mode of transport. This issue is complex and is affected by many random factors which cannot be determined.

Studying various EU documents related to the development of the transport and logistics component, it can be argued that EU policy is aimed at ensuring the greening of cities in general, which should be primarily achieved by reducing urban traffic and improving the ecology of transport hubs, including airports.

Whilst noting the desire of countries and the EU as a whole to minimise transit freight flows in cities, which is being addressed through a range of measures, the delivery of goods in cities beyond the first and last mile is inevitable and needs to be successfully addressed. It should be noted that cases of insensitivity of urban transport management systems in queues directly affect the speed of cargo delivery in road and air transportation, as the delivery of special categories of cargo, especially perishable goods, requires minimising the time, including delivery within the city, at the intersection of cargo and passenger flows in cities.

One of the effective tools to reduce private car traffic is the active promotion of green mobility practices. Additional tools for improving the urban ecology include

measures related to infrastructure planning, optimising traffic flow through intersections, and reducing congestion. It is the latter two aspects that are the focus of the paper.

2 Literature review and defining the problem

As part of the presented scientific research, it is reasonable to determine aspects of the queuing theory studied in previous research papers. In the scientific work of Shen et al [1] proposed the authors' solution to the problem of evaluating the space of flow tables on the basis of queuing theory. The authors' unique contribution is to create a probabilistic model of routing strategies to quantize the impact of path selection, which in our opinion is an interesting solution within the framework of queuing theory.

In the context of the problems solved in [2] an analytical approach was applied using the open queuing network theory of quadratic assignment problems.

The authors proposed a metaheuristic approach to optimization that should be recognized as an interesting authors' achievement. Studies of the use of electric vehicles have traditionally relied on queuing theory to model their arrival and departure times and estimate the required capacity of charging stations, in particular Zhu et al [3]. However, Varshosaz et al [4] considered the limitations of the queuing system due to the implementation of a scenario-based queueing simulation to estimate the capacity of the charging station per day ahead using random inputs of six types of electric

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vehicles. This allows a much more accurate estimation of the required charging station capacity, which determines the practical relevance of the study. Queuing theory is also used to solve the problem of coordinated location and inventory determination in a supply chain with random supply failures, in particular as shown by Liu et al [5].

As noted by Kelathodi Kumaran et al. [6] modern information technologies allow the development of uncontrolled managed intelligent traffic signalling systems, and the authors proposed the measurement of urban traffic parameters using a modified Dirichlet process mixture model based on clusters. Choudhary et al [7] also devoted the study to modelling and assessment of road congestion using queuing theory.

The study of Oumaima et al [8] proposed a new simulation model of vehicular mobility of the modular principle, based on queuing theories and implemented by scenarios. Queuing theories are also used in the formation of a new concept of the capacity of metro stations, as proposed by Xu et al [9]. One of the first studies in which a model that considers a road section as a series of many queue counters is proposed, should be recognized the work by Wu and Rakha [10].

Transit signal priority is a widely used strategy at signalized intersections for urban traffic. Wu and Guler [11] considered the influence of this signal in mixed traffic environment. Determination of the influence factors on modelling the traffic flows dynamics in cities was done by Ozerova et al [12]. The peculiarities of urban logistics development in the underground system in terms of integrated public transport development are extremely relevant [13]. Urban logistics is inextricably linked to ensuring interaction with freight flows.

Some scientific researches [14-16] are devoted to the study of this issue. The works concerning the development of appropriate mathematical models that are designed to provide such interaction should also be noted [17-20]. The queuing system methodology for urban logistics is based on the use of various approaches from probability theory. Classical tools should be considered derivatives of the theory of the flow of homogeneous events, with the development of which this direction was initiated. Design method of intelligent touchpoint was studied by Li et al [21].

Modern supply chain management methodologies [22-24] have greatly optimized this process. New methods to ensure population mobility [25-27] have also significantly improved the organizational component of urban logistics.

The most interesting and relevant methodological scientific achievements in the development of the queuing system will be analyzed further. The implementation of a dual-purpose mathematical model for the design of an urban logistics distribution network is intended to minimize economic and environmental costs [28]. The application of this model will create a methodological basis for the implementation of the economic and environmental sustainable development principle, which is defined as fundamental for the success of developed countries in general. In the framework of the study of urban logistics, multimodal passenger-and-package sharing was proposed Ji et al [29]. It should be noted that

the offered model belongs to the class of mixed integer linear programming models with scenario estimates. The application of the compromise principle for its balancing, as well as the integrity of taking into account passenger and freight urban flows, should also be recognized as the scientific novelty of the work.

The most recent and most interesting scientific work is the paper on one-dimensional service networks and batch service queues by P. Nain et al [30], in which the authors investigated the features of the functioning of a one-dimensional service network, in particular, the Laplace-Stieltjes transformation of the distribution of sojourn time was calculated, which should be considered as a scientific novelty. Features of railway transportation are presented in [31-32].

Based on the described methodology, the authors proposed a solution to the problem of generalizing cases of insensitive queuing system operation for urban logistics. Overall, it should be noted that the general features of ensuring the functioning of an insensitive queuing system for urban logistics in its multimodal interaction with other modes of transport is a complex solution that requires detailed elaboration. An important feature of the movement of vehicles through an intersection is that traffic light control at intersections has minimal (interchangeable) intervals for changing traffic lights.

3 Research aim and objectives

The purpose of the study is generalising cases of insensitive queuing city traffic management systems and their impact on the delivery of goods by air and road.

This improvement includes the development of a conceptual scheme for calculating stages of vehicle queues appearance in cities, as well as identifying general features of vehicle queues in cities. To achieve this aim, the following objectives have been solved:

- develop the authors' method of determination the occurrence of vehicles queues in cities using mathematical modelling tools for three scenarios of crossing intersections;
- to propose the conceptual scheme for calculating the occurrence of the queue of vehicles.

4 Overview of key findings

4.1 Stages calculating the occurrence of the queue of vehicles

The regulation of the movement of passengers and vehicles at intersections isn't always effective, as a result of which congestion occurs under various conditions of transport flows. Hence, as a consequence, a queue of vehicles appears at the congestion point, which also blocks neighbouring intersections.

Taking into account the above mentioned, we will consider such a queuing system in which the service device alternately operates and doesn't operate during time periods.

Let the input flow of the system be random with a parameter λ . Assume that the service requirements leave the system at regular intervals T when the service device operates. In fact, vehicles making up the queue start moving at regular intervals, except for the first car, which is late. However, this additional length of time is easily included in the red signal duration; meanwhile the red signal period will actually mean time period the duration of which is slightly more than the exact phase duration. Approximately the same way the yellow signal duration can be eliminated.

The selection of research methods was determined by the nature of the actual data and the task of the study. The set of applied methods provides the possibility of generalization, complex and systematic understanding of the origin and peculiarities of the urban transport flows' development. The methodological basis of scientific research is represented by theories of transport systems and logistics.

The proposed methodology contains a number of steps shown in Fig. 1. It considers vehicles as waiting objects instead of pedestrians.

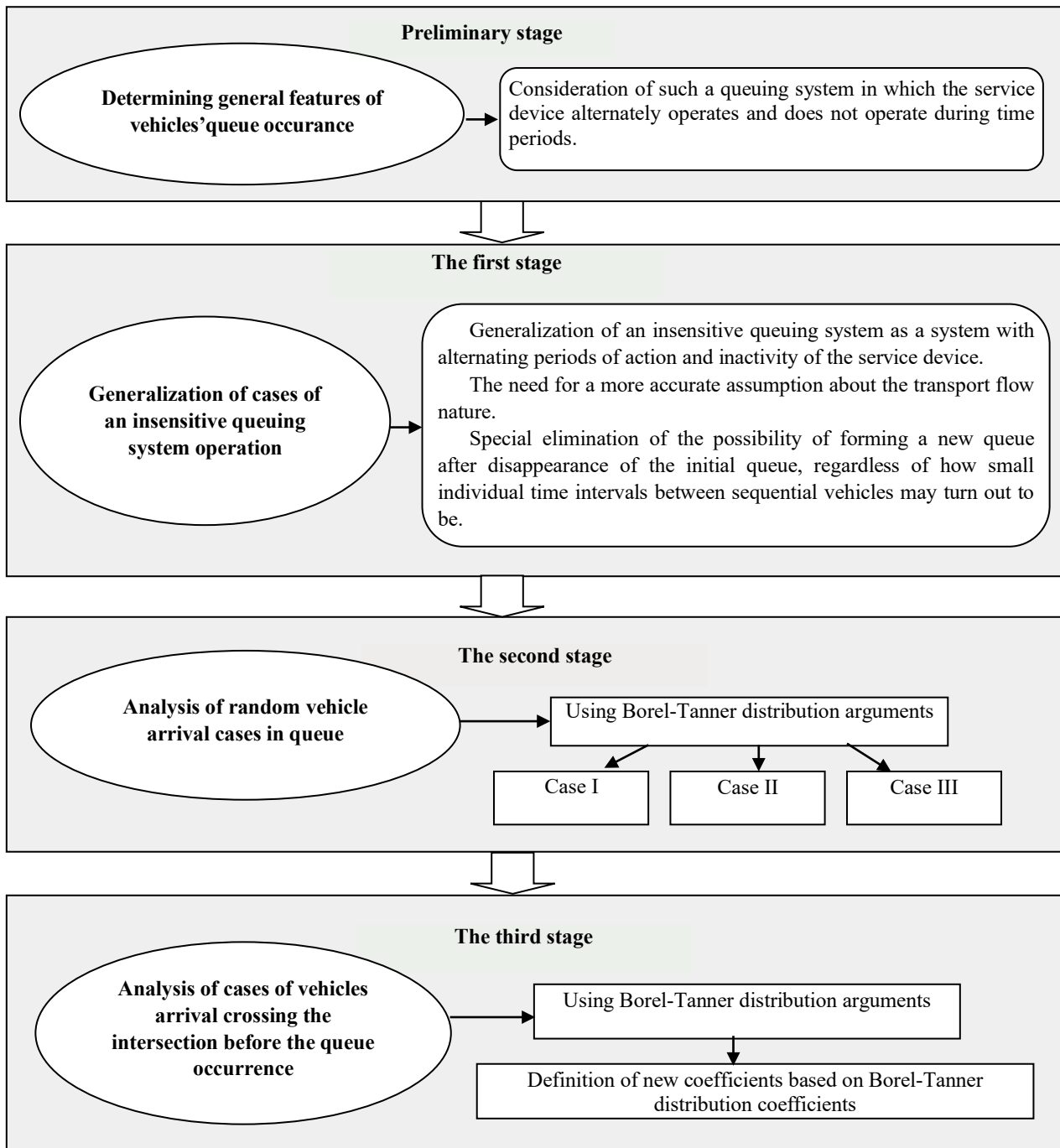


Fig. 1. The conceptual scheme for calculating the occurrence of the queue of vehicles

It is quite obvious that free and blocked time intervals formed by transport flow of the main street correspond quite accurately to the periods of red and

green traffic signals, regardless of whether the signal duration is constant or it is determined by the presence of vehicles.

4.2 General features of vehicle queue occurrence

Depending on local rules and conditions, it is considered either as a red or green signal. Denoting the length of time interval between consecutive moments of vehicle departure by T means drawing a parallel between this value and time needed by the pedestrian to cross the street, which has also been denoted through T before.

In fact, the value of T is constant service duration; in this case, it will have such a meaning. Since within the task of pedestrians crossing the street the issue of a queue occurrence wasn't considered, confusion in the interpretation of T was avoided.

The insensitive queuing system considered in the transport flows theory was previously defined as a system with alternating periods of action and inactivity of the service device. It is interesting to note that this concept can be generalized. For example, by requiring that the moment of entry into the turnstile coincides exactly with the passage of the partition beginning, then it makes sense to note that the service device almost always doesn't work.

Consider a typical phase of a red signal of β duration. Let Z denotes the number of vehicles waiting for the start of the red signal period, and X denotes the number of vehicles waiting at the end of this period.

Since the service isn't performed, and the arrival of vehicles occurs randomly, the distribution of the random variable $X - Z$ has the following form:

$$p = \frac{(\lambda\beta)^n e^{-\lambda\beta}}{n!}, n = 1, 2, \dots \quad (1)$$

To make a corresponding conclusion about green signal of α duration a more accurate assumption about the transport flow nature is necessary.

Assume that by the time the queue disappears for the first time, the service duration is constant and the arrival of vehicles occurs randomly, and before the next phase of the red signal begins, the transport flow freely crosses the intersection without leading to traffic congestion.

Making this assumption, we specifically deny the possibility of forming a new queue after the initial queue disappears, regardless of how small the individual time intervals between sequential vehicles can be.

If T is the duration of the time interval between departure times of vehicles, then the assumption won't be fulfilled for the time intervals between sequential vehicles less than T .

Therefore, suppose that T is the length of time interval between sequential vehicles that form a queue. As soon as the initial queue completely disappears, the length of time intervals between sequential vehicles arriving later (during a green signal) at the crossing intersection remains the same as at the time of arrival at the intersection; in some cases, it may be less than T .

If N is the maximum number of vehicles that make up the queue that can cross the intersection during the green signal, that is:

$$\alpha = NT + \theta T, 0 \leq \theta < 1, \quad (2)$$

Then N can be considered as the number of "gaps" during the green signal. From the point of view of the queuing theory, the transport flow intensity (during green signal periods) is defined as:

$$\sigma = \lambda T \approx \frac{\alpha\lambda}{N}. \quad (3)$$

4.3 Analysis of random vehicle arrival cases in queue

Consider the queue in which vehicles often arrive at random. Assume that the service duration is constant, at the initial moment there are r vehicles in the queue. The probability that before the queue disappears for the first time n vehicles cross the intersection has a Borel-Tanner distribution.

The density of this distribution in multiple forms is written as:

$$b(n, r) = A(n, r)e^{-\rho n} \sigma^{n-r}, n = r, r+1, \dots, \quad (4)$$

where

$$A(n, r) = \frac{r}{(n-r)!} n^{n-r-1}. \quad (5)$$

Among the arguments of the Borel-Tanner distribution, we do not explicitly mention σ , since it is assumed that the value is always given by formula (3). Coefficients $A(n, r)$ contain multipliers that are definitely independent of σ .

Then:

$$u(x | z) = P(X = x | Z = z) \quad (6)$$

and

$$v(z | x) = P(Z = z | X = x). \quad (7)$$

– probabilities that at the beginning of green and red signals periods there are X and Z vehicles, respectively, if at the beginning of previous periods of red and green signals there were Z and X vehicles, respectively. Let's start with calculating $v(z | x)$.

Case I ($x > N$). The number of vehicles that cross the intersection exactly equals to N . Therefore, in order for z vehicles not to have time to cross the intersection, $z - x + N$ random arrivals of vehicles must take place. So,

$$v(z | x) = p(z - x + N, \alpha\lambda), x > N. \quad (8)$$

Case II ($Z = 0, x \leq N$). By the end of the green signal phase, the queue must disappear completely, and for that to happen, the queue must disappear under one of the values $x, x + 1, \dots, N$.

Since these individual probabilities are distributed according to the Borel-Tanner law, the following has been got:

$$v(0 | x) = \sum_{j=x}^N b(j, x), x \leq N. \quad (9)$$

Case III ($z > 0, x \leq N$). This case is a bit more complicated. The reason for this can be explained by the following fact: certain values of X and Z don't have to be related to the number of $N - X + Z$ vehicles arriving with a green signal. It may turn out that at first the queue with X vehicles disappears, and then $N - X - Z$ vehicles arrive that immediately cross the intersection without forming an excessive flow.

It is the situational analysis for different possible cases of vehicle queues that can provide an improved theoretical justification for these tasks within the framework of queuing theory.

A scheme of practical calculations of the time spent by passengers moving through the city is shown in Fig. 2.

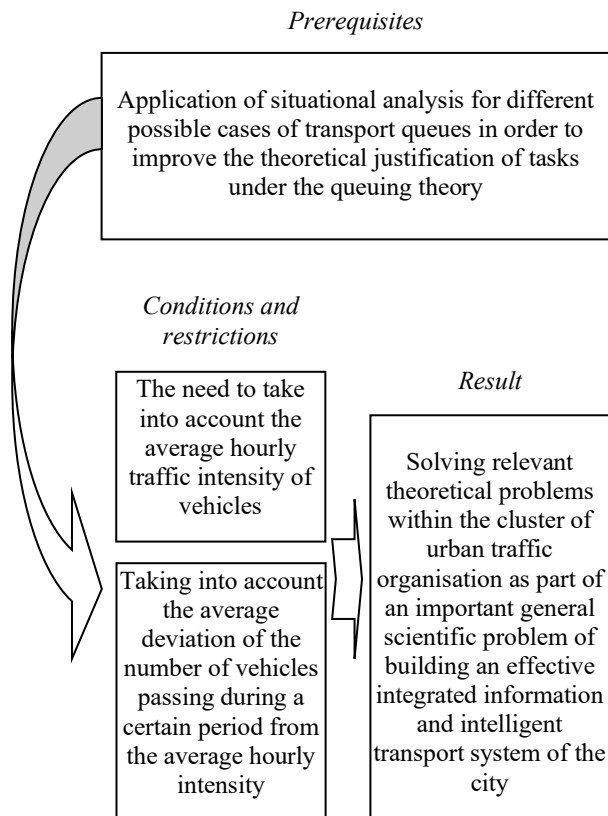


Fig. 2. Scheme of practical calculations of the time spent by passengers moving through the city

In practical calculations of the time spent by passengers on moving around the city, the average hourly traffic intensity of vehicles, the average deviation of the number of vehicles that have passed during certain period (often five-minute interval or other small time interval) from the average hourly intensity should be taken into account.

The proposed mathematical modelling allowed to solve important theoretical problems within a particular traffic management cluster in the city, as part of an important general scientific problem of building an

effective integrated information-intelligent transport system of the city.

The comprehensive development of such systems in the vast majority of cities around the world represents the future.

Moreover, the current uneven development of urban transport systems in different countries worldwide significantly complicates transport mobility and accessibility for international travel.

5 Conclusions

Thus, as stated in the study, it was determined that when forming a queue at traffic lights in the city, it is advisable to consider not pedestrians but vehicles as waiting objects, while the queuing system should be one in which the service device alternately acts and does not act during time intervals.

In this case, the insensitive queuing system was characterized as a system with alternating periods of action and inaction of the service device.

A number of specifying assumptions about the nature of the traffic flow were made in order to form a conclusion about the duration of the green traffic signal. The definitions of the transport flow intensity were characterized from the point of view of the queuing theory.

The cases of intersection crossing by cars under different conditions have been analyzed and theoretically substantiated, which can reduce the probability of traffic jams in the urban transport network of large cities.

Mathematical modelling shows that the queue length depends on two parameters – the intensity of the transport flow and its degree of congestion. Moreover, the influence of the second parameter often leads to congestion of vehicles at the intersection.

Thus, in calculating the duration of the movement of vehicles, it is important to take into account the average delay of vehicles at the intersections of the entire route. The simulation shows that studies of the degree of transport flows unevenness can further reduce the probability of congestion, and as a result, reduce the duration of passenger transportation by urban passenger transport.

The proposed modelling can be used in the development of urban logistics systems in the context of their integration into the general systems of countries and regions.

Implementation of the well-known principles of mobility and transport accessibility for passengers in large cities through the proposed tools can provide a significant reduction in the time for non-productive trips, and therefore create an opportunity for more effective use of the total time.

In general, improving the effectiveness of urban passenger transport operation, including with the use of the proposed tools, can encourage city residents to significantly reduce the use of personal transport and give preference to public urban transport, which in turn will have a positive impact on the urban environment. All this is fully correlated with the Handbook on

Sustainable Urban Mobility and Spatial Planning 2020 developed by the United Nations Economic Commission for Europe.

Future research directions should be related to: analysing the case of vehicles arriving crossing the intersection before the queue occurs; improvement of traffic management system strategies; development of methods and models for optimising air cargo transportation in the context of international integration; software implementation of the task of optimising the organisational and technological processes of air cargo transportation.

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