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METHOD OF DETERMINING THE DISTRIBUTION OF THREAD CAPACITY BY LANES ON MULTI-LANE HIGHWAYS IN THE CONDITIONS OF THE CURRENT STATE OF URBANIZATION OF UKRAINE

Stashenko M. S.,
archdepo7@gmail.com, ORCID: 0000-0001-8671-0721

Odesa State Academy of Civil Engineering and Architecture

Abstract. Urban planning is a complex multifaceted activity of society aimed at creating a material and spatial environment for human life in settlements and settlement areas. The street network of the city - the network of ground communication routes should be designed for a very long period of use without significant reconstructions that are too expensive. The speed of traffic, time spent, the capacity of the transport network, the degree of traffic safety and other important indicators are largely determined by the planning structure of the city. The article examines the problems of overloading the road network, which lead to traffic jams, an increased level of accidents, delays, overspending of energy resources, and a negative impact on the environment. The relevance of the work lies in the search for new approaches to the optimization of traffic flows, taking into account the complex patterns of their distribution and dynamics.

The methodology presented in the study is based on theoretical provisions about the carrying capacity of traffic flows and takes into account the relationship between the intensity, speed and density of the flow on different traffic lanes. The paper also investigates the phenomenon of congestion that occurs when the maximum flow density is reached – the so-called bifurcation point, after which the capacity decreases and road delays increase. Determining this critical point is of key importance for predicting traffic jams and making management decisions. The article offers an analytical approach to determining the optimal bandwidth and possible scenarios for its change. The developed method of determining the distribution of carrying capacity can be used in the process of designing highways, city arteries and transport junctions. It will contribute to increasing traffic safety, reducing traffic jams and improving environmental performance through more rational use of road infrastructure. The results of the study can become the basis for the further development of transport models and be used in the formation of recommendations for the organization of traffic on multi-lane highways.

Key words: traffic flow, bifurcation, traffic management, urban highways, multilane highways, traffic congestion, traffic intensity.

Introduction. The basis of urban planning or the formation of an urban planning system are the three most important social categories of human existence - work, life, and recreation. According to the Law of Ukraine On Regulation of Town Planning Activities 2011 and DBN B.2.2-12:2019 Planning and construction of town planning territories covers a wide range, namely: socio-economic – creation of comfortable living conditions for the population, rational use of the town territory; sanitary and hygienic – provision of healthy living conditions in cities – normal microclimate, clean air and water space, insolation of premises and ventilation of the built-up area; engineering – arrangement of city engineering networks, organization of city transport and road network; architectural – creation of a complete and individual volume-planning composition of each inhabited city with the use and enrichment of the local landscape. The street network of the city – the network of ground communication routes should be designed for a very long period of use without significant reconstructions that are too expensive [6, 7]. The speed of traffic, time spent, the capacity of the transport network, the degree of traffic safety and other important indicators are largely determined by the planning structure of the city. The capacity of the street-road network is the maximum number of cars that can pass through it in a unit of time while ensuring the specified speed and traffic safety. Too high density of the network ensures the minimum length of pedestrian approaches to the main streets, but has serious disadvantages – significant capital investments in the construction of the network, high operating costs for its maintenance, as well as low speed of traffic due to frequent intersections. Excessively low density of the street and road network, characterized by a significant length of pedestrian approaches, which leads to a large expenditure of time for movement. For the correct organization of traffic, it is necessary to take into account: the location of entrances to residential buildings; placement of entrances to the neighborhood; location of entrances to schools and children's institutions; location of garages, parking lots, areas for servicing shops; configuration of passageways according to the nature of traffic. The system of passageways should be simple, safe for traffic and pedestrians, and should not intersect with the main pedestrian flows [8, 12].

The growing complexity of modern transportation systems necessitates the development of effective methods for managing traffic flow on multi-lane highways. Ensuring the optimal distribution of traffic volume across lanes is essential to prevent congestion, minimize travel delays, reduce accident rates, and improve energy efficiency. One of the key challenges lies in determining the lane-specific capacity, which directly influences traffic performance, environmental sustainability, and operational safety. This paper focuses on developing a method to determine the distribution of lane capacity across multi-lane highways by incorporating theoretical and empirical models of traffic flow. The approach aims to account for the dynamic relationships between traffic parameters such as speed, density, and flow rate, while recognizing the non-linear behavior of transportation systems at peak loads. Special attention is given to the onset of congestion, which occurs at critical density thresholds, disrupting the system’s equilibrium and reducing overall capacity. Understanding the bifurcation points – where traffic transitions from smooth to congested flow – is pivotal for both forecasting traffic conditions and devising effective traffic management strategies.

Analysis of the recent research and publications. Determining the lane capacity of multi-lane highways has been a subject of study for many experts. Researchers such as G.D. Dubiler, A.K. Birulia, V.I. Guk [2, 3], D. Drew, G. Greenberg, F. Heidt, M.S. Fishelson, A.A. Polyakov, D.S. Samoilov, R. Watson, V.F. Babakov, Ya.V. Khomyak, V.V. Silianov, and V.V. Filipov have examined the relationship between traffic intensity, speed, and density. However, their models do not account for the dynamics of individual vehicles, fluctuations in density, or the complexities introduced by multi-lane traffic flows. In contrast, works by I. Prigogine, M. Kramer, A.A. Gavrilov, G.P. Soldatov, and A.S. Agamerzyan treat traffic flow as a probabilistic process. For instance, the distribution of time intervals between vehicles in a flow may not be strictly deterministic but rather random, which provides a more realistic assessment for different observation points. According to Ukrainian state building codes (DBN) [1], the lane capacity for uninterrupted traffic flow is specified as 1400 vehicles per hour for a single lane on high-speed roads and 1200 vehicles per hour for urban arterial roads [4, 5].

Statement of the objective. Urban transportation of passengers and goods serves as a driving force for the economic and social development of cities. On the one hand, it reflects trends such as the specialization and cooperation of industries, along with population growth; on the other hand, it addresses the increasing number of new, dynamic models of passenger cars, trucks, buses, trolleybuses, and trams, contributing to greater urban mobility. The rise in transportation activity transforms urban traffic from a series of individual movements into a mass process, characterized by continuous flows of dense vehicular and pedestrian traffic that approach the limits of road capacity.

During peak hours, over-saturation of traffic frequently occurs, leading to unproductive delays, congestion, increased accident rates, environmental pollution, and excessive consumption of energy resources. As a result, the issue of roadway width – and thus the capacity of urban streets and roads – becomes a priority among urban transportation challenges. Identifying reserves and justifying new methods to improve the capacity of streets and roads, both at the design stage and in urban traffic management, must be based on understanding the patterns inherent to saturated traffic flows. This requires uncovering the internal characteristics, causal relationships, and complex interconnections within these flows, all of which must be consolidated into a fundamental scientific framework for design calculations.

Main material and results. Assessment of the street-road network is an essential and initial component of urban planning, including general plans (in sections related to comprehensive transportation schemes – CTS), detailed planning projects (DPP), integrated traffic management schemes (ITMS), and traffic organization projects (TOP).

When determining the lane capacity and addressing the challenges of safe traffic flow in the design of multi-lane highways, it is necessary to consider the key principles of traffic capacity theory:

1) **Integrity of the traffic flow:** The movement of following vehicles closely mirrors the behavior of the leading vehicle, meaning that «the integrity of the flow is primary, while the position and speed of individual vehicles are secondary» [4] ($N = Q_m \cdot V_0 (1 - V / V_0)(1 - Q / Q_m)$).

2) Continuous flow of dynamic vehicle dimensions at the lane capacity level ($P = 3600 \cdot V/L_d$).

3) Distribution of time gaps between vehicles as they pass through an intersection, observed at the lane capacity level ($N = 3600 / t_c$).

4) Optimal density and positioning of vehicles within the lane at the capacity threshold ($Q_{\text{опт}} = 0{,}5 \cdot Q_m$).

5) Maximum density of the traffic flow during congestion ($Q_{\max}$);

6) Influence of speed on flow intensity $N(V)$.

7) Free-flow speed when no other vehicles impact the movement of a vehicle (V_0).

8) Optimal traffic flow speed at lane capacity ($V_{\text{опт}} = 0{,}5 \cdot V_0$).

9) Interrelation of maximum traffic flow parameters at the lane capacity level ($N_m = V_0 \cdot Q_m \cdot 0{,}5$);

10) Impact of speed changes on flow intensity (dN/dt, dV/dt);

11) Distribution of lane capacity based on a multi-lane coefficient ($K_{\text{б}} = \sum N_i / N_{m1}$);

12) Intensity distribution along the length of the lane, following the principle of specific intensity ($U = N / L$);

13) Interrelation between vehicle intervals and the values of specific intensity ($U(t_c)$);

14) Different speeds across lanes to enable lane changes ($V_1 < V_2 < V_3 < V_4 < \ldots$);

15) Congestion formation when speeds are equal across all lanes ($V_1 = V_2 = V_3 = V_4 \geq$ congestion);

16) Comprehensive consideration of traffic characteristics on highways to determine their real capacity [4].

Since the potential of the traffic flow depends on the number of vehicles distributed along the road section, it reflects the transportation component within the equation of movement. In the «traffic flow» system, there is a continuous interchange between road and traffic potentials. This dynamic suggests that fluctuations occur within the system, and optimal traffic conditions can only be achieved with:

$$E\textit{д} + ET = E = const. \tag{1.1}$$

when the system operates at a stable performance level, supported by efficient road design and traffic management.

Lane capacity must be evaluated not at a single point but across the highway's length, considering how intensity varies along the lane length L. The speed of the flow V is influenced by these intensity fluctuations, indicating a critical relationship between traffic speed and flow intensity across the entire lane:

$$V(t) = CdN(t) / dt \tag{1.2}$$

where the coefficient C has the dimension of km·h/veh and defines the portion of space between vehicles in the traffic flow $C = L/N$ [4].

It is described as a characteristic representing the tension within the flow due to the decreasing distance between vehicles. At the same time, the inverse characteristic of flow tension indicates the share of flow intensity allocated along a specific section of the lane (*L).* This is known as the specific intensity U, defined as:

$U = N / L$ with the dimension of veh/h·km.

$$U = C^{-1} \tag{1.3}$$

Equation (1.1), considering the relationship in equation (1.3), provides an explicit description of the dependence of intensity N(t) on speed over time when the intensity either increases or decreases, i.e., when dN(t)/dt takes non-zero values. This relationship has not been thoroughly explored yet.

By integrating equation (1.1), we find: $N(t) = U\int_0^t V(t)dt + N(0)$,

$$N(t) - N(0) = U\int_0^t V(t)dt\,, \tag{1.4}$$

where $N(0)$ – is the initial intensity at the starting moment, $t = 0$.

When the traffic flow begins to form into discrete groups, $N(t)$ becomes a discontinuous function, meaning that $dN(t)/dt$ does not exist, and equation (1.4) has no solution. To address this, we perform a change of variables by introducing a unit characteristic of motion (distance) $L(t)$, where it is known that: $L(t) = \int V(t)dt$ and therefore: $V(t) = dL(t)/dt$. Here, speed $V(t)$ is always a continuous function of time.

Taking into account equation (1.4) and the fact that the approximating curve passes through the origin, we derive the equation for variation when $N(t)$=0:

$$L(t) = N(t)/U \quad \text{або} \quad dL(t) = dN(t)/U\,. \tag{1.5}$$

Thus, following [13, 14], the growth of traffic flow intensity can be expressed by one of the following equations:

$$N = U \cdot L\,; N = U\int V(t)dt\,;\ L = N/U\,;\ V = 1/U \cdot dN/dt\,. \tag{1.6}$$

Accordingly, the specific intensity will be determined as:

$$U = N/L\,. \tag{1.7}$$

It is reasonable to define the lane section length as an elementary 1-kilometer segment, considering the distribution of maximum flow density per kilometer. At the same time, the intensity $N(t)$ should account for changes in speed $V(t)$ under the influence of density (Q, veh/km)

$$N(t) = Q \cdot V(t)\,. \tag{1.8}$$

The density of the traffic flow is an instantaneous variable characterizing the distribution of vehicles along the highway lanes and acts as resistance to speed. The technical and economic significance of density, denoted as $Q(t, L)$, reflects the level of highway load, the utilization rate of its capacity, and the possibility of uninterrupted movement, i.e., the highway's throughput. However, measuring density through field observations is labor-intensive. Only aerial photography allows for the instant capture of vehicles on the highway lanes during motion. Consequently, more attention has been given to studying the dependencies of speed $V(Q)$ and intensity $N(Q)$.

The fundamental linear relationship $V(Q)$, which has been studied through experimental observations [2, 11] and methods from queuing theory, is expressed as [13, 14]:

$$V(Q) = V_0 \left(1 - Q / Q_m\right), \tag{1.9}$$

where V_0 – is the free-flow speed within the range allowed by traffic regulations;

Q_m – is the maximum density under congestion conditions (which depends on vehicle lengths and the composition of the traffic flow).

Notably, when $Q = 0$, $V = V_0$; when $Q = Q_m$, $V = 0$.

For traffic flows composed of passenger vehicles, the maximum density, according to [9, 10], is approximately 100–125 vehicles per kilometer per lane. The dependence of the intensity on the density, taking into account , and substituting into equation (2.61), we get the form:

$$N(Q) = Q \cdot V(1 - Q/Q_m), \tag{1.10}$$

This equation indicates that when $Q = 0$, $N = 0$; and when $Q = Q_m$, $N = 0$, meaning that no movement occurs, and all vehicles are stopped.

Through straightforward transformations, we can derive the dependence of intensity on traffic flow speed $N(V)$:

$$N(V) = Q_m \cdot V(1 - V/V_0). \tag{1.11}$$

The relationships between intensity and density (2.58) and between intensity and speed (1.11) allow us to determine the specific intensity $U = N / L$ for a given section length L. This yields the following equations:

$$U(Q) = V_0 \cdot Q(Q - Q_m) / LQ_m, \tag{1.12}$$

$$U(V) = Q_m \cdot V(V_0 - V) / L \cdot V_0. \tag{1.13}$$

When determining the values of lane section length L in equations (2.64) and (2.65), it is necessary to account for the distribution of maximum density along the section during congestion.

Specific intensity allows for the comparison of various urban highways and roads based on the distribution of traffic intensity. It also helps evaluate their operational performance over time (hourly, daily, annually) and spatially.

An analysis of equations (1.12) and (1.13) for determining the maximum lane capacity under optimal free-flow speeds and maximum density indicates a capacity of 2,500 vehicles per hour, consistent with the recommendations found in [4].

Specific intensity determines the intervals between vehicles as they pass a given section of the lane. For example, with 50 vehicles per kilometer and a 2-second interval, the lane capacity reaches 1,800 vehicles per hour. With a 1.44-second interval, the capacity increases to 2,500 vehicles per hour.

If the interval drops to 1 second, the intensity reaches 3,600 vehicles per hour.

To determine the actual coefficients affecting the capacity of different lanes, an extensive and long-term study was conducted on the six-lane Autobahn (A5) near Frankfurt am Main, Germany [4].

The Autobahn is equipped with dual inductive loop detectors on each lane. The detector system records individual vehicle signals and average speeds for both passenger cars and trucks within each sampling interval.

From the large volume of spatial and temporal data published in field observations, specific sections and times were selected, focusing on the pre-congestion queues during platoon movements. Observation results over various hours and months were summarized in tables.

It is important to note that the authors of these publications focused on changes in traffic flow intensity and speed primarily at the onset of congestion, tracking its duration and its impact on traffic management. However, the emergence of congestion beyond the bifurcation point — the state of maximum lane capacity—is of particular scientific and practical interest for forecasting lane-specific capacity.

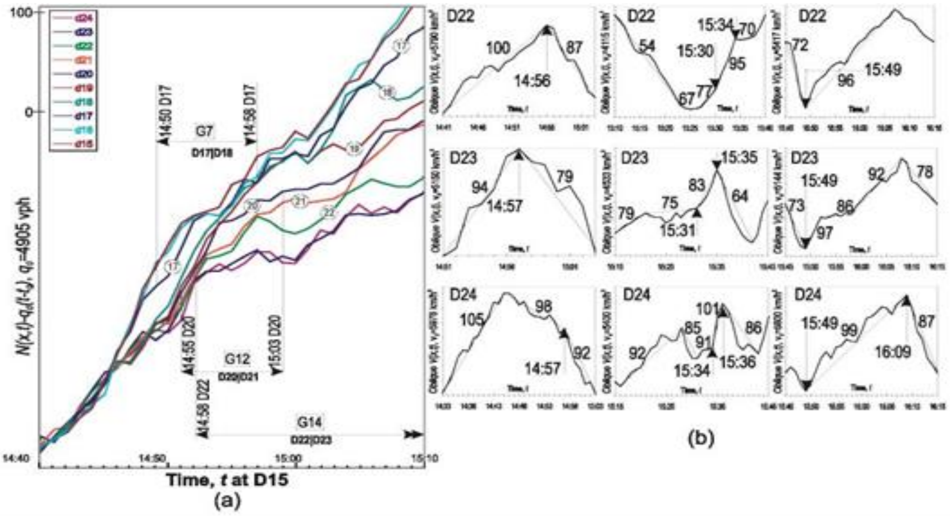

Fig. 1. Change of intensity N(x, t) and speed V(x, t) in the interval D15-24

Comclusions.

1. An equation has been formulated that enables the explicit description of the relationship between traffic flow intensity $N(t)$ and speed for instances when an increase or decrease in intensity occurs $dN(t)/dt$. This relationship remains insufficiently studied in the current body of research, warranting further investigation to uncover underlying dynamics and behaviors.

2. According to theoretical modeling, the law of traffic flow intensity growth can be expressed through one of four equations. Traffic flow density serves as an instantaneous variable that characterizes the spatial distribution of vehicles along the lanes of a highway and acts as a form of resistance to speed. The density parameter has significant technical and economic implications, as it reflects the level of highway utilization, the extent to which its capacity is exploited, and the feasibility of uninterrupted vehicle movement. In essence, it defines the *road serviceability*, i.e., the extent to which the highway allows efficient vehicle travel under prevailing conditions.

3. The concept of specific intensity, defined as the traffic intensity per unit length, provides a valuable metric for comparing various urban highways and roads based on the spatial distribution of traffic flow. This measure allows for the characterization of road performance both temporally (e.g., per hour, day, or year) and spatially across different road segments. As such, specific intensity is an essential indicator of the operational efficiency of road infrastructure and can support the strategic planning of urban mobility networks.

4. To determine the real-world coefficients influencing lane capacity, an extensive and long-term study of traffic flow was conducted on a six-lane Autobahn (A5) near Frankfurt am Main, Germany. The study offers a wealth of primary data relevant to the objectives of capacity research. The analyzed highway section spans 30 kilometers, with 30 fixed measurement points that capture vehicle speeds and counts. The road's slope does not exceed 2.6%, ensuring minimal elevation-induced impact on vehicle dynamics. The large-scale data collection from this study is highly valuable for refining models of traffic flow and lane capacity distribution.

5. The authors of the study focused on the patterns of changes in traffic intensity and speed primarily during the onset of traffic congestion (referred to as *congestion events* or *congestions*).

They examined the duration of these events and their relevance to traffic management strategies. However, the occurrence of congestion beyond the *bifurcation point*—the critical state at which maximum lane capacity is reached—represents a key area of both scientific and practical interest. Predicting this point for each lane is essential for effective highway capacity planning and congestion mitigation efforts.

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МЕТОД ВИЗНАЧЕННЯ РОЗПОДІЛУ ПРОПУСКНОЇ СПРОМОЖНОСТІ ПО СМУГАМ НА БАГАТОСМУГОВИХ МАГІСТРАЛЯХ В УМОВАХ СУЧАСНОГО СТАНУ УРБАНІЗАЦІЇ УКРАЇНИ

Сташенко М. С.,
archdepo7@gmail.com, ORCID: 0000-0001-8671-0721

Одеська державна академія будівництва та архітектури

Анотація. Містобудування – комплексна багатогранна діяльність суспільства, що спрямована на створення матеріально-просторового середовища життєдіяльності людини у поселеннях та районах розселення. Вулична мережа міста - мережа наземних шляхів сполучення повинна бути розрахована на дуже тривалий період використання без істотних перебудов, що обходяться надто дорого. Швидкість руху транспорту, витрати часу, пропускна здатність транспортної мережі, ступінь безпеки руху та інші важливі показники значною мірою обумовлюються планувальною структурою міста. У статті розглядаються проблеми перевантаження дорожньої мережі, які призводять до виникнення заторів, підвищеного рівня аварійності, затримок, перевитрати енергоресурсів і негативного впливу на довкілля. Актуальність роботи полягає у пошуку нових підходів для оптимізації транспортних потоків з урахуванням складних закономірностей їх розподілу та динаміки.

Методика, представлена в дослідженні, базується на теоретичних положеннях про пропускну спроможність транспортних потоків та враховує взаємозв'язок між інтенсивністю, швидкістю та щільністю потоку на різних смугах руху. У роботі також досліджено явище конгестії, що виникає при досягненні граничної щільності потоку – так званої точки біфуркації, після якої пропускна спроможність знижується, а затримки на дорогах зростають. Визначення цієї критичної точки має ключове значення для прогнозування заторових ситуацій та прийняття управлінських рішень. У статті запропоновано аналітичний підхід до визначення оптимальної пропускної спроможності та можливих сценаріїв її зміни. Розроблений метод визначення розподілу пропускної спроможності може бути використаний у процесі проектування магістралей, міських артерій та транспортних розв'язок. Він сприятиме підвищенню безпеки руху, зменшенню заторів і покращенню екологічних показників завдяки більш раціональному використанню дорожньої інфраструктури. Результати дослідження можуть стати основою для подальшого розвитку транспортних моделей і застосовуватися при формуванні рекомендацій щодо організації руху на багатосмугових магістралях.

Ключові слова: транспортний потік, біфуркація, управління рухом, міські магістралі, багатосмугові автомагістралі, перенасичення руху, інтенсивність руху.