УДК 656.13.05 DOI: 10.33744/2308-6645-2024-1-58-133-141
UDC 656.13.05

APPLYING ENERGY PRINCIPLES TO THE ASSESSMENT OF ROAD TRAFFIC SAFETY

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ЗАСТОСУВАННЯ ЕНЕРГЕТИЧНИХ ПРИНЦИПІВ ДО ОЦІНКИ БЕЗПЕКИ ДОРОЖНЬОГО РУХУ

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Introduction.

In contemporary urban landscapes, efficient road traffic management stands as a linchpin for sustainable development and societal well-being. The dynamic interplay between increasing vehicular volumes, evolving infrastructural demands, and pressing environmental concerns necessitates a holistic approach to traffic management. Central to this approach is the delicate balance between enhancing traffic efficiency and ensuring road safety. Efforts in modern traffic management have traditionally focused on two primary objectives: optimizing traffic flow to alleviate congestion and enhancing safety measures to mitigate accident risks. However, achieving these objectives simultaneously presents a multifaceted challenge, influenced by a myriad of factors including road conditions, traffic patterns, weather conditions, and human behavior. This article delves into the complexities of contemporary traffic management, with a particular emphasis on reconciling the sometimes conflicting goals of efficiency and safety. By examining the relationship between key metrics such as the safety coefficient (Ka) and the uniformity coefficient (Kb), we aim to develop a comprehensive understanding of traffic dynamics [4,6,17]. Through empirical analysis and advanced statistical techniques, we seek to elucidate the interdependencies between these metrics and explore their implications for real-time traffic management strategies. Furthermore, this study addresses the critical gap in existing literature by proposing an integrated approach to traffic management, wherein safety and efficiency considerations are harmonized through a unified criterion. By leveraging insights from both safety and efficiency metrics, we endeavor to enhance decision-making processes in traffic control centers and optimize resource allocation for maximum societal benefit. This research holds significant implications for policymakers, urban planners, and transportation authorities tasked with enhancing the resilience and sustainability of urban transportation systems. By fostering a deeper understanding of the intricate relationship between safety and efficiency in traffic management, this study aims to pave the way for more effective and adaptive approaches to address the evolving challenges of modern mobility. In the subsequent sections, we present a comprehensive analysis of safety and efficiency metrics, elucidating their interplay and implications for real-world traffic management scenarios. Through empirical validation and practical insights, we seek to offer actionable recommendations for enhancing road traffic safety, efficiency, and sustainability in the urban context [6, 19-21]. Overall, this study contributes to the burgeoning body of knowledge in transportation science and underscores the importance of adopting an integrated perspective in addressing the complex challenges of urban mobility. Through interdisciplinary collaboration and datadriven analysis, we strive to advance the frontier of road traffic management and pave the way for safer, more efficient, and sustainable transportation systems [1, 4, 6].

Methodology.

Typically, when optimizing road traffic conditions, both in urban and rural areas, a dual task is addressed. On one hand, there is a need to maximize the speed of movement, which unequivocally characterizes the efficiency of transportation processes. On the other hand, ensuring the guaranteed safety of the process is essential, which is precisely associated with certain adequate speed limitations, albeit from the perspective of minimizing the severity of potential consequences. From a modern perspective on traffic organization, along with enhancing traffic efficiency (ensuring necessary speeds, reducing vehicle delays, etc.), significant attention is directed towards improving road safety. The compromise between these two opposing demands is determined by the relationship between road conditions and traffic flows [6], influenced by the constraints of the road network and weather conditions. Naturally, an improved traffic organization should provide both an adequate level of road safety and the necessary level of service for road users, thereby determining the ultimate efficiency of road traffic. Additionally, achieving the maximum possible utilization of the road network's capacity and reducing negative environmental impacts are essential goals. Clearly, simultaneously meeting such diverse and sometimes opposing demands is a highly challenging task and should be addressed based on specific numerical characteristics that define the aforementioned requirements to some extent. Therefore, it is advisable to formulate some comprehensive criteria capable of compromise to satisfy various road traffic conditions requirements. It is worth noting that while the aspect of increasing traffic efficiency, especially in terms of ensuring necessary speeds and reducing forced vehicle stops during movement, currently has solid theoretical foundations and practical implementation methods, another aspect related to improving safety is still considered insufficiently developed, and existing practical methods are rather specific. A separate relevant task is forecasting and preventing potential conflict situations and road traffic accidents under real conditions based on continuous monitoring of relevant traffic flow characteristics through automatic control of these characteristics. This task is particularly important in the context of automated management on sections and nodes of road networks. Unfortunately, adequate recommendations regarding the specification of these control parameters, as well as informative criteria that could be calculated in real-time "online", are lacking. Consequently, further research is necessary in this direction, primarily aimed at developing more or less universal criteria and evaluation methods for assessing road safety conditions. The aim of this article is to attempt to determine the qualitative and quantitative relationship between the existing indicator for assessing potential road safety in the form of the safety coefficient and acceleration noise, which is an energy indicator of the actual state of the traffic flow. Establishing this connection will allow the application of the safety coefficient to assess the actual state of the traffic flow and, furthermore, enable the formulation of a universal criterion for evaluating the level of road safety [6 , 22].

The safety coefficient (K_b) [3] is a criterion widely used for assessing potential traffic safety on individual sections of the roadway and is typically applied during the road design stage [1, 6, 18]. It is determined using the formula:

$$K_b = \frac{V_m}{V_{en}}, \tag{1}$$

V_m – the maximum possible speed of vehicle movement along the road section under consideration;

V_{en} – the maximum possible speed of vehicles entering the section.

The physical meaning of this criterion lies essentially in assessing the potential unevenness of vehicle speed along the given section relative to the speed at the entrance to that section. It is evident that this indicator has a spatial context and therefore is purely computational. It is applied to construct a linear graph of the safety coefficient for the designed road. Then, sections with K b < 0.6 K b <0.6 are identified for taking appropriate measures to reduce it. It is worth noting that the application of most road signs on highways is determined precisely based on this indicator [6, 18].

A significant drawback of this criterion is the complexity of its application on sections of existing roads, considering the actual current values of traffic flow characteristics [21].

It is worth noting that there are quite a few significant works in the field of studying the uniformity and safety of traffic flow in real-time [22, 23]. Among the main evaluative indicators of uniformity and safety of traffic flow, the following can be mentioned: acceleration noise (the root mean square value of acceleration variations of individual vehicles relative to the mean acceleration value of the traffic flow), which is determined by the formula [25]:

$$\sigma_a = \left[\frac{1}{n} \sum_{i=1}^{n} (a_i - a_{cp})^2 \right]^{\frac{1}{2}} \tag{2}$$

Characterizes the level of additional fuel losses incurred due to braking or acceleration of vehicles, i.e., energy expenditures.

Speed noise (the root mean square of the variations in speeds of individual vehicles relative to the mean speed of the traffic flow) [1, 6, 25]:

$$\sigma_v = \left[\frac{1}{n} \sum_{i=1}^{n} (V_i - V_{cp})^2 \right]^{\frac{1}{2}}, \tag{3}$$

which characterizes the level of safety of vehicle movement.

In the formulas (1, 2): a_i; V_i; $(a_i{\cdot}V_i)$ – The values of the respective parameters of the i-th vehicles; a_{avg}; V_{avg}; $(a{\cdot}V)_{avg}$ – their arithmetic mean values; n – the number of vehicles used to form the specified criteria.

When determining the experimental value of σ_a, one can apply one of the numerical formulas provided in the literature on safety and traffic management, which allows its determination directly from the observed data of the speed of individual vehicles [6, 25]:

$$K_a = \sigma_a = \left\{ \frac{1}{T} \sum_{i=1}^{n} \left(\frac{\Delta V_i}{t_i} \right)^2 - \left(\frac{V_T - V_0}{T} \right)^2 \right\}^{\frac{1}{2}}, \tag{4}$$

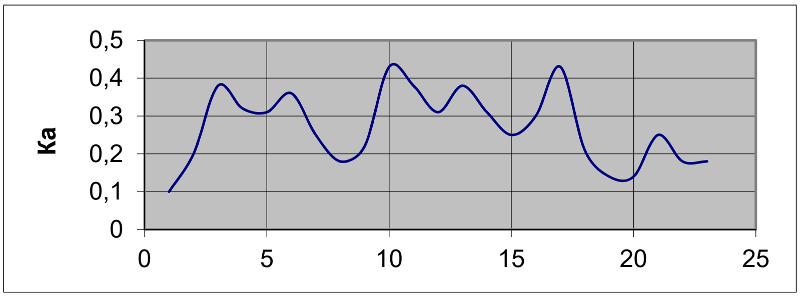
V_0 ; V_T – Initial and final values of the mean spatial velocity of the traffic flow on the studied section [4]; ΔVi the difference between similar velocities for the i-th vehicles; ti – the time of passage of the i-th vehicle of this section; T – observation interval. In formula (4) and further, the acceleration noise will be denoted as K_a.

Note that the safety coefficient (Ka) in its physical sense is closer to σa, as it also characterizes, to some extent, the change in the speed of movement on the section under consideration. This suggests the assumption that there is a certain relationship between these indicators, the establishment of which would allow using the experimentally obtained value of Ka to determine the value of Kb and vice versa. To confirm this hypothesis, let's compare the linear graphs of the changes in the values of Ka(L) and Kb(L) on the section of the road (see Fig. 1a, b), constructed based on the data in Table 1: The length L on the graphs represents the number of sections of size 50 m.

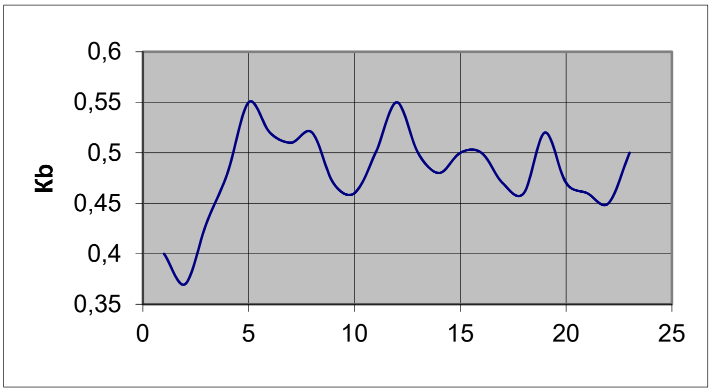
Even a simple comparison of the graphs allows us to assert that both graphs have almost the same character of changes in the road space [6, 24], which already indicates the presence of a mutual connection.

Table 1 – Regression analysis results of the study findings
Таблиця 1 – Результати регресійного аналізу результатів дослідження

Ka	0,1	0,2	0,38	0,32	0,31	0,36	0,25	0,18	0,22	0,43	0,38
Kb	0,4	0,37	0,43	0,48	0,55	0,52	0,51	0,52	0,47	0,46	0,5
Ka	0,31	0,38	0,31	0,25	0,3	0,43	0,21	0,14	0,14	0,25	0,18
Kb	0,55	0,5	0,48	0,5	0,5	0,47	0,46	0,52	0,47	0,46	0,45



a)



b)

Figure 1 – Dependencies $K_a(L)$ (**a**) i $K_b(L)$ (**b**)
Рисунок 1 – Залежності $K_a(L)$ (**a**) і $K_b(L)$ (**b**)

For a more rigorous demonstration of this relationship and its numerical assessment, a regression analysis of the data in Table 1 was conducted. However, the results of the regression analysis (regression equation y = 0.097x + 0.4551, where y = Ka; x = Kb; coefficient of determination R2 = 0.0468) completely refute the hypothesis of mutual dependence. Obviously, in conducting the regression analysis, it was necessary to take into account that initially the value of the acceleration index Ka changes, and then, as a consequence, a change in the safety coefficient Kb should be observed under its influence. Considering this circumstance, when conducting the regression analysis, each pair of values of Ka(L) (a) and Kb(L+ΔL) should be selected with a certain spatial shift ΔL. We chose ΔL = 2. After conducting the regression analysis with this shift taken into account, a decision was made, as shown in Figure 2, which indicates a significant correlation between the specified indicators.

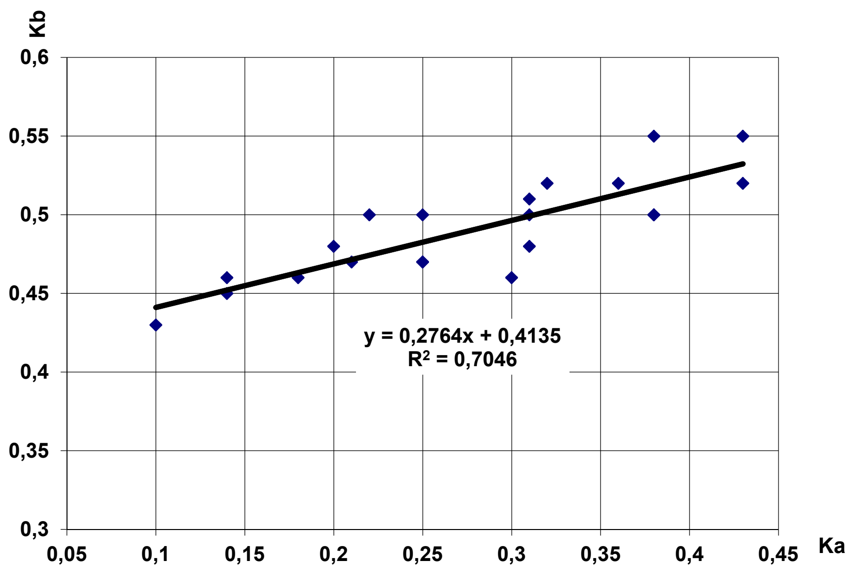


Figure 2 – Results of the regression analysis of the dependency $Kb = f(Ka)$
Рисунок 2 – Результати регресійного аналізу залежності $Kb = f(Ka)$

The obtained coefficient of determination R^2 = 0.7046 (which corresponds to the correlation coefficient R = 0.839) fully confirms the hypothesis of the mutual relationship between Kb and Ka, allowing, based on the regression equation shown in Figure 2, to substitute the indicators for each other depending on the problem being solved.

Conclusion.

In studies examining the impact of public transit on other traffic flow safety, the safety of movement was assessed using an analysis of the speed variance of buses and other vehicles [1, 4, 24]. This approach was applied in accordance with the principles of traffic flow theory [6], which suggests using energy characteristics of traffic flow to evaluate safety. Considering that public transit vehicles typically travel at lower speeds and can obstruct the movement of other vehicles, the use of the Ka index for such vehicle types is relevant and appropriate. Therefore, it is reasonable to investigate the possibility of utilizing the relationship between Ka and Kb for public transit vehicles and to identify patterns and conditions for replacing Ka and Kb specifically for buses, which is planned to be addressed in future studies.

The study has shed light on the interrelationship between safety coefficients Ka and Kb in assessing the safety of traffic flow. Through empirical analysis and regression modeling, we have demonstrated a significant correlation between these coefficients, providing valuable insights into their mutual influence. Furthermore, our findings suggest the potential for utilizing Ka as a proxy for Kb, particularly in the context of public transit vehicles. This opens avenues for simplifying safety evaluations and streamlining traffic management strategies. Moving forward, further research is warranted to explore the applicability of this relationship across various transportation contexts and to develop refined methodologies for integrating Ka and Kb into safety assessment frameworks. By enhancing our understanding of these safety indicators, we can contribute to the development of more efficient and effective traffic safety measures, ultimately promoting safer and smoother transportation systems for all road users.

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ABSTRACT

Polishchuk V.P., Nahrebelna L.P., Vyhovska I.A., Popov S. Yu. Applying energy principles to the assessment of road traffic safety. Visnyk National Transport University. Series «Technical sciences». Scientific, scientific and industrial journal. – K.: NTU, 2024. – Issue 1 (58).

In the contemporary realm of traffic management, achieving a balance between enhancing road traffic efficiency and ensuring safety remains paramount. This delicate equilibrium is influenced by the interplay between road conditions, traffic flows, and environmental factors.

The object of the study – patterns of safety in the movement of traffic vehicle.

Purpose of the study – establishing the relationship between the acceleration index and the safety coefficient of traffic, and their impact on traffic safety.

Methods of the study – regression analysis of traffic safety methods and vehicle acceleration noise has been conducted.

The optimization of traffic management systems must not only prioritize safety and service quality but also maximize the utilization of road capacities while minimizing environmental impact. A crucial challenge lies in the prediction and prevention of potential conflicts and road accidents through continuous monitoring of relevant traffic characteristics, especially in the context of automated traffic management systems. However, the absence of adequate recommendations for specifying monitoring parameters and real-time informative criteria poses a significant hurdle. This study explores the concept of a composite criterion to harmonize diverse demands on road conditions. Specifically, it investigates the relationship between the safety coefficient (Ka) and the uniformity coefficient (Kb) as indicators of traffic flow stability and safety. While initial regression analysis suggested no significant correlation, further examination with spatial shifts in data pairs revealed a substantial association, thereby supporting the hypothesis of interdependence between Kb and Ka. The findings offer insights into substituting these indicators based on specific operational requirements, facilitating more informed decision-making in traffic management. Overall, this integrated approach underscores the complexity of balancing safety and efficiency in road traffic management and provides a methodological framework for addressing these challenges effectively.

KEYWORDS: TRAFFIC MANAGEMENT, ROAD TRAFFIC SAFETY, SAFETY COEFFICIENT, REGRESSION ANALYSIS, CONFLICT PREDICTION, ACCIDENT PREVENTION

РЕФЕРАТ

Поліщук В.П. Застосування енергетичних принципів до оцінки безпеки дорожнього руху / В.П. Поліщук, Л.П. Нагребельна, І.А. Виговська, С.Ю. Попов // Вісник Національного транспортного університету. Серія «Технічні науки». Науковий, науково-виробничий журнал. – К.: НТУ, 2024. – Вип. 1 (58).

Сучасні дослідження управління дорожнім рухом розгядають досягнення балансу між підвищенням ефективності дорожнього руху та забезпеченням безпеки дорожнього руху, що залишається першочерговим завданням. Вказані умови впливають на взаємодію між дорожніми умовами, транспортним потоком та екологічними факторами.

Об'єкт дослідження – закономірності безпеки руху транспортних засобів.

Мета роботи – встановити звязок показника прискорення та коефіцієнтом безпеки руху, та їх вплив на безпеку руху.

Методи дослідження – проведенно регресійний аналіз методик безпеки рух та шуму прискорень транспортних засобів.

Оптимізація систем управління транспортом повинна не лише пріоритизувати безпеку та якість обслуговування, але й максимізувати використання дорожніх пропускних здатностей, зменшуючи при цьому вплив на довкілля. Ключовим викликом є передбачення та запобігання можливих конфліктів та ДТП шляхом постійного моніторингу відповідних характеристик дорожнього руху, особливо в контексті автоматизованих систем управління транспортом. Однак відсутність належних рекомендацій для визначення параметрів моніторингу та критеріїв реального часу ускладнює ситуацію. В дослідженні наводиться концепція композитного критерію для узгодження інших факторів до дорожніх умов. Зокрема, вивчається взаємозв'язок між коефіцієнтом безпеки (Ka) та

коефіцієнтом рівномірності (Kb) як показниками стабільності та безпеки руху транспорту. Хоча початковий регресійний аналіз не підтвердив значущої кореляції, подальший аналіз зі зміщенням даних показав значний зв'язок, підтверджуючи гіпотезу про взаємозалежність між Kb та Ka. Знайдені результати надають уявлення про заміну цих показників з урахуванням конкретних експлуатаційних вимог, що сприяє більш інформованому прийняттю рішень в управлінні дорожнім рухом. Загалом, цей інтегрований підхід підкреслює складність забезпечення балансу між безпекою та ефективністю у управлінні дорожнім рухом і надає методологічну основу для ефективного вирішення цих проблем.

КЛЮЧОВІ СЛОВА: УПРАВЛІННЯ ДОРОЖНІМ РУХОМ, БЕЗПЕКА ДОРОЖНЬОГО РУХУ, КОЕФІЦІЄНТ БЕЗПЕКИ, РЕГРЕСІЙНИЙ АНАЛІЗ, ПРОГНОЗУВАННЯ КОНФЛІКТІВ, ЗАПОБІГАННЯ ДТП.

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