TRANSPORT TECHNOLOGIES

Vol. 6, No. 1, 2025

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https://doi.org/10.23939/tt2025.01.048

DISTRIBUTION OF VEHICLE SPEEDS IN TRAFFIC FLOW ON MULTILANE ROADS APPROACHING MAJOR AND METROPOLITAN CITIES

Summary. *The distribution characteristics of vehicle speeds on multilane highways approaching major and metropolitan cities, using a six-lane segment of the M-05 Kyiv – Odesa highway as a case study, are investigated in this paper. The research methodology is based on field observations employing frame-by-frame video analysis with an accuracy of 0.04 seconds, enabling precise identification of time headways between vehicles and calculating their instantaneous speeds. Both theoretical and empirical speed distribution curves were constructed. Typical speed ranges for different traffic lanes were identified, and the conformity of the observed data to the normal distribution law was statistically verified.*

The research identified several key analytical directions in the study of vehicle speed distribution on multilane highways. Specifically, the investigation focused on assessing the conformity of empirical data to the normal distribution model, establishing characteristic speed ranges by vehicle type, and evaluating the influence of traffic volume and traffic flow composition on speed parameters. The authors also examined the spatiotemporal structure of traffic flow, including the daily distribution of traffic volumes, lane-by-lane and directional variation, and empirical and theoretical speed distribution curves. Relationships among key traffic parameters – volume, density, and speed – were analyzed. A linear regression method was applied to describe the lane-wise distribution of vehicles, enabling the derivation of analytical dependencies N_1, N_2, *and* N_3 *on total traffic volume N using the least squares method.*

The results showed that the speed distribution on the studied highway segment aligns well with the normal distribution, with observed deviations being random. The obtained 85th percentile speed (98 km/h) can serve as a reference for setting recommended speed limits, modeling roadway capacity, and developing intelligent traffic management systems components

Key words: *highway, traffic volume, traffic lane, speed, multi-lane highway, empirical study.*

1. INTRODUCTION

The increase in private and commercial vehicles in Ukraine has led to a substantial rise in traffic volumes on major highways, particularly on approaches to large cities. These sections are characterized by complex traffic conditions, a variable composition of traffic flows, and significant speed differences between lanes. As a result, there is a growing need for up-to-date empirical data to gain deeper insights into the speed distribution patterns of vehicles under such conditions.

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One of the key parameters affecting road safety, roadway capacity, and travel comfort is the actual speed of the traffic flow. Excessive speeds or significant variations in speed between individual vehicles increase the risk of road accidents, especially on the approaches to urban agglomerations, where traffic density begins to rise. Therefore, a precise analysis of speed profiles – considering the traffic lane, flow composition, and traffic volume – is essential for modern transportation planning.

Despite the existence of numerous theoretical models, most were developed in previous decades and do not reflect current changes in vehicle dynamics, traffic flow structure, or driver behavior. Moreover, the impact of road geometry and infrastructure characteristics on speed distribution remains insufficiently studied under modern conditions.

This paper presents the results of a field study conducted on a six-lane section of the M-05 Kyiv–Odesa highway near Kyiv. The aim of the study is to evaluate the applicability of the normal distribution law to real-world speed profiles and identify the influence of traffic composition and lane structure on speed variations. The findings provide an essential empirical foundation for further developing adaptive traffic management systems.

The purpose of this article is to analyze the distribution of vehicle speeds on multilane highways approaching major and metropolitan cities and to identify the underlying patterns that determine the impact of traffic volume, traffic flow composition, and lane usage on the speed characteristics of traffic flows.

The following research tasks were formulated to achieve the stated objective:

– to conduct field observations of vehicle movements on a multilane road segment with high traffic volumes;
– to determine the actual speed distribution of the traffic flow depending on lane usage, traffic volume, and traffic flow composition;
– to verify the conformity of the speed distribution to the normal distribution law using statistical criteria;
– to assess the results' applicability for optimizing traffic flow organization and determining typical speeds when planning approaches to large and major cities.

2. STATEMENT OF THE PROBLEM AND RELEVANCE OF THE STUDY

The rapid growth of the vehicle fleet in Ukraine, particularly in urban agglomerations and on the approaches to major cities, places an increasing burden on the road infrastructure. This necessitates a precise analysis of the speed modes of traffic flows to improve safety, enhance roadway capacity, and optimize traffic organization. One of the critical factors affecting accident rates and travel comfort is speeding, especially on the approaches to populated areas. Existing analytical models of speed distribution have been developed primarily based on studies conducted in previous decades, and they do not account for current changes in traffic flow composition, vehicle dynamics, or the updated regulatory framework. Moreover, most of these models are theoretical and require validation using up-to-date empirical data. Therefore, there is a clear need for field studies of vehicle speed distribution on multilane highways leading to large cities. These studies are essential for updating forecasting models and ensuring alignment between actual traffic conditions and theoretical assumptions.

Therefore, it is highly relevant to conduct studies on the impact of traffic volume and traffic flow composition on vehicle speed.

One of the most critical areas for improving road safety and enhancing the efficiency of transport infrastructure is the investigation of actual traffic flow characteristics, particularly speed. Approaches to large cities are typically high-load zones, where high traffic volume, a mixed vehicle fleet, and variable road conditions coexist. Under such conditions, even minor violations of speed limits can lead to critical situations, reduced capacity, traffic congestion, and increased accident rates. Although the topic of speed distribution has been studied in transport science for decades, most existing models are based on theoretical assumptions or outdated data that do not reflect current trends, such as changes in the typical traffic flow composition, the new dynamic characteristics of vehicles, or the implementation of intelligent transport systems. In particular, there is a noticeable lack of up-to-date field studies in the Ukrainian context that could confirm or challenge the applicability of traditional statistical distributions (e.g., the normal distribution) to real-world data. The relevance of this research is in the urgent need to update empirical data on vehicle speeds on multilane roads within the influence zones of major cities. Such data are critical for adaptive traffic management, enhancing transport safety, adjusting speed limits, designing interchanges, and informing infrastructure policy. Therefore, studying the actual distribution of vehicle speeds, considering traffic volumes, traffic flow composition, and lane use, is a highly relevant task in both transport science and practice.

3. ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

The issue of analyzing vehicle speeds, particularly in the context of road safety and transport system efficiency, remains highly relevant in contemporary scientific research. In [1], an energy-based approach to assessing road traffic safety was proposed, emphasizing the relationship between the kinetic characteristics of the traffic flow and accident rates. This highlights the importance of studying speed modes as a critical factor in ensuring traffic safety.

In study [2], a digital control tower model was proposed within the urban transport management system, which also relies on analyzing dynamic parameters, including speed. Meanwhile, [3] examined the modeling of traffic flow distribution within a network; however, their research did not focus in detail on the empirical distribution of speeds across individual lanes.

Considerable attention has been given to the collection and processing of speed data in the works of international researchers. Study [3] examined traffic speed prediction methods using probabilistic models, particularly relevant in dynamic traffic conditions. Studies [4, 5] provided an overview of modern techniques for collecting speed-related information, highlighting the potential of video analysis – an approach also employed in our research. Furthermore, a computer-oriented system was developed in [6] for automated speed detection, further supporting the applicability of digital technologies in field-based traffic studies.

In the context of driver behavior and the influence of road conditions on speed, it is worth mentioning studies [4, 7], which examined the impact of temporary rumble strips on vehicle speed. Additionally, publication [8] analyzed micromobility-related risks at various speed levels.

It is also important to emphasize the relevance of integrating the results of such studies into intelligent traffic management systems. In particular, studies [7, 9] propose approaches to trajectory optimization for automated vehicles, based on precise speed profiles.

Thus, the reviewed studies confirm the necessity of refining empirical speed parameters under specific conditions, particularly on approaches to large cities. However, most of these studies do not provide a detailed analysis of speed distribution across individual lanes, taking into account vehicle type and traffic volume on urban approaches. This highlights both the scientific and practical relevance of the present study.

4. MAIN PART

Traffic volume varies across individual highway lanes, with three lanes in one direction. An increase in the number of lanes in a single direction leads to a redistribution of vehicles (V) among the lanes, depending on the dynamic characteristics of the vehicles [10, 11]. This contributes to the efficient use of the carriageway on multilane roads. Observations show that a wide range of factors influence lane-by-lane traffic volume distribution, the most significant being: traffic volume in a given direction, the composition of the traffic flow, and the number of traffic lanes.

Due to the variability of numerous factors – such as traffic volume, traffic flow composition, and vehicle dynamics – that influence traffic movement and may not accurately reflect the actual conditions on these segments [12, 13], it was necessary to conduct field observations to compare the current lane-wise distribution of vehicles with previously established patterns.

The schematic layout of the observation site is shown in Fig. 1.

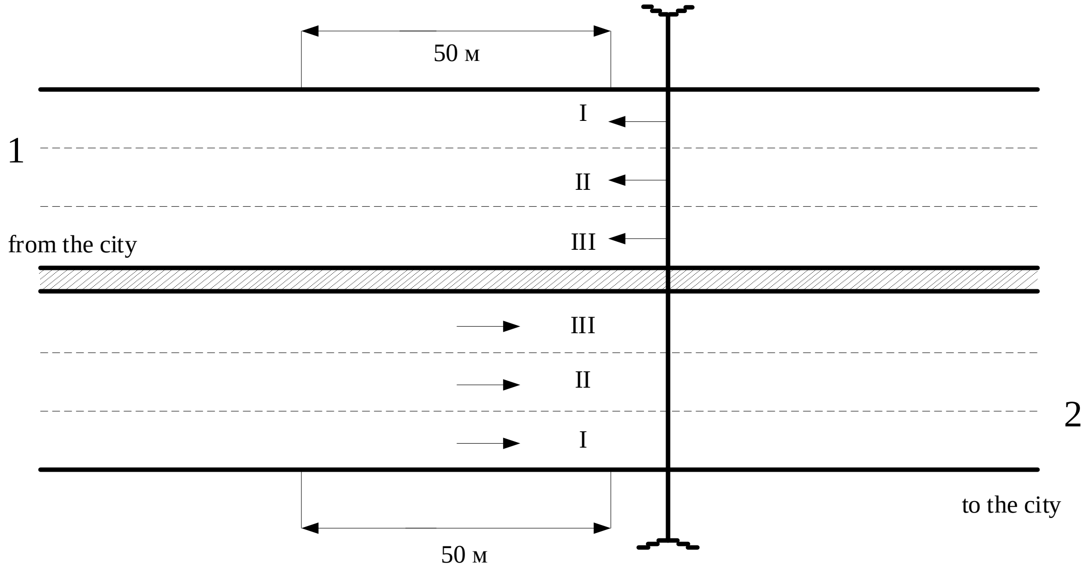

Fig. 1. Observation site layout

The study was conducted through digital video data processing, capturing traffic flow movement. The observation period was divided into 15-minute intervals to enable subsequent verification of measurement accuracy. The research was conducted under traffic conditions with 3,000 vehicles per hour [14, 15]. The hourly distribution of traffic volume is shown in Fig. 2 and Fig. 3.

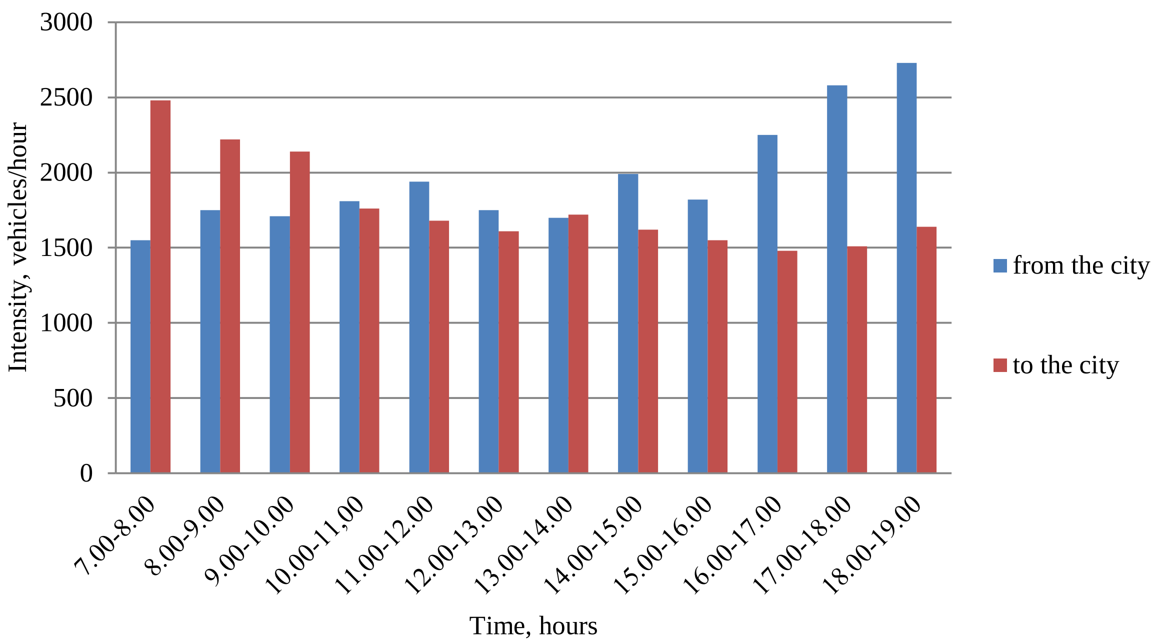

Fig. 2. Distribution of traffic volumes by hour on the M-05 Kyiv–Odesa highway segment (Tuesday)

Observations showed that the six-lane highway is not evenly utilized under low traffic volumes, below the average of 680 vehicles per hour per lane. The lane utilization resembles that of a four-lane road, as the traffic volume in the far-left lane in such cases ranges from 12 to 80 vehicles per hour. The far-left lane is typically used for overtaking and by individual vehicles traveling at exceptionally high speeds.

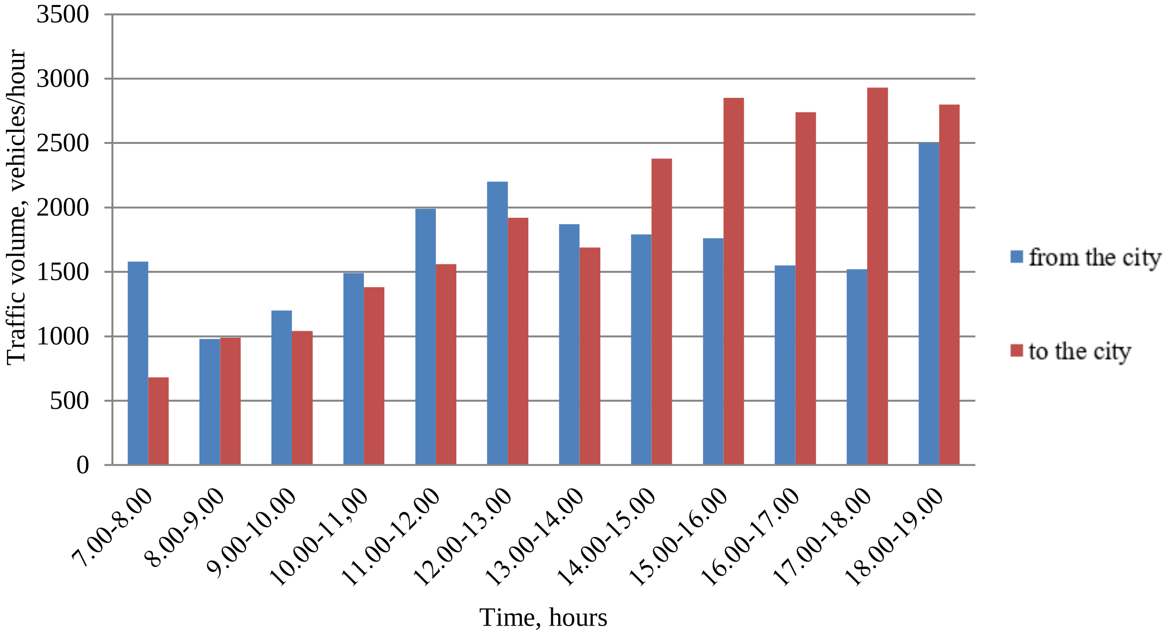

Fig. 3. Distribution of traffic volumes by hour on the M-05 Kyiv – Odesa highway segment (Sunday)

As a result of processing the observational data on lane-wise traffic volume distribution, it was found that when the traffic volume in one direction ranges from 200 to 1,200 vehicles per hour, the distribution of traffic volume (N_1, N_2, N_3) across lanes on six-lane roads is well approximated by a linear equation [16, 17]. For the far-right lane N_1=0.407 N+50; for the middle lane N_2=0.441 N–18; for the far-left lane N_3=0.168 N–42. These equations are valid when the traffic flow contains 38–42 % passenger cars. In the studied segment, the share of passenger cars in traffic flow ranged from 69 % to 86 %. The hourly distribution of vehicles by type is shown in Figs. 4–5.

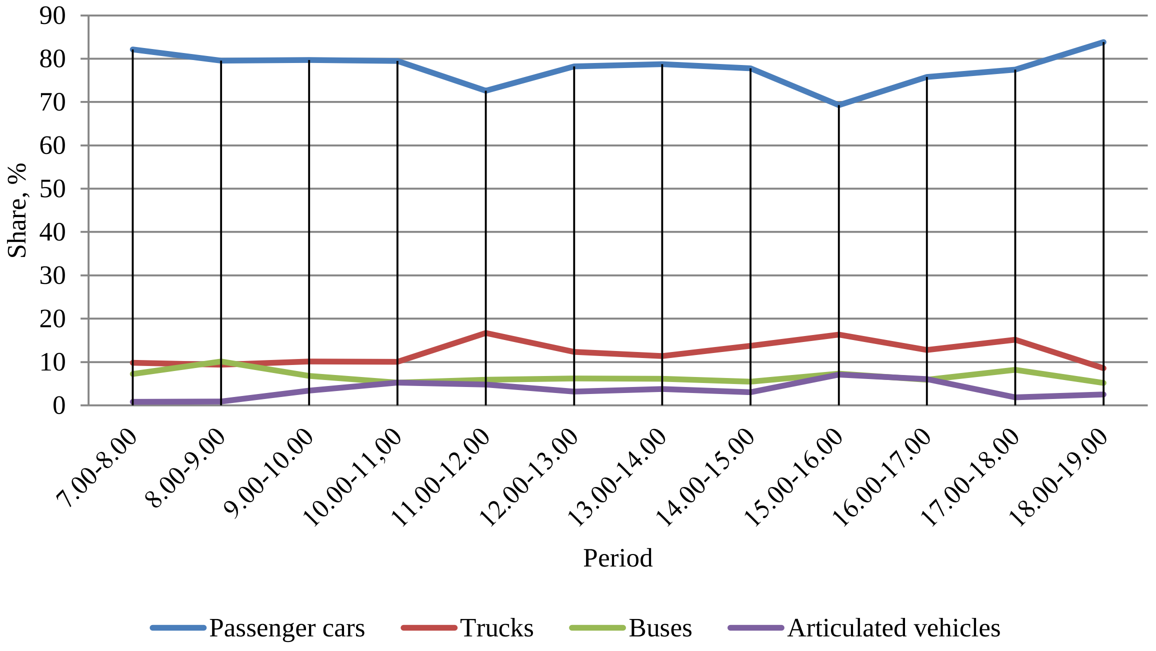

Fig. 4. Traffic Flow Composition by Hour of the Day (Direction: from the city).

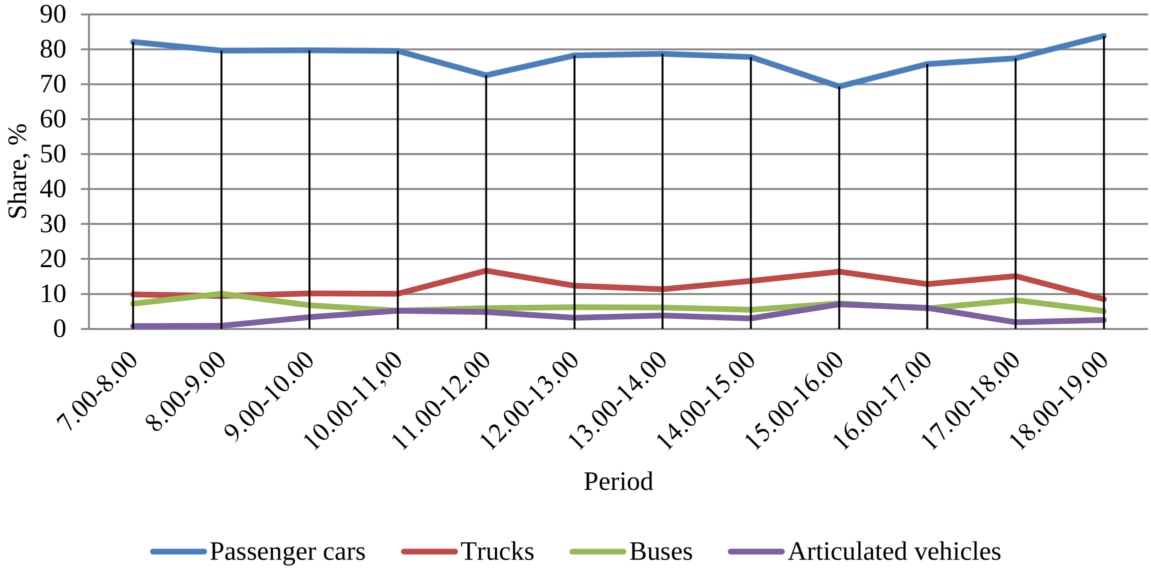

Fig. 5. Traffic Flow Composition by Hour of the Day (Direction: to the city)

Distribution coefficients were obtained for six-lane highways based on the actual lane-by-lane vehicle distribution data. A coefficient value of 1 was assigned to the most heavily loaded lane under traffic flow conditions (Table 1).

Table 1

Distribution of Vehicles across Lanes

Traffic Volume in One Direction, vehicles/hour	Share of Passenger Cars in the Flow, %	Lane Distribution Coefficient		
		Right	Middle	Left
Less 500	More than 75 %	0.33	1	0.26
500–1000		0.38	1	0.35
1000–1500		0.45	1	0.52
1500–2000		0.57	1	0.65
2000–2500		0.64	1	0.77
2500–3000		0.71	1	0.86
3000–3500		0.81	1	0.95
More 3500		0.87	1	1

Video data processing was carried out using frame-by-frame analysis with high precision, up to 0.04 seconds. This enabled the accurate determination of time intervals between vehicles for subsequent calculation of their travel speeds. Such an approach ensured the reliability of the collected data and allowed for a detailed analysis of traffic dynamics in each lane. The data collection procedure is illustrated in Fig. 6.

The observation results were consolidated into a database. The structure of the database fields is presented in Table 2.

Fig. 6. Interface of the software module for processing traffic flow data on a six-lane section of the M-05 Kyiv – Odesa highway

Table 2

Structure of the Vehicle Registration Database

Traffic Lanes														
I					II					III				
No.	Vehicle Type	Vehicle Detection Time, t, s	V, km/h	Time Headway, s	№	Vehicle Type	Vehicle Detection Time, t, s	V, km/h	Time Headway, s	No.	Vehicle Type	Vehicle Detection Time, t, s	V, km/h	Time Headway, s
1	P	4.50 8.31	47.32	1.07	1	P	0.73 2.80	87.12	1.14	1	P	1.60 3.30	106.01	0.94
2	P	5.77 9.38	49.92	0.43	2	P	1.74 3.94	81.74	13.44	2	P	2.54 4.24	105.76	1.67
3	P	6.64 9.81	56.78	9.64	3	B A	14.71 17.38	67.42	0.40	3	P	4.14 5.91	101.75	1.30
4	P	15.38 19.45	44.23	7.51	4	P	15.22 17.78	70.18	5.21	4	P	5.57 7.21	110.09	2.63
5	P	24.29 26.96	67.42	12.14	5	P	20.39 22.99	69.15	5.47	5	P	8.04 9.84	100.00	2.77
6	P	35.20 39.10	46.15	2.44	6	P	26.09 28.46	75.95	1.40	6	P	10.68 12.61	93.12	7.54
7	T	37.90 41.54	49.45	8.08	7	P	27.53 29.86	77.15	1.94	7	P	18.05 20.15	85.71	1.37
8	B A	45.51 49.62	43.80	10.77	8	P	30.03 31.80	101.75	1.57	8	P	19.29 21.52	80.57	1.63
9	P	58.06 60.39	77.25	2.17	9	P	31.56 33.37	99.61	10.87	9	B	20.92 23.15	80.72	2.48
10	P	58.82 62.56	48.13	1.77	10	P	41.54 44.24	66.67	1.77	10	P	23.52 25.63	85.47	1.60

Note: P – passenger cars; T – trucks; B – buses; A – articulated vehicles.

Based on the observation results, the following were determined: the distribution of traffic volume throughout the day and by lanes; the composition of the traffic flow by direction during the day; theoretical and empirical vehicle speed distributions; the distribution of time headways; key relationships, including volume–density, speed–density, and speed–volume. The linear regression method was applied to empirical data to derive the equations describing the lane-wise distribution of traffic volume. Dependencies N_1, N_2, and N_3 on total volume N were constructed and approximated using the least squares method. The resulting equations characterize the typical flow distribution on the studied road segment:

$$v_1 = 80.5 - 0.0375 \cdot N_1$$
$$v_2 = 87.0 - 0.02 \cdot N_2 \quad , \qquad (1)$$
$$v_3 = 110.5 - 0.0325 \cdot N_3$$

Observations were conducted exclusively on straight, level segments of six-lane roads near the city to eliminate the influence of road conditions on traffic flow behavior. Simultaneously with speed measurements, the traffic volumes and composition were continuously recorded for each traffic lane.

The speed distribution curves on six-lane roads under low one-directional traffic volumes exhibit two to three peaks, stretched along the x-axis and compressed relative to the y-axis (Fig. 7).

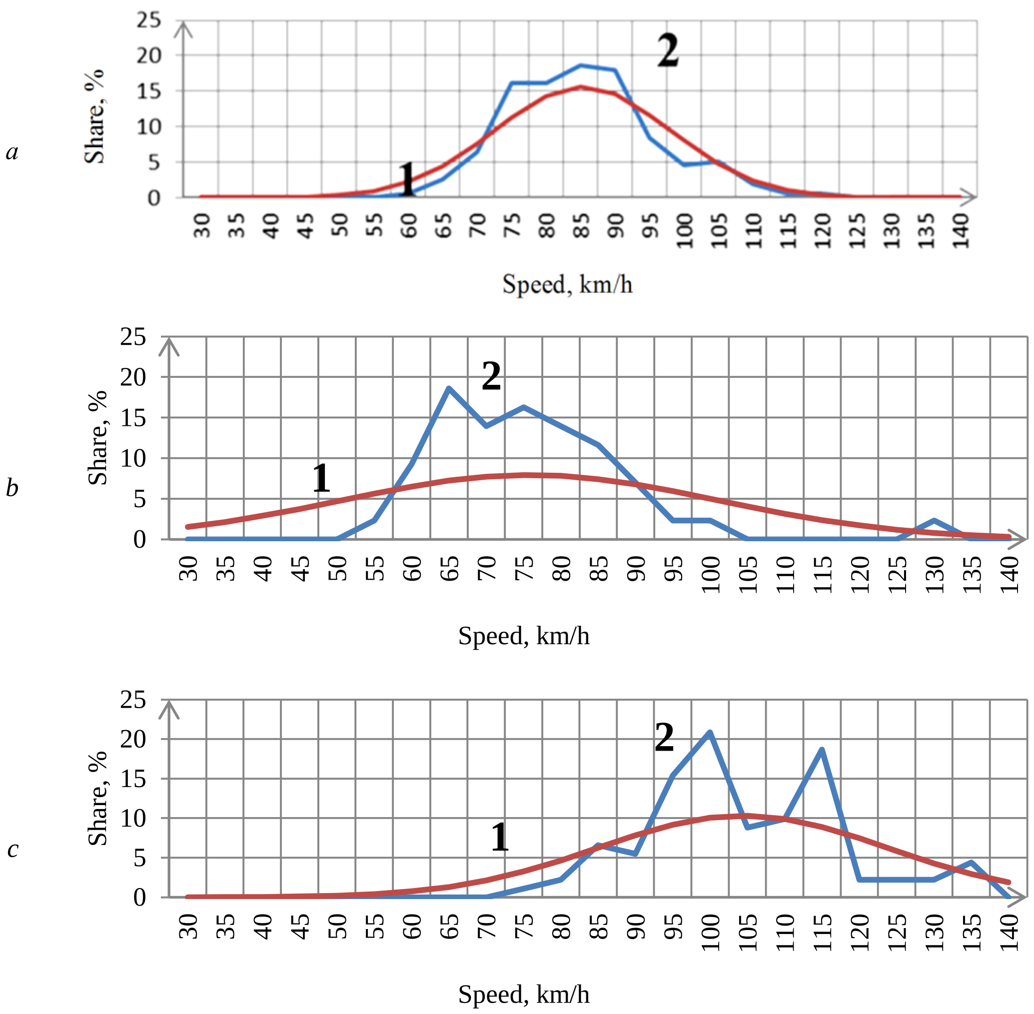

Fig. 7. Theoretical (1) and empirical (2) speed distribution on a six-lane highway segment at the city entrance (M-05 Section): a – N=632 vehicles/hour, middle lane (72 % passenger cars in the flow); b – N=596 vehicles/hour, right lane (58 % passenger cars in the flow); c – N=372 vehicles/hour, left lane (95 % passenger cars in the flow).

It can be explained by the fact that the most frequently observed vehicle speeds differ significantly. Under low traffic volume, the most common speeds range between 50 and 120 km/h. At the same time, as traffic volume increases, vehicle speeds become more uniform, and the distribution curve becomes unimodal (Fig. 8). It is worth noting that when the share of passenger cars in the flow increases to 80 %, the proportion of vehicles traveling at speeds above 100 km/h also increases. Under high traffic volumes, the composition of the traffic flow primarily affects the position of the peak of the distribution curve.

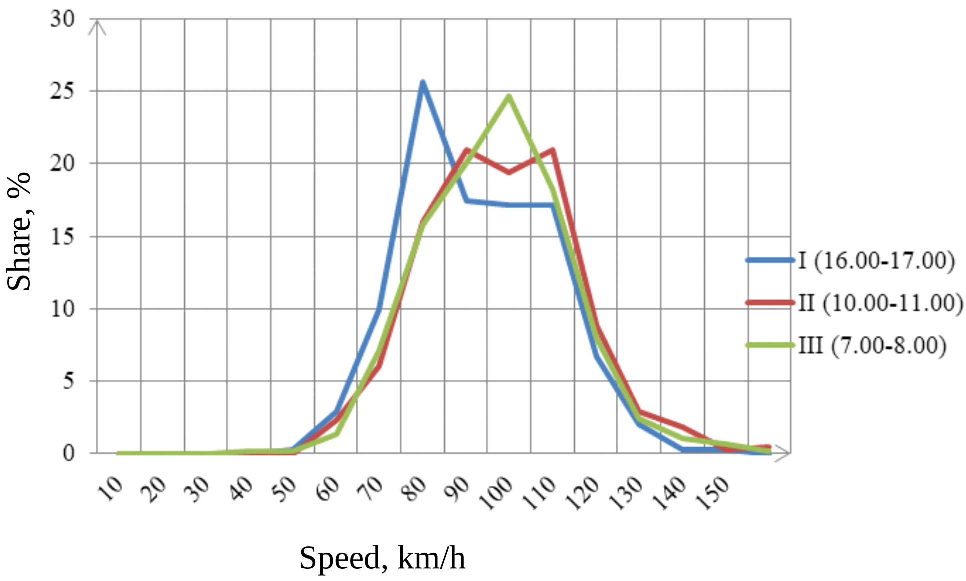

Fig. 8. Speed distribution at high traffic volume
(N = 3648 vehicles/hour)

The analysis of speed distribution by traffic lane revealed that the overall shape of the distribution curves depends on traffic volume. In contrast, the traffic flow composition influences the curve peak's position. On multilane roads, the peak of the distribution curve shifts to the right, from the far-right lane toward the far-left lane. In cases where the share of passenger cars in the right lane is 18–26 % of the total lane composition and in the left lane 80–89 %, the speed difference between lanes ranges from 10 to 20 km/h. When the share of passenger cars in the right lane increases to 61 % and in the left lane to 96 %, the speed difference between lanes reaches 13 km/h. Figs. 7–8 show the adjusted empirical speed distribution curves. The graphs indicate that the theoretical curves follow the Laplace–Gaussian (normal) distribution. In all cases, they retain the properties of a statistical distribution. Table 3 presents the speed distribution of the traffic flow.

Table 3

Distribution of Traffic Flow Speed

Speed values, km/h		Frequency, M_i	Probability Density Function of the Normal Distribution	Scaled PDF Value	Expected Frequency, $M_i^`$	Accumulated theoretical purity	Accumulated practical cleanliness
Instant speed	Interval Midpoint, X_i						
1	2	3	4	5	6	7	8
25…30	27.50	0	0.0000	0.0000023	0.00023	0.0002	0
30.01…35	32.50	0	0.0000	0.0000141	0.00141	0.0016	0
35.01…40	37.50	0	0.0002	0.0000733	0.00733	0.0090	0
40.01…45	42.50	0	0.0008	0.0003242	0.03242	0.0414	0
45.01…50	47.50	0	0.0031	0.0012222	0.12222	0.1636	0
50.01…55	52.50	2	0.0098	0.0039276	0.39276	0.5564	1
55.01…60	57.50	4	0.0269	0.0107584	1.07584	1.6322	4
60.01…65	62.50	3	0.0629	0.0251205	2.51205	4.1443	5

Table continuation 3

1	2	3	4	5	6	7	8
65.01…70	67.50	13	0.1251	0.0499995	4.99995	9.1442	13
70.01…75	72.50	24	0.2123	0.0848319	8.48319	17.6274	28
75.01…80	77.50	17	0.3070	0.1226902	12.2690	29.8964	38
80.01…85	82.50	20	0.3785	0.1512576	15.1257	45.0222	51
85.01…90	87.50	18	0.3978	0.1589576	15.89576	60.9179	62
90.01…95	92.50	17	0.3564	0.1423974	14.23974	75.1577	72
95.01…100	97.50	12	0.2721	0.1087376	10.87376	86.0314	79
100.01…105	102.50	14	0.1771	0.0707805	7.07805	93.1095	88
105.01…110	107.50	6	0.0983	0.0392740	3.92740	97.0369	91
110.01…115	112.50	4	0.0465	0.0185760	1.85760	98.8945	94
115.01…120	117.50	5	0.0187	0.0074896	0.74896	99.6434	97
120.01…125	122.50	2	0.0064	0.0025741	0.25741	99.9009	98
125.01…130	127.50	0	0.0019	0.0007541	0.07541	99.9763	98
130.01…135	132.50	1	0.0005	0.0001883	0.01883	99.9951	99
135.01…140	137.50	2	0.0001	0.0000401	0.00401	99.9991	100

The discrepancy between the theoretical and empirical distributions was evaluated using the chi-squared (χ^2) goodness-of-fit test based on the method using the chi-squared (χ^2) goodness-of-fit test with a simplified normalized test statistic:

$$R = (X^2 - v)\big/\sqrt{2v}, \qquad (2)$$

where v – is the number of degrees of freedom.

This criterion significantly simplifies the application of the chi-squared (χ^2) test in assessing discrepancies between experimental and theoretical frequencies: if R≥3, the discrepancy is considered significant; if R≤3, it is considered random. Based on the data from Table 2, a speed distribution histogram was constructed (Fig. 9), which indicates the speed at which the largest number of vehicles travel. This is the average speed on road segments approaching major and metropolitan cities.

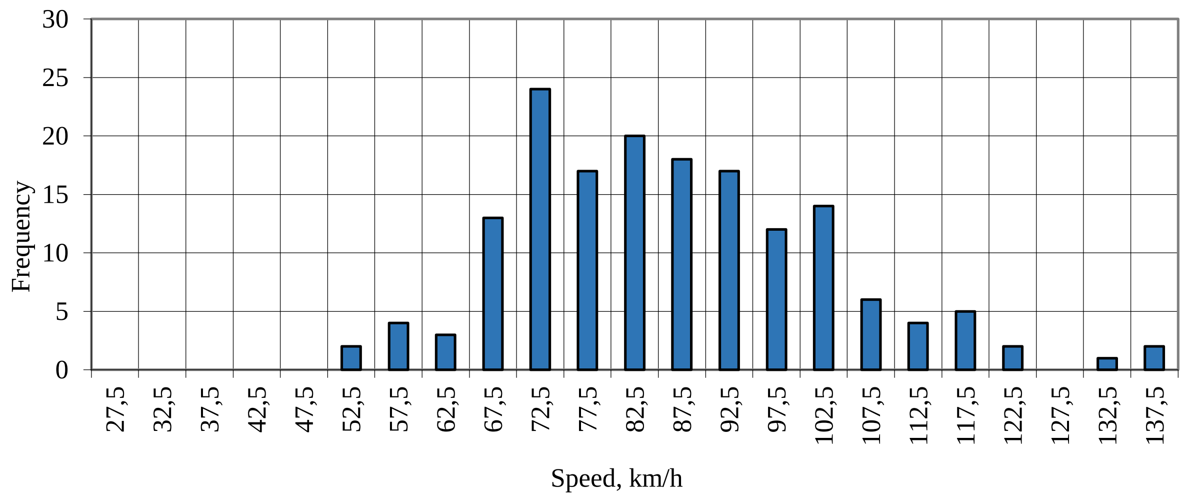

Fig. 9. Distribution of travel speeds

Fig. 10 shows the cumulative curve of the traffic flow speed distribution.

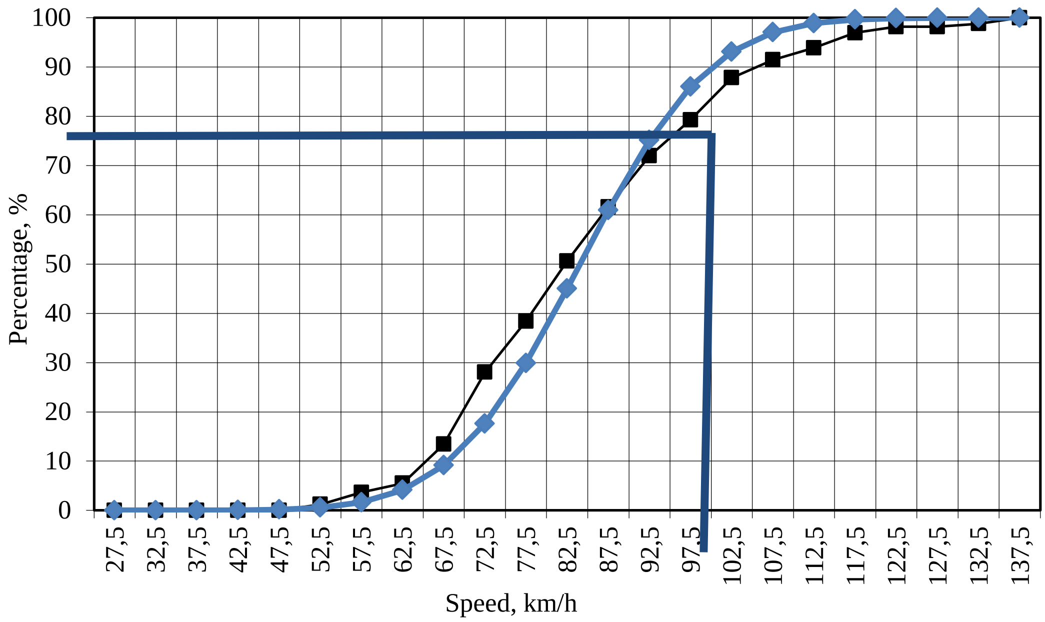

Fig. 10. Cumulative speed distribution curve

Based on the obtained empirical data, it was established that the vehicle speed corresponding to the 85th percentile (V_{85}) on the studied segment approaching major and metropolitan cities is 98 km/h. This indicator is critically essential in transportation modeling and design, as the 85th percentile speed is widely used in global practice as a reference for defining typical, permissible, or recommended travel speeds. This approach is based on the assumption that under normal conditions, 85 % of drivers choose a safe and comfortable driving speed that reflects both roadway characteristics and the surrounding environment. Therefore, the use of V_{85} enables the formulation of speed limits that reflect the actual behavior of most drivers, rather than relying solely on regulatory values. The application of this metric is especially relevant on approaches to urban agglomerations, where traffic density increases, vehicle types vary, and there is a growing need for dynamic speed management. Furthermore, the V_{85} speed can be used as an input parameter for safety assessments, infrastructure planning, speed limit signage, and integration into intelligent traffic management systems. Thus, the proposed approach provides an accurate interpretation of field observation results and offers practical recommendations for improving the safety and efficiency of traffic flows on approaches to large cities.

5. CONCLUSIONS AND PROSPECTS FOR FURTHER RESEARCH

The empirical study on highways approaching major cities demonstrated that the normal distribution well approximates the speed distribution on multilane segments. The observed discrepancies between theoretical and empirical data were found to be random, confirming the validity of applying the normal distribution for predicting traffic flow modes and calculating the capacity of multilane roads. It was established that the optimal speed of vehicles on approaches to major and metropolitan cities, depending on the lane, ranges from 43 to 87 km/h. This range reflects fundamental differences in speed behavior based on lane type, vehicle type, and traffic volume. The lower bound (43 km/h) is typically associated with the rightmost lane and a higher proportion of heavy vehicles. In comparison, the upper bound (87 km/h) corresponds to the leftmost lane dominated by passenger cars. Future studies are planned on other segments of multilane highways with varying geometric characteristics and different traffic flow compositions. These investigations will help identify regional specificities, expand the empirical dataset, and improve the accuracy of speed prediction models. Key directions for further research include the development of models that account for driver behavior, vehicle types, and dynamic performance characteristics, as well as integrating such models into intelligent traffic management systems, particularly for adaptive speed regulation based on real-time traffic flow composition and volume. It is also advisable to enhance speed distribution models statistically by employing lognormal, gamma, and bimodal distributions and by applying clustering techniques and machine learning methods to identify structured groups of road users and analyze their behavioral patterns.

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Received date 10.04.2025; Accepted date: 26.05.2025; Published date: 06.06.2025.

РОЗПОДІЛ ШВИДКОСТЕЙ РУХУ ТРАНСПОРТНИХ ЗАСОБІВ ПОТОКУ НА БАГАТОСМУГОВИХ ДОРОГАХ НА ПІДХОДАХ ДО ЗНАЧНИХ ТА НАЙЗНАЧНІШИХ МІСТ

Анотація. *У статті досліджено особливості розподілу швидкостей руху транспортних засобів на багатосмугових автомобільних дорогах на підходах до значних та найзначніших міст на прикладі шестисмугової ділянки автомобільної дороги М-05 Київ – Одеса. Методика дослідження ґрунтується на натурному спостереженні з використанням покадрового відеоаналізу з точністю 0,04 с, що дало змогу визначити часові інтервали між транспортними засобами та отримувати моментальну швидкість руху. У ході аналізу було побудовано теоретичні та фактичні криві розподілу швидкостей, визначено типові швидкісні діапазони для різних смуг та перевірено відповідність отриманих даних нормальному закону розподілу.*

У ході дослідження розподілу швидкостей транспортних засобів на багатосмугових автомобільних дорогах було визначено ключові напрями аналізу. Зокрема, дослідження спрямовувалося на перевірку відповідності емпіричних даних статистичній моделі нормального розподілу, встановлення характерних швидкісних діапазонів залежно від типу транспортного засобу, а також на оцінювання впливу інтенсивності руху та структурного складу потоку на параметри швидкості.

У межах дослідження проаналізовано просторово-часову структуру транспортного потоку: встановлено добовий розподіл інтенсивності руху, його варіацію за смугами та напрямками, а також визначено фактичні та теоретичні криві розподілу швидкостей. Досліджено залежності між основними параметрами потоку – інтенсивністю, щільністю та швидкістю. Для опису закономірностей розподілу транспортних засобів по смугах застосовано метод лінійної регресії, що дало змогу побудувати аналітичні залежності N_1, N_2, N_3 *від загальної інтенсивності N з використанням методу найменших квадратів.*

Результати дослідження показали, що розподіл швидкостей на дослідженій ділянці достатньо добре узгоджується із нормальним розподілом, а виявлені відхилення є випадковими. Отримане значення швидкості 85 % забезпеченості (98 км/год) можна використовувати як орієнтир для встановлення рекомендованих обмежень швидкості, моделювання пропускної здатності та розроблення елементів інтелектуального управління дорожнім рухом.

Ключові слова: *автомобільна дорога, інтенсивність руху, смуга руху, швидкість, багатосмугова автомобільна дорога, емпіричне дослідження.*