ISSN 2308-6645
e-ISSN 2523-496X

ВІСНИК
НАЦІОНАЛЬНОГО ТРАНСПОРТНОГО УНІВЕРСИТЕТУ

Том 30 | № 2 | 2026

Видавець:
Національний транспортний університет
Рік заснування: 1997

Рекомендовано до друку та поширення
через мережу Інтернет Вченою радою
Національного транспортного університету
(протокол № 6 від 25 червня 2026 р.)

Рішення Національної ради України
з питань телебачення і радіомовлення № 2217 від 23.10.2025, протокол № 23.

Журнал включено до категорії «Б» Переліку наукових фахових видань України у галузях G2 – Технології захисту навколишнього середовища; G11 – Машинобудування (за спеціалізаціями); G18 – Геодезія та землеустрій; G19 – Будівництво та цивільна інженерія; J5 – Морський та внутрішній водний транспорт; J7 – Залізничний транспорт; J8 – Автомобільний транспорт (наказ Міністерства освіти і науки України №928 від 11.06.2026).

Кластер журналу: Промислові і будівельні технології, логістика, транспорт.

Журнал представлено у міжнародних наукометричних базах даних, репозитаріях та пошукових системах:
Національна бібліотека України імені В. І. Вернадського, Litmaps, J-Gate

Адреса редакції:
Національний транспортний університет
01010, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
E-mail: ntu@ntu-bulletin.com
https://ntu-bulletin.com/uk

ISSN 2308-6645
e-ISSN 2523-496X

BULLETIN

THE NATIONAL TRANSPORT UNIVERSITY

VOL. 30 | No. 2 | 2026

Publisher:
National Transport University
Year of foundation: 1997

Recommended for printing and distribution
via the Internet by the Academic Council
of National Transport University.
(Minutes No. 6 of June 25, 2026)

Decision of the National Council
of Television and Radio Broadcasting of Ukraine No. 2217 dated 23.10.2025, Minutes No. 23.

The journal is included in category "B" of the List of Scientific Professional Publications of Ukraine in the following fields: 0712 – Environmental protection technology; 0715 – Mechanics and metal trades; 0532 – Earth sciences; 0732 – Building and civil engineering; 1041 – Transport services (Order of the Ministry of Education and Science of Ukraine No. 928 of 11 June 2026).

Journal cluster: Industrial and Construction Technologies, Logistics, Transport.

Journal is presented international scientometric databases, repositories and scientific systems:
Vernadsky National Library of Ukraine, Litmaps, J-Gate

Editors office address:
National Transport University
01010, 1 M. Omelianovych-Pavlenko Str., Kyiv, Ukraine
E-mail: ntu@ntu-bulletin.com
https://ntu-bulletin.com/en

РЕДАКЦІЙНА КОЛЕГІЯ

Головний редактор	**Микола Дмитриченко** – Доктор технічних наук, професор, заслужений діяч науки і техніки, радник ректора, Національний транспортний університет, Україна
Заступник головного редактора	**Олена Славінська** – Доктор технічних наук, професор, проректор з наукової роботи, Національний транспортний університет, Україна
Національні члени редколегії	
Андрій Бубела	Доктор технічних наук, професор, декан факультету транспортного будівництва, Національний транспортний університет, Україна
Георгій Прокудін	Доктор технічних наук, професор, завідувач кафедри міжнародних перевезень та митного контролю, Національний транспортний університет, Україна
Микола Цюман	Кандидат технічних наук, професор, завідувач кафедри двигунів і теплотехніки, Національний транспортний університет, Україна
Олена Барабаш	Доктор технічних наук, професор, в.о. завідувача кафедри екології та технологій захисту навколишнього середовища, Національний транспортний університет, Україна
Олена Тимощук	Доктор технічних наук, професор, директор Навчально-Наукового Київського інституту водного транспорту імені гетьмана Петра-Конашевича Сагайдачного, Національний транспортний університет, Україна
Олександр Добровольський	Кандидат технічних наук, доцент, декан автомеханічного факультету, Національний транспортний університет, Україна
Віктор Мироненко	Доктор технічних наук, професор, завідувач кафедри управління комерційною діяльністю залізниць Київського інституту залізничного транспорту, Національний транспортний університет, Україна
Ольга Куницька	Кандидат технічних наук, доцент, професор кафедри транспортних систем та безпеки дорожнього руху, Національний транспортний університет, Україна
Костянтин Мамонов	Доктор економічних наук, професор, завідувач кафедри земельного адміністрування та геоінформаційних систем, Харківський національний університет міського господарства імені О. М. Бекетова, Україна
Марина Пілічева	Кандидат технічних наук, доцент, доцент кафедри земельного адміністрування та геоінформаційних систем, Харківський національний університет міського господарства імені О. М. Бекетова, Україна
Дмитро Курган	Доктор технічних наук, професор, професор кафедри транспортної інфраструктури, Український державний університет науки і технологій, Україна
Каріна Бєлоконь	Кандидат технічних наук, доцент, заступник директора з наукової роботи Інженерного навчально-наукового інституту ім. Ю.М. Потебні, Запорізький національний університет, Україна
Ганна Кірейцева	Доктор технічних наук, доцент, професор кафедри екології та природоохоронних технологій, Державний університет «Житомирська політехніка», Україна
Дмитро Рубан	Доктор технічних наук, доцент, професор кафедри автомобілів і тракторів, Львівський національний університет ветеринарної медицини та біотехнологій імені С. З. Ґжицького, Україна
Володимир Корогодський	Доктор технічних наук, професор, професор кафедри двигунів внутрішнього згоряння, Харківський національний автомобільно-дорожній університет, Україна
Анжеліка Батракова	Доктор технічних наук, професор, перший проректор, Харківський національний автомобільно-дорожній університет, Україна
Ігор Грицук	Доктор технічних наук, професор, професор кафедри автомобільного транспорту та галузевого машинобудування, Національний Університет “Чернігівська політехніка”, Україна
Анна Яковлєва	Доктор філософії, доцент, старший дослідник, науковий співробітник кафедри авіоніки, Кошицький технічний університет, Україна

РЕДАКЦІЙНА КОЛЕГІЯ

Міжнародні члени редколегії	
Антоніо Комі	Доктор, професор, професор кафедри транспортних систем факультету інженерії підприємств імені Маріо Лучертіні, Університет Риму Тор Вергата, Італія
Лука Персія	Кандидат технічних наук, доцент, професор з планування сталого транспорту, Римський університет Сапієнца, Італія
Стеліан Тарулеску	Доктор філософії, професор, доцент кафедри автомобільної та транспортної інженерії, Університет «Трансільванія» у Брашові, Румунія
Марта Кіанікова	Доктор філософії, доцент, декан факультету спеціальних технологій, Університет імені Олександра Дубчека в Тренчині, Словаччина
Алена Брезницька	Доктор філософії, доцент, доцент факультету спеціальних технологій, Університет Олександра Дубчека в Тренчині, Словаччина

EDITORIAL BOARD

Editor-in-Chief	**Mykola Dmytrychenko** – Doctor of Technical Sciences, Professor, Honoured Scientist and Engineer, Advisor to the Rector, National Transport University, Ukraine
Deputy Editor-in-Chief	**Olena Slavinska** – Doctor of Technical Sciences, Professor, Vice-Rector for Research, National Transport University, Ukraine
National Members of the Editorial Board	
Andriy Bubela	Doctor of Technical Sciences, Professor, Dean of the Faculty of Transport Engineering, National Transport University, Ukraine
Georgy Prokudin	Doctor of Technical Sciences, Professor, Head of the Department of International Transport and Customs Control, National Transport University, Ukraine
Mykola Tsuman	PhD in Technical Sciences, Professor, Head of the Department of Engines and Thermal Engineering, National Transport University, Ukraine
Olena Barabash	Doctor of Technical Sciences, Professor, Acting Head of the Department of Ecology and Environmental Protection Technologies, National Transport University, Ukraine
Olena Tymoshchuk	Doctor of Technical Sciences, Professor, Director of the Hetman Petro Konashevych Sagaidachny Kyiv Institute of Water Transport, National Transport University, Ukraine
Oleksandr Dobrovolskyi	PhD in Technical Sciences, Associate Professor, Dean of the Faculty of Automotive Engineering, National Transport University, Ukraine
Victor Mironenko	Doctor of Technical Sciences, Professor, Head of the Department of Railway Commercial Operations at the Kyiv Institute of Railway Transport, National Transport University, Ukraine
Olga Kunitskaya	PhD in Technical Sciences, Associate Professor, Professor in the Department of Transport Systems and Road Safety, National Transport University, Ukraine
Konstantin Mamonov	Doctor of Economic Sciences, Professor, Head of the Department of Land Administration and Geoinformation Systems, O.M. Beketov National University of Urban Economy, Kharkiv, Ukraine
Marina Pilicheva	PhD in Technical Sciences, Associate Professor, Associate Professor in the Department of Land Administration and Geoinformation Systems, O.M. Beketov National University of Urban Economy, Kharkiv, Ukraine
Dmytro Kurgan	Doctor of Technical Sciences, Professor, Professor in the Department of Transport Infrastructure, Ukrainian State University of Science and Technology, Ukraine
Karina Belokon	PhD in Technical Sciences, Associate Professor, Deputy Director for Research at the Y.M. Potebnya Engineering and Research Institute, Zaporizhzhia National University, Ukraine
Anna Kireytsova	Doctor of Technical Sciences, Associate Professor, Professor in the Department of Ecology and Environmental Protection Technologies, Zhytomyr Polytechnic State University, Ukraine
Dmytro Ruban	Doctor of Technical Sciences, Associate Professor, Professor in the Department of Cars and Tractors, S.Z. Gzhytskyi Lviv National University of Veterinary Medicine and Biotechnology, Ukraine
Volodymyr Korogodskyi	Doctor of Technical Sciences, Professor, Professor in the Department of Internal Combustion Engines, Kharkiv National University of Automobile and Highway Engineering, Ukraine
Angelica Batrakova	Doctor of Technical Sciences, Professor, First Vice-Rector, Kharkiv National University of Automobile and Highway Engineering, Ukraine
Ihor Hrytsuk	Doctor of Technical Sciences, Professor, Professor in the Department of Automotive Transport and Industrial Engineering, Chernihiv Polytechnic National University, Ukraine
Anna Yakovleva	PhD, Associate Professor, Senior Researcher, Research Fellow at the Department of Avionics, Košice University of Technology, Ukraine

EDITORIAL BOARD

International Members of the Editorial Board	
Antonio Comi	Doctor, Full Professor, Full professor in transportation at the Department of Enterprise Engineering "Mario Lucertini", Tor Vergata University of Rome, Italy
Luca Persia	PhD in Technical Sciences, Associate Professor, Professor of Sustainable Transport Planning, Sapienza University of Rome, Italy
Stelian Tarulescu	PhD, Professor, Associate Professor in the Department of Automotive and Transport Engineering, Transilvania University of Brașov, Romania
Marta Kianicová	PhD, Associate Professor, Dean of the Faculty of Special Technologies, Alexander Dubček University in Trenčín, Slovakia
Alena Breznická	PhD, Associate Professor, Faculty of Special Technologies, Alexander Dubček University in Trenčín, Slovakia

ЗМІСТ /CONTENTS

С. Павловський, Ю. Чайка, Р. Ткаченко, С. Романенко, С. Алфьоров
Адаптивні системи опалення та вентиляції для досягнення оптимального мікроклімату в сучасних будівлях 8
S. Pavlovskyi, Yu. Chaika, R. Tkachenko, S. Romanenko, S. Alforov
Adaptive heating and ventilation systems for achieving an optimal microclimate in modern buildings 8

С. Сахно, А. Добровольська
Ієрархічне нечітке моделювання ризиків автоперевезень небезпечних вантажів з урахуванням впливу людського фактору 20
S. Sakhno, A. Dobrovolska
Hierarchical fuzzy modelling of risks in road transportation of dangerous goods taking into account the influence of the human factor 20

Вадим Панченко
Удосконалення методики врахування впливу кількісного фактору навігаційних небезпек на ймовірність безпеки плавання 30
Vadym Panchenko
Improving the methodology for assessing the influence of the quantitative factor of navigational hazards on the probability of safe navigation 30

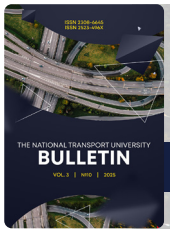
П. Стрілецький
Інформаційне моделювання в аналізі стану малих мостових споруд у сільській дорожній мережі: виклики та рішення 41
P. Striletskyi
Information modelling in the analysis of the condition of small bridge structures in rural road network: Challenges and solutions 41

В. Порфіренко, А. Луговцов
Дослідження точки беззбитковості електромобілів у бізнес-процесах підприємницької діяльності 53
V. Porfirenko, A. Luhovtsov
Break-even analysis of electric vehicles in business operations 53

Є. Данілейко
Механізм балансування вантажопотоків між міжнародними автомобільними пунктами пропуску в умовах нерівномірного навантаження прикордонної інфраструктури 65
Ye. Danileiko
Mechanism for balancing freight flows between international road border crossing points under conditions of uneven border infrastructure utilisation 65

Д. Ткаченко, І. Виговська
Критерій зменшення затримок руху на виїзді з кільцевого перехрестя за наявності зупинки міського транспорту 73
D. Tkachenko, I. Vyhovska
Criterion for reducing traffic delays at a roundabout exit in the presence of a public transport stop 73

Р. Ловга
Експлуатаційна ефективність вантажних транспортних засобів за енергетичними та екологічними критеріями 83
R. Lovha
Operational efficiency of cargo vehicles in terms of energy and environmental criteria 83



BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 30 | №2 | 2026
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X

Received: 12.02.2026. Revised: 28.05.2026. Accepted: 25.06.2026. Published: 06.07.2026.

UDC 697.1 DOI: 10.33744/2308-6645-2026-2-30-8-19

Adaptive heating and ventilation systems for achieving an optimal microclimate in modern buildings

Serhii Pavlovskyi*
PhD in Technical Sciences, Associate Professor
O.M. Beketov National University of Urban Economy in Kharkiv
61002, 17 Marshal Bazhanov Str., Kharkiv, Ukraine
https://orcid.org/0000-0002-9891-2133

Yurii Chaika
PhD in Technical Sciences, Professor
O.M. Beketov National University of Urban Economy in Kharkiv
61002, 17 Marshal Bazhanov Str., Kharkiv, Ukraine
https://orcid.org/0000-0003-1021-4662

Roman Tkachenko
PhD in Technical Sciences, Associate Professor
O.M. Beketov National University of Urban Economy in Kharkiv
61002, 17 Marshal Bazhanov Str., Kharkiv, Ukraine
https://orcid.org/0000-0003-3899-1826

Serhii Romanenko
Senior Lecturer
O.M. Beketov National University of Urban Economy in Kharkiv
61002, 17 Marshal Bazhanov Str., Kharkiv, Ukraine
https://orcid.org/0009-0005-8811-3070

Serhii Alforov
Postgraduate Student
O.M. Beketov National University of Urban Economy in Kharkiv
61002, 17 Marshal Bazhanov Str., Kharkiv, Ukraine
https://orcid.org/0000-0003-3451-1004

Abstract. The relevance of the study is due to the need to improve the energy efficiency of buildings and create a comfortable microclimate in the context of growing requirements for environmental friendliness and energy savings. The purpose of the study was to assess how different approaches to heating and ventilation systems increase comfort and energy efficiency in buildings. Methods of technology efficiency analysis and comparative evaluation of energy systems were used to determine optimal solutions in the field of microclimate automation and integration of renewable energy sources. The results showed that adaptive heating and ventilation systems substantially increase energy efficiency. Heat pumps combined with geothermal technologies maintain a stable indoor temperature even under variable external conditions. Ventilation systems with heat recovery reduce energy loss by retaining heat during air exchange. Automation of the microclimate using sensors and control systems allows adjusting the parameters of heating and ventilation depending on the occupancy of the premises, humidity level, and air composition. The integration of renewable energy sources, such as solar collectors and biomass, shows high efficiency in reducing the consumption of traditional energy resources. Analysis of facilities in different countries demonstrated that the best

Suggested Citation: Pavlovskyi, S., Chaika, Yu., Tkachenko, R., Romanenko, S., & Alforov, S. (2026). Adaptive heating and ventilation systems for achieving an optimal microclimate in modern buildings. *Bulletin of the National Transport University*, 30(2), 8-19. doi: 10.33744/2308-6645-2026-2-30-8-19.

*Corresponding author (*spavlovskyi645@gmail.com*)

Copyright © The Author(s). This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/)

results were achieved thanks to an integrated approach that combines modern technologies and adaptive solutions. Buildings with integrated adaptive systems maintain a stable microclimate regardless of external conditions, which has a positive effect on user comfort. Optimising energy consumption also reduces operating costs, making such solutions economically feasible for long-term use. Adaptive systems not only provide comfortable conditions but also substantially reduce energy consumption in buildings for various purposes

Keywords: energy efficiency; heat pumps; geothermal technologies; heat recovery; automation; renewable energy sources

Introduction

In construction, one of the main goals is to create comfortable conditions for people with minimal energy consumption. Heating and ventilation systems are among the most energy-intensive in buildings, so it is important to develop adaptive technologies that effectively regulate the microclimate depending on changing conditions. Adaptive heating and ventilation systems automatically adjust the temperature, humidity, and air exchange according to the needs and surrounding conditions. Due to the introduction of smart technologies such as heat pumps, geothermal systems and heat recovery systems, it is possible to drastically reduce energy consumption and ensure an optimal indoor microclimate. Automated control systems increase efficiency by dynamically adapting heating and ventilation settings to real-world conditions, such as temperature, humidity, or room occupancy. These technologies help to maximise the use of energy resources and improve comfort in buildings.

The problem of effective microclimate management in modern buildings using adaptive heating and ventilation systems is relevant, as it affects the energy saving and comfort of residents. D. Bui *et al.* (2021) noted that adaptive heating and ventilation systems made it possible to effectively adjust the microclimate parameters depending on external and internal conditions, which helped to reduce energy consumption. The authors also stressed the importance of automation to maintain a stable temperature in buildings without overspending energy. Z. Liu *et al.* (2023) stated that the integration of heat pumps and geothermal installations helped to ensure a stable temperature regime in buildings while substantially reducing energy costs. According to them, this also allowed reducing the impact of seasonal temperature fluctuations on heating efficiency. T. Pekdogan *et al.* (2021) investigated the role of heat recovery systems in reducing energy costs during ventilation, which substantially reduced the cost of heating rooms. It was also noted that such systems improve the air quality in buildings, keeping them warm even at high levels of air exchange. C. Lin *et al.* (2022) focused on mechanical ventilation systems that can adapt to changes in the number of people in rooms, improving the efficiency of air exchange. Such technologies optimise energy consumption, considering the specific needs of each room. G. Qiang *et al.* (2023) stressed the importance of automating heating and ventilation processes, which allowed dynamic adjustment of system parameters depending on changes in environmental conditions. According to the researchers, this not only increased the efficiency of the systems but also provided comfort throughout the year.

P. Lamsal *et al.* (2023) evaluated the effectiveness of adaptive systems in office buildings, emphasising that they can reduce energy costs while maintaining optimal working conditions. According to their estimates, such systems provided a better microclimate and helped increase employee productivity. A. Hassan & K. El-Rayes (2021) believe that the integration of renewable energy sources, such as solar collectors and biomass, into heating and ventilation systems substantially reduces dependence on traditional energy resources. They added that this combination has helped reduce greenhouse gas emissions and increase the sustainability of buildings' energy supply. S. Ahmed *et al.* (2021) in their study emphasised the importance of using solar collectors in temperate climates to reduce the need for traditional energy sources. This provided for the reduced heating costs and load on the overall energy system of the building. P. Zheng *et al.* (2022) underlined that adaptive heating and ventilation systems were most effective for large buildings, such as business centres, where constant regulation of temperature and air exchange is necessary. The authors pointed out that such systems can substantially reduce energy costs while maintaining a comfortable environment for a large number of people. A. Adegbenro *et al.* (2021) emphasised the need for continuous monitoring and adaptive management to maintain high efficiency of heating and ventilation systems throughout their life cycle. They noted that without regular monitoring, adaptive systems could lose their effectiveness due to changes in operating conditions. Thus, although numerous studies confirm the effectiveness of adaptive heating and ventilation systems, there is a need to review their application in different types of buildings, in particular, in different climatic zones and considering economic aspects.

The purpose of the study was to analyse ventilation technologies and their role in maintaining a comfortable indoor microclimate, assess the economic advantages, and disadvantages of adaptive systems considering the conditions of different climatic zones, and evaluate the impact of the integration of renewable energy sources on reducing energy costs in heating and ventilation systems.

Materials and Methods

This study covered various aspects of integrating adaptive heating, ventilation, and energy systems, in particular, technologies that can substantially reduce energy

consumption in buildings that run on traditional fuels while reducing operating costs. The efficiency assessment of such systems was conducted on the basis of an analysis of scientific publications that include energy consumption data and a review of existing studies, which allowed for determining their effectiveness in real operating conditions. An important aspect of this study was the analysis of ventilation systems with heat recovery, the effectiveness of which was evaluated by examining their ability to recover heat from the exhaust air and redirect it to heat the supply stream. This determined the potential of such systems in improving the energy efficiency of buildings and reducing heating costs, especially in cold climates.

Special attention was paid to the operation of sensors that monitor key parameters of the microclimate, such as temperature, humidity, and carbon dioxide (CO_2) levels. The influence of automated systems based on these sensors on the optimisation of energy consumption, and precise regulation of equipment operation, which helps to reduce the load on the system and provides comfort for users was assessed. In addition, the introduction of renewable energy sources, such as solar collectors, photovoltaic panels, and biomass, into the energy systems of buildings was considered based on the analysis of climatic features of regions, the amount of available resources, and the technological compatibility of equipment with existing systems. This enabled the evaluation of the renewable energy sources' potential to reduce energy costs and greenhouse gas emissions, ensuring sustainable energy supply for buildings.

The efficiency of different systems was compared using the example of buildings in Germany (Maier *et al.*, 2022), Denmark (Johansen & Werner, 2022), Sweden (Behzadi & Sadrizadeh, 2024), and Ukraine (Sotnyk *et al.*, 2024). The analysis concentrated on assessing energy consumption, economic indicators such as system payback and operating costs, and user comfort levels. Special attention was paid to various climatic conditions: in Germany and Ukraine, the effectiveness of adaptive systems was researched in temperate continental climates, in Denmark – in marine climates, and in Sweden – in cold northern climates. In addition, the specifics of buildings were considered: in Germany, mainly office buildings with high ventilation requirements were analysed, in Denmark – residential buildings with the integration of renewable energy sources, in Sweden – public buildings with high energy-saving standards, and in Ukraine – multi-storey residential buildings with traditional heating and ventilation systems. Energy savings, reduced operating costs, and the ability to adapt to temperature changes throughout the year were compared.

The final stage of the study included the comparison of the efficiency of different heating and energy-saving systems in buildings in different countries. The efficiency assessment was based on criteria such as reduced energy consumption, improved air quality, and reduced CO_2 emissions, initial costs, and terms of return on investment. Lowering energy consumption and improving air quality were assessed by indicators of energy consumption and the concentration of harmful substances on the premises.

Results

In buildings where energy efficiency is a priority, the integration of adaptive heating systems is an important element not only to reduce energy costs but also to provide a comfortable environment for residents. One of the promising areas in this area is the use of heat pumps and geothermal installations, which automatically regulate the temperature depending on external weather conditions and user needs. Heat pumps and geothermal installations are critical elements of adaptive heating systems, each of which has its own characteristics and operational features. Heat pumps operate on the principle of heat exchange, converting heat from the environment (air, water, or land) into energy for heating buildings. They are efficient even in cold winter conditions, which lessens the consumption of traditional energy sources such as gas and electricity. This makes such a heating system a sustainable and cost-effective solution. One of the fundamental parameters is the energy conversion factor, which can reach values of 3-5, which means the production of three to five units of heat for each unit of electricity consumed (Cui *et al.*, 2024). Geothermal installations, on the other hand, use the heat stored in the ground. Geothermal pumps are able to use a stable ground temperature (approximately 10-15°C) for heating in winter and cooling in summer, which makes them very effective in temperate regions. They provide sustainable energy regardless of weather changes, have a long service life and high energy efficiency. According to a study by the European Environment Agency, geothermal systems can reduce CO_2 emissions by 50-70% compared to traditional gas or coal-fired systems (Adebayo *et al.*, 2024).

Due to automation and intelligent control systems that regulate the operation of these installations, it is possible to reduce energy consumption depending on environmental changes. The systems can automatically adapt to changes in temperature and weather conditions and the internal needs of users, which allows providing maximum comfort at minimal cost. Adaptive heating systems that use heat pumps and geothermal installations have a number of advantages and disadvantages that should be considered when adapting them to specific climatic conditions. The main advantage of such systems is reduced heating costs due to high energy efficiency. According to the studies, heat pumps can provide an energy conversion rate of 3-5, which means producing 3-5 units of heat for every unit of electricity consumed, even in cold climates (Mahmoud *et al.*, 2021). Geothermal installations use a stable soil temperature that remains relatively constant at depth, allowing them to operate efficiently even at low ambient temperatures. An additional advantage is environmental friendliness: the use of renewable energy sources, such as geothermal and solar, substantially reduces greenhouse gas emissions. For example, switching to heat pumps reduces CO_2 emissions on average, by

50-70% compared to traditional heating systems that run on gas or coal (Rane *et al.*, 2024). The economic benefits of such systems include low operating costs. The average return on investment period for heat pumps is 5-7 years, depending on climatic conditions and the level of energy subsidies in the country. Therewith, the disadvantages are high initial costs for equipment, design, and installation, which can vary depending on climatic conditions and the type of buildings. For example, in regions with extremely low winter temperatures (northern Sweden, north-western Canada, Iceland), heat pumps may require additional energy sources, such as electric heaters, which may affect overall energy efficiency. In addition, in warm climates (southwestern United States, southern Spain, Australia), the efficiency of geothermal installations may be limited due to the insufficient temperature gradient of the soil.

The need for energy efficiency and comfort in buildings requires the introduction of innovative technologies that reduce energy costs and create optimal conditions for residents. One of these solutions is ventilation systems with heat recovery, which improve air quality and substantially reduce the energy consumption of buildings. This was an important step in the development of construction technologies, as it allows efficient use of exhaust air heat and minimises the need for additional energy resources for indoor heating (Loni *et al.*, 2021). The basic principle of operation of a ventilation system with heat recovery is to transfer part of the heat energy contained in the outgoing air to the air entering the room using heat exchangers, without mixing them. Even in the cold period of the year, the air entering the room already has a comfortable temperature, which reduces the load on the heating system. The use of such systems can substantially reduce heating costs since the exhaust air that is removed from the premises usually has a high temperature, providing for effective use. It also lowers the need for additional energy sources to heat the air coming from outside, especially during the cold winter months. The indoor air quality does not suffer since the recovery system does not mix the incoming and outgoing air, thus providing a high degree of purification and ventilation.

Heat recovery systems have substantial advantages for residential, commercial, and industrial buildings, as they allow achieving sustainable and efficient energy consumption. According to scientific research, the introduction of such systems can reduce energy costs by up to 40%, depending on the size of the building and its operating conditions (Gaur *et al.*, 2021). In addition, these technologies reduce greenhouse gas emissions because they use less energy from traditional sources, such as gas or electricity. Despite the obvious advantages, the heat recovery system has certain requirements for installation and maintenance. An important condition for its efficient operation is regular cleaning of filters and heat exchangers, which will ensure smooth operation of the system and maintain indoor air quality. In addition, it is important to properly configure the system according to the needs of users to avoid excessive power consumption.

In places where comfort and efficiency are priorities in residential and commercial buildings, microclimate automation is becoming an important element for creating optimal conditions. Due to technological advances, it is possible to dynamically control the parameters of temperature, humidity, and carbon dioxide content, which opens up new prospects for achieving a high level of comfort and energy efficiency. The installation of sensors that measure these parameters allows you to automatically adjust the microclimate in the room depending on the number of people in it. This not only provides comfort but also reduces energy consumption, which is important for sustainable development (Rane *et al.*, 2024). One of the main principles of microclimate automation is the integration of temperature, humidity, and carbon dioxide sensors, which allows accurately determining the parameters of indoor air and responding to changes in real time. For example, an increase in temperature or carbon dioxide levels, which often occurs due to an increase in the number of people in a room, can automatically activate the ventilation or air conditioning system, creating a comfortable environment for stay. Temperature and humidity sensors provide precise control of the level of comfort in the room, as these parameters directly affect the feeling of warmth or coolness. According to these indicators, the system adjusts the operation of the air conditioner or heater to maintain the desired temperature without excessive fluctuations, which usually require additional energy costs.

Carbon dioxide sensors are important for keeping the air fresh, as CO_2 elevated levels may indicate the need for ventilation, which reduces gas concentrations and improves air quality. Automation has the advantage of being able to adapt the system to changes in the number of people in a room. For example, in large offices or public buildings, where the number of visitors may vary throughout the day, the system automatically adjusts the level of ventilation and temperature depending on changes in attendance. If there are a lot of people in the room, the system increases the intensity of ventilation to improve air quality and reduce carbon dioxide levels. When the number of people decreases, the system automatically reduces energy consumption, adjusting the microclimate parameters to new conditions. Such automated systems not only increase comfort but also provide substantial energy savings. Since ventilation, heating, and air conditioning only work as needed, rather than continuously, energy costs are substantially diminished. This is an important factor for ensuring sustainable development, lessening the ecological footprint of buildings without compromising the comfort and health of residents.

The introduction of microclimate automation has multifaceted consequences. In addition to saving energy, such systems can substantially improve indoor air quality, reducing the health risks associated with insufficient ventilation or excessive humidity. They also help maintain optimal working conditions, increasing people's productivity and overall well-being. Climate change and energy efficiency issues are becoming particularly important,

and combining traditional heating and ventilation systems with renewable energy sources is an important step towards achieving sustainable development (Kozakevich & Kotyakova, 2021). The use of solar collectors, photovoltaic panels, and biomass substantially reduces the carbon footprint and energy costs, making buildings not only energy efficient but also environmentally friendly. Integrating these technologies into everyday life is essential to reduce the negative impact on the environment and achieve global goals in the fight against climate change (Østergaard *et al.*, 2022).

Solar collectors are one of the most cost-effective and common solutions for using renewable energy sources in buildings. They convert solar radiation into thermal energy that can be used to heat water or rooms. Solar collectors not only reduce the consumption of traditional energy sources but also help reduce the cost of heating and hot water while providing clean energy. In temperate and sunny climates, such systems can substantially increase the energy independence of buildings. Photovoltaic panels allow generating electrical energy from solar radiation. Their installation on the roof or walls of buildings can cover part of the building's energy needs and reduce dependence on centralised energy suppliers. Photovoltaic systems also have a long service life and high reliability, making them a profitable investment for building owners. They can become the main source of electricity for small and medium-sized buildings, especially in sunny regions with high solar radiation intensity. Another promising source of energy is biomass, which includes organic materials such as wood, agricultural waste, and biological waste. Biomass can be used to generate heat and electricity, which allows not only to meet the energy needs of buildings but also to efficiently dispose of waste, such as wood pellets or agricultural residues, which can be processed into energy resources using boilers or biogas plants. In some countries, such as Sweden, Poland, and the United Kingdom, biomass is widely used for district heating, where agricultural and forest waste is processed into energy supplied to the grid or directly to buildings (Saira, 2021). Biomass is also used for the production of biogas in specialised installations, which provides energy and reduces the amount of organic waste. It is a renewable energy source that helps reduce dependence on fossil fuels such as coal or oil. However, for efficient use of biomass, it is important to correctly calculate the capacity of the system and consider the energy needs of a particular building.

The combination of renewable energy sources with heating and ventilation systems can not only save energy but also reduce carbon dioxide emissions into the atmosphere, which is a crucial factor in the fight against global warming. The use of these technologies helps to reduce the level of environmental pollution, contributing to the achievement of sustainable development goals. Research shows that buildings that use renewable energy sources can reduce their carbon emissions by up to 50% compared to buildings that use only traditional energy sources (Tejani & Toshniwal, 2023). Integrating renewable energy into buildings also reduces operating costs, as energy from solar or biomass is cheaper compared to traditional fuels. For example, the cost of electricity generated by solar panels in 2023 ranged from USD 0.03 to USD 0.06 per kilowatt-hour, depending on the region, while the cost of electricity produced based on fossil fuels averaged USD 0.08-0.12 per kilowatt-hour. In the case of biomass, the cost of thermal energy varies between USD 20-30 per megawatt-hour, which is substantially lower than the cost of gas-based energy, which often exceeds USD 40-50 per megawatt-hour. These indicators indicate the economic feasibility of switching to renewable energy sources both to reduce costs and improve the energy efficiency of buildings (Heptonstall & Gross, 2021). These technologies contribute to improving the energy efficiency of buildings, which, in turn, increases their competitiveness in the real estate market. By reducing energy costs and carbon emissions, such buildings become more attractive to investors and potential buyers who pay attention to environmental friendliness and energy efficiency.

Climate change and energy efficiency issues are becoming particularly important, and combining traditional heating and ventilation systems with renewable energy sources is an important step towards sustainable development. Approaches to the design and operation of buildings include the integration of advanced technologies, in particular, renewable energy sources, with intelligent control systems, which allows achieving maximum results in reducing energy consumption and improving the quality of the internal environment. Comparing the efficiency of different systems in different countries shows that the best results are achieved when applying integrated solutions, including microclimate automation, the use of renewable energy sources, and the integration of intelligent control systems. Analysis of buildings in European countries such as Germany, Denmark, and Sweden shows that the introduction of solar collectors, geothermal heating systems, and intelligent ventilation systems can substantially reduce energy consumption and improve indoor microclimate (Table 1).

Table 1. Comparison of the efficiency of different energy supply systems in buildings in different countries

Country	Technologies	Energy consumption reduction	Air quality improvement	CO_2 emissions reduction	Initial costs (%)	Return on investment (years)
Germany	Solar panels, heat pumps, automated control	30-40%	–	25-30%	20-25%	5-7
Denmark	Intelligent ventilation systems with heat recovery	15-20%	10-15%	–	25-30%	4-6

Table 1, Continued

Country	Technologies	Energy consumption reduction	Air quality improvement	CO_2 emissions reduction	Initial costs (%)	Return on investment (years)
Sweden	Biomass, intelligent heating and ventilation control systems	25-35%	–	20-25%	30-35%	6-8
Ukraine	Solar collectors, heat pumps, automated microclimate control systems	10-15%	5-10%	10-15%	40-50%	7-10

Note: initial costs include the cost of equipment (solar panels, heat pumps, ventilation units, sensors), design, installation, integration with infrastructure, and software configuration

Source: compiled by the authors

In Germany, where the climate is temperate continental with cool winters and warm summers, the use of solar panels and heat pumps is a rational choice. A substantial level of solar radiation allows for stable energy generation throughout the year, and the combination of these technologies with automated control systems effectively regulates the temperature conditions in buildings. A special feature of such solutions is their use both in multi-storey residential buildings and in private cottages, where high-quality thermal insulation helps to minimise energy losses. For example, hybrid systems that combine solar panels, heat pumps, and automated control systems provide optimal response to changing external weather conditions and internal needs (Maier *et al.*, 2022). In Denmark, which is famous for its environmental initiatives, intelligent ventilation systems with heat recovery are most widely used. This technology is particularly relevant for public buildings and offices, where ensuring high air quality is essential for employee health and productivity. Automation systems integrated with sensors for carbon dioxide levels, temperature, and humidity adjust the intensity of ventilation depending on the number of people in the room, thereby reducing energy costs. This combination of economy and environmental friendliness provides Denmark with high energy efficiency indicators (Johansen & Werner, 2022). Sweden, which has traditionally focused on renewable energy sources, is actively implementing biomass-based technologies. The use of biomass as a fuel is relevant for residential buildings and municipal facilities, such as schools or hospitals, especially in the northern regions of the country with harsh climates. The intelligent heating and ventilation control systems that ensure optimal heat distribution reduce carbon dioxide emissions and also help to achieve high energy efficiency. In addition, such systems allow reducing resource consumption by fine-tuning real-time operation parameters (Behzadi & Sadrizadeh, 2024).

Analysis of the effectiveness of various solutions shows that the integration of modern technologies with intelligent control systems has many advantages. Such systems can reduce energy consumption by automating and adapting to changing conditions, such as ambient temperature or the number of people in the room. They help to improve the comfort of residents, creating optimal conditions for work and recreation. In addition, such solutions are cost-effective in the long term, as they can substantially reduce the cost of energy supply to buildings. Notably, the introduction of intelligent control systems requires a substantial initial investment in the development and installation of the necessary equipment, which can become a barrier for some building owners. However, in the long run, because of energy savings and reduced operating costs, such investments pay off and become cost-effective.

In Ukraine, climatic conditions vary substantially, which requires flexible approaches to the energy supply of buildings. In 2023, solar collectors, heat pumps, and automated microclimate management systems were introduced in residential and commercial buildings, which helps reduce energy consumption. Of particular interest are pilot projects in Kyiv that demonstrate the potential of such technologies in multi-storey buildings. The introduction of heat recovery systems can substantially reduce energy losses and environmental impacts. Despite the high initial costs, such initiatives show positive economic dynamics due to reduced operating costs (Deshko *et al.*, 2021). Adaptive heating and ventilation systems are becoming an important tool for reducing operating costs in buildings due to their ability to optimise energy consumption and reduce heat loss. One of the key aspects of such systems is automation, which adapts the microclimate parameters to changing conditions, such as outdoor temperature, humidity and indoor carbon dioxide levels. This ensures not only a reduction in power consumption but also a reduction in the load on the system, lowering the cost of its maintenance (Table 2).

Table 2. Comparison of operating costs for traditional and adaptive systems in buildings

Parameter	Traditional systems (average value)	Adaptive systems (average value)	Savings
Energy costs (kWh/m² per year)	1,500	900	40%
Maintenance costs (UAH/year)	500	300	40%
Heat consumption (kWh/m² per year)	1,200	750	37.5%

Table 2, Continued

Parameter	Traditional systems (average value)	Adaptive systems (average value)	Savings
Savings on energy consumption (UAH/year)	1,200	1,800	50%
Installation cost (thousand UAH)	200	250	–
System return on investment period (years)	7	5	–
Environmental savings (CO_2 emissions, t/year)	2.5	1.5	40%

Source: compiled by the authors on the basis of data obtained by Y. Alassaf (2024)

One of the most effective ways to achieve savings is to use heat recovery technologies. Ventilation systems with recuperation allow using exhaust air energy to heat or cool the supply air, which substantially reduces the cost of energy supply to buildings. These technologies are important for reducing costs, as the heat that is usually removed through the ventilation system is returned to the system and used to maintain a comfortable microclimate without additional energy costs. Optimisation of energy consumption is also achieved by using heat pumps and geothermal installations. These technologies can substantially reduce the need for traditional heating fuel, as they use renewable energy sources. Heat pumps can operate in both heating and cooling modes, maintaining a stable indoor temperature without constantly recharging the system with fuel. Equally important is automation, which is conducted using temperature, humidity, and CO_2 sensors, which allows dynamically changing system parameters depending on user needs. This provides for substantially reduced energy costs since the system operates only when necessary, and with maximum efficiency. Thereby, such control reduces the need for constant maintenance of complex mechanisms and prevents overloading of systems. A comparison of building maintenance costs with traditional and adaptive systems shows that the latter can substantially reduce overall energy costs. Energy savings offset the high initial costs of installing such systems, making them profitable in the long run. Due to an integrated approach that includes the use of renewable energy sources and intelligent management systems, substantial resource savings can be achieved, which has a positive impact not only on financial performance but also on the environmental situation in the region.

Discussion

The study on adaptive heating and ventilation systems for optimising the microclimate in modern buildings has shown their substantial potential for improving energy efficiency and comfort in residential and commercial premises. The analysis showed that these systems can automatically adjust the temperature and humidity depending on the external conditions and needs of users, providing a stable microclimate with minimal energy consumption. This reduces operating costs and contributes to long-term resource savings. A. Rieser *et al.* (2021) also investigated this issue, confirming that adaptive heating and ventilation systems regulate microclimate parameters depending on external conditions and the needs of residents. The use of temperature, humidity, and motion sensors automates the process, providing comfort with minimal energy costs. This is especially important for buildings with different functional purposes, where the requirements for the microclimate change throughout the day. H. Farzaneh *et al.* (2021) determined that adaptive systems can reduce power consumption by 30-40% due to precise adjustment of operating parameters. They can lower the temperature or turn off ventilation in empty rooms during non-working hours. This not only saves resources but also reduces the carbon footprint of buildings that meet modern environmental standards. However, the effectiveness of adaptive systems largely depends on the quality of the equipment and proper configuration. Incorrectly installed or uncalibrated sensors can reduce the accuracy of the system, resulting in energy losses. The introduction of such technologies requires an initial investment, which, although it pays off over time, can become a barrier to widespread adoption in residential buildings.

Research on heat pumps and geothermal installations has shown how these technologies optimise energy consumption through the use of renewable energy sources. Heat pumps provide efficient heating and cooling and operate without constant refuelling, which reduces dependence on fossil fuels and reduces the carbon footprint of buildings. The results showed that the use of such systems in a variable climate can substantially reduce energy costs while maintaining comfort. E. Hałaj *et al.* (2021) concluded that heat pumps and geothermal systems efficiently use soil, water, or air energy to heat or cool buildings. Due to their high energy conversion rate, they can provide up to 4 kW of heat or cold for every kW of electrical energy consumed. This can substantially reduce the consumption of traditional energy sources, increasing the energy efficiency of buildings. Upgrading the district heating system through the integration of modular heat pumps, geothermal water, and photovoltaic installations can contribute to creating sustainable urban energy, further improving energy efficiency and reducing dependence on non-renewable energy sources.

A. Hoang & X. Nguyen (2021) determined that geothermal installations maintain a stable temperature due to the use of soil thermal inertia, which ensures stable operation regardless of weather conditions. These systems are effective even in extreme climatic conditions. When combined with other renewable sources, such as solar panels, they create efficient systems with minimal carbon dioxide emissions. These results confirm previous studies conducted in countries with different climatic conditions, in particular, in Germany and Sweden, where the introduction of heat pumps and geothermal systems has shown substantial energy savings, reducing heating

costs. An increase in the efficiency of systems in temperate and cold climates was also recorded, which indicates their ability to work under temperature fluctuations, confirming the practicality of such technologies for different regions with different climatic characteristics. Another important aspect of the study was the ventilation system with heat recovery. It was identified that these systems restore some of the thermal energy of the exhaust air and use it for heating or cooling the supply air, which reduces the cost of heating and cooling buildings. Heat recovery has become an effective tool for combating energy costs, enabling a substantial reduction of the amount of energy discharged from rooms through ventilation ducts.

N. Asim *et al.* (2022), concluded that ventilation systems with heat recovery can store up to 90% of the thermal energy normally lost through ventilation. They work on the principle of heat transfer from the exhaust air to the supply air, providing a comfortable microclimate in the room. This not only increases the energy efficiency of the building but also improves air quality by removing pollution and moisture. J. Li *et al.* (2021) also demonstrated that the use of heat recovery plants can substantially reduce the cost of heating in winter and cooling in summer since the system minimises energy losses. For example, in residential buildings with modern heat recovery installations, energy costs can be reduced by 20-30%. This makes such systems attractive for both the private sector and commercial facilities, especially in the face of rising energy tariffs.

The conclusions of researchers correlate with the conclusions of the authors since they confirm the effectiveness of heat recovery technologies in reducing energy consumption. The use of such systems ensures an optimal combination of energy efficiency and comfortable indoor conditions. These examples of cost reduction confirm the real financial benefits, which makes these technologies particularly relevant in the context of modern energy challenges. Automation of the microclimate was evaluated on the example of using temperature, humidity, and carbon dioxide (CO_2) sensors. Studies have shown that the use of such sensors allows the system to dynamically adjust the parameters of the microclimate depending on the number of people in the room or changing environmental conditions. This ensures efficient use of energy resources since the system operates only when necessary, and with maximum efficiency, minimising energy costs.

S. Croce & S. Tondini (2022) also conducted a study that confirmed that modern microclimate automation systems use temperature, humidity, lighting, and motion sensors to continuously monitor indoor conditions. Due to this, the systems can adapt their work in real time, providing maximum comfort for users. Such technologies not only increase convenience but also contribute to more efficient use of resources, reducing energy consumption during non-working hours or in empty rooms. F. Carlucci *et al.* (2023) also discovered that dynamic microclimate control reduces energy consumption by fine-tuning the operation of systems depending on actual needs. Motion sensors can automatically turn off heating or lighting when the room is not in use, which saves up to 20-30% of energy. Combined with intelligent control algorithms, this creates opportunities for implementing energy-efficient solutions in residential, office, and industrial buildings, and the energy flexibility of building systems in future scenarios, optimising the dynamic shading management strategy, and defining a new energy flexibility metric can further improve the efficiency of such solutions.

Comparing the results of the study, it can be concluded that automation of the microclimate using sensors has a substantial impact on reducing energy consumption. The results show that the integration of sensors with control systems provides for achieving an optimal balance between comfort and efficiency. This is confirmed by pract ical examples of reducing energy costs in buildings where such systems are implemented. As for the integration of renewable energy sources, the results of the study indicated that the use of solar collectors, photovoltaic panels, and biomass can substantially reduce dependence on traditional energy sources. These technologies have helped reduce the carbon footprint of buildings and ensure energy independence. The study suggested that the integration of renewable energy sources with adaptive heating and ventilation systems is an important step towards sustainable development in the construction sector.

A. Pascaris *et al.* (2021) concluded that the use of renewable energy sources such as solar panels, geothermal installations, and biomass ensures that buildings are independent of fossil fuels. The integration of these systems into the building allows not only to generate energy but also to store its surplus for further use. This approach is the basis of a modern "smart home" that meets the principles of energy efficiency and sustainable development. L. Paraschiv & S. Paraschiv (2023) stated that solar collectors effectively heat water, reducing gas or electricity consumption, which leads to a reduction in greenhouse gas emissions. The use of biomass, in particular, pellets or wood waste as an energy source, also contributes to reducing the carbon footprint since the process of burning them is carbon-neutral. Together, these solutions allow buildings to meet modern environmental standards and reduce energy costs.

Analysing the results of the study, it can be concluded that the integration of renewable energy sources into building systems has substantial potential for reducing the carbon footprint. The use of solar collectors and biomass reduces dependence on traditional energy sources and actively contributes to the achievement of goals to reduce greenhouse gas emissions. This is confirmed by data on reducing energy costs and improving the environmental situation in regions where such technologies are actively used. The study confirmed that adaptive heating and ventilation systems combined with renewable energy sources and automation can substantially improve the energy efficiency of buildings and provide a comfortable environment for residents. The results of a comparative analysis of various technologies showed that the best results are achieved precisely through the integration of

modern technologies with intelligent control systems that reduce energy consumption, improve the microclimate, and reduce operating costs.

Conclusions

The study showed that adaptive heating and ventilation systems are an effective tool for achieving an optimal microclimate in modern buildings. The use of such technologies can substantially increase energy efficiency, reducing energy supply costs, and simultaneously providing comfortable conditions for residents. Heat pumps and geothermal systems that regulate indoor temperatures reduce energy consumption through the use of renewable energy sources, which is an important advantage over traditional fossil fuel heating methods. Ventilation systems with heat recovery have become one of the main elements that can substantially reduce energy costs. The use of waste heat for preheating or cooling the supply air reduces the need for energy for heating and air conditioning, which saves energy without compromising air quality.

Automation of the microclimate in buildings using temperature, humidity and CO_2 level sensors substantially optimises power consumption. Automatic adjustment of system parameters depending on changes in environmental conditions and the number of people in the room allows reducing energy costs and providing a stable level of comfort, which is important for improving the quality of life of residents. The use of renewable energy sources such as solar collectors, photovoltaic panels, and biomass has become an important step in reducing the carbon footprint of buildings. The integration of these technologies into heating and ventilation systems reduces dependence on traditional energy sources, such as gas or coal, which has a positive impact on the environmental situation. Analysis of the efficiency of various technologies in different countries has shown that the best results are achieved when integrating adaptive heating and ventilation systems with intelligent control systems that allow optimising energy use and improving the indoor microclimate. Such systems demonstrate maximum efficiency in reducing energy consumption and energy costs. Considering climatic conditions is crucial for the selection and efficiency of adaptive heating systems, such as heat pumps and geothermal installations. In cold regions, geothermal installations may be more efficient due to the stability of the Earth's temperature, while in warm climates, heat pumps that use air or water may be more optimal for reducing energy consumption and providing comfort in buildings.

The results of the study confirmed that the introduction of adaptive technologies in heating and ventilation systems is an effective tool for reducing energy costs and improving the quality of life in buildings. The use of intelligent systems and renewable energy sources can not only increase energy efficiency but also reduce the environmental impact of buildings, which is an important step towards sustainable development. Prospects for further research are to study the long-term efficiency of the integration of adaptive heating and ventilation systems with various types of renewable energy sources in different climatic zones.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Adebayo, P., Jathunge, C.B., Darbandi, A., Fry, N., Shor, R., Mohamad, A., Wemhöner, C., & Mwesigye, A. (2024). Development, modeling, and optimization of ground source heat pump systems for cold climates: A comprehensive review. *Energy and Buildings*, 320, article number 114646. doi: 10.1016/j.enbuild.2024.114646.

[2] Adegbenro, A., Short, M., & Angione, C. (2021). An integrated approach to adaptive control and supervisory optimisation of HVAC control systems for demand response applications. *Energies*, 14(8), article number 2078. doi: 10.3390/en14082078.

[3] Ahmed, S.F., Khalid, M., Vaka, M., Walvekar, R., Numan, A., Rasheed, A.K., & Mubarak, N.M. (2021). Recent progress in solar water heaters and solar collectors: A comprehensive review. *Thermal Science and Engineering Progress*, 25, article number 100981. doi: 10.1016/j.tsep.2021.100981.

[4] Alassaf, Y. (2024). Comprehensive review of the advancements, benefits, challenges, and design integration of energy-efficient materials for sustainable buildings. *Buildings*, 14(9), article number 2994. doi: 10.3390/buildings14092994.

[5] Asim, N., Badiei, M., Mohammad, M., Razali, H., Rajabi, A., Chin Haw, L., & Jameelah Ghazali, M. (2022). Sustainability of heating, ventilation and air-conditioning (HVAC) systems in buildings – an overview. *International Journal of Environmental Research and Public Health*, 19(2), article number 1016. doi: 10.3390/ijerph19021016.

[6] Behzadi, A., & Sadrizadeh, S. (2024). Advanced smart HVAC system utilizing borehole thermal energy storage: Detailed analysis of a Uppsala case study focused on the deep green cooling innovation. *Journal of Energy Storage*, 99, article number 113470. doi: 10.1016/j.est.2024.113470.

[7] Bui, D.K., Nguyen, T.N., Ghazlan, A., & Ngo, T.D. (2021). Biomimetic adaptive electrochromic windows for enhancing building energy efficiency. *Applied Energy*, 300, article number 117341. doi: 10.1016/j.apenergy.2021.117341.

[8] Carlucci, F., Negendahl, K., & Fiorito, F. (2023). Energy flexibility of building systems in future scenarios: Optimization of the control strategy of a dynamic shading system and definition of a new energy flexibility metric. *Energy and Buildings*, 289, article number 113056. doi: 10.1016/j.enbuild.2023.113056.

[9] Croce, S., & Tondini, S. (2022). Fixed and mobile low-cost sensing approaches for microclimate monitoring in urban areas: A preliminary study in the city of Bolzano (Italy). *Smart Cities*, 5(1), 54-70. doi: 10.3390/smartcities5010004.

[10] Cui, P., Yang, W., Zhang, W., Zhu, K., Spitler, J.D., & Yu, M. (2024). Advances in ground heat exchangers for space heating and cooling: Review and perspectives. *Energy and Built Environment*, 5(2), 255-269. doi: 10.1016/j.enbenv.2022.10.002.

[11] Deshko, V., Bilous, I., Sukhodub, I., & Yatsenko, O. (2021). Evaluation of energy use for heating in residential building under the influence of air exchange modes. *Journal of Building Engineering*, 42, article number 103020. doi: 10.1016/j.jobe.2021.103020.

[12] Farzaneh, H., Malehmirchegini, L., Bejan, A., Afolabi, T., Mulumba, A., & Daka, P.P. (2021). Artificial intelligence evolution in smart buildings for energy efficiency. *Applied Sciences*, 11(2), article number 763. doi: 10.3390/app11020763.

[13] Gaur, A.S., Fitiwi, D.Z., & Curtis, J. (2021). Heat pumps and our low-carbon future: A comprehensive review. *Energy Research & Social Science*, 71, article number 101764. doi: 10.1016/j.erss.2020.101764.

[14] Hałaj, E., Kotyza, J., Hajto, M., Pełka, G., Luboń, W., & Jastrzębski, P. (2021). Upgrading a district heating system by means of the integration of modular heat pumps, geothermal waters, and PVs for resilient and sustainable urban energy. *Energies*, 14(9), article number 2347. doi: 10.3390/en14092347.

[15] Hassan, A.A., & El-Rayes, K. (2021). Optimizing the integration of renewable energy in existing buildings. *Energy and Buildings*, 238, article number 110851. doi: 10.1016/j.enbuild.2021.110851.

[16] Heptonstall, P.J., & Gross, R.J. (2021). A systematic review of the costs and impacts of integrating variable renewables into power grids. *Nature Energy*, 6, 72-83. doi: 10.1038/s41560-020-00695-4.

[17] Hoang, A.T., & Nguyen, X.P. (2021). Integrating renewable sources into energy system for smart city as a sagacious strategy towards clean and sustainable process. *Journal of Cleaner Production*, 305, article number 127161. doi: 10.1016/j.jclepro.2021.127161.

[18] Johansen, K., & Werner, S. (2022). Something is sustainable in the state of Denmark: A review of the Danish district heating sector. *Renewable and Sustainable Energy Reviews*, 158, article number 112117. doi: 10.1016/j.rser.2022.112117.

[19] Kozakevich, I., & Kotyakova, M. (2021). Analysis of the influence of sources of distributed generation on the power quality. *Journal of Kryvyi Rih National University*, 19(1), 175-179. doi: 10.31721/2306-5451-2021-1-52-175-179.

[20] Lamsal, P., Bajracharya, S.B., & Rijal, H.B. (2023). A review on adaptive thermal comfort of office building for energy-saving building design. *Energies*, 16(3), article number 1524. doi: 10.3390/en16031524.

[21] Li, J., Yang, Z., Li, H., Hu, S., Duan, Y., & Yan, J. (2021). Optimal schemes and benefits of recovering waste heat from data center for district heating by CO_2 transcritical heat pumps. *Energy Conversion and Management*, 245, article number 114591. doi: 10.1016/j.enconman.2021.114591.

[22] Lin, C.J., Wang, K.J., Dagne, T.B., & Woldegiorgis, B.H. (2022). Balancing thermal comfort and energy conservation – a multi-objective optimization model for controlling air-condition and mechanical ventilation systems. *Building and Environment*, 219, article number 109237. doi: 10.1016/j.buildenv.2022.109237.

[23] Liu, Z., Xie, M., Zhou, Y., He, Y., Zhang, L., Zhang, G., & Chen, D. (2023). A state-of-the-art review on shallow geothermal ventilation systems with thermal performance enhancement – system classifications, advanced technologies and applications. *Energy and Built Environment*, 4(2), 148-168. doi: 10.1016/j.enbenv.2021.10.003.

[24] Loni, R., Najafi, G., Bellos, E., Rajaee, F., Said, Z., & Mazlan, M. (2021). A review of industrial waste heat recovery system for power generation with Organic Rankine Cycle: Recent challenges and future outlook. *Journal of Cleaner Production*, 287, article number 125070. doi: 10.1016/j.jclepro.2020.125070.

[25] Mahmoud, M., Ramadan, M., Naher, S., Pullen, K., & Olabi, A.-G. (2021). The impacts of different heating systems on the environment: A review. *Science of the Total Environment*, 766, article number 142625. doi: 10.1016/j.scitotenv.2020.142625.

[26] Maier, L., Schönegge, M., Henn, S., Hering, D., & Müller, D. (2022). Assessing mixed-integer-based heat pump modeling approaches for model predictive control applications in buildings. *Applied Energy*, 326, article number 119894. doi: 10.1016/j.apenergy.2022.119894.

[27] **Østergaard**, P.A., Duic, N., Noorollahi, Y., & Kalogirou, S. (2022). Renewable energy for sustainable development. *Renewable Energy*, 199, 1145-1152. doi: 10.1016/j.renene.2022.09.065.

[28] Paraschiv, L.S., & Paraschiv, S. (2023). Contribution of renewable energy (hydro, wind, solar and biomass) to decarbonization and transformation of the electricity generation sector for sustainable development. *Energy Reports*, 9(9), 535-544. doi: 10.1016/j.egyr.2023.07.024.

[29] Pascaris, A.S., Schelly, C., Burnham, L., & Pearce, J.M. (2021). Integrating solar energy with agriculture: Industry perspectives on the market, community, and socio-political dimensions of agrivoltaics. *Energy Research & Social Science*, 75, article number 102023. doi: 10.1016/j.erss.2021.102023.

[30] Pekdogan, T., Tokuç, A., Ezan, M.A., & Başaran, T. (2021). Experimental investigation of a decentralized heat recovery ventilation system. *Journal of Building Engineering*, 35, article number 102009. doi: 10.1016/j.jobe.2020.102009.

[31] Qiang, G., Tang, S., Hao, J., Di Sarno, L., Wu, G., & Ren, S. (2023). Building automation systems for energy and comfort management in green buildings: A critical review and future directions. *Renewable and Sustainable Energy Reviews*, 179, article number 113301. doi: 10.1016/j.rser.2023.113301.

[32] Rane, N.L., Choudhary, S.P., & Rane, J. (2024). Enhancing thermal comfort through leading-edge design, monitoring, and optimization technologies: A review. *Sustainable and Clean Buildings*, 1(1), 123-146.

[33] Rieser, A., *et al.* (2021). Integration of energy-efficient ventilation systems in historic buildings – review and proposal of a systematic intervention approach. *Sustainability*, 13(4), article number 2325. doi: 10.3390/su13042325.

[34] Saira, H. (2021). *The role of waste and solid biofuels in heating and power sector; cases of Sweden, Poland and UK*. (Master's thesis, Lappeenranta-Lahti University of Technology, Lappeenranta, Finland).

[35] Sotnyk, I., Sotnyk, M., Kurbatova, T., Prokopenko, O.V., & Telizhenko, O. (2024). Shaping cost-optimal and environmentally friendly strategies for household heating systems: Case of Ukraine. *Energy Policy Journal*, 27(3), 161-192. doi: 10.33223/epj/191811.

[36] Tejani, A., & Toshniwal, V. (2023). Enhancing urban sustainability: Effective strategies for combining renewable energy with HVAC systems. *ESP International Journal of Advancements in Science & Technology*, 1(1), 47-60. doi: 10.56472/25839233/IJAST-V1I1P107.

[37] Zheng, P., Wang, C., Liu, Y., Lin, B., Wu, H., Huang, Y., & Zhou, X. (2022). Thermal adaptive behavior and thermal comfort for occupants in multi-person offices with air-conditioning systems. *Building and Environment*, 207, article number 108432. doi: 10.1016/j.buildenv.2021.108432.

Адаптивні системи опалення та вентиляції для досягнення оптимального мікроклімату в сучасних будівлях

Сергій Павловський
Кандидат технічних наук, доцент
Харківський національний університет міського господарства імені О. М. Бекетова
61002, вул. Маршала Бажанова, 17, м. Харків, Україна
https://orcid.org/0000-0002-9891-2133

Юрій Чайка
Кандидат технічних наук, професор
Харківський національний університет міського господарства імені О. М. Бекетова
61002, вул. Маршала Бажанова, 17, м. Харків, Україна
https://orcid.org/0000-0003-1021-4662

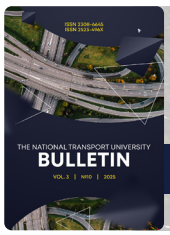
Роман Ткаченко
Кандидат технічних наук, доцент
Харківський національний університет міського господарства імені О. М. Бекетова
61002, вул. Маршала Бажанова, 17, м. Харків, Україна
https://orcid.org/0000-0003-3899-1826

Сергій Романенко
Старший викладач
Харківський національний університет міського господарства імені О. М. Бекетова
61002, вул. Маршала Бажанова, 17, м. Харків, Україна
https://orcid.org/0009-0005-8811-3070

Сергій Алфьоров
Аспірант
Харківський національний університет міського господарства імені О. М. Бекетова
61002, вул. Маршала Бажанова, 17, м. Харків, Україна
https://orcid.org/0000-0003-3451-1004

Анотація. Актуальність дослідження зумовлена необхідністю підвищення енергоефективності будівель та створення комфортного мікроклімату в умовах зростаючих вимог до екологічності й економії енергоресурсів. Дослідження мало на меті оцінити, як різні підходи до систем опалення та вентиляції підвищують комфорт і енергоефективність у будівлях. Для визначення оптимальних рішень у сфері автоматизації мікроклімату та інтеграції відновлювальних джерел енергії були використані методи аналізу ефективності технологій та порівняльної оцінки енергетичних систем. Результати показали, що адаптивні системи опалення та вентиляції значно підвищують енергоефективність. Теплові насоси у поєднанні з геотермальними технологіями підтримують стабільну температуру в приміщеннях навіть за змінних зовнішніх умов. Вентиляційні системи з рекуперацією тепла знижують втрати енергії, зберігаючи тепло під час повітрообміну. Автоматизація мікроклімату за допомогою датчиків і систем керування дозволяє регулювати параметри опалення та вентиляції залежно від заповненості приміщень, рівня вологості та складу повітря. Інтеграція відновлюваних джерел енергії, таких як сонячні колектори та біомаса, показала високу ефективність у зменшенні споживання традиційних енергоресурсів. Аналіз об'єктів у різних країнах показав, що найкращих результатів досягають завдяки комплексному підходу, що поєднує сучасні технології та адаптивні рішення. Будівлі з інтегрованими адаптивними системами зберігають стабільний мікроклімат незалежно від зовнішніх умов, що позитивно впливає на комфорт користувачів. Оптимізація енергоспоживання також знижує експлуатаційні витрати, роблячи такі рішення економічно доцільними для довгострокового використання. Адаптивні системи не лише забезпечують комфортні умови, а й значно скорочують споживання енергоресурсів у будівлях різного призначення

Ключові слова: енергоефективність; теплові насоси; геотермальні технології; рекуперація тепла; автоматизація; відновлювані джерела енергії



BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 30 | №2 | 2026
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X

Received: 30.01.2026. Revised: 01.06.2026. Accepted: 25.06.2026. Published: 06.07.2026.

UDC 656.073:519 DOI: 10.33744/2308-6645-2026-2-30-20-29

Hierarchical fuzzy modelling of risks in road transportation of dangerous goods taking into account the influence of the human factor

Serhii Sakhno*
Postgraduate Student
National Transport University
01010, 1 M. Omelyanovych-Pavlenko Str., Kyiv, Ukraine
https://orcid.org/0009-0008-7332-2293

Anna Dobrovolska
PhD in Technical Sciences, Associate Professor
National Transport University
01010, 1 M. Omelyanovych-Pavlenko Str., Kyiv, Ukraine
https://orcid.org/0000-0002-5912-0678

Abstract. The aim of the study was to develop a hierarchical fuzzy model for assessing the risks of road transportation of dangerous goods, taking into account the influence of the human factor to increase the accuracy and informativeness of decision-making in the field of transport security. The study employed a systematic approach, analysis and synthesis, expert assessment, comparative analysis, and fuzzy modelling based on the Mamdani algorithm, implemented in MATLAB, to assess human factor risks. The research resulted in the development of a hierarchical fuzzy framework for evaluating risks associated with the road transportation of dangerous goods. A key focus of the model is the assessment of human factors based on three input variables: the driver's health status, their experience in transporting dangerous goods (measured in tonne-kilometres), and the duration of accident-free operation. The fuzzy model, implemented using the Mamdani algorithm, includes 27 fuzzy logic rules and has demonstrated stable behaviour even under varying input parameters. Testing the model on four real drivers produced scores reflecting the quality of the human factor, ranging from 28.5 to 62.6 points. These scores indicate the model's sensitivity to individual personnel characteristics. An integrated assessment of overall risk is generated through a two-level aggregation of results from sub-models, allowing the system to adapt to different transportation scenarios. This model can be effectively incorporated as a critical component of a logistics operator's Decision Support System for dynamic risk analysis prior to each transport operation

Keywords: decision support system; expert evaluation; accident-free experience; membership function; logistics safety

Introduction

Transporting dangerous goods by road is one of the riskiest aspects of logistics. Accidents during such transportation can have severe consequences for human life, property, and the environment. Traditional risk assessment methods rely largely on deterministic or stochastic models, which fail to consider the complex interactions among various risk factors, including regulatory, logistical, physical, and human elements. Furthermore, these methods are less effective when dealing with incomplete, unclear, or subjective data. This is particularly crucial when evaluating human factors, such as a driver's health, fatigue, or experience in handling dangerous goods. Despite the

Suggested Citation: Sakhno, S., & Dobrovolska, A. (2026). Hierarchical fuzzy modelling of risks in road transportation of dangerous goods taking into account the influence of the human factor. *Bulletin of the National Transport University*, 30(2), 20-29. doi: 10.33744/2308-6645-2026-2-30-20-29.

*Corresponding author (*Mojapochta1@ukr.net*)

Copyright © The Author(s). This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/)

growing interest in using fuzzy logic and multicriteria approaches to address these issues, this area remains underdeveloped. Therefore, there is a need to create a hierarchical fuzzy model that considers the influence of the human factor as a key source of risk in the transportation of dangerous goods by road. This model should offer a more accurate and flexible risk assessment by processing both quantitative and qualitative data, ultimately making the decision-making process in safe logistics more efficient.

An analysis of the literature published in scientific journals reveals a growing interest among the scientific community in risk assessment in logistics, particularly regarding the influence of human factors. Modern research increasingly employs approaches such as fuzzy logic, multi-criteria analysis, and machine learning to model situations where personnel behaviour, condition, or errors are critical. Significant attention is devoted to various aspects, including driver fatigue, instruction violations, underestimation of risks in warehouse or transportation operations, and the effects of psychological stress on the quality of logistics procedures. N. Vojinović *et al.* (2021) considered the results of the latest trends in the development of fuzzy modelling for assessing the activities of road transport companies engaged in the transportation of dangerous goods: the method of improved fuzzy step-by-step analysis of weighting coefficients; the method of decision-making by multiple criteria (MCDM Method); the method of finding an alternative to rough measurement and ranking based on a compromise solution (R-MARCOS – "Rough Measurement Alternatives and Ranking according to the Compromise Solution" method). As a result of the fuzzy modelling, the authors obtained rating scores for 11 companies that operate in the service market.

S. Benchkovska *et al.* (2020) introduced an innovative method for risk assessment that emphasises the role of "human errors". The main idea behind this method is to evaluate and model the human factor as a primary cause of road traffic accidents. To quantify the parameter relating to the human factor, fuzzy logic techniques are utilised. This model calculates the probability of a road accident occurring during the transportation of hazardous goods. This new approach to risk assessment considers various factors, including how the human element influences the likelihood of accidents, and recognises the diversity of the different segments that comprise the overall route for transporting dangerous cargo. The method is valuable for assessing risk variability and accounts for the human factor on both planned and existing routes. It also takes into consideration the classification of road sections, categorisation of hazardous materials, and the potential impact of various scenarios and risks on transportation safety. A comparative analysis of risk models for transporting dangerous goods by rail may be useful for examining similar models for road transportation, particularly in fuzzy risk modelling (Benchkovska *et al.*, 2020). T.D. Milošević *et al.* (2021) discussed the development of a fuzzy Mamdani model designed to assess the quality of routes used for the transportation of dangerous goods by road. The evaluation of these routes is based on five specific criteria. Each input variable is represented by three membership functions, while the output variable is determined through five membership functions. The rules within the fuzzy logic system are created using the Aggregation of Weighted Preconditions (ATPP) method, which helps build a knowledge base grounded in expert experience and intuitive reasoning. Given the number of input variables and their respective membership functions, a total of 243 rules has been defined. To establish the weights for the membership functions, three experts from the Ministry of Defence were consulted, and the weight values were determined using the Full Consistency Method (FUCOM). B. Matić *et al.* (2022) developed a fuzzy model of road infrastructure based on multicriteria analysis. The determination of weighting coefficients for evaluation criteria in fuzzy models is discussed in a paper by Ž. Stević *et al.* (2022) in the field of applied mathematics.

S.A. Beczkowska & I. Grabarek (2021) discussed the key role of the human factor in ensuring safety during the transportation of dangerous goods. The authors examine common staff errors, the causes of safety violations, and how the psychological and physical well-being of employees can influence risk levels. They placed particular emphasis on the need to consider behavioural and organisational aspects when evaluating threats in transportation processes. The article highlights the significance of a systematic approach to enhancing safety, which includes training, monitoring, and management of human factors. The article by T. Panchyshyn *et al.* (2024) presented an analysis of international experience in investing in human capital development. The authors explore the key trends and effective strategies of states and corporations to improve the quality of education, training and innovation activity of employees. Particular attention is paid to the role of investment in the formation of a competitive economy in the context of digital transformation. The article by K.M. Bozhko *et al.* (2024a) presented a method for assessing the effectiveness of investments in the human capital of an enterprise using fuzzy modelling based on linear and logarithmic scales of input data. In another article by K. Bozhko *et al.* (2024b) considered an approach to evaluating start-up projects from the investor's perspective based on fuzzy models. They proposed the use of variable evaluation criteria to take into account the uncertainty and subjectivity of investment decisions. Thus, a review of the literature indicated the relevance of applying fuzzy modelling to assess the risks associated with the transport of dangerous goods by road, which encourages the author to continue research in this direction.

Despite the existence of some studies on risk modelling in the transportation of dangerous goods, several important aspects remain underdeveloped. First, there is no holistic hierarchical model that would simultaneously cover all key groups of risk factors – regulatory, logistical, physical, and human – in a single fuzzy environment. Secondly, the human factor, despite its critical role in accidents, is often considered in a fragmented manner

or without taking into account the interrelationships with other risk groups. There is also a lack of models that would allow quantitative assessment of the human factor based on variables of the driver's health, experience, and behavioural characteristics in dynamic transportation conditions. Additionally, the challenge of adapting input linguistic or fuzzy data to a formalised multi-level evaluation structure is still relevant, complicating the practical application of these models within logistics information systems. Most existing approaches also lack a mechanism for comparative analysis based on qualitative criteria, which would allow for ranking routes or carriers through an integrated risk assessment. Therefore, the development of a hierarchical fuzzy model that includes a comprehensive assessment of the human factor as a separate module remains essential and inadequately addressed in current scientific and applied research. This article aimed to design and substantiate a hierarchical fuzzy model for assessing risks in the road transportation of dangerous goods, with particular emphasis on integrating the human factor into a comprehensive risk assessment framework. The objectives of the study included the formalisation of key risk factor groups, the development of a fuzzy model for evaluating the human factor, the construction of a hierarchical structure of the integrated risk model, and the validation of its applicability using empirical data to support managerial decision-making in the transportation of dangerous goods.

Materials and Methods

The research materials comprised regulatory and legal acts and specialised regulations in the field of road transport of dangerous goods, academic publications on transport risk assessment, and results of pilot testing of a fuzzy model based on data from four drivers. The study employed a systematic approach, as well as methods of analysis and synthesis, expert assessment, fuzzy modelling, and comparative analysis. Fuzzy logic was used to formalise dependencies between human factor parameters, and the model was constructed using the Mamdani algorithm. The feasibility of applying this algorithm was determined by a combination of factors, including its effectiveness under conditions of a small sample size and its suitability for supporting management decision-making with limited input data. In addition, the Mamdani algorithm is widely implemented in the MATLAB package, which enables the rapid development and adjustment of fuzzy models through a graphical interface. It has been traditionally used in fuzzy risk assessment models, where excessive precision is not required, whereas efficiency in decision-making is prioritised. The model was based on the hypothesis of a normal distribution of input data. The input data were empirical and obtained from annual reports of Ukrainian motor transport enterprises. The study examined the human factor assessment module of a two-level hierarchical risk model for the transport of dangerous goods by road. In the basic fuzzy model, only the driver was considered as the main agent in the process, without including other transport participants such as logistics specialists, mechanics, system administrators, or freight forwarders. The Human Factor model contained three input variables – Health, Volume, and Safetime – and one output variable, Hum, which reflected an integrated score of the human factor quality. The Health variable characterised the driver's state of health and was assessed on a ten-point scale based on expert medical evaluation. The Volume variable reflected accumulated experience in transporting dangerous goods and was measured in millions of tonne-kilometres. The Safetime variable characterised the duration of continuous accident-free driving before the journey. Gaussian membership functions were applied to the input variables, while triangular membership functions were used for the output variable; the knowledge base of the model contained 27 fuzzy logic rules. In the human factor submodel, all weighting coefficients were set equal to 1. The procedure for forming the base of 27 fuzzy inference rules was carried out by the authors acting as experts. Additional information was obtained through oral surveys of managers of motor transport enterprises. The ranges of variables were defined as follows: Health $\in$ [1; 10], Volume $\in$ [0; 1], Safetime $\in$ [0; 1,000], Hum $\in$ [0; 100]. If actual values exceeded the defined limits during modelling, boundary values were applied. The parameters of the membership functions were determined using the MATLAB environment during the development of the fuzzy model in interactive mode:

- for input Health $\sigma = 1.529$; average membership values were 1; 5.5; 10;
- for input Volume $\sigma = 0.17$; average membership values were 0; 0.5; 1;
- for input Safetime $\sigma = 152.9$; average membership values were 100; 550; 1,000;
- for output Hum, vertex coordinates were 0; 50; 100 points.

The assessment of drivers' health status was conducted by a qualified medical professional using a ten-point scale in accordance with the ethical principles set forth in the Declaration of Helsinki of the World Medical Association (WMA, 2024), ensuring confidentiality of personal data and obtaining informed consent from all participants. Input data for model validation were generated for four drivers based on pre-trip medical checks, transported cargo volume, and accident-free driving records. Model validation was performed using functional testing in the Fuzzy Designer MATLAB environment, with average input values: Health = 5 points, Volume = 0.5 million tkm, Safetime = 550 hours. The MATLAB environment was used for modelling and processing results, including implementation of model structure, membership functions, rule base, and defuzzification procedure.

Results and Discussion

The preliminary analysis indicates that all possible risk factors for the transportation of dangerous goods by road can be grouped into common features: regulatory; logistical; physical. Regulatory features include a set of legal

rules and regulations governing the transportation of dangerous goods, as well as the degree of compliance with their requirements by the carrier. Logistical factors include coordinating the complexity of the route with the regulations, continuous online monitoring of its progress, and optimising the schedule for the busiest sections. Physical features include material factors of the driver-vehicle-environment system: readiness of the vehicle for the transportation of dangerous goods; quality of the road surface; meteorological and air pollution conditions. All three groups of factors have a certain impact on the human factor. The human factor provides feedback to other groups of risk factors. For example, the optimal route logistics from the driver's point of view is one that will provide him with sufficient rest without reducing his salary. Structuring the risk factors into groups leads to a hierarchical fuzzy model with two levels, the first of which contains four fuzzy models for each group, and the second level contains a model with four inputs and the results of the evaluations performed by the first level models. The output of the second-level model provides a score for the total risk of dangerous goods transportation. Thus, fuzzy risk modelling uses a set of five models on the full set of factors M:

$$M = Reg \cup Log \cup Ph \cup Hum, \quad (1)$$

where Reg – regulatory factors (regulations); Log – logistics factors; Hum – human factor.

The human factor is considered. For the basic fuzzy model, only the driver is taken into account as the main subject of the process, while other participants (logistics specialists, mechanics, system administrators, freight forwarders, etc.) are not considered. For the integrated assessment of the human factor, three main parameters are selected:

- driver's health condition – Health;
- experience: the volume of dangerous goods transportation over the entire driver's career – Volume;
- period of continuous trouble-free operation on the day of transportation – Safetime.

The block diagram of the two-level fuzzy risk model for the transportation of dangerous goods by road is shown in Figure 1.

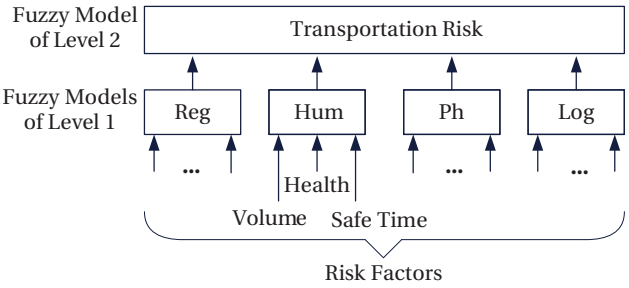


Figure 1. Two-level fuzzy risk model for road transportation of dangerous goods

Note: Reg – regulations; Hum – human factor; Ph – physical environmental influences; Log – logistics

Source: created by the authors

At the first level of the fuzzy model, the following parameters were identified: Reg (regulations), Hum (human factor), Ph (physical environmental influences), and Log (logistics). The human factor assessment module represented one of the principal components of the first-level model and reflected the influence of driver-related characteristics on overall risk formation. The second level is a fuzzy risk assessment. Within the scope of this study, consideration was limited to the fuzzy model of the human factor in the road transportation of dangerous goods. For all three input factors of the model, corresponding values and evaluation scales were defined within the adopted methodological framework. Experience in the transportation of dangerous goods was measured in million tonne-kilometres of transported cargo (million tkm). The accident-free driving record was measured in hours spent behind the wheel. The ranges for all three input variables were subsequently defined: Health ∈ [1; 10], Volume ∈ [0; 1], Safetime ∈ [0; 1,000], Hum ∈ [0; 100]. If the range limits of any of the functions are exceeded, the modelling saves its limit value. The Hum output function has a 100-point rating scale Hum [0; 100]. The section of the four-dimensional surface along the Safetime coordinate has the shape of a surface with a convex shape, which indicates the monotonicity of the output function (Fig. 2).

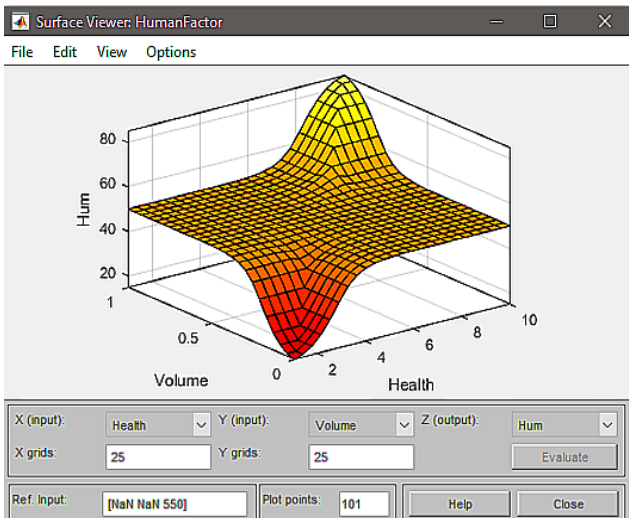


Figure 2. Decision surface for the human factor fuzzy model in coordinates "Health – Volume"

Source: created by the authors

Figure 2 illustrates a cross-section of the decision surface for the HumanFactor fuzzy model, with Safetime fixed at 550 hours. The plotted relationship demonstrates the variation of the integral human factor assessment (Hum) under the influence of two input variables: Health and Volume. The non-linear surface indicates that improvements in driver health parameters and accumulated transport experience correlate with an increase in the overall assessment. This confirms the model's capacity to account for the synergistic, rather than isolated, influence of input parameters on the final result. Model

effectiveness is verified via the "Rules" option within the "View" menu of the MATLAB Fuzzy Designer module. Initially, the model adopts average values for all input parameters:

- health: 5 points;
- experience: 500,000 tonne-kilometres of dangerous goods transported;
- uninterrupted period of accident-free transport prior to the start of the expedition: 550 hours.

The result of modelling under such conditions is 50 points of human factor quality (Fig. 3). The higher the score, the lower the risk for transportation. In a comparative analysis (rating) of carriers, the highest level in the quality scale will be occupied by those agents with the highest score.

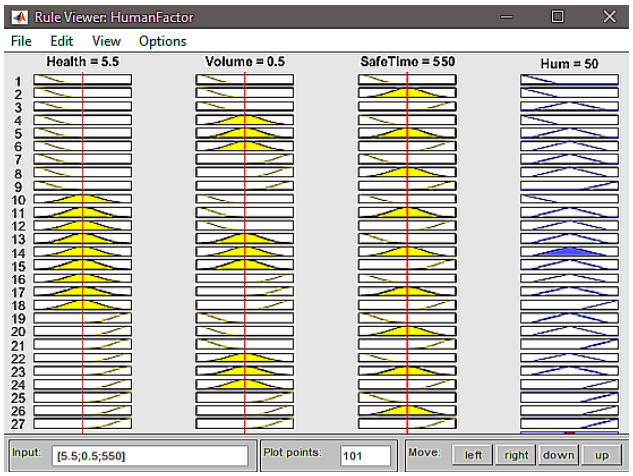


Figure 3. Unclear assessment of the human factor (score equal to 50 points)
Source: created by the authors

The result shown in Figure 3 indicates that, for Health = 5.5 points, Volume = 0.5 million tkm and Safetime = 550 hours, the fuzzy HumanFactor model produces an output value of Hum = 50 points. This corresponds to the average level of human factor assessment and confirms the model's consistency for an average combination of input characteristics. The highest human factor quality score in this fuzzy model is 85.4 points, and the lowest is 14.6 points. Low risk has a range from 85.4 to 68.9 points; medium risk has a range from 68.8 to 41.8 points; high risk has a range from 41.7 to 14.6 points. The specificity of fuzzy modelling is that it does not provide hard boundary estimates, since the values are formed on the basis of membership functions that reflect the degree of membership in linguistic terms, rather than clear boundaries. If the user of a fuzzy expert system needs exactly the boundary scores (0 and 100 points), then it is necessary to stretch the range of the output function in both directions or apply normalisation of the results after defuzzification. This will allow the model to be adapted to the requirements of a specific application task, for example, for comparison with traditional rating scales. Determining the threshold value for decision-making is the prerogative of the user of the expert system based on a fuzzy model, that is, the manager or responsible person of the transport enterprise. The fuzzy model of the human factor was tested at the premises of ALA-TRUCK Ltd (Kyiv) between 1 June 2025 and 10 June 2025. Four drivers (D1-D4) with documented experience in the transport of dangerous goods took part in the pilot testing. The sample included adult drivers with a valid driving licence for the relevant category, existing experience in the transport of dangerous goods, and a complete set of input data for modelling. The grounds for exclusion were the absence of voluntary consent to participate, the absence of confirmed experience in the relevant transport operations, incomplete input data, and medical contraindications to the performance of professional duties at the time of assessment. A general practitioner with nine years of professional experience assessed the Health indicator. This specialist was responsible for conducting pre-trip health checks on drivers at the company. He carried out the initial medical assessment of the drivers' condition on a 10-point scale, with the results subsequently used in a fuzzy model. The Volume and Safetime indicators were derived from drivers' work data documented by ALA-TRUCK Ltd. Table 1 shows the values of the human risk factor components for four drivers (D1, D2, D3, D4).

Table 1. Values of human risk factor components for drivers

No.	Name	Health, balls	Volume, TKM	Safe time, hours
1	D1	9	0	80
2	D2	7	0.1	150
3	D3	5	0.5	300
4	D4	8	1	220

Source: created by the authors

Table 1 presents the initial values of the three human risk factor components for four drivers, which were used as input data for the HumanFactor fuzzy model. A comparison of the indicators reveals variations in drivers' individual characteristics, including health status, the volume of dangerous goods transported, and accident-free driving records. Driver D1 has the highest health rating, but lacks experience in transporting dangerous goods and has the lowest Safe Time value. Driver D4, conversely, combines a high level of health with the highest transport volume, whilst D3 has average or moderate values across all three indicators. The data presented in the table serve as the basis for further fuzzy evaluation of the human factor and for a comparative ranking of drivers. The results of the fuzzy human risk factor assessment for four drivers are shown in Figures 4-7.

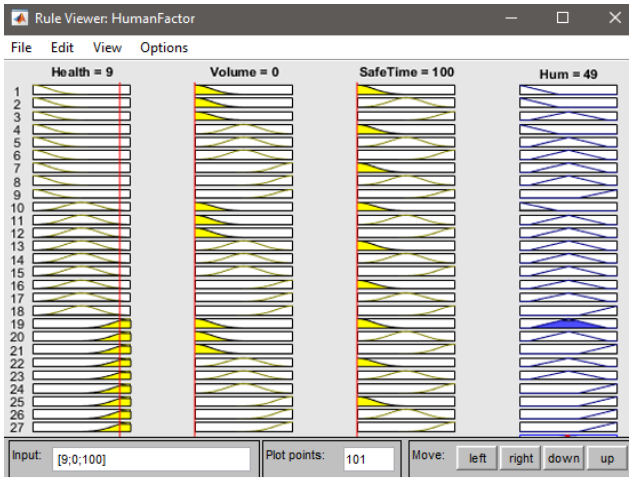


Figure 4. Unclear assessment of the human risk factor (D1 received 49 points)
Source: created by the authors

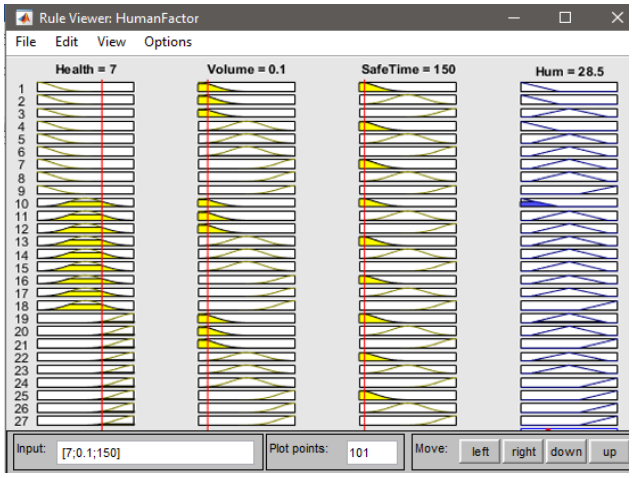


Figure 5. Unclear assessment of the human risk factor (D2 received 28.5 points)
Source: created by the authors

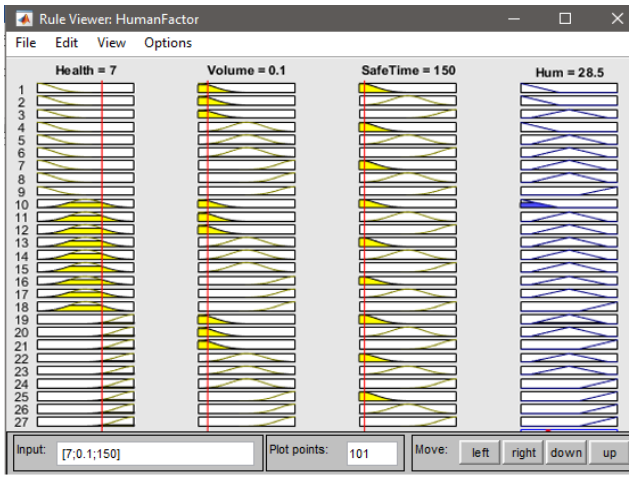


Figure 6. Unclear assessment of the human risk factor (D3 received 49.5 points)
Source: created by the authors

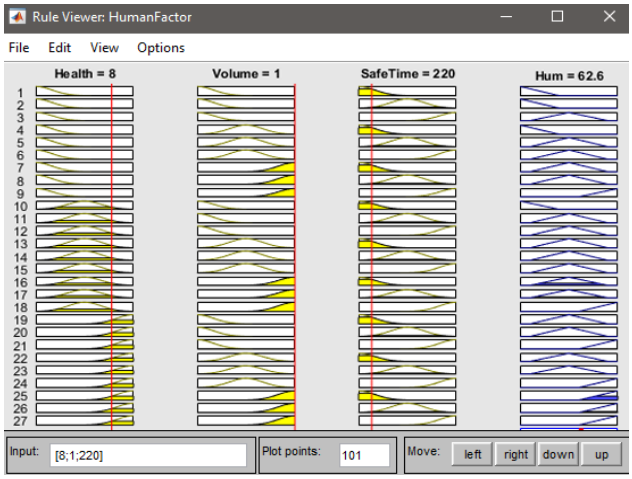


Figure 7. Unclear assessment of the human risk factor (D4 received 62.6 points)
Source: created by the authors

Figure 4 demonstrates the results obtained for driver D1, for whom the model generated a score of 49 points. This value corresponds to an average human factor rating and indicates a moderate level of risk associated with the influence of human-related factors. Figure 5 presents the assessment results for driver D2, who scored 28.5 points. This value represents a low score on the 100-point scale and indicates an increased level of risk associated with potential human error. Figure 6 illustrates the results obtained for driver D3, for whom the model assigned a score of 49.5 points. Similar to driver D1, this value corresponds to an average human factor rating and reflects a moderate level of risk. Figure 7 presents the assessment results for driver D4, who scored 62.6 points, representing the highest value among the evaluated drivers. This result indicates a relatively low level of risk associated with human-error-related accidents. As follows, Figures 4-7 shows the results of the fuzzy assessment of the human factor for the four drivers. Driver D1 scored 49 points, D2 scored 28.5 points, D3 scored 49.5 points, and D4 scored 62.6 points. The values obtained indicate that drivers D1 and D3 have an average human factor rating, D2 has a low rating, and D4 has the highest rating among the study group, corresponding to the lowest level of risk. The results of fuzzy modelling of the human risk factor for road transportation of dangerous goods are summarised in Table 2.

Table 2. Rating assessment by human risk factor based on fuzzy modelling

No.	Driver	Human factor, score	Place in the ranking
1	D1	49	3
2	D2	28.5	4
3	D3	49.5	2
4	D4	62.6	1

Source: created by the authors

Drivers were assessed based on three criteria: health status, the volume of dangerous goods transported, and accident-free record. The scores achieved through this evaluation allowed for comparative analysis and ranking. According to the results, D4 demonstrated the highest quality regarding human factors, scoring 62.6 points and securing first place in the ranking. D3 followed in second place with a score of 49.5 points, while D2 came in third with 49 points. The lowest score of 28.5 points was recorded by D1, who occupied the last position. This ranking enables the logistics operator or employees of security service to make informed decisions about route assignments and to determine the need for additional monitoring or staff training. To summarise the modelling results, the developed fuzzy model of the human factor demonstrated the ability to classify drivers by risk level based on the combined effects of health parameters, experience in transporting dangerous goods, and accident-free driving history. The scores obtained and the resulting ranking confirmed the model's sensitivity to individual driver characteristics and demonstrated its potential for comparative analysis in the field of transport safety. This provides grounds for considering the HumanFactor model as a functionally suitable component of a two-level hierarchical system for assessing the risks of road transport of dangerous goods.

The results obtained confirm the validity of using fuzzy modelling to assess the risks associated with the road transport of dangerous goods, combining quantitative indicators with expert judgements. This approach is generally consistent with the study by M.M. Aliabadi *et al.* (2024), which consider the human factor as one of the key causes of accidents in the transport of dangerous goods. In particular, in the article by M.M. Aliabadi *et al.* the assessment of human error is combined with artificial intelligence methods and fuzzy inference tools. Unlike studies focusing primarily on transport routes, infrastructure conditions, or individual risk scenarios, as shown in the work of Z. Wang (2018) and M.M. Aliabadi *et al.* (2024), the present study identified the human factor as a separate functional module within a hierarchical assessment system. Z. Wang (2018) proposed a fuzzy model for assessing the transportation routes of dangerous goods, which includes two indicators: a probability indicator and a reliability indicator. The goal of this model is to identify the optimal route schedule that minimises risk while maintaining specific levels of probability and confidence. Research on transport accidents reveals that the human factor is the most significant contributor to the occurrence of these accidents. Therefore, understanding the level of driver unreliability and examining driver behaviour during the transportation of dangerous goods requires thorough investigation. The authors employ fuzzy logic to describe driver actions. In this model, human behaviours are expressed using linguistic terms. The model based on an author's questionnaire and expert research that identified particular features of human behaviour. The output parameter of the model represents the intensity of human error that can lead to accidents. M.M. Aliabadi *et al.* (2024) investigated the identification of human errors and risk assessment during the road transportation of petroleum products. The study proposed the application of the SHERPA method combined with fuzzy modelling techniques. An overview of current research into the challenges arising from the risk assessment of dangerous goods transport is provided in the article by F. Ma *et al.* (2025). An original development of the Fine-Kinne fuzziness risk assessment model, based on the Pythagorean fuzzy set, can be found in work S.R. Satıcı & S. Mete (2024). At that time, M. Gul *et al.* (2022) improved the Fine-Kinne fuzzy model by calculating weighting coefficients for risk factors. The resulting model was tested at petrol stations. V. Tsopa *et al.* (2022) devoted to the multi-factor fuzzy assessment of occupational risks for lorry drivers. S. Vahabzadeh *et al.* (2025) presented the use of fuzzy modelling for assessing risks associated with the transport of dangerous goods and provided a comparative analysis of the Fane-Kinne model and the fuzzy analytic-hierarchical model. T. Luan *et al.* (2024) focused on the application of a fuzzy Bayesian statistical model for risk assessment in the transportation of dangerous goods through road tunnels. A distinctive feature of this approach is the mechanism for compensating for errors caused by insufficient input data. Such compensation is possible through fuzzy data representation and fuzzy inference rules. In doing so, the authors calculated the risks for the network formed by motorways and tunnels and used the monitoring of each transport node to correct the assessment of accident probability in real time.

However, the role of the human factor as a separate subsystem within the model's multi-level architecture is not explored. An important result was that the final assessment proved to be sensitive primarily to the combination of input parameters rather than to any single indicator in isolation. This finding highlighted the complex nature of risk and confirmed the advantages of fuzzy logic in modelling interdependencies between a driver's health, experience, and accident-free driving. In this respect, the proposed model complemented existing research, including the work of V. Tsopa *et al.* (2022), where fuzzy approaches were applied to the ranking of alternatives, route selection, and occupational risk assessment. However, the results of this work should be interpreted with certain limitations in mind. The model covered only a small number of variables and does not include the driver's dynamic psychophysiological characteristics, journey situational factors, or telematics data. Furthermore, the practical accuracy of the study depends on the quality of the membership functions and the rule base, which is a typical limitation of fuzzy models, as indirectly indicated by F. Ma *et al.* (2025). Consequently, hierarchical fuzzy modelling is promising for assessing the safety of road transport of dangerous goods, as it integrates the human factor into a multi-level risk model without sacrificing interpretability or practical value.

Conclusions

The study demonstrated the feasibility of applying fuzzy approaches for expert risk assessment in the road transportation of dangerous goods. These methods effectively handled incomplete, linguistic, and subjective data typical of the transport sector. A two-level multifactor model was developed, aggregating risks into four categories: regulatory, logistical, physical, and human. This approach enabled the calculation of an integrated transportation hazard indicator while maintaining transparency for expert interpretation. A key outcome was the development and validation of the "human factor" model, which was tested using real driver data. The model enabled rapid ranking of personnel according to risk level, taking into account health status, professional experience, and accident-free records. It was established that even minor variations in these parameters significantly affected the overall risk rating, confirming the critical role of the human factor in shaping transportation risk. At the same time, the study covered only one module of the first level of the hierarchy, namely the human factor. The mechanisms for aggregating results at the second level were not implemented at this stage. The proposed model was considered as a foundation for a comprehensive decision support system capable of automatically updating risk assessments before each trip, incorporating dynamic data on the driver, route, and weather conditions. It was anticipated that integration with telematics systems and HR platforms would improve the accuracy of input data and the responsiveness to critical changes. The system could provide dispatchers with visual risk dashboards, automated alerts, and recommendations for route adjustments or driver replacement, thereby enhancing transportation safety. Thus, the developed hierarchical fuzzy model provided a basis for an integrated risk management system in the transportation of dangerous goods and demonstrated strong potential for further automation of decision-making processes. Prospects for further research included expanding the model structure through the incorporation of dynamic indicators, calibration of weighting coefficients, and integration with route optimisation tools to improve the accuracy of risk assessment.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Aliabadi, M.M., Mohammadfam, I., & Khorshidikia, S. (2024). Human error identification and risk assessment in loading and unloading of petroleum products by road trucks using the SHERPA and fuzzy inference system method. *Heliyon*, 10(15), article number e34072. doi: 10.1016/j.heliyon.2024.e34072.

[2] Beczkowska, S.A., & Grabarek, I. (2021). The importance of the human factor in safety for the transport of dangerous goods. *International Journal of Environmental Research and Public Health*, 18, article number 7525. doi: 10.3390/ijerph18147525.

[3] Benchkovska, S., Choromansky, V., & Grabarek, I. (2020) Risk and human factor in carriage of dangerous goods by road. *Transport Problems*, 15(4), 19-28. doi: 10.21307/tp-2020-044.

[4] Bozhko, K., Antonenko, N., Ilchenko, V., Navrotska, T., Halak, I., & Zaplitna, T. (2024a). Assessment of investment efficiency in human capital of a company using fuzzy modeling method based on linear and logarithmic input scales. In R.E. Khoury & N. Nasrallah (Eds.), *Intelligent systems, business, and innovation research. Studies in systems, decision and control* (Vol. 489, pp. 151-166). Cham: Springer. doi: 10.1007/978-3-031-36895-0_14.

[5] Bozhko, K., Antonenko, N., Masalitina, V., Turpak, T., Petrovska, S., & Shcherbakova, N. (2024b). Variable assessment of a start-up projects by an investor based on fuzzy models. In R. El Khoury (Ed.), *Technology-driven business innovation: Unleashing the digital advantage. Studies in systems, decision and control* (Vol. 2, pp. 161-173). Cham: Springer. doi: 10.1007/978-3-031-62656-2_15.

[6] Erküvün, K.S., Usta, S., & Güneri, A.F. (2025). Risk assessment of hazardous materials transportation with fuzzy Fine Kinney and fuzzy AHP methods. *International Journal of Reliability, Quality and Safety Engineering*, 33(2). doi: 10.1142/S0218539325500524.

[7] Fornalchyk, Y., Afonin, M., Postranskyy, T., & Boikiv, M. (2021). Risk assessment during the transportation of dangerous goods considering the functional state of the driver. *Transport Problems*, 16(1), 135-146. doi: 10.21307/tp-2021-012.

[8] Gul, M., Yucesan, M., & Ak, M.F. (2022). Control measure prioritization in Fine-Kinney-based risk assessment: A Bayesian BWM-fuzzy VIKOR combined approach in an oil station. *Environmental Science and Pollution Research*, 29(39), 59385-59402. doi: 10.1007/s11356-022-19454-x.

[9] Luan, T., Zhang, X., Li, H., Wang, K., & Li, X. (2024). Dynamic risk analysis of hazardous materials highway tunnel transportation based on fuzzy Bayesian network. *SSRN*. doi: 10.2139/ssrn.4777441.

[10] Ma, F., Wu, R., Xue, B., Li, J., & Wang, X. (2025). Transportation risk assessment for hazardous chemical road transport companies using an extreme gradient boosting model. *Transportation Research Record: Journal of the Transportation Research Board*, 2679(6), 770-784. doi: 10.1177/03611981251320383.

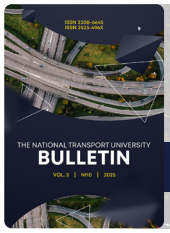
[11] Matić, B., Marinković, M., Jovanović, S., Sremac, S., & Stević, Ž. (2022). Intelligent novel IMF D-SWARA – rough MARCOS algorithm for selection construction machinery for sustainable construction of road infrastructure. *Buildings*, 12(7), article number 1059. doi: 10.3390/buildings12071059.
[12] Milošević, T.D., Pamučar, D.S., & Chatterjee, P. (2021). Model for selecting a route for the transport of hazardous materials using a fuzzy logic system. *Military Engineering Bulletin*, 69(2), 355-390. doi: 10.5937/vojtehg69-29629.
[13] Mohammadfam, I., Zarei, E., Yazdi, M., & Gholamizadeh, K. (2022). Quantitative risk analysis on rail transportation of hazardous materials. *Mathematical Problems in Engineering*, 2022(1), article number 162829. doi: 10.1155/2022/6162829.
[14] Panchyshyn, T., Loik, R., & Demchyshak, N. (2024). Investing in human capital development in the conditions of intellectualization of the economy. *Economy and Society*, 69. doi: 10.32782/2524-0072/2024-69-143.
[15] Satıcı, S.R., & Mete, S. (2024). Fine-Kinney-based occupational risk assessment using Pythagorean fuzzy AHP-COPRAS for the lifting equipment in the energy distribution and investment sector. *Gazi University Journal of Science*, 37(2), 854-873. doi: 10.35378/gujs.1227756.
[16] Stević, Ž., Das, D.K., Tešić, R., Vidas, M., & Vojinović, D. (2022). Objective criticism and negative conclusions on using the fuzzy SWARA method in multi-criteria decision making. *Mathematics*, 10(4), article number 635. doi: 10.3390/math10040635.
[17] Tsopa, V., Borodina, N., Cheberiachko, S., Deryugin, O., Hilpert, V., & Borovytskyi, O. (2022). Assessment of professional risks of the driver of a technological truck for forestry conditions. *Social Development and Security*, 12(5), 93-110. doi: 10.33445/sds.2022.12.5.9.
[18] Vahabzadeh, S., Haghshenas, S.S., Ghoushchi, S.J., Guido, G., Simic, V., & Marinkovic, D. (2025). A new framework for risk assessment of road transportation of hazardous substances. *Facta Universitatis, Series: Mechanical Engineering*, 23(3), 479-509. doi: 10.22190/FUME240801007V.
[19] Vojinović, N., Sremac, S., & Zlatanović, D. (2021). A novel integrated fuzzy-rough MCDM model for evaluation of companies for transport of dangerous goods. *Complexity*, 2021(1), article number 5141611. doi: 10.1155/2021/5141611.
[20] Wang, Z., Zhao, L., Cao, N., Yu, M., & Chen, M. (2018). The route choice of hazardous material transportation with value-at-risk model using chance measure in uncertain environments. *Advances in Mechanical Engineering*, 10(2). doi: 10.1177/1687814017753801.
[21] WMA. (2024). *WMA Declaration of Helsinki – ethical principles for medical research involving human participants.* Retrieved from https://www.wma.net/policies-post/wma-declaration-of-helsinki/.

Ієрархічне нечітке моделювання ризиків автоперевезень небезпечних вантажів з урахуванням впливу людського фактору

Сергій Сахно
Аспірант
Національний транспортний університет
01010, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
https://orcid.org/0009-0008-7332-2293
Анна Добровольська
Кандидат технічних наук, доцент
Національний транспортний університет
01010, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
https://orcid.org/0000-0002-5912-0678

Анотація. Метою дослідження було розроблення ієрархічної нечіткої моделі для оцінювання ризиків автомобільного перевезення небезпечних вантажів з урахуванням впливу людського фактора, що дозволяє підвищити точність та інформативність прийняття рішень у сфері транспортної безпеки. У дослідженні застосовано системний підхід, методи аналізу і синтезу, експертного оцінювання, порівняльного аналізу, а також нечітке моделювання на основі алгоритму Мамдані, реалізованого в середовищі MATLAB, для оцінювання ризиків, пов'язаних із людським фактором під час автомобільного перевезення небезпечних вантажів. У результаті дослідження було розроблено ієрархічну нечітку модель оцінювання ризиків перевезення небезпечних вантажів автомобільним транспортом. Ключовим елементом моделі є оцінювання людського фактора, що ґрунтується на трьох вхідних змінних: стані здоров'я водія, його досвіді перевезення небезпечних вантажів (вимірюваному в тонно-кілометрах) та тривалості безаварійної роботи. Нечітку модель було реалізовано із застосуванням алгоритму Мамдані; вона включає 27 правил нечіткої логіки. Модель продемонструвала стійку поведінку за умов варіювання вхідних параметрів. Апробація моделі на даних чотирьох реальних водіїв забезпечила отримання оцінок якості людського фактора в діапазоні від 28,5 до 62,6 бала, що свідчить про її чутливість до індивідуальних характеристик персоналу. Інтегральне оцінювання загального ризику формується шляхом дворівневої агрегації результатів підмоделей, що забезпечує адаптацію системи до різних сценаріїв перевезень. Запропонована модель може бути ефективно інтегрована як ключовий компонент системи підтримки прийняття рішень логістичного оператора для динамічного аналізу ризиків перед кожним транспортним рейсом

Ключові слова: система підтримки прийняття рішень; експертне оцінювання; безаварійний стаж; функція належності; безпека логістики



BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 30 | №2 | 2026
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X

Received: 04.02.2026. Revised: 23.05.2026. Accepted: 25.06.2026. Published: 06.07.2026.

UDC 656.61.052:519.2 DOI: 10.33744/2308-6645-2026-2-30-30-40

Improving the methodology for assessing the influence of the quantitative factor of navigational hazards on the probability of safe navigation

Vadym Panchenko*
Master
National University "Odesa Maritime Academy"
65052, 8 Didrikhson Str., Odesa, Ukraine
https://orcid.org/0009-0009-4526-6447

Abstract. This study aimed to enhance the methodology for evaluating the probability of safe navigation by incorporating the quantitative influence of navigational hazards. A set of mathematical models was developed to assess how the number and arrangement of hazards affect the likelihood of safe passage. Variance and correlation analyses were employed to quantify the impact of key risk factors. The findings revealed that the primary determinants of navigational safety include the distance to hazards, the accuracy of vessel position determination, the ship's manoeuvring characteristics, and prevailing hydrometeorological conditions. For hazard distances exceeding 1.5 nautical miles, the probability of safe passage surpassed 0.99; however, at 0.8 miles, it declined to 0.78. When navigating between two hazards, the probability ranged from 0.97 to 0.995, depending on their spatial configuration. An increase in the number of hazards correlated with a reduced probability of safe passage: with five hazards, this probability could drop to as low as 0.65. Analysis of navigational measurement errors indicated that position determination with 0.5-mile accuracy yielded a safety probability of 0.995, whereas an error of 2 miles reduced it to 0.75. The implementation of integrated navigation systems improved safety levels by 5-10%. The results substantiate the effectiveness of a comprehensive navigation planning approach, integrating several core principles: precise coordinate determination via integrated systems, adaptive routing based on hazard density and situational variability, dynamic speed regulation according to environmental conditions, and proactive obstacle avoidance through predictive modelling and real-time data. This methodological framework holds significant practical value for enhancing navigational efficiency and resilience in areas of high complexity, enabling risk mitigation and route stability even under adverse conditions

Keywords: collision risk; manoeuvring characteristics; spatial arrangement; adaptive routes; hydrometeorological conditions

Introduction

Maritime safety remains a cornerstone of modern navigation, as it directly affects both the preservation of human life and the economic efficiency of global shipping operations. With the increasing intensity of traffic on major sea routes, the advancement of automated navigation systems, and the growing demand for precision in vessel positioning, the problem of accurately accounting for navigational hazards has become increasingly critical.

Traditional approaches to risk assessment in maritime navigation are often grounded in simplified models that fail to consider the quantitative dimensions of navigational hazards – such as proximity to obstacles, their spatial configuration, and the likelihood of critical incidents. These models typically emphasise general hazard classification or the designation of high-risk zones without conducting a detailed quantitative analysis. As a result, they rely on

Suggested Citation: Panchenko, V. (2026). Improving the methodology for assessing the influence of the quantitative factor of navigational hazards on the probability of safe navigation. *Bulletin of the National Transport University*, 30(2), 30-40. doi: 10.33744/2308-6645-2026-2-30-30-40.

*Corresponding author (*Vadym.Panchenko11@outlook.com*)

Copyright © The Author(s). This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/)

averaged risk indicators that neglect environmental variability and do not facilitate dynamic route adjustments in response to changes in obstacle density. This leads to diminished accuracy in risk prediction and highlights the pressing need to refine safety assessment methodologies.

A key limitation of conventional analytical techniques lies in their static nature, which overlooks the dynamic and rapidly evolving conditions of the navigational environment. For instance, the study by I. Gritsuk *et al.* (2023) on adaptive route planning demonstrated that static hazard maps are inadequate for real-time prediction of safe navigational pathways under changing maritime conditions. The researchers emphasised that the mere increase in the number of hazards is not sufficiently captured by existing risk assessment models. Further insight into the problem is provided by O. Melnyk *et al.* (2025), who investigated the influence of navigational inaccuracies on maritime safety. Their findings indicate that a positional error of 2 nautical miles can substantially reduce the probability of safe passage – especially for vessels with limited manoeuvring capabilities. However, the deployment of integrated navigation systems has been shown to mitigate these risks, enhancing overall safety levels by 5-10%. Equally important is the challenge of adaptively correcting navigation routes in light of the spatial distribution of hazards. Instead of treating threats as isolated objects, O. Melnyk *et al.* (2023) proposed a route optimisation method that considers the mutual positioning of dangerous elements. Their modelling results revealed that when navigating between two hazardous objects, the probability of safe passage ranges from 0.97 to 0.995, depending on the separation between hazards and the vessel's handling characteristics. Nonetheless, even such models fall short in addressing the full spectrum of real-time environmental changes. Additionally, hydrometeorological factors represent a vital aspect of navigational risk. A. Maternová *et al.* (2022) demonstrated that strong winds and wave conditions significantly impair the manoeuvring performance of vessels, thereby increasing the likelihood of navigational errors. While the adaptive speed control algorithms proposed in their work partially reduce these risks, they still do not account for the cumulative impact of the quantitative characteristics of hazards present within the vessel's navigational zone.

Statistical analysis methods have increasingly attracted attention as tools for enhancing the accuracy of navigational risk assessments. In particular, the study by H. Huy-Tien *et al.* (2023) highlighted the applicability of correlation analysis in establishing relationships between the number of hazards and the overall safety level of a vessel's passage. While their results confirmed a statistically significant association, the method's primary limitation was its inability to account for nonlinear dependencies, which are often inherent in complex and dynamic navigational environments. Technical characteristics of vessels also play a crucial role in shaping navigational risk. According to A. Rawson *et al.* (2021a), ships with limited manoeuvrability are particularly susceptible to risk in narrow waterways with high concentrations of navigational hazards. However, their model lacks real-time dynamic course correction capabilities, reducing its practical effectiveness in fast-changing operational settings. Further contributions to the modelling of navigational risk include the work by A. Rawson *et al.* (2021b), who developed a theoretical model incorporating the number of hazards within a vessel's transit area. While this model represents a step forward in quantifying navigational complexity, it has not undergone empirical validation. Its theoretical status limits its utility in real-world applications, where environmental conditions and vessel behaviours exhibit significant variability. A broader perspective on risk integration is presented in the concept of integrated risk analysis proposed by W. Zhang *et al.* (2022). Their framework combines mathematical modelling, statistical evaluation, and adaptive route planning. Although promising, the model does not account for real-time fluctuations in the navigation environment, which undermines its capacity to fully address situational dynamics – a critical shortcoming for practical deployment.

Collectively, existing research underscored the significance of incorporating the quantitative dimension of navigational hazards into safety assessments. However, there remains a distinct gap: no existing methodology effectively integrates all key risk factors – including hazard density, spatial configuration, vessel manoeuvrability, measurement uncertainties, and environmental dynamics – into a unified and adaptive safety assessment framework. Therefore, the present study sought to develop an improved methodology for evaluating navigational safety, with a particular focus on the quantitative characteristics of navigational hazards. The core objectives of the research included the development of mathematical models, their validation through ship movement simulations, and a comprehensive analysis of how key risk factors influence the probability of safe vessel passage.

Materials and Methods

The research employed the navigational and manoeuvring characteristics of the Project 58155 "Gyurza-M" small armoured artillery boat (Ukraine) as a representative vessel. This type of surface ship was selected due to its extensive operational use in coastal environments, which are typical for the Black and Azov Seas. The modelling incorporated the vessel's key tactical and technical parameters, including a length of 23 m, a draft of up to 1 m, an average cruising speed of 25 knots, minimal turning radius, braking characteristics, and control response time. The methodological framework was cantered on the development of mathematical models that reflect the influence of the quantitative factor of navigational hazards on the probability of safe navigation. These models were subsequently verified through simulation of ship movements under realistic navigational conditions.

Key components of the methodology included: accuracy analysis of vessel position determination using both visual bearings and radar data; assessment of navigational safety when passing either a single hazard or

navigating between two hazards; comparative analysis of safety probabilities in navigational areas as a function of the number and spatial configuration of hazards. The probability of safe passage through a given navigational zone was calculated using approximate analytical formulas derived from empirical relationships, supported by probability data from the Maritime Tactical Table MT-75 (1975). This enabled the integration of vessel behaviour models with environmental and hazard-related inputs, forming a comprehensive tool for evaluating navigational risk. The experimental component of the study involved a comprehensive analysis of factors influencing navigational safety, with particular emphasis on errors in vessel positioning, ship manoeuvring characteristics, and the spatial distribution of navigational hazards. The vessel's motion parameters were considered in detail, including drift, course, speed, inertial behaviour, and the influence of hydrometeorological conditions.

Analytical methods rooted in probability theory were applied to evaluate the likelihood of safe passage. Specifically, calculations were based on the normal distribution of positioning errors and the Laplace function, following the approach outlined by K.I. Kuhlman (2013). These probabilistic models allowed for the quantification of risk under various operational and environmental conditions. A retrospective analysis of maritime incidents was conducted using publicly available data sources, including reports from the International Maritime Organization (IMO, n.d.) and archives of the Ukrainian Research Institute of Shipping. The focus was on incidents occurring in zones with high concentrations of navigational hazards, where primary causal factors included measurement errors, failure to maintain recommended safe distances, and limitations in vessel manoeuvrability – often exacerbated by dense maritime traffic. To model the relationship between safety levels and vessel interactions in constrained navigation environments, high-traffic scenarios were simulated. These included conditions characteristic of narrow straits, port approaches, and internal waters where manoeuvrability is severely restricted. The probability of safely navigating a given section was calculated using the following expression, adapted from MT-75 tactical probability data (1):

$$P = \prod_{i=1}^{n} P_i, \tag{1}$$

where n is the number of navigational hazards along the route, P_i is the probability of safely passing the i^{th} obstacle, P is the total probability of safe passage through the navigational section. Each individual probability P_i was defined using the formula (2):

$$P_i = 1 - exp\left(-\frac{D_i}{M_i}\right)^2, \tag{2}$$

where: D_i is the minimum distance from the vessel's trajectory to the i^{th} hazard (nautical miles), M_i is the radial root mean square error (RMSE) of vessel position determination near the i^{th} hazard.

To account for the interaction of multiple hazards (up to five), the refined RMSE M_i was determined using the formula (3):

$$M_i = \sqrt{M_0^2 + (0.7K_c^t)^2}, \tag{3}$$

where: M_o is the RMSE of the most recent navigation observation, K_c is the course accuracy coefficient, t is the travel time (in hours) from the last observation to the risk assessment point, 0.7 is an empirically derived coefficient accounting for inertial propagation of course error.

Additionally, navigation measurement errors and variations in the estimation of vessel coordinates were taken into account, which allowed for more accurate forecasts of possible threats during movement. The dependence of the safety level on the density of navigation hazards, the type of vessel and its manoeuvring characteristics was analysed. The influence of meteorological conditions, navigation equipment errors and human factors on the accuracy of determining the vessel's location was separately considered. The marginal measurement error was 2% at a confidence level of 95%. An analysis of various marine traffic scenarios was also conducted, taking into account the variable navigational situation, including collision risks and the need for operational avoidance of obstacles.

The study provided for a comparative analysis of various methods for determining navigational safety, including classical methods of course setting, assessment of the accuracy of navigation system sensors and the influence of vessel motion parameters on the probability of safe passage. Methods of numerical modelling and graphical interpretation of results were used to compare calculated and experimental values. Additionally, ship passage through potentially dangerous areas was simulated using historical navigation data and predictive calculations of the impact of changes in course and ship speed on the overall probability of safe navigation. The study analysed methods for minimising risks, including preliminary route planning taking into account permissible distances to navigational hazards, modelling emergency manoeuvres with a change in course by a fixed angle when a critical distance is reached, building adaptive routes with real-time course correction when navigation errors increase, and using Z-shaped and circular manoeuvres in limited water areas. The effectiveness of each method was assessed by the change in the probability of safe passage of the ship.

Results

The results of the study were obtained by computer modelling the passage of surface ships through navigationally difficult areas of the sea, taking into account the different number and configuration of hazards. For this purpose, mathematical models were used that take into account the distance to navigational objects, the accuracy of determining the location of the ship, the inertial and manoeuvring characteristics of the ship, as well as the errors of navigational measurements. The calculation of the

probability of safe passage was carried out according to the formulas (1, 2, 3) given in the methodological part, using the probability tables of the Maritime Tactical Table MT-75, adapted to specific scenarios of the navigational situation. Analysis of navigational safety data showed that the probability of safe passage of a ship significantly depended on its distance from the navigational hazard and the accuracy of determining the location of the ship (Table 1). For distances over 1.5 miles, the probability of safe passage remained high (0.99 and above), while at distances less than 1 mile it decreased to 0.78. When passing between two hazards, the probability of safe passage ranged from 0.97 to 0.995, depending on the spatial arrangement of the obstacles.

Table 1. Probability of safe passage of a navigation section at different distances to hazards

Distance to first hazard (miles)	Distance to second hazard (miles)	Ship's root mean square error (miles)	Passing probability P
1.2	–	0.5	0.997
0.8	–	0.5	0.78
1.5	–	0.5	0.99
1.6	3.4	1.2	0.97
2	5	0.8	0.995

Source: calculated by the author based on Maritime Tactical Table MT-75 (1975)

The assessment of navigational safety when manoeuvring near one or between two navigational hazards revealed that the decisive factor influencing the probability of safe passage is the accuracy of the vessel's positioning and its distance from the sources of potential threat. Data analysis demonstrated that, when passing near a single navigational hazard, the probability of safe passage significantly decreased as the distance decreased. Specifically, if the distance to the hazard exceeded 1.5 miles, the safety of navigation remained at a high level (0.99 or greater). However, when approaching the object at a distance of 0.8 miles, the probability of safe passage decreased to 0.78, indicating a significant increase in the risk of an emergency. A detailed analysis further showed that risks increase markedly when passing between two navigational hazards. For example, in the case where the vessel passed between obstacles located 1.6 miles and 3.4 miles apart, with the accuracy of position determination at 1.2 miles, the overall probability of safe passage decreased to 0.97. This situation is explained by the fact that even minor deviations in navigational position can lead to the vessel's actual course being dangerously close to hazardous objects. Conversely, when the navigational hazards were situated at considerably greater distances – 2 miles and 5 miles – and the accuracy of position determination was maintained at 0.8 miles, the probability of safe passage increased to 0.995, representing an almost complete guarantee of the absence of emergencies.

Separately, it should be noted that the accuracy of position determination significantly impacts the overall level of safety. It has been established that insufficient accuracy in navigational measurements can considerably reduce the probability of safe passage, even if the distance to the hazards is relatively large. This occurs because errors may cause the vessel to follow an unplanned trajectory, increasing the risk of entering a dangerous zone. For example, with a positioning error of 1.2 miles, even at a distance of 1.6 miles to the nearest hazard, the safety level was only 0.97, indicating the necessity of employing more accurate navigation methods. A critical aspect in ensuring navigational safety is the influence of hydrometeorological factors on the accuracy of determining the vessel's coordinates. Variations in conditions such as wind force, current direction, and wave height can significantly affect the vessel's trajectory. Under calm conditions (wind ≤ 5 m/s, waves ≤ 1 point, no currents), the vessel's deviation from the calculated course, with a root mean square error of 0.8 miles, did not exceed 0.3 miles. However, in stormy conditions (wind exceeding 12 m/s, waves of 4-5 points, side current ≥ 1 knot), the actual deviation could reach 0.7-1 mile, which substantially exceeds the permissible level and reduces the probability of safe passage by 10-15%. In such circumstances, navigational calculations require mandatory correction, taking into account the influence of weather factors, particularly when navigating near hazardous areas with limited manoeuvring space.

The study of the influence of the number of navigational hazards on the probability of safe navigation revealed a clear relationship between the level of risk and the density of obstacles (Table 2). The analysis of navigational situations was conducted for routes of 10 to 20 nautical miles in length, typical of complex traffic zones in coastal and restricted areas. In these zones, vessel passages were simulated with varying numbers of potential threats – from one to five or more – with fixed distances between hazards ranging from 1.2 to 3 miles. The numerical probability values presented in the table were calculated using the combined probability formula. Tabular values from the Maritime Tactical Table MT-75, adapted to the conditions of the scenarios, were employed for these calculations. It was found that as the number of navigational hazards increases over a fixed route length, the probability of safe passage gradually decreases – from 0.995 for one hazard to 0.65 for five or more densely spaced obstacles along the route. This trend is explained by the cumulative effect of risk and the reduction in available manoeuvring space to avoid each subsequent threat.

Table 2. Effect of the number of navigational hazards on the probability of safe passage

Number of hazards	Distance between hazards (miles)	Probability of safe passage P
1	≥ 3	0.995
2	2.5	0.98
3	2	0.92
4	1.5	0.85
5 or more	≤ 1.5	0.78-0.65

Source: calculated by the author based on Maritime Tactical Table MT-75 (1975)

In the case of single navigational hazards located at a distance of at least 3 miles from the vessel, the probability of safe passage remained consistently high (0.995). This is explained by the fact that the vessel has sufficient manoeuvring space to adjust its course even under adverse weather conditions or minor navigational errors. This situation indicates that isolated obstacles, although present, do not pose a critical threat provided the route is properly planned. When two navigational hazards were situated approximately 2.5 miles apart, the probability of safe passage decreased slightly to 0.98. Although this still represents a high level of safety, there was a tendency for manoeuvring to become more complex, particularly if the vessel had limited manoeuvrability or additional hydrometeorological factors were present. In such cases, maintaining safe passage required more precise calculation of movement parameters and continual course adjustments. More significant changes in safety levels were observed when the number of hazards increased to three or more. Specifically, with obstacles spaced about 2 miles apart, the probability of safe passage decreased to 0.92. This indicates that the possibility of safe manoeuvring diminished markedly, and the risk of entering a danger zone increased. Under such conditions, the vessel was required to perform more precise evasive manoeuvres, as any deviation from the prescribed trajectory could substantially increase the risk of an emergency. The critical case arose when the number of navigational hazards exceeded three and the distance between them was reduced to 1.5 miles. Under such conditions, the probability of safe passage dropped to 0.85 or lower, indicating significant navigational challenges. For example, in the scenario of a vessel passing through a section with five navigational hazards spaced 1.5 miles apart, the probability of safe passage was only 0.78. If the distance between hazards was further reduced to 1.2 miles, the probability could fall to 0.65. This reflects a critical level of risk, where any navigational error or unexpected deviation from course could result in a collision with a hazard.

It is important to highlight the influence of positioning errors. Even when the distance between hazards is relatively large, inaccuracies in navigational measurements can significantly affect the probability of safe passage. For instance, in high-density hazard zones, an error in determining the vessel's coordinates by just 0.5-1 mile can substantially alter the vessel's trajectory and increase the risk of entering the danger zone. This underlines the necessity of employing high-precision navigation systems and ensuring continuous real-time course correction. Another major factor influencing safety levels is the hydrometeorological environment. In stormy conditions or under strong winds, vessels may deviate from the calculated course, increasing the likelihood of entering a hazardous area. This is particularly critical in regions with a high density of navigational hazards, where even minor course deviations can result in collisions. For example, strong crosswinds or currents causing a drift of 0.5-1 mile from the intended route can reduce the probability of safe passage by 5-10%, even when corrective manoeuvres are applied.

Based on the findings, it is evident that maritime navigation in areas with a high density of hazards necessitates a comprehensive approach. This includes precise navigational planning, the use of advanced technologies for determining the vessel's coordinates, and real-time course correction. The adoption of adaptive routing, which accounts for possible variations in the vessel's movement and changing hydrometeorological conditions, can significantly enhance the overall level of navigational safety. The analysis also demonstrated that the accuracy of determining the vessel's location is one of the key factors affecting the probability of safe passage through a navigational section (Table 3). Errors in coordinate determination can significantly alter the calculated and actual course, thereby increasing the risk of entering a hazardous zone. The calculations were conducted with consideration of various values of systematic and random errors characteristic of modern navigation systems.

Table 3. Effect of vessel positioning error on the probability of safe passage

Ship location error (miles)	Probability of safe passage P
≤ 0.5	0.98-0.995
1	0.95-0.97
1.5	0.85
2	0.75

Source: calculated by the author

The main factors affecting the level of navigational safety were systematic and random errors in navigational measurements, delays in data transmission, the presence of radio interference, and the compatibility of different navigational systems with each other. The study was conducted by comparing the performance of various types of equipment, analysing their accuracy under real navigational conditions, and assessing the impact of their characteristics on the overall probability of safe passage through a navigational section. The results confirmed that the accuracy of determining the vessel's position is directly dependent on the type and quality of navigational equipment used, as well as on the conditions under which it operates.

When using a modern satellite Global Positioning System in combination with inertial navigation systems, the average error in determining the vessel's coordinates did not exceed 0.5 miles. This enabled a high probability of safe passage – within the range of 0.98 to 0.995 – even in complex navigational situations, such as passing between two closely spaced hazards. In open sea conditions, where there is minimal radio interference or significant atmospheric anomalies, the accuracy of satellite navigation remained stable, allowing the vessel to maintain a designated course effectively, even in situations with limited visibility. However, when satellite navigation was used in isolation – without correction from additional systems – periodic increases in positioning errors of up to 1 mile were observed. These deviations could result from signal transmission delays, multipath reflections in coastal zones, or electromagnetic interference, particularly under conditions of high maritime traffic. In such cases, the probability of safe passage decreased to 0.95-0.97. In areas with dense shipping activity, mutual interference from signals emitted by other vessels or coastal radio stations can lead to short-term malfunctions in navigational systems, which is especially hazardous when transiting narrow passages.

Significantly lower navigational safety indicators were observed when only radio navigation systems or traditional methods of position fixing – such as radar bearings and optical observations – were used. In such cases, the average positioning error reached 1.5-2 miles, corresponding to a reduction in the probability of safe passage to between 0.75 and 0.85. This is attributable to the lower accuracy of radar-based methods compared with satellite systems, particularly under conditions of poor visibility or in areas with a high concentration of navigational objects, where significant coordinate errors may occur. Situations became especially hazardous when vessels transited areas with closely spaced navigational hazards (less than 1.5 miles apart) and position fixing relied solely on radar measurements or optical control. Under such conditions, atmospheric factors (e.g., rain, fog), along with potential errors in the functioning of navigational equipment, could reduce the probability of safe passage to as low as 0.65. This highlights the fact that increased navigational complexity can substantially elevate the risk of collision or entry into danger zones.

The effectiveness of integrated navigation systems – combining multiple technologies such as satellite navigation, inertial systems, and radar control – was also analysed. The use of such composite solutions enabled the positioning error to be maintained within 0.5-0.8 miles, thereby ensuring a high level of safety even under challenging conditions. For instance, when passing between two hazards spaced 1.5 miles apart, the use of an integrated navigation system allowed the safety probability to be maintained at 0.95 or higher. In contrast, relying on a single source of navigational data could result in this figure dropping to 0.85 or lower. An additional factor influencing the accuracy of navigational measurements was the stability of navigation equipment under conditions of variable magnetic fields and electromagnetic interference. The analysis demonstrated that in areas characterised by strong magnetic anomalies – such as those near underwater volcanoes or regions of intensive industrial activity – temporary malfunctions in magnetic compasses and other navigational devices may occur. These disturbances can further complicate the accurate determination of vessel coordinates.

The data obtained indicate that navigational accuracy depends not only on the technical quality of the equipment but also on the appropriateness of its operational strategy. The implementation of automated vessel course correction methods, based on multifactorial data analysis, along with the utilisation of multiple independent sources of navigational information, significantly reduces the risks associated with positional errors. This approach is particularly crucial in complex navigational areas, where even minor deviations from the planned route can result in emergency situations. The analysis of vessel movement simulations through potentially hazardous areas showed that the effectiveness of avoiding navigational hazards depends largely on route characteristics and the precision of navigational measurements (Table 4). Several representative scenarios of transit through complex areas were modelled, each involving a different number of navigational hazards, varying hydrometeorological conditions, and diverse manoeuvring strategies.

Table 4. Probability of safe passage as a function of number of hazards and hydrometeorological conditions

Number of hazards	Distance between hazards (miles)	Hydrometeorological conditions	Probability of safe passage P
1-2	≥ 3	Favourable	0.98-0.995
1-2	≥ 3	Moderate disturbance	0.96-0.98
1-2	≥ 3	Strong wind, current	0.9-0.95
3-4	2-2.5	Favourable	0.94-0.96
3-4	2-2.5	Moderate disturbance	0.9-0.92

Table 4, Continued

Number of hazards	Distance between hazards (miles)	Hydrometeorological conditions	Probability of safe passage P
3-4	2-2.5	Strong wind, current	0.85-0.88
5 or more	≤ 1.5	Favourable	0.88-0.9
5 or more	≤ 1.5	Moderate disturbance	0.82-0.85
5 or more	≤ 1.5	Strong wind, current	0.75-0.8

Source: calculated by the author

Several main strategies were considered: plotting an optimal route taking into account navigational hazards, employing evasive manoeuvres, adjusting vessel speed, and utilising adaptive course control through modern navigation technologies. Analysis of the modelling results indicated that the level of navigational safety largely depends on the risk minimisation strategies applied when transiting potentially hazardous areas. The use of pre-planned optimal routes enabled a reduction in the probability of entering dangerous zones even before the commencement of navigation. Analysis of routes developed using mathematical models and navigational charts demonstrated that, with appropriate trajectory planning, it was possible to maintain a probability of safe passage at 0.95 or higher, even under challenging conditions. However, this method proved less effective in dynamically changing navigational situations or when immediate course alterations were required due to unforeseen circumstances.

The most effective strategies were active manoeuvring methods, which reduced the risk of entering hazardous zones without significant deviation from the primary route. Evasive manoeuvre simulations showed that employing variable courses with short-term adjustments increased the probability of safe passage, particularly in areas with a high density of navigational hazards. For instance, in scenarios involving passage between three or more hazards, the application of adaptive manoeuvres improved the probability of safe passage by 5-10% compared with static routing. Adjusting vessel speed according to the navigational context also demonstrated notable effectiveness. In high-risk areas, reducing speed helped decrease positional error and provided additional time for course correction by the crew. In scenarios where vessel speed was reduced by 20-30% of the optimal cruising speed, the probability of safe passage increased by 3-7% relative to cases where the vessel maintained constant speed. Another significant factor was the use of integrated navigation systems for real-time situational analysis. The combination of satellite, radar, and inertial navigation data substantially reduced risk in confined navigational areas. In practice, the use of such systems in scenarios involving a high density of navigational hazards (five or more obstacles) maintained the probability of safe passage at approximately 0.85. In contrast, the absence of integrated systems could result in a reduction of this indicator to 0.75 or lower. In conclusion, the findings of the study confirm that effective management of a vessel's route in complex conditions should involve a combination of strategies: optimal route planning, active manoeuvring, speed regulation, and the application of modern navigation technologies. Collectively, these measures contribute to a significant reduction of risk, even in high-threat navigational environments.

Discussion

The analysis of the obtained results indicates a critical dependence of navigational safety on both the distance to potential hazards and the accuracy of determining the vessel's position. The findings align with those of S. Gucma *et al.* (2022), who observed that navigational risk increases markedly as the distance between a vessel and a hazard decrease. Specifically, their study demonstrated that the probability of safe passage remains above 0.99 when the vessel maintains a distance greater than 1.5 nautical miles from hazards – corroborating the findings of T. Chang & H. Wang (2023), who emphasised that navigational safety deteriorates significantly when this distance falls below 1 mile. The results of the current study further confirm the critical role of positional accuracy in ensuring safe navigation. As noted by J. Bi *et al.* (2022), even minor errors in the determination of the vessel's coordinates can lead to incorrect trajectory assessments. This observation is consistent with the present data, which indicate that a positional error of 1.2 nautical miles can reduce the probability of safe passage to 0.97, even at relatively safe distances from hazards. This finding is in line with the conclusions of A. Nowy *et al.* (2021), who stressed the necessity of employing high-precision navigation systems to mitigate such risks.

Particular attention should be paid to scenarios involving passage between two navigational hazards. The results indicate that the probability of safe passage varies significantly depending on the spatial arrangement of obstacles, consistent with the findings of L. Bowo *et al.* (2024). For instance, with hazards spaced between 1.6 and 3.4 miles apart and a location error of 1.2 miles, the probability of safe passage was measured at 0.97. This supports the conclusions of A. Misuri *et al.* (2021), who demonstrated that even minor positional discrepancies can materially alter the vessel's route and affect the overall safety margin. The study also highlighted the substantial influence of a vessel's manoeuvrability on the level of navigational safety. Ships with higher manoeuvrability exhibited a significantly greater likelihood of avoiding hazards, aligning with the findings of P. Han *et al.* (2024). Conversely, E. Uflaz *et al.* (2022) reported that for vessels with limited manoeuvrability, even routes considered relatively safe can become critical – a conclusion that is likewise supported by the results obtained in this study. Hydrometeorological conditions emerged as another key factor

affecting the accuracy of navigational measurements and the general level of maritime safety. The research findings of C. Zhao *et al.* (2021) demonstrated that strong winds and currents can lead to considerable deviations from the intended course, a trend that is also evident in this study. For instance, under calm conditions, the position determination error might be limited to 0.8 miles; however, in stormy conditions, this error can increase significantly, echoing the conclusions of Z. Qiao *et al.* (2021).

An important aspect influencing navigational safety is the number of hazards encountered along the route. Analysis of the collected data confirmed that an increase in the number of hazardous objects leads to a decline in the probability of safe passage, a finding consistent with the study by Y. Chen *et al.* (2021). For example, when navigating a section with five hazards spaced 1.5 nautical miles apart, the probability of safe passage decreased to 0.78. This corresponds with the conclusions of Ü. Öztürk *et al.* (2021), who identified a critical escalation in risk in densely trafficked navigational areas. Further analysis revealed that when the number of hazards increases to seven, the probability of safe passage may drop below 0.7 – approaching or crossing the safety threshold. This deterioration is largely due to the increased frequency of required manoeuvres and the reduced ability to accurately predict and maintain a safe course in confined waters. Moreover, in high-traffic areas, the complexity of vessel interactions further exacerbates the risk of collision, which supports the findings of R. Fışkın *et al.* (2021). These results underscore the importance of route optimisation strategies that aim to avoid or minimise exposure to zones of elevated hazard density as a key approach to enhancing navigational safety.

In contrast to the assertion by L. Pham & L. Van Hoang (2024) – who argue that safety levels are determined solely by proximity to navigational hazards – the results of the present study demonstrate that the accuracy of positional measurements is equally critical. Even when hazards are situated at relatively safe distances, errors in determining the vessel's location can significantly reduce the probability of safe passage, a factor overlooked in their research. The findings on positional accuracy also align with the conclusions of Y. Liu & Y. Ma (2023), who reported that the exclusive use of radio navigation systems – without satellite correction – leads to substantial navigation errors. Meanwhile, P. Antão *et al.* (2023) argue that autonomous inertial navigation systems can partially mitigate such errors, a position partially corroborated by this study. Furthermore, Z. Wang *et al.* (2023) note that modern satellite navigation systems are capable of maintaining a positional error margin of within 0.5 miles, which aligns with the current data. However, T. Liu *et al.* (2024) cautioned that even these technologies may prove unreliable under adverse conditions – a concern substantiated by the current analysis in challenging operational environments.

The evaluation of different manoeuvring strategies is also consistent with the findings of S. Wang *et al.* (2022), who assert that adaptive manoeuvres are effective in reducing navigational risk, even in areas of high hazard density. This effectiveness is attributed to dynamic course adjustments based on real-time situational data, which improve the vessel's ability to avoid hazards and increase decision-making flexibility. Additionally, adaptive manoeuvring strategies help mitigate the impact of adverse hydrometeorological conditions – such as strong currents or gusting winds – as confirmed by field observations. Conversely, the findings also support the position of S. Fu *et al.* (2021), who highlighted the limitations of static route planning in dynamic navigation environments. The current study shows that static routing, especially under variable traffic and environmental conditions, contributes to increased errors in estimating the vessel's optimal trajectory and reduces overall safety margins. Taken together, the findings strongly support the necessity of a comprehensive and dynamic approach to route planning. This includes the integration of adaptive threat-avoidance algorithms, real-time environmental monitoring, and predictive navigation models that allow for informed and flexible decision-making in complex maritime conditions.

Considerable attention must be given to the vessel's speed, as it significantly influences manoeuvrability and the ability to respond promptly to navigational hazards. J. Froese (2022) demonstrated that reducing speed by 20-30% from the vessel's standard cruising speed can increase the probability of safe passage by 3-7%, a finding that aligns closely with the results of this study. This improvement is largely attributed to the additional time available for situational assessment and course correction, which is particularly beneficial in scenarios involving restricted visibility or high densities of navigational hazards. Conversely, H. Ha *et al.* (2023) argue that speed is not a decisive factor in navigational safety, asserting that vessel manoeuvrability and the accuracy of navigational systems exert a more pronounced influence. However, the present findings suggest that in complex navigational environments, speed reduction remains an effective risk mitigation strategy and should not be underestimated. Furthermore, L. Pham & L. Van Hoang (2024) highlight the value of intelligent navigation systems that integrate predictive modelling with real-time navigational data. This perspective is fully consistent with the current study, which confirms that the combined application of multiple technological solutions significantly enhances safety. In particular, the integration of satellite-based positioning, automated maritime traffic analysis, and meteorological forecasting facilitates timely responses to emerging threats and reduces the influence of unpredictable external factors. Adaptive navigation systems, capable of real-time route adjustments, further enable the avoidance of high-risk areas without necessitating substantial deviations from the intended course.

The evidence obtained clearly indicates that the adoption of such technologies can substantially lower accident rates and improve the overall efficiency of maritime transport operations. In conclusion, effective vessel route

management in challenging environments requires a comprehensive approach – one that incorporates high-precision navigational equipment, adaptive route planning, and dynamic speed regulation. Together, these elements contribute to a marked improvement in navigational safety, even under adverse or rapidly changing maritime conditions.

Conclusions

The analysis of navigational safety data confirmed the critical influence of the distance to potential hazards and the accuracy of ship position determination on the probability of safe passage. It was established that when the distance to hazards exceeded 1.5 miles, the probability of safe passage remained high (0.99 or above). However, when this distance decreased to 0.8 miles, the probability dropped significantly to 0.78, indicating a substantial increase in navigational risk. For passages between two navigational hazards, the overall probability of safe passage ranged from 0.97 to 0.995, depending on both the accuracy of navigational measurements and the spacing between obstacles.

The study confirmed that errors in ship position determination constitute a key risk factor. For instance, with an error of 1.2 miles, even at relatively large distances from hazards, the probability of safe passage fell to 0.97. These findings highlight the necessity of employing high-precision navigation systems to mitigate the effects of both systematic and random errors. Furthermore, an increase in the number of navigational hazards along the route corresponded to a gradual decline in safety levels. Specifically, navigating a section with five hazards reduced the probability of safe passage to 0.78, while increasing obstacle density to seven lowered it further to 0.65 – approaching the threshold for unacceptable risk. Additional factors influencing navigational safety included the vessel's manoeuvrability and prevailing hydrometeorological conditions. Vessels with high manoeuvrability exhibited a greater likelihood of safe passage in close-proximity scenarios, owing to their capacity for rapid course adjustments. Conversely, adverse weather conditions such as strong winds, currents, and waves adversely affected the precision of navigational measurements, increasing the risk of deviation from the planned route.

Future research should focus on the development and implementation of adaptive routing strategies that dynamically account for variable navigational and environmental conditions. The integration of satellite-based positioning, radar data, and inertial navigation systems within comprehensive navigation solutions is recommended to enhance situational awareness. Additionally, active manoeuvring and speed adjustment protocols tailored to the level of navigational risk should be further investigated and applied in practice. The study's limitations include its reliance on idealised models that do not incorporate human factors or the fluctuating intensity of maritime traffic under real-world conditions. Subsequent research could address these gaps by designing algorithms for real-time automatic course correction, thereby further improving navigational safety in challenging sea areas.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Antão, P., Sun, S., Teixeira, Â., & Soares, C. (2023). Quantitative assessment of ship collision risk influencing factors from worldwide accident and fleet data. *Reliability Engineering & System Safety*, 234, article number 109166. doi: 10.1016/j.ress.2023.109166.

[2] Bi, J., Gao, M., Zhang, W., Zhang, X., Bao, K., & Xin, Q. (2022). Research on navigation safety evaluation of coastal waters based on dynamic irregular grid. *Journal of Marine Science and Engineering*, 10(6), article number 733. doi: 10.3390/jmse10060733.

[3] Bowo, L., Gusti, A., Waskito, D., Puriningsih, F., Muhtadi, A., & Furusho, M. (2024). Comprehensive analysis of navigational accidents using the MAART method: A novel examination of human error probability in maritime collisions and groundings. *TransNav: The International Journal on Marine Navigation and Safety of Sea Transportation*, 18(3), 565-563. doi: 10.12716/1001.18.03.10.

[4] Chang, T., & Wang, H. (2023). Analysis and exploration of the impact of average sea level change on navigational safety in ports. *Water*, 15(14), article number 2570. doi: 10.3390/w15142570.

[5] Chen, Y., Xie, C., Chen, S., & Huang, L. (2021). A new risk-based early-warning method for ship collision avoidance. *IEEE Access*, 9, 108236-108248. doi: 10.1109/ACCESS.2021.3099831.

[6] Fışkın, R., Atik, O., Kişi, H., Nasibov, E., & Johansen, T. (2021). Fuzzy domain and meta-heuristic algorithm-based collision avoidance control for ships: Experimental validation in virtual and real environment. *Ocean Engineering*, 220, article number 108502. doi: 10.1016/j.oceaneng.2020.108502.

[7] Froese, J. (2022). Standardization of risk assessment in navigation. *Journal of Physics: Conference Series*, 2311, article number 012015. doi: 10.1088/1742-6596/2311/1/012015.

[8] Fu, S., Goerlandt, F., & Xi, Y. (2021). Arctic shipping risk management: A bibliometric analysis and a systematic review of risk influencing factors of navigational accidents. *Safety Science*, 139, article number 105254. doi: 10.1016/J.SSCI.2021.105254.

[9] Gritsuk, I., Nosov, P., Dyagileva, O., & Masonkova, M. (2023). Improving safety of navigation by constructing a dynamic model of the navigator's actions in the conditions of navigation risks. *Transport Systems and Technologies*, 41, 84-95. doi: 10.32703/2617-9059-2023-41-7.
[10] Gucma, S., Ślączka, W., & Bąk, A. (2022). Assessment of ship manoeuvring safety in waterway systems by relative navigational risk. *Archives of Transport*, 64(4), 119-134. doi: 10.5604/01.3001.0016.1230.
[11] Ha, J., Roh, M., & Lee, H. (2021). Quantitative calculation method of the collision risk for collision avoidance in ship navigation using the CPA and ship domain. *Journal of Computational Design and Engineering*, 8(3), 894-909. doi: 10.1093/jcde/qwab021.
[12] Han, P., Zhu, M., & Zhang, H. (2024). Interaction-aware short-term marine vessel trajectory prediction with deep generative models. *IEEE Transactions on Industrial Informatics*, 20, 3188-3196. doi: 10.1109/TII.2023.3302304.
[13] Huy-Tien, H., Tuyet Lan, N., Chung, P.V., & Nguyen, T.-L. (2023). Improvement model of navigational safety for inland waterway transport. *Transactions on Maritime Science*, 12(1), 29-44. doi: 10.7225/toms.v12.n01.003.
[14] International Maritime Organization. (n.d.). *Maritime safety*. Retrieved from https://surl.lt/wcgtjw.
[15] Kuhlman, K.L. (2013). Review of inverse Laplace transform algorithms for Laplace-space numerical approaches. *Numerical Algorithms*, 63(2), 339-355. doi: 10.1007/s11075-012-9625-3.
[16] Liu, T., Ma, J., & Zhou, Y. (2024). Research on spatiotemporal distribution characteristics of ship traffic flow in port waters based on AIS data. *Frontiers in Humanities and Social Sciences*, 4(2), 1-11. doi: 10.54691/nwfyf729.
[17] Liu, Y., &, Ma, Y. (2023). A field theory-based novel algorithm for navigational hazard index. *Journal of Marine Science and Engineering*, 11(1), article number 178. doi: 10.3390/jmse11010178.
[18] Maritime Tactical Table MT-75. (1975). Moscow: USSR Ministry of Defense.
[19] Maternová, A., Materna, M., & Dávid, A. (2022). Revealing causal factors influencing sustainable and safe navigation in Central Europe. *Sustainability*, 14(4), article number 2231. doi: 10.3390/su14042231.
[20] Melnyk, O., Burmaka, I., Zaporozhets, A., Onishchenko, O., Burlachenko, D., & Nykytuik, P. (2025). In-depth analysis of strategies and techniques of navigational safety improvement and ship collision risk reduction. In O. Melnyk, O. Onishchenko & A. Zaporozhets (Eds.), *Maritime systems, transport and logistics I* (pp. 65-87). Cham: Springer. doi: 10.1007/978-3-031-82027-4_5.
[21] Melnyk, O., Bychkovsky, Y., Onishchenko, O., Onyshchenko, S., & Volianska, Y. (2023). Development of the method of shipboard operations risk assessment quality evaluation based on experts review. In A. Zaporozhets (Ed.), *Systems, decision and control in energy V* (pp. 695-710). Cham: Springer. doi: 10.1007/978-3-031-35088-7_40.
[22] Misuri, A., Landucci, G., & Cozzani, V. (2021). Assessment of risk modification due to safety barrier performance degradation in Natech events. *Reliability Engineering & System Safety*, 212, article number 107634. doi: 10.1016/J.RESS.2021.107634.
[23] Nowy, A., Łazuga, K., Gucma, L., Androjna, A., Perkovič, M., & Srše, J. (2021). Modeling of vessel traffic flow for waterway design – Port of Świnoujście case study. *Applied Sciences*, 11(17), article number 8126. doi: 10.3390/app11178126.
[24] Öztürk, Ü., Boz, H., & Balcisoy, S. (2021). Visual analytic based ship collision probability modeling for ship navigation safety. *Expert Systems with Applications*, 175, article number 114755. doi: 10.1016/J.ESWA.2021.114755.
[25] Pham, L., & Van Hoang, L. (2024). A navigational risk evaluation of ferry transport: Continuous risk management matrix based on fuzzy Best-Worst Method. *PLOS One*, 20(3), article number e0320794. doi: 10.1371/journal.pone.0309667.
[26] Qiao, Z., Zhang, Y., & Wang, S. (2021). A collision risk identification method for autonomous ships based on field theory. *IEEE Access*, 9, 30539-30550. doi: 10.1109/ACCESS.2021.3059248.
[27] Rawson, A., Brito, M., & Sabeur, Z. (2021a). Spatial modeling of maritime risk using machine learning. *Risk Analysis*, 42(10), 2291-2311. doi: 10.1111/risa.13866.
[28] Rawson, A., Sabeur, Z., & Brito, M. (2021b). Intelligent geospatial maritime risk analytics using the Discrete Global Grid System. *Big Earth Data*, 6(3), 294-322. doi: 10.1080/20964471.2021.1965370.
[29] Uflaz, E., Celik, E., Aydin, M., Erdem, P., Akyuz, E., Arslan, O., Kurt, R., & Turan, O. (2022). An extended human reliability analysing under fuzzy logic environment for ship navigation. *Australian Journal of Maritime & Ocean Affairs*, 15(2), 189-209. doi: 10.1080/18366503.2022.2025687.
[30] Wang, S., Zhang, H., & Luo, X. (2022). Ship navigation safety assessment based on neural network. In *Proceedings of the 22nd international conference on computer and information science* (pp. 71-75). Zhuhai: IEEE. doi: 10.1109/ICIS54925.2022.9882416.
[31] Wang, Z., Yan, X., & Wu, B. (2023). Prioritization of influencing factors for remote control intelligent ships collision based on fuzzy fault tree analysis. In *Proceedings of the 7th international conference on transportation information and safety* (pp. 1380-1388). Xian: IEEE. doi: 10.1109/ICTIS60134.2023.10243827.
[32] Zhang, W., Meng, X., Yang, X., Lyu, H., Zhou, X., & Wang, Q. (2022). A practical risk-based model for early warning of seafarer errors using integrated Bayesian network and SPAR-H. *International Journal of Environmental Research and Public Health*, 19(16), article number 10271. doi: 10.3390/ijerph191610271.

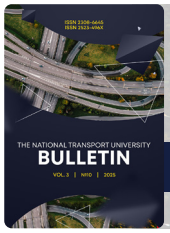
[33] Zhao, C., Wu, B., Yip, T., & Lv, J. (2021). Use of fuzzy fault tree analysis and noisy-OR gate Bayesian network for navigational risk assessment in Qingzhou port. *TransNav: The International Journal on Marine Navigation and Safety of Sea Transportation*, 15(4), 765-771. doi: 10.12716/1001.15.04.07.

Удосконалення методики врахування впливу кількісного фактору навігаційних небезпек на ймовірність безпеки плавання

Вадим Панченко
Магістр
Національний університет «Одеська морська академія»
65052, вул. Дідріхсона, 8, м. Одеса, Україна
https://orcid.org/0009-0009-4526-6447

Анотація. Метою дослідження було вдосконалення методики оцінки ймовірності безпеки плавання з урахуванням кількісного фактора навігаційних небезпек. Методологія включала розробку математичних моделей, що враховують вплив кількості небезпек на ймовірність безпечного проходу, їх аналіз проводився із застосуванням методів дисперсійного та кореляційного аналізу, що дозволило оцінити вплив основних факторів ризику. Дослідження показало, що основними факторами, що впливають на рівень безпеки, є відстань до навігаційних небезпек, точність визначення місця корабля, маневрові характеристики судна та гідрометеорологічні умови. Для відстані понад 1,5 милі ймовірність безпечного проходу перевищувала 0,99, тоді як при 0,8 милі вона знижувалася до 0,78. При проходженні між двома небезпеками ймовірність змінювалася від 0,97 до 0,995 залежно від їх просторового розташування. Збільшення кількості небезпек призводило до зниження ймовірності безпечного проходу: при п'яти небезпеках вона могла зменшитися до 0,65. Аналіз впливу похибок навігаційних вимірювань показав, що при точності визначення місця судна 0,5 милі ймовірність безпеки становила 0,995, а при похибці 2 милі – 0,75. Використання інтегрованих навігаційних систем дозволяло підвищити рівень безпеки на 5-10 %. Отримані результати підтверджують ефективність комплексного підходу до навігаційного планування, який базується на поєднанні кількох ключових принципів: використанні інтегрованих систем для точного визначення координат судна, застосуванні адаптивних маршрутів, що враховують щільність небезпек і змінність навігаційної ситуації, динамічній корекції швидкості руху залежно від зовнішніх умов, а також оперативному ухиленні від перешкод на основі прогнозного моделювання та реальних навігаційних даних. Такий підхід має високу практичну цінність для підвищення ефективності управління судноплавством у районах з підвищеною навігаційною складністю, що дозволяє мінімізувати вплив ризиків і забезпечити стабільність маршрутів навіть у несприятливих умовах

Ключові слова: ризик зіткнення; маневрові характеристики; просторове розташування; адаптивні маршрути; гідрометеорологічні умови



BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 30 | №2 | 2026
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X

Received: 16.01.2026. Revised: 27.05.2026. Accepted: 25.06.2026. Published: 06.07.2026.

UDC 624.138.5:004.6 DOI: 10.33744/2308-6645-2026-2-30-41-52

Information modelling in the analysis of the condition of small bridge structures in rural road network: Challenges and solutions

Pavlo Striletskyi*
Postgraduate Student
National University of Water and Environmental Engineering
33028, 11 Soborna Str., Rivne, Ukraine
https://orcid.org/0000-0001-6533-0121

Abstract. The study aimed to identify effective approaches to the use of digital technologies for assessing the condition and planning the rehabilitation of small transport crossings, incorporating limited resources and data interoperability requirements. The methodology combined comparative analysis, Building Information Modelling, case studies of regional examples and systematisation of international experience. Digital methods have been shown to provide millimetre-level measurement accuracy, reduce data collection time, and can be used to create detailed 3D models, as well as predict wear using deep learning algorithms. In Zhytomyr, Volyn, Cherkasy and Odesa regions of Ukraine, defects in bridge structures were recorded: in Zhytomyr – damage from military operations, in Volyn – cracks in concrete and soil erosion, in Cherkasy – the effects of prolonged operation for more than 50 years, and in Odesa – corrosion of steel elements combined with an aggressive coastal environment. The study confirmed that the integration of data into the Digital Twin Building Information Modelling environment increased the accuracy of forecasts by up to 95% (in China), and a 40-65% reduction in time and labour costs was recorded when using deep learning algorithms in Germany. The use of unmanned aerial vehicles with Light Detection and Ranging and photogrammetry was used for the inspection of bridges with minimal impact on traffic and human factors, which is essential in remote or dangerous areas. Based on a synthesis of international experience in implementing innovative methods in bridge construction, the use of open formats and simplified models was recommended, which reduced survey costs and time for preparing documentation. The results can be used by road services to plan repairs, manage the life cycle of bridges and rehabilitate structures in Ukraine with increased transparency and lower environmental impact

Keywords: digital twins; open formats; lifecycle; cross-platform compatibility; wear prediction; semantic enrichment; automated monitoring

Introduction

Bridge management is undergoing a rapid digital transformation. Building Information Modelling (BIM), Bridge Information Modelling (BrIM), and Digital Twins (DT) technologies are becoming key tools for improving safety, optimising maintenance and reducing operating costs. The growth of infrastructure data and the emergence of affordable tools for processing it are creating new opportunities, even for facilities that were previously overlooked due to limited funding or remote locations. International initiatives on open data exchange standards (openBIM) are enhancing interoperability and facilitating collaboration between organisations. In the context of Ukraine, these technologies are gaining importance due to the combination of the challenges of rebuilding infrastructure after destruction and the need to utilise limited resources. Remote bridge inspections have become more efficient by combining data from condition monitoring systems with DT to provide early detection of defects, reduce the number of visits and accelerate decision-making. A. Hagen & T.M. Andersen (2024) demonstrated that the accuracy of

Suggested Citation: Striletskyi, P. (2026). Information modelling in the analysis of the condition of small bridge structures in rural road network: Challenges and solutions. *Bulletin of the National Transport University*, 30(2), 41-52. doi: 10.33744/2308-6645-2026-2-30-41-52.

*Corresponding author (*pavstriletskyi@hotmail.com*)

Copyright © The Author(s). This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/)

assessments is not lost, and the safety of inspections is improved. The study noted the consistency of vibration indicators with damage indicators in the digital model, which enhances the reliability of triggers for unscheduled inspections. This confirmed the effectiveness of the approach in conditions of limited access to structures, when traditional inspections are risky or expensive. The implementation of open BIM in infrastructure is hampered by uneven standards, the lack of a unified Employer's Information Requirements (EIR)/BIM Execution Plan (BEP) and gaps in staff training. This was illustrated by a systematic review by A. Salzano *et al.* (2023), summarising a large body of work and outlining the priorities of open formats. The study demonstrated the need to start with unified EIR/BEP-light and standard IFC templates to reduce the cost of coordination and ensure cross-platform compatibility at the level of regional services.

In the Ukrainian context, information modelling is seen as a catalyst for transformation in design and management. A study by O.M. Protsenko *et al.* (2024) proved that regulatory consolidation of BIM processes and the launch of industry digital platforms are key to practice scaling. They showed managerial steps that can accelerate digitalisation, which formed the institutional prerequisites for adapting BIM/BrIM to small bridges. The widespread use of BIM in Ukraine is constrained by CAD/BIM compatibility, regulatory gaps, and a lack of government support. This was highlighted by M. Surianinov *et al.* (2024), proposing steps to standardise requirements and training. Removing these barriers creates the conditions for deploying solutions on a network of small facilities. The study demonstrated what system conditions should be provided for solutions to be operational on a network of small facilities. In addition, rapid damage assessment in crisis conditions is possible through multi-level schemes that combine satellite data, deep learning, and crowdsourcing, as demonstrated by N. Kopiika *et al.* (2025) by generating rapid damage maps to prioritise interventions. The approach is compatible with integration into BIM/DT life-cycle loops, providing a realistic channel for cheaper data collection that is compatible with further integration into BIM/DT life-cycle loops. Over the life cycle of a bridge, DT technology delivers significant economic and environmental benefits, reducing downtime, optimising resource consumption and stabilising the intervention schedule. T. Cherniavska & B. Cherniavskyi (2025) proved that the integration of DT into the reconstruction and management of infrastructure in Ukraine can increase the efficiency of the use of funds and provide more predictable planning of repair work, even in conditions of limited resources. This directly supported the focus on small bridge networks, where such practices yield economic benefits without the need for excessive expansion of information models.

Integration of data into a common Digital Twin-BIM environment improves the accuracy of condition forecasts and the timeliness of repairs through connectivity and traceability of information. The study by Z. Dvulit *et al.* (2023) demonstrated that the use of DT for planning and forecasting resource requirements in the post-war reconstruction of Ukraine would ensure the scalability of models from a single facility to a portfolio of structures, while maintaining the accuracy and relevance of the data. This approach was in line to create a single "point of truth" for geometry, defects and performance parameters, which was identified as a key efficiency factor. The scalability of BIM in bridge construction depends on cross-platform compatibility and clear information requirements. The study by A.I. Bielova *et al.* (2020) emphasised that the implementation of BIM in Ukraine on the path to European integration is impossible without the unification of standards and the harmonisation of the regulatory framework with European requirements. For the regional road services of Ukraine, this meant the expediency of starting with simple IFC/EIR templates and gradually expanding their functionality without being tied to one software.

Despite a wide range of research in the field of BIM/BrIM and DT, the issues of scaling them up for small bridges in rural road networks remain insufficiently studied, especially in conditions of limited resources, increased risks of military operations and economic constraints. There is also a lack of practical cases of openBIM implementation in public infrastructure projects in Ukraine, and the integration of low-cost solutions into national reconstruction programmes is still at an early stage. Therefore, the study aimed to identify and justify effective approaches to the implementation of BIM/BrIM and digital twin technologies in small bridge rehabilitation projects in Ukraine, incorporating limited resources, interoperability requirements, and the potential of low-cost solutions.

Materials and Methods

The study was conducted from December 2024 to July 2025 and covered the substantiation of approaches to the implementation of digital technologies in the design, inspection and operation of small bridges in Ukraine in Zhytomyr, Volyn, Cherkasy and Odesa regions. These regions were selected due to the representativeness of their bridge structures: in Zhytomyr region due to significant damage caused by military operations, which assessed the effectiveness of digital methods in restoring bridges after combat impacts (State Restoration Service of Ukraine, 2024b), in Volyn region – problems with soil erosion and cracks in concrete (State Restoration Service of Ukraine, 2024a), in Cherkasy region, an example of bridges in critical technical condition due to long-term operation (over 50 years), which verified approaches to wear forecasting and prioritisation of repairs (Cherkasy Regional State Administration, 2023), and in Odesa region, the impact of aggressive coastal environment and corrosion of steel elements (Odesa Regional State Administration, 2021). This sample incorporated different types of structures and a wide range of damages to form a representative base and develop practical recommendations.

The international experience of such countries as Canada, Portugal, China, Egypt, USA, Brazil, Poland,

Germany, Great Britain was incorporated, which was used to adapt effective practices to Ukrainian conditions and to align them with the world practices of bridge infrastructure management, and the current regulatory requirements (DBN V.2.3-26:2024, 2025; BN01:4868-1755-9511-2275, 2025), which define the basic principles of design and assessment of bridge structures in Ukraine, European Union (EU) standards (Eurocode 1, 2003; Eurocode 2, 2005), Guideline for the implementation… (2019) and materials on the national implementation of ISO 19650-1:2018 (2018) in Ukraine.

The study included 5 stages. At the first stage, a method of comparative analysis of traditional and digital methods was conducted to determine the differences between approaches to the inspection of small bridges in terms of measurement accuracy, data collection speed, economic costs and ease of use of the information obtained. At the second stage, the method of step-by-step detailing was used to describe the process of creating BIM models of small bridges, formed as a theoretical generalisation of existing approaches and confirmed by international experience. The data collection and preparation involved the analysis of geometric characteristics such as length, width, height, span, structural materials (concrete and steel classes), as well as information from inspection reports and archival drawings, following applicable standards and guidelines. To determine the modelling tools, the literature was analysed, which justified the use of UAV photogrammetry, light detection and ranging (LiDAR) and computer vision algorithms to obtain the output data. For 3D geometric modelling of bridge structures, examples included Autodesk Revit, Civil 3D, Allplan Bridge, and Tekla Structures software. For the semantic enrichment of the models, standardised Property Sets (IFC 4.3) were used to ensure the unification of attributes. The models were validated using CloudCompare, Navisworks or Solibri to check their accuracy and compliance with the requirements. Integration with the life cycle involved the use of IoT platforms to monitor the condition of structures and Life Cycle Assessment (LCA)/5D (5-Dimensional) BIM methods to assess sustainability and life-cycle costs.

The third stage was to classify a matrix of key parameters to establish quality and interoperability requirements for BIM models in bridge construction. It incorporated the level of detail (LOD), interoperability, reliability and safety indicators, as well as environmental aspects of the life cycle. This was necessary to formulate uniform criteria for evaluating models at different stages of their life cycle and integrating them with digital counterparts. At the fourth stage, a case study method was used to analyse the technical condition and rehabilitation needs of small bridge structures, which involved consideration of regional examples of small bridge structures from Zhytomyr, Volyn, Cherkasy and Odesa regions of Ukraine. At the fifth stage, the method of systematisation of international experience in the implementation of innovative technologies in bridge construction and operation was applied. Examples from Canada, Portugal, China, Egypt, the United States, Brazil, Poland, Germany and the United Kingdom were selected for analysis, reflecting trends in this area. The study systemised the technologies: Bridge Information Modelling (BrIM) with LCA and Life Cycle Costing (LCC) integration, Building Digital Twins (BDT) with Internet of Things (IoT) and Artificial Intelligence (AI)/Machine Learning (ML), Digital Twins (DT) with Geographic Information Systems (GIS) and BIM integration, BrIM framework for Reinforced Concrete (RC) bridges, unified DT framework for bridges, BIM with Mixed Reality (MR) Immersive Digital Twin Platform (IBDTP), Deep learning for geometry reconstruction from drawings, Long Short-Term Memory (LSTM) with BIM for management, data integration framework for RC bridges. Sources for generalisation highlighted the experience of applying these technologies in different countries to outline the range of modern digital solutions of the 21st century in bridge construction. This was necessary to adapt effective practices to the Ukrainian context of small bridge rehabilitation, as well as to formulate practical recommendations for the implementation of digital technologies in the design and operation of small bridges in Ukraine.

Results and Discussion

Design features of small automotive bridges and comparison of traditional and digital methods for their inspection

Small road bridges in the rural road network are structures with a span length of up to 25 m, designed to maintain the continuity of traffic flows on local roads that are not part of main arteries. Typical structural solutions include reinforced concrete girder bridges (monolithic and prefabricated), metal girder and frame structures made of steel profiles, as well as combined systems for the joint operation of steel (reinforcing steel of A400C class and structural steel of S235-S355) and concrete (classes B20-B30). BIM in bridge construction is an integrated approach to the creation, management and operation of digital models at all stages of the construction life cycle (Guideline for the implementation..., 2019). There are two main approaches to bridge inspection and condition assessment: traditional methods (visual inspection and instrumental measurements) and digital technologies, including BIM, laser scanning, photogrammetry and the use of unmanned aerial vehicles (UAVs). Traditional methods provide only moderate accuracy, with results heavily dependent on the engineer's skill and equipment quality, while visual inspection can miss hidden defects, and instrumental methods provide localised but not comprehensive data (Alsharif *et al.*, 2025). These approaches are slow and labour-intensive, but their affordability makes them relevant for baseline surveys. Data are usually recorded in reports and acts, which makes further analysis and long-term use difficult.

Digital technologies, on the other hand, are much more accurate and efficient. Laser scanning can be used for detailed 3D models with millimetre resolution, while photogrammetry and drones provide high accuracy of geometric measurements, although less informative about

materials (Jrade *et al.*, 2023). BIM technologies act as an integrated environment for processing and analysing this data, ensuring effective information management throughout the entire life cycle of a building (Nhamage *et al.*, 2025). Studies show that digital twins can radically improve the quality of bridge management and monitoring by combining data from different sources into a single system (Gao *et al.*, 2024). The integration of BIM with GIS is already being used for practical operation and maintenance tasks, providing centralised management and planning of repairs. The unification of digital approaches is emphasised, as common frameworks for digital bridge twins that enable standardised data exchange and application in different contexts are being developed. New solutions also include the use of mixed reality for visualisation and inspection of bridge structures in a BIM environment (Martins *et al.*, 2024). In addition, 3D reconstruction methods from 2D drawings show the potential to create digital bridge models, which is especially relevant for the reconstruction and modernisation of existing structures (Poku-Agyemang & Reiterer, 2023).

The creation of BIM models of small bridges is a step-by-step process that combines the collection of primary data, the formation of 3D geometry, semantic enrichment of the information model, data validation and federation, and integration into the full life cycle of the structure. Each stage has specific tasks, tools and methods, the choice of which depends on the technical requirements, LOD level and available resources. Table 1 demonstrates the data in detail.

Table 1. Stages and tools for creating BIM models of small bridges

Stage	Characteristic	Tools and methods
Data collection and preparation	Analysis of available documentation: 2D plans, archive drawings, inspection reports. Digitise analogue drawings with a resolution of 300-600 DPI for accurate reference. Field surveys to identify areas of interest (ROI) where the structure has critical or potentially dangerous defects. Photogrammetry (UAVs, cameras) and/or LiDAR scanning to create georeferenced point clouds. Computer vision algorithms (OpenCV) for semi-automatic selection of bridge elements from photos and videos.	Equipment: UAVs with a camera, LiDAR laser scanners, and high-resolution digital cameras. Methods: photogrammetry, LiDAR scanning, algorithmic image processing (OpenCV).
3D geometric modelling	Creation of a parametric 3D model from the main components (beams, supports, abutments, roadway slab). Semi-automatic reconstruction from 2D plans: vectorisation, topological analysis, transition to 3D space, interpolation of curves by cubic splines. Model optimisation to reduce file weight without losing critical data. Export to IFC 4.3 format with appropriate property sets for interoperability. Convert to GLTF or 3D Tiles for integration with GIS and web visualisation.	Software: Autodesk Revit, Civil 3D, Allplan Bridge, and Tekla Structures. Formats: IFC 4.3, GLTF, 3D Tiles. Methods: parametric modelling, spline interpolation, and topological analysis.
Semantic enrichment and data integration	Adding non-geometric data: materials, strength classes, repair history, inspection results. Modelling defects (cracks, corrosion, deformation) digitally, for example, through JSON structures. Use of ontologies and standard property sets (Psets) to ensure uniformity. Integration with structural analysis software (FEA) for verification of residual load-carrying capacity. Colour coding of elements by degree of damage.	Tools: JSON, Abaqus, Midas Civil, IFC ontologies. Methods: semantic modelling, integration of FEA results, colour coding of defects.
Model validation and federation	Geometric verification of the model by overlaying an as-built point cloud on the BIM model. Model checking – automatically checks for collisions and BEP compliance. Combining submodels of different disciplines (architecture, structures, engineering) into a single CDE. Model versioning for tracking changes and updates. Update the model from IoT sensor data or after inspections.	Tools: CloudCompare, Navisworks, Solibri, CDE platforms (Trimble Connect, BIM 360). Methods: geometric analysis, collision control, model versioning.
Integration with the life cycle	Extend the model to 4D (time schedules) and 5D (cost) for repair and maintenance planning. Creating reports and visualisations for customers and operational services. Integration with digital twins for continuous status monitoring. Connecting IoT sensors (deformation, humidity, temperature) to obtain real-time data. Performing a life cycle analysis (LCA) to assess long-term performance.	Tools: Xeokit, Caesium, Twinmotion, IoT platforms. Methods: 4D/5D BIM, LCA analysis per ISO 14040, Digital Twin integration.

Source: compiled by the author based on Y. Xenidis *(2021), M. Fawad et al.* (2024), B. Faltin *et al.* (2024)

The stages of creating BIM models of small bridges combined survey data, 3D modelling and digital twins into a single system. For rural regions of Ukraine, in particular Zhytomyr and Volyn, this is relevant as it can rapidly

digitalise outdated bridges, integrate the results into CDE platforms and connect IoT sensors for monitoring. This approach improves the accuracy of the assessment of the condition of structures and facilitates effective planning of repairs in remote communities. The quality and functionality of BIM models for small bridges are determined by a set of requirements covering the level of detail, interoperability and data management, reliability and safety of structures, as well as consideration of environmental factors and the entire life cycle of the structure. In accordance with international (Eurocode 1, 2003; Eurocode 2, 2005) and Ukrainian standards (DBN V.2.3-26:2024, 2025; BN01:4868-1755-9511-2275, 2025), each of these parameters is of practical importance for the design, operation and modernisation of bridge structures. The parameters are listed in Table 2.

Table 2. Requirements for the level of detail, interoperability and life cycle of BIM bridge models

Parameters	Description	Practical application
LOD	LOD 300-400 – used for the detailed design stage, when precise element geometry and attributes are required. LOD 200-250 – used in the conceptual and preliminary stages to save resources. All key parameters are specified: materials, compressive strength class, geometric dimensions, and data from previous inspections and repairs. For as-maintained models, LOD 350 can be used with an emphasis on the elements to be maintained.	Inclusion of attributes in the model for analytical calculations. Minimisation of detail at an early stage to save time and money. Gradual increase in LOD as the project develops.
Interoperability and data management	Support of export and import in IFC 4.3 format to ensure compatibility between different software products. Use of CDE (Common Data Environment) for centralised storage and management of models. Models should incorporate limit states, deformation effects, as well as hydraulic and environmental factors (flow velocity, flooding, ice drift).	Establishment of constant data exchange between the project and operational teams through CDE. Modelling of the impact of water flow on pylons to predict scour. Use of standard Psets for data transfer.
Reliability and security	Estimated service life of 50-100 years, covering the possibility of replacing individual elements (e.g., guardrails, expansion joints). Access for inspections (integration into the model of ladders, inspection platforms). Use of a colour coding system to indicate the status of elements: red – critical defect, yellow – warning, green – satisfactory condition.	Design of accessible points for maintenance. Automatic visualisation of the state of elements in a digital twin. Priority of repairs based on colour coding.
Environmental and life cycles	Integration of LCA to assess the environmental impact of materials (concrete, steel). Use of simplified functional units for small bridges, e.g. 1 m² deck. Environmental scenario modelling to assess long-term impacts and optimise materials.	Comparative analysis of material options based on LCA. Reduction of the carbon footprint by choosing more environmentally friendly materials. Preparation of reports for environmental certification.

Source: compiled by the author based on R.K. Raya & R. Gupta (2022)

The stages of creating BIM models of small bridges provide a full cycle, from data collection to integration with digital twins. For the rural regions of Ukraine, this can be used for rapid digitisation of bridges, centralised data storage, and increased efficiency in monitoring and maintenance. Therefore, the integration of BIM, DT and remote monitoring can streamline the process of assessing the technical condition of small bridges, reducing costs and increasing the safety of inspections. These observations correlate with the study by D.R. Polania *et al.* (2025), developing an integrated BIM methodology for bridge monitoring and assessment. The authors showed that combining data from different sources, from inspections and sensors to geospatial models, in a single digital environment can be used for high accuracy of assessments and efficient planning of repairs. They emphasised the flexibility of the methodology, which can be applied to large infrastructure assets as well as small bridges in local networks. The current results confirmed this conclusion, as the implementation of such integrated models in rural regions of Ukraine ensures that they work even with a limited set of attributes, gradually expanding the data model.

Safe remote access and inspection of bridges in the study by F. Luleci *et al.* (2022) were implemented by combining a monitoring system with virtual reality, which created a virtual reality (VR) environment for virtual inspections and provided safe access to complex or damaged areas of structures. The study demonstrated that this approach reduces risks to personnel and increases the detail of defect detection without physical contact with the object, and the results are in line with current research that also confirms the effectiveness of safe remote inspection methods, in particular for bridges in restricted areas or in war zones. The approach of

F. Luleci *et al.* can be effectively adapted to the Ukrainian realities, where the issue of inspection safety is becoming more relevant in this context. G. Hodge & J.M. Gattas (2026) highlighted the use of variable aerial photogrammetry data for semi-automated detection and measurement of geometric parameters of bridges. The study demonstrated that the use of LiDAR point cloud processing algorithms improves accuracy of identification of key structural elements and significantly reduces the amount of manual work during engineering surveys. The current study results also confirmed the value of this approach for rural regions of Ukraine, where the speed of data collection determines the possibility of conducting repairs in a short time. Moreover, such methods can be effectively integrated into the BIM environment, ensuring compatibility with international standards such as IFC 4.3.

H. Abdel-Maksoud (2024) proved the effectiveness of combining UAV-LiDAR and photogrammetry to improve accuracy, flexibility of access, and reduce inspection costs. Following the study, the use of UAVs for data collection significantly reduces the duration of inspections and reduces the impact of human error. This correlates with the current research findings: the use of drones with LiDAR and photogrammetry can be used for rapid initial inspections of bridges without stopping traffic and with minimal human intervention. In conclusion, this approach can be considered promising for the sustainable management of bridge infrastructure in conditions of limited resources. Thus, the introduction of integrated digital solutions in bridge monitoring and management optimises the life cycle of structures and reducing the risk of accidents. The combination of BIM, DT and remote inspection methods is a versatile and scalable tool for improving the efficiency of bridge maintenance in various operating conditions.

Regulatory and technical aspects and digital strategies for effective management of small bridges in Ukraine

In Ukraine, the implementation of BIM is regulated by Eurocode 1 (2003) and Eurocode 2 (2005), harmonised with the Guideline for the implementation… (2019) and ISO 19650-1:2018 (2018). The regulatory framework for the design of small bridges includes DBN V.2.3-26:2024 (2025) and BN01:4868-1755-9511-2275 (2025). The current policy of adapting standards is aimed to harmonise with European standards to improve compatibility with EU engineering practice. According to DBN V.2.3-26:2024 (2025), small bridges are regulated by separate requirements for loads, structural solutions and durability.

The main defects of small bridges in the rural network of Zhytomyr, Volyn, Cherkasy and Odesa regions of Ukraine include corrosion of steel elements (due to lack of proper protection in aggressive environments), deformation and wear of the pavement (cracks, damage to the protective layer, fatigue cracks). These problems are exacerbated by long-term operation, insufficient maintenance in remote areas and environmental influences (erosion, vibrations from transport). In reinforced concrete structures, there is a loss of stability of secondary elements, excessive plastic deformation and damage to drainage (Kirichenko, 2024). The analysis of specific regional examples of rehabilitation of small bridges in the rural road network of Ukraine was used to assess the characteristic design solutions, technical condition and typical problems of these facilities. In the Zhytomyr region, major repairs were conducted on the bridge over the Litky River at km 169+189 of the M-07 Kyiv-Kovel-Yagodin motorway (State Restoration Service of Ukraine, 2024b). This structure is a single-span reinforced concrete structure with a length of up to 25 metres and provides transport links to rural areas. The main problems with the structure were damage caused by military operations, in particular, deformation of the superstructure and corrosion of the reinforcement elements, which led to a reduction in its load-bearing capacity. In the Volyn region, a major repair of the bridge at km 35+085 of the M-19 Domaniv-Kovel-Chernivtsi-Terebleche motorway was conducted (State Restoration Service of Ukraine, 2024a). The bridge, which is 25 metres long, is a reinforced concrete beam structure that are substantial in connecting rural areas and ensuring interregional transport links. The main defects were worn and tear of the road surface, cracks in the concrete and a reduction in traffic capacity due to erosion of the soil foundations of the supports.

In the Cherkasy region, the 2024 infrastructure development programme envisages the rehabilitation of bridges on local roads in the rural network (Cherkasy Regional State Administration, 2023). Most of them are reinforced concrete structures up to 25 metres long, located mainly across small rivers. The main problem with these facilities is their emergency technical condition, caused by more than half a century of operation, corrosion damage and the destruction of individual elements under overload. In Odesa region, the Regional Development Strategy for 2021-2027 plans to reconstruct small bridges in rural areas (Odesa Regional State Administration, 2021). These are mainly slab or beam structures made of concrete or reinforced concrete up to 25 metres long. The main problems are soil erosion in the coastal zone, corrosion of steel elements, and cracks in the top layer of the road surface. Examples from the regions of Ukraine have shown that the problems of small bridges are common, ranging from corrosion damage and cracks in concrete to erosion of foundations and the effects of warfare, and their rehabilitation is integrated into the broader context of post-war reconstruction and digital transformation of infrastructure.

Existing technologies in bridge engineering cover a wide range of digital solutions, from information modelling and digital twins to artificial intelligence and mixed reality (Shen *et al.*, 2023). Their application aims to improve the accuracy of surveys, optimise the planning and life cycle management of bridge structures, reduce operating costs and ensure safety. Table 3 provides a comparative analysis of the implementation of key technologies, demonstrating their potential and limitations in bridge rehabilitation and maintenance.

Table 3. Characteristics and examples of implementation of innovative methods in bridge construction and operation

Technology/ Method	Advantages	Disadvantages	Implementation
BrIM with LCA/ LCC integration	Improved data integration for performance evaluation, reduced errors, time savings (up to 4.5 months of construction), better stakeholder collaboration, and data visualisation for monitoring.	Lack of standardisation for O&M, data compatibility issues, high upfront costs (70% of total cost), difficulties with data exchange for older bridges.	In Canada, a bridge reconstruction project was considered as part of the Construction 4.0 concept, where the BIM model of the bridge was integrated with LCA/LCC data to assess the carbon footprint, maintenance costs, and optimise design solutions. As a result, the construction period was reduced by approximately 4.5 months, and the choice of materials was optimised in terms of durability and sustainability.
BDT with BrIM, IoT, AI/ML integration	Improved visualisation, interoperability via IFC, automated damage monitoring, real-time analysis, and hybrid models for accuracy.	Lack of standardisation, interoperability issues, complexity of data processing, high hardware costs (laser scanning), and manual intervention for components.	In Portugal, a digital twin of a large transport bridge was introduced, integrating sensors and a BrIM model for automated defect detection and wear forecasting. The system provided timely detection of fatigue damage to components and reduced inspection costs by automating data collection and analysis.
DT with GIS and BIM integration	Real-time monitoring, optimisation of Operations and Maintenance (O&M) (drones for inspection), better visualisation of defects, graph algorithms for logistics, forecasting.	Limited extensibility of defect modelling (JavaScript Object Notation (JSON) instead of Industry Foundation Classes (IFC)), platform compatibility issues, and loss of detail in BIM-GIS integration.	In China, a digital twin project was implemented for the River Neath Swing Bridge, where drone data was integrated into a GIS-BIM platform to plan repairs, optimise traffic routes, and predict technical condition. The system was used for real-time traffic redirection and increased the efficiency of inspections.
BrIM framework for RC bridges	Improved visualisation of defects (3D models), automated report generation, centralised database for exchange, prioritisation of repairs through colour coding.	Limited for O&M (focus on design), complexity for inspectors, equipment costs (Unmanned Aerial Vehicle (UAV) with 3D scanners), narrow focus on RC bridges.	In Egypt, a BrIM model of a reinforced concrete bridge in Cairo was developed, which integrated survey, photo and laser scanning data. The model classified defects according to a colour-coded repair prioritisation scheme, which increased planning efficiency and reduced decision-making time.
A unified DT framework for bridges	Automated assessments, reduced inspection costs, data reuse, integration of UAVs and robots for monitoring.	The need for significant initial investment in the creation and maintenance of DT (data collection infrastructure, software systems, staff training), the complexity of processing large amounts of raw data, the lack of unified BrIM standards and incomplete source information.	In the US, the DT approach is used to analyse and prevent catastrophic failures, based on the experience of the I-35W bridge collapse in Minneapolis. The DT system was used for remote monitoring of the condition of structures and automatic assessment of the risk of failure, which could have prevented the tragedy if it had been used at the time.
BIM with MR (mixed reality)	Improved communication, accurate defect identification through augmented reality (AR), simplified inspection, data standardisation (IFC, BIM Collaboration Format (BCF)).	High upfront costs for equipment (UAVs), need for specialised knowledge, budgetary barriers for agencies, and dependence on BMS.	In Brazil, MR technology was used on the Coimbra I Viaduct by inspectors to visualise defects in the reinforced concrete structure in augmented reality, which significantly improved diagnostic accuracy and reduced the time required for inspections (no quantitative performance indicators available).
Immersive DT platform (IBDTP)	Automation of structural health monitoring (SHM), improved visualisation through AR, scalability, integration with IoT for monitoring.	High implementation costs and the need for skilled personnel; compatibility issues with different sensors and BIM standards; dependence on a stable internet connection; limited scalability with many objects.	In Poland, a digital model with IoT sensors was created for a concrete arch bridge, which provided real-time data on loads, deformations and damage to be obtained and visualised in an AR interface. This ensured accurate damage verification and accelerated repair decisions.
Deep learning for reconstructing geometry from drawings	Automation of 3D model creation from archived 2D drawings, fast digitalisation of old bridges, integration with BIM/openBIM (IFC), and reduction of field measurement costs.	The need for high-quality drawings, limited accuracy in the absence of some drawings, the need to adjust algorithms to local standards, and initial costs for developing a pipeline.	In Germany (Freiburg), deep learning was used to automatically reconstruct the 3D geometry of three bridges over the Dreisam River. The algorithm generated BIM models from PDF and CAD plans, which reduced the volume of field measurements by 65% and reduced the time required to prepare documentation by 40%.

Table 3, Continued

Technology/ Method	Advantages	Disadvantages	Implementation
LSTM with BIM for control	3D visualisation of defects, degradation prediction accuracy (95%), low error rate (0.15%).	The need for a large amount of historical data to train models; difficulty in setting up and integrating with existing BIM systems; high computational cost for long-term forecasts; risk of errors with incorrect or incomplete data.	In China, a condition prediction system has been developed for small concrete girder bridges on highways that can predict the wear rate of elements with an accuracy of 95%. This optimised repair schedules and reduced operating costs.
Data integration framework for RC bridges	Automation of BIM-FE data exchange, visualisation of results, resource optimisation, DT support.	Increased resources for detailed assessments, manual data exchange, need for expertise, and interoperability issues.	In the UK, Revit-Dynamo-Abaqus was used for the automated analysis of damaged reinforced concrete bridges. The system was used to quickly create a damage model and perform calculations to select the optimal repair strategy.

Source: compiled by the author

Innovative methods in bridge construction show significant potential for improving the accuracy of surveys, automating monitoring and optimising costs. The experience of the countries listed in Table 3 confirms the effectiveness of such technologies in reducing design and repair time, improving safety, and increasing the durability of bridges. For Ukraine's rural regions, the implementation of such solutions could become the basis for rapid digitalisation and more efficient use of limited resources. Based on international experience and Ukrainian realities, practical recommendations for the adaptation of BIM/BrIM technologies for small bridges in the rural road network have been developed. The presented areas include the determination of the minimum required data, the use of simplified models and open standards, the integration of digital solutions into the work of road services, as well as the harmonisation of national requirements with international standards (Table 4).

Table 4. Practical recommendations for the implementation of digital technologies in the design and operation of small bridges in Ukraine

Area	Description	Examples of implementation in Ukraine
Minimal dataset	Definition of the basic attribute composition for the bridge model: geometric parameters (length, width, height, span), materials (concrete, steel, wood), condition of elements (visual assessment, defects), operational characteristics (load capacity, date of last repair). Minimisation of data reduces the cost of collecting and processing information, which is especially relevant for rural bridges.	Use of IFC 4.3 Property Sets (Psets) with a limited set of properties for bridges in rural areas. Pilot bridge passports in the DREAM system with a minimum data structure for inventory. Minimal Information Data-Modelling (MID) approach using a low-cost monitoring system (~£370) for a short span bridge, providing a basic set of attributes for further integration into a BIM/openBIM environment.
Simplified models and standards	Use of the LOD 200300 levels of detail in the initial stages to quickly create models. IFC 4.3 format as the main format for data exchange, use of open libraries of typical bridge elements (spans, piers, guardrails), support for free viewers to increase accessibility.	Modelling of typical girder bridges in open viewers for regional road services; implementation of modular libraries in university curricula. Use of the openBIM (IFC 4.3) approach for modelling typical girder bridges, ensuring interoperability and integration with other engineering platforms.
Integration into the work of road services	Organisation of pilot projects using available technologies: UAVs for surveying, photogrammetry, and simplified 3D reconstructions. Involvement of construction students in training and practical work. Gradual incorporation of models into the maintenance planning system.	Pilot modelling of 1-2 bridges in each region using photogrammetry, cooperation with universities that use LSTM+BrIM for condition monitoring.
Adaptation of international standards	Development of unified BIM model templates for bridges in accordance with EU standards, integration into the DREAM platform. Marking of combat damage zones in the model (considering the requirements of recovery after military operations).	Development of IFC regional templates synchronised with DBN V.2.3-26:2024 (2025). Use of BEP/EIR to coordinate restoration projects in regions.

Source: compiled by the author

The integration of BIM/BrIM technologies into the design and operation of small bridges in Ukraine is justified for several key reasons. Firstly, small bridges form the basis of transport accessibility in rural areas, where the speed and cost of surveys are critical. The use of BIM/BrIM with minimal data sets can reduce the burden on local budgets while maintaining the required level of accuracy (O'Higgins *et al.*, 2023). Secondly, simplified models and open standards (IFC 4.3, openBIM) ensure interoperability and accessibility for regional road services,

which is substantial in a resource-limited environment. Thirdly, integration into the DREAM system and harmonisation with European standards create a single digital ecosystem for bridge inventory and rehabilitation, including battle damage marking. These technologies improve the efficiency of repair planning and ensure the long-term operation of facilities in the post-war environment. At the same time, Ukraine still faces significant challenges in restoring infrastructure after military destruction and the need to work with limited financial and technical resources, which necessitate adapted digital solutions.

The results of the study showed that the introduction of a minimal set of data in BIM models of bridges, only key geometric parameters, materials and basic operational characteristics, can significantly reduce the cost of collecting and processing information, which is relevant for rural bridges. This was correlated with the findings of Z. Sun *et al.* (2024), proving that even a limited set of attributes in digital twins can support efficient maintenance and repair forecasting that combines multi-source data and expert knowledge without losing the accuracy of the estimates. The study determined that this approach helps to optimise resource consumption and extends the service life of structures without increasing the budget. The current results confirmed this effect in the context of the Ukrainian reality, where access to bridges in rural areas is often limited and a rapid inventory is needed. The use of simplified models with a level of detail of LOD 200-300 and open libraries of standard elements in the pilot projects ensured quick model creation and the ability to integrate them into repair plans. This proved to be effective for regional road services working with a large number of small facilities and limited funding. This was confirmed by K. Clute (2023), who found that standardised information templates greatly simplified the exchange of data between contractors and customers and guaranteed long-term compatibility of models between different software platforms. The study showed that eliminating redundant elements in the early stages of design speeds up the approval of working documents and reduces transaction costs. The results of this study also showed that this approach can be used to scale modelling from single objects to entire regional bridge networks without significant modifications.

The results of the study demonstrated that the pilot implementation of BIM templates adapted to the IFC 4.3 standard, with the marking of combat damage zones, showed the possibility of effective integration of these solutions into the DREAM platform and regional management systems. This correlated with the results of E.E. Tita *et al.* (2023), demonstrating that the scalable Digital Twin-BIM architecture creates a single source of reliable information and ensures interoperability between all bridge management stakeholders. The study emphasised that the gradual increase in detail can avoid overloading the model and maintain its suitability for long-term use. This methodology can be successfully used in the context of a limited data set, typical for post-war reconstruction in Ukraine. DT bridges are evolving towards practical application and efficient management. The review by V. Mousavi *et al.* (2024) highlighted the current conceptual obstacles and proposed a multi-level framework for digital twins in bridge management, with the integration of decision support systems and data fusion technology. This complements the current findings that a sustainable and scalable DT-BIM architectural approach with the ability to dynamically evaluate and automate the interaction of life cycle elements is a key direction for the development of bridge digitalisation.

Thus, the implementation of the proposed areas of BIM/BrIM adaptation for small bridges in Ukraine will significantly optimise the inspection and repair planning processes, reducing the cost of data collection and processing. The use of standardised models and open formats will ensure interoperability between organisations and create a basis for scaling digital solutions to other transport infrastructure facilities, from culverts to overpasses. Additionally, it will improve the accuracy of engineering calculations, transparency of rehabilitation investments, and the introduction of long-term condition monitoring.

Conclusions

The results of the study of the structural features of small road bridges in the rural road network of Ukraine and the possibilities of digital technologies for their inspection showed that most of these structures have significant wear and tear due to long-term operation, insufficient maintenance and the impact of aggressive natural and man-made factors, including military operations. Traditional survey methods provide only local and fragmented data, while digital technologies (BIM/BrIM, laser scanning, photogrammetry, UAVs) ensure the creation of complex 3D models integrated into a single information environment, speeding up surveys, increasing the accuracy of technical condition assessment and optimising operating costs. Their use has proven effective in Canada, where construction time was reduced by about 4.5 months; in Germany, the volume of field measurements was reduced by 65% and the time for preparing documentation was reduced by 40%; in China, the accuracy of predicting the degradation of bridge elements reached 95% with an error of 0.15%; in the UK, the use of minimal sensors for short-span bridges limited monitoring costs to 370 GBP.

Several strategic measures were recommended to adapt digital solutions to the conditions of Ukraine, including reducing the amount of data to save resources, using models with a basic level of detail of LOD 200-300, introducing tools into the activities of road services, harmonising standards with European norms, and testing technologies through pilot projects in different regions. The systematic application of BIM/BrIM with open data exchange formats will ensure consistency between participants in the design and operational processes, create a basis for the expansion of digital solutions to other transport facilities, and increase investment transparency. The integration of digital twins and IoT technologies into

bridge monitoring will help to quickly detect damage and improve the safety of their operation. The use of digital technologies to analyse the life cycle of bridges will help select environmentally sustainable materials and reduce environmental impact.

Limitations of the study include the lack of a unified national methodology for collecting and processing data for small bridges, as well as the high cost of equipment, which can complicate implementation in remote regions. Further research should focus on creating national open libraries of typical bridge elements, developing low-cost sensor monitoring systems, and expanding DT integration with road infrastructure management systems in Ukraine.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Abdel-Maksoud, H. (2024). Combining UAV-LiDAR and UAV-photogrammetry for bridge assessment and infrastructure monitoring. *Arabian Journal of Geosciences*, 17(4), article number 144. doi: 10.1007/s12517-024-11897-5.

[2] Alsharif, M.A., Thermou, G., Ninic, J., & Tizani, W. (2025). Data integration framework for multi-level information modelling and numerical analysis of deteriorated RC bridges. *Advances in Engineering Software*, 202, article number 103860. doi: 10.1016/j.advengsoft.2024.103860.

[3] Bielova, A.I., Zhuravska, N.Y., & Kochedikova, A.Y. (2020). Promising directions for the development of BIM technologies in Ukraine on its way to European integration. In V. Onyshchenko, G. Mammadova, S. Sivitska & A. Gasimov (Eds.), *Proceedings of the 2nd international conference on building innovations* (pp. 533-544). Cham: Springer. doi: 10.1007/978-3-030-42939-3_53.

[4] BN01:4868-1755-9511-2275. (2025). *DBN V.2.3-22:2025 "Bridges and pipes. Basic design requirements"*. Retrieved from https://e-construction.gov.ua/laws_detail/3879650731606672546?doc_type=2.

[5] Cherkasy Regional State Administration. (2023). *Program of economic and social development of Cherkasy region for 2024*. Retrieved from https://surl.li/wxlbjj.

[6] Cherniavska, T., & Cherniavskyi, B. (2025). Digital reconstructor: Integration of digital twins for the reconstruction and remediation of war-affected territories in Ukraine. *UKLO Proceedings*, 1(1), 137-145. doi: 10.20544/AISC.1.1.25.P13.

[7] Clute, K. (2023). *Building Information Modeling (BIM) for bridges and structures – Phase II*. Retrieved from https://rip.trb.org/View/2265815.

[8] DBN V.2.3-26:2024. (2025). *Bridges and pipes. Design of steel structures*. Retrieved from https://dbn.co.ua/load/normativy/dbn/1-1-0-1003.

[9] Dvulit, Z., Maznyk, L., Maznyk, K., Brych, L., Dvulit, M.-M., Iwaszczuk, N., & Iwaszczuk, A. (2023). Using digital twin (DT) technology for workforce demand forecasting in the post-war reconstruction of Ukraine. In N. Shakhovska (Ed.), *Proceedings of the SmartIndustry 2025: 2nd international conference on smart automation & robotics for future industry* (pp. 199-212). Lviv: SmartIndustry.

[10] Eurocode 1: Actions on structures – Part 2: Traffic loads on bridges. (2003, November). Retrieved from https://www.phd.eng.br/wp-content/uploads/2015/12/en.1991.2.2003.pdf.

[11] Eurocode 2: Design of concrete structures – Part 2: Concrete bridges – Design and detailing rules. (2005, October). Retrieved from https://www.phd.eng.br/wp-content/uploads/2015/12/en.1992.2.2005.pdf.

[12] Faltin, B., Schönfelder, P., Gann, D., & König, M. (2024). Reconstructing as-built beam bridge geometry from construction drawings using deep learning-based symbol pose estimation. *Advanced Engineering Informatics*, 62, article number 102808. doi: 10.1016/j.aei.2024.102808.

[13] Fawad, M., Salamak, M., Chen, Q., Uscilowski, M., Koris, K., Jasinski, M., Lazinski, P., & Piotrowski, D. (2024). Development of immersive bridge digital twin platform to facilitate bridge damage assessment and asset model updates. *Computers in Industry*, 164, article number 104189. doi: 10.1016/j.compind.2024.104189.

[14] Gao, Y., Xiong, G., Hu, Z., Chai, C., & Li, H. (2024). Bridge digital twin for practical bridge operation and maintenance by integrating GIS and BIM. *Buildings*, 14(12), article number 3731. doi: 10.3390/buildings14123731.

[15] Guideline for the implementation of BIM Execution Plans (BEP) and Exchange Information Requirements (EIR) on European level based on EN ISO 19650-1 and -2. (2019, December). Retrieved from https://architecturaltechnology.com/static/4758f33d-1f0e-4cc4-852a1d5fd37a8f41/bep-eir-guidance-based-on-iso19650.pdf.

[16] Hagen, A., & Andersen, T.M. (2024). Asset management, condition monitoring and Digital Twins: Damage detection and virtual inspection on a reinforced concrete bridge. *Structure and Infrastructure Engineering*, 20(7-8), 1242-1273. doi: 10.1080/15732479.2024.2311911.

[17] Hodge, G., & Gattas, J.M. (2026). Semi-automated methods for detection and measurement of bridge assets from variable aerial LiDAR. *Australian Journal of Civil Engineering*, 24, 92-108. doi: 10.1080/14488353.2025.2533670.

[18] ISO 19650-1:2018. (2018). *Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) – information management using building information modelling. Part 1: Concepts and principles*. Retrieved from https://www.iso.org/standard/68078.html.

[19] Jrade, A., Jalaei, F., Zhang, J.J., Jalilzadeh Eirdmousa, S., & Jalaei, F. (2023). Potential integration of bridge information modeling and life cycle assessment/life cycle costing tools for infrastructure projects within Construction 4.0: A review. *Sustainability*, 15(20), article number 15049. doi: 10.3390/su152015049.

[20] Kirichenko, A. (2024). *Bridges on national roads: Examples of rehabilitation in the DREAM ecosystem*. Retrieved from https://iaa.org.ua/articles/bridges-on-national-roads-examples-of-rehabilitation-in-the-dream-ecosystem/.

[21] Kopiika, N., Karavias, A., Krassakis, P., Ye, Z., Ninic, J., Shakhovska, N., Argyroudis, S., & Mitoulis, S. (2025). Rapid post-disaster infrastructure damage characterisation using remote sensing and deep learning technologies: A tiered approach. *Automation in Construction*, 170, article number 105955. doi: 10.1016/j.autcon.2024.105955.

[22] Luleci, F., Li, L., Chi, J., Reiners, D., Cruz-Neira, C., & Catbas, F.N. (2022). Structural health monitoring of a foot bridge in virtual reality environment. *Procedia Structural Integrity*, 37, 65-72. doi: 10.1016/j.prostr.2022.01.060.

[23] Martins, A.C.P., Castellano, I.R., Júnior, K.M.L.D., De Carvalho, J.M.F., Bellon, F.G., De Oliveira, D.S., & Ribeiro, J.C.L. (2024). BIM-based mixed reality application for bridge inspection. *Automation in Construction*, 168, article number 105775. doi: 10.1016/j.autcon.2024.105775.

[24] Mousavi, V., Rashidi, M., Mohammadi, M., & Samali, B. (2024). Evolution of digital twin frameworks in bridge management: Review and future directions. *Remote Sensing*, 16(11), article number 1887. doi: 10.3390/rs16111887.

[25] Nhamage, I.A., Horas, C.S., Dang, N., Matos, J.A.C.E., & Martins, J.P. (2025). Strategies for maximising the value of digital twins for bridge management and structural monitoring: A systematic review. *Archives of Computational Methods in Engineering*, 32, 4555-4586. doi: 10.1007/s11831-025-10280-1.

[26] O'Higgins, C., Hester, D., McGetrick, P., Cross, E.J., Ao, W.K., & Brownjohn, J. (2023). Minimal information data-modelling (MID) and an easily implementable low-cost SHM system for use on a short-span bridge. *Sensors*, 23(14), article number 6328. doi: 10.3390/s23146328.

[27] Odesa Regional State Administration. (2021). *Strategy for the development of Odesa region for 2021-2027*. Retrieved from https://oda.od.gov.ua/ua/strategiya-rozvytku-odeskoyi-oblasti-na-2021-2027-roky.

[28] Poku-Agyemang, K.N., & Reiterer, A. (2023). 3D reconstruction from 2D plans exemplified by bridge structures. *Remote Sensing*, 15(3), article number 677. doi: 10.3390/rs15030677.

[29] Polania, D.R., Tondolo, F., Osello, A., Piras, M., Di Pietra, V., & Grasso, N. (2025). Bridges monitoring and assessment using an integrated BIM methodology. *Innovative Infrastructure Solutions*, 10(2), article number 59. doi: 10.1007/s41062-025-01864-8.

[30] Protsenko, O.M., Gerasimenko, V.V., & Sopov, V.P. (2024). Information model as a catalyst of transformations in the system of design and management in the construction industry of Ukraine. *Building Production*, 75, 9-16. doi: 10.36750/2524-2555.75.9-16.

[31] Raya, R.K., & Gupta, R. (2022). Application of BIM framework on rural infrastructure. *Asian Journal of Civil Engineering*, 23(2), 249-268. doi: 10.1007/s42107-022-00421-3.

[32] Salzano, A., Intignano, M., Mottola, C., Biancardo, S.A., Nicolella, M., & Dell'Acqua, G. (2023). Systematic literature review of open infrastructure BIM. *Buildings*, 13(7), article number 1593. doi: 10.3390/buildings13071593.

[33] Shen, C., Jiang, B., & Yue, L. (2023). LSTM combined with BIM technology in the management of small and medium-sized span highway concrete beam bridges. *Results in Engineering*, 20, article number 101539. doi: 10.1016/j.rineng.2023.101539.

[34] State Restoration Service of Ukraine. (2024a). *Report on the results of the analysis of current prices for in accordance with the procedure for material resources within the framework of the project "Overhaul of the bridge at km 354085 of the AB highway Domanov (to the city of Brest) – Kovel – Chernivtsi – Ter Terebleche (to the city of Bucharest), Volyn region"*. Retrieved from https://vl.restoration.gov.ua/diialnist/7728/71373/71375.pdf.

[35] State Restoration Service of Ukraine. (2024b). *Report on the results of the analysis of current prices for material resources within the framework of the project "Overhaul of the bridge over the Litka River at km 169+189 of the public highway of state importance M-07 Kyiv – Kovel – Yagodyn, Zhytomyr region"*. Retrieved from https://surl.li/lwlepo.

[36] Sun, Z., Liang, B., Liu, S., & Liu, Z. (2024). Data and knowledge-driven bridge digital twin modeling for smart operation and maintenance. *Applied Sciences*, 15(1), article number 231. doi: 10.3390/app15010231.

[37] Surianinov, M., Kirichenko, D., Chuchmai, O., & Stashenko, M. (2024). BIM technologies in Ukraine: State and development prospects. *Applied Mechanics and Materials*, 924, 173-179. doi: 10.4028/p-4tcdif.

[38] Tita, E.E., Watanabe, G., Shao, P., & Arii, K. (2023). Development and application of digital twin – BIM technology for bridge management. *Applied Sciences*, 13(13), article number 7435. doi: 10.3390/app13137435.

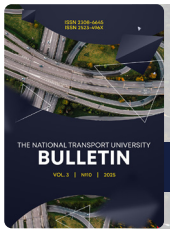
[39] Xenidis, Y. (2021). Building information modeling for bridge design and construction. In C. Pellegrino, F. Faleschini, M.A. Zanini, J.C. Matos, J.R. Casas & A. Strauss (Eds.), *Proceedings of the 1st conference of the European Association on Quality Control of Bridges and Structures (EUROSTRUCT 2021)* (pp. 777-784). Cham: Springer. doi: 10.1007/978-3-030-91877-4_88.

Інформаційне моделювання в аналізі стану малих мостових споруд у сільській дорожній мережі: виклики та рішення

Павло Стрілецький
Аспірант
Національний університет водного господарства та природокористування
33028, вул. Соборна, 11, м. Рівне, Україна
https://orcid.org/0000-0001-6533-0121

Анотація. Метою дослідження було визначення ефективних підходів до використання цифрових технологій для оцінки стану та планування відновлення невеликих транспортних переходів з урахуванням обмежених ресурсів та вимог сумісності даних. Методологія поєднувала порівняльний аналіз, створення Building Information Modelling, кейс-стаді регіональних прикладів та систематизацію міжнародного досвіду. Було встановлено, що цифрові методи забезпечують міліметрову точність вимірювань, скорочують час збору даних та дають змогу створювати детальні 3D-моделі, а також прогнозувати знос завдяки алгоритмам глибокого навчання. У Житомирській, Волинській, Черкаській та Одеській областях України були зафіксовані дефекти мостових споруд: у Житомирській – пошкодження від воєнних дій, у Волинській – тріщини в бетоні та ерозія ґрунтів, у Черкаській – наслідки тривалої експлуатації понад 50 років, а в Одеській – корозія сталевих елементів у поєднанні з агресивним прибережним середовищем. Підтверджено, що інтеграція даних у середовище Building Information Modelling Digital Twin підвищувала точність прогнозів до 95 % (у Китаї), а також фіксувалось скорочення часу та трудових витрат на 40-65 % при використанні алгоритмів deep learning у Німеччині. Застосування безпілотних літальних апаратів із Light Detection and Ranging та фотограмметрією дозволило обстежувати мости з мінімальним впливом на рух і людський фактор, що суттєво у віддалених чи небезпечних районах. На основі узагальнення міжнародного досвіду впровадження інноваційних методів у мостобудуванні було рекомендовано використання відкритих форматів і спрощених моделей, що сприяють зниженню витрат на обстеження та скороченню часу підготовки документації. Результати можуть бути використані дорожніми службами для планування ремонтів, управління життєвим циклом мостів та відновлення споруд в Україні з підвищеною прозорістю й меншим екологічним впливом

Ключові слова: цифрові двійники; відкриті формати; життєвий цикл; міжплатформна сумісність; прогнозування зносу; семантичне збагачення; автоматизований моніторинг



BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 30 | №2 | 2026
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X

Received: 11.02.2026. Revised: 03.06.2026. Accepted: 25.06.2026. Published: 06.07.2026.

UDC 629.331 DOI: 10.33744/2308-6645-2026-2-30-53-64

Break-even analysis of electric vehicles in business operations

Volodymyr Porfirenko*
PhD in Economics, Associate Professor
National Transport University
01010, 1 M. Omelianovych-Pavlenko Str., Kyiv, Ukraine
https://orcid.org/0000-0003-0329-6217

Anton Luhovtsov
Student
National Transport University
01010, 1 M. Omelianovych-Pavlenko Str., Kyiv, Ukraine
https://orcid.org/0009-0004-1342-706X

Abstract. The electrification of commercial transport is regarded as a promising approach to reducing operating costs and local emissions; however, the economic benefits of electric vehicles are not universal and depend on the conditions of use. The relevance of this study is driven by the need for businesses to have quantitative criteria for choosing between an electric commercial vehicle and a comparable fossil-fuel-powered alternative under different operating conditions and energy pricing structures. The aim of the study was to develop a calculation-based approach for determining the break-even annual mileage above which the use of an electric vehicle becomes economically viable, as well as the maximum acceptable purchase price of an electric vehicle below which its acquisition is economically justified. The research methods included a comparative analysis of the economic feasibility of alternative technologies; analysis of secondary data on prices, tariffs, and maintenance costs to establish model input parameters; economic and mathematical modelling based on total cost of ownership; analytical methods for deriving break-even formulas; scenario analysis of different electric vehicle charging options; and consideration of the time value of money through the application of a discount rate and an annuity present value factor. Within the framework of a model case study (10-year horizon, 5% discount rate), it was established that the break-even annual mileage of an electric van ranges from 34,529 to 200,932 km depending on the tariff and charging method, while at an annual mileage of 60,000 km, the maximum economically justified purchase price ranges from UAH 2.25 million to UAH 4.44 million. The article analyses the factors determining the feasibility of transitioning to electric vehicles, evaluates the impact of initial investments, operating costs, and existing support mechanisms on the overall economic viability of electric vehicle use in business activities, and proposes formulas for calculating both the break-even mileage of electric vehicles and the maximum initial purchase price below which their acquisition is economically advantageous for different types of commercial use. The practical value of the study lies in the possibility of applying the proposed formulas by transport and logistics companies and commercial fleet operators to support fleet renewal decisions based on the present value of ownership costs

Keywords: total cost of ownership; annual mileage; operating costs; threshold purchase price; internal combustion engines; economic viability

Introduction

The electrification of commercial transport in business operations requires a quantitative justification, as the higher purchase price of an electric vehicle is offset by lower operating costs only under certain conditions

Suggested Citation: Porfirenko, V., & Luhovtsov, A. (2026). Break-even analysis of electric vehicles in business operations. *Bulletin of the National Transport University*, 30(2), 53-64. doi: 10.33744/2308-6645-2026-2-30-53-64.

*Corresponding author (*porfirenko@gmail.com*)

Copyright © The Author(s). This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/)

regarding mileage, electricity tariffs, service life and assumptions regarding residual value. Additional uncertainty arises from differences in charging availability (own infrastructure, commercial stations), tariff fluctuations, and varying vehicle usage profiles in logistics and service business processes. Under such conditions, it is essential to provide a quantitative justification of the economic viability of electric transport compared to traditional solutions equipped with internal combustion engines.

Current studies on the transition to electrification show that the pace of implementation depends on infrastructure and energy constraints, as well as on government support and planning. H. Kostenko (2023) emphasises the need to align the development of electric transport with the capabilities of the power system. The impact of incentives and policy on the dynamics of the electric transport market in Ukraine and Europe is highlighted by S. Matusiak & E. Romaniuta (2025), whilst the broader context of electric mobility development in Ukraine and its institutional constraints are explored by O. Stetsiuk *et al.* (2024). Global trends and possible directions for Ukraine's integration into the electric vehicle ecosystem are systematised by E. Prushkivska *et al.* (2024), which reinforces the argument that the transition is a process of economic and technological significance.

International publications also consistently point to the multifactorial nature of electrification barriers and the need for comprehensive solutions. A. Pamidimukkala *et al.* (2023) empirically assess groups of barriers to the adoption of electric transport, highlighting financial and infrastructure factors, whilst L. Delina & L. Shi (2025) demonstrate in a comparative policy analysis that the success of the transition is determined by a combination of incentives, infrastructure and institutional capacity. Institutional constraints on scaling up infrastructure solutions for the freight sector are examined by A. Scherrer *et al.* (2026). Meanwhile, J. Dixon *et al.* (2023) emphasise that even in the presence of common strategies, the outcomes of the transition depend on the local context and the coordination of stakeholders' actions. Among the practical constraints of electric transport in commercial operation are range and charging time, which can affect the continuity of the transport process. In this context, V. Porfirenko & Y. Kudin (2024) justify the advantages of a modular approach to the sectional release and replacement of battery packs for international transport as a means of reducing "refuelling" time, whilst Y. Li *et al.* (2024) develop a standardised modular approach to battery replacement and charging as a means of enhancing the operational flexibility of electric transport.

Alongside technological and infrastructural factors, economic viability remains a key criterion for businesses; in academic literature, this is typically assessed in terms of the total cost of ownership. P. Romeral & E. Zancul (2025) summarise the critical factors that determine the total cost of ownership of electric vehicles and emphasise that conclusions depend on the composition of costs and the assumptions made regarding energy sources, service life and residual value. The literature also highlights that no universally accepted "single formula" for total cost of ownership has been established, as researchers differ in their definitions of cost components, including or excluding specific expenditure categories, applying different approaches to modelling residual value and service life, and using alternative methods to account for the time value of money. Additional variation arises from different energy price scenarios and charging regimes, which affect variable costs and consequently the overall assessment of economic viability. This is precisely why evaluating electric transport solely on the basis of purchase price is insufficient for business purposes, as the higher initial cost of an electric vehicle can be offset by lower costs for energy, maintenance and certain operational components throughout its useful life. At the same time, such compensation does not occur automatically, but depends on the intensity of the vehicle's use, access to cheaper charging, tariff stability, route structure and the duration of ownership. For commercial transport, annual mileage is of particular importance, as it is through the accumulation of mileage that savings in variable costs are generated, capable of offsetting the initial cost difference between an electric vehicle and its internal combustion engine counterpart. In this context, the total cost of ownership presented here serves not only as a tool for comparing alternatives but also as a methodological basis for determining the threshold conditions under which electric transport becomes economically viable for a business. A separate strand consists of publications describing break-even analysis as a practical way of interpreting the difference between higher initial investment and lower operating costs of electric transport. H. Hafsah *et al.* (2024) apply the break-even approach to compare electric and conventional vehicles in the Indonesian market and highlight the scenario-dependent nature of the threshold conditions in relation to mileage and cost structure.

The aim of the study was to develop a calculation approach based on the present value of total cost of ownership for determining the break-even annual mileage of an electric commercial vehicle and the threshold (maximum acceptable) purchase price at which cost parity is achieved with a comparable vehicle equipped with an internal combustion engine.

Materials and Methods

The article proposes analytical relationships for determining the break-even annual mileage of an electric commercial vehicle and the threshold maximum purchase price at which parity in the present value of ownership costs is achieved with a comparable vehicle equipped with an internal combustion engine. When the purchase price is below this threshold, an economic advantage of the electric vehicle is established according to the criterion of discounted ownership costs. To demonstrate the application of the proposed formulas, a model case study was developed using secondary data on market prices of vans, electricity tariffs under different charging regimes, energy

prices for conventional vehicles, as well as maintenance and related operating costs. The time frame for the preparation and execution of the analytical calculations covered the period from 1 April 2025 to 25 June 2025.

Operating conditions are described by the usage horizon T (years), the discount rate r, and the annual mileage L (km/year). Operating costs are divided into fixed annual costs F, which are independent of mileage, and variable costs per kilometre V, which depend on mileage. For electric vehicles, the value of is defined on a scenario basis according to the charging regime, enabling the impact of electricity tariffs on the threshold conditions of economic viability to be taken into account. The formulas were developed according to the principle of the classical break-even point, adapted for the comparison of the present value of total cost of ownership, PV(TCO). Unlike the conventional total cost of ownership (TCO), the present value of total cost of ownership, PV(TCO), incorporates the time value of money through the discounting of costs (Twin, 2025; APS Smart, 2025). To convert uniform annual costs into present value terms, the annuity present value factor was applied:

$$A(r,T) = \sum_{t=1}^{T} \frac{1}{(1+r)^t} = \frac{1-(1+r)^{-T}}{r}, \quad (1)$$

where A(*r,T*) – annuity discount factor; *r* – discount rate; *T* – valuation horizon (service life), in years.

The present total cost of ownership of a vehicle over the usage period T is determined using the well-known formula as the sum of the present capital component (taking into account the residual value), present fixed costs and present variable costs, proportional to the annual mileage:

$$PV(TCO) = P \times (1 - *(1+r)^{-T}) + \\ + (F \times A(r, T)) + (V \times L \times A(r, T)), \quad (2)$$

where PV (TCO) – the present value of total cost of ownership of the alternative under consideration (either the electric vehicle or the comparable internal combustion engine vehicle); P is the initial cost (purchase price of a new or used vehicle); F represents fixed costs; V represents variable costs (commonly referred to in the literature as operating costs), calculated per kilometre travelled; L is the average (or expected) annual mileage; *T* is the vehicle service life; *α* is the residual value (the expected resale value or percentage of the vehicle's remaining value at the end of its service life); A(*r,T*) is the annuity present value factor; and *r* is the discount rate.

The subsequent threshold formulas were derived by analytically solving this equality with respect to either annual mileage or the purchase price of the electric vehicle while holding the operating parameters constant. The break-even annual mileage, TB_m в was determined from the condition of parity between the present value of ownership costs of the electric vehicle, $PV(TCO)_{EV}$, and those of its comparable internal combustion engine counterpart, $PV(TCO)_{ICE}$, by solving the equation with respect to L:

$$TB_m = \frac{P_{EV}(1-\alpha_{EV}*(1+r)^{-T}) - P_{ICE}(1-\alpha_{ICE}*(1+r)^{-T}) + (F_{EV}-F_{ICE})*A(r,T)}{(V_{ICE}-V_{EV}) * A(r,T)}, \quad (3)$$

where P_{EV} – the initial purchase cost of the electric vehicle; P_{ICE} – the initial purchase cost of the vehicle equipped with an internal combustion engine (ICE); V_{EV} – the annual variable costs associated with the electric vehicle; V_{ICE} – the annual variable costs associated with the internal combustion engine vehicle; $_{EV}$ – the residual value of the electric vehicle, expressed as a percentage,%; $_{ICE}$ – the residual value of the internal combustion engine vehicle, expressed as a percentage, %; F_{EV} – the annual fixed costs of the electric vehicle; F_{ICE} – the annual fixed costs of the internal combustion engine vehicle; r is the discount rate; T is the service life, in years; and A(*r, T*) is the annuity present value factor.

The threshold (maximum economically acceptable) purchase price of an electric vehicle P_{EV}^{max} is determined from the same condition of parity, $PV(TCO_{EV}) = PV(TCO_{ICE})$, but by solving the equation with respect to P_{EV} for a given annual mileage L:

$$P_{EV}^{max} = \frac{P_{ICE}*(1 - {}_{ICE}(1+r)^{-T}) + (F_{ICE}-F_{EV})*A(r,T) + (V_{ICE}-V_{EV})*L*A(r,T)}{1-\alpha_{EV}(1+r)^{-T}}, \quad (4)$$

where P_{EV} – the initial purchase cost of the electric vehicle; P_{ICE} – the initial purchase cost of the vehicle equipped with an internal combustion engine (ICE); V_{EV} – the annual variable costs associated with the electric vehicle; V_{ICE} – the annual variable costs associated with the internal combustion engine vehicle; $_{EV}$ – the residual value of the electric vehicle, expressed as a percentage; $_{ICE}$ – the residual value of the internal combustion engine vehicle, expressed as a percentage; F_{EV} – the annual fixed costs of the electric vehicle; F_{ICE} – the annual fixed costs of the internal combustion engine vehicle; *r* – cthe discount rate; *T* – the service life, in years; and A(*r, T*) – the annuity present value factor.

When assessing the threshold purchase price of a used electric vehicle, it is advisable to account for additional one-off costs, C_{one}, associated with uncertainty regarding the vehicle's technical condition. These may include diagnostic inspections, costs of bringing the vehicle into operational condition, unplanned repairs, and potential expenditures related to high-voltage system components. In the model example, calculations were performed for new vans, as the cost parameters for such vehicles are more clearly defined and the risk of unforeseen one-off expenditures is partly mitigated by warranty coverage and predictable maintenance schedules. Owing to the absence of reliable statistical data concerning the probability and

magnitude of such one-off costs for used electric vans, the demonstration case assumes $C_{one} = 0$ UAH. Verification of the break-even condition was carried out for the threshold prices P_{EV}^{max} by substituting the calculated values into the formula for the present value of ownership costs, PV(TCO)$_{EV}$ according to Equation (2), and by checking compliance with the parity condition between the present value of ownership costs of the electric vehicle, PV(TCO)$_{EV}$ and those of its comparable internal combustion engine counterpart, PV(TCO)$_{ICE}$ subject to rounding precision. The calculations were implemented in a spreadsheet environment, ensuring reproducibility of the results when input parameters are modified.

Results and Discussion

Over recent years, electric vehicles have gained substantial popularity and have become more accessible to consumers. Various automotive manufacturers now offer a wide range of electric vehicle models with differing technical specifications, price ranges, and propulsion systems (E-AUTO, 2023; Encyclopedia, n.d.). To define the scope of the study correctly, it is useful to distinguish between different types of electrified vehicles according to their energy source and propulsion principle. This classification serves as a reference framework for selecting the modelling object and interpreting the results. The different categories of electric vehicles are presented in Figure 1.

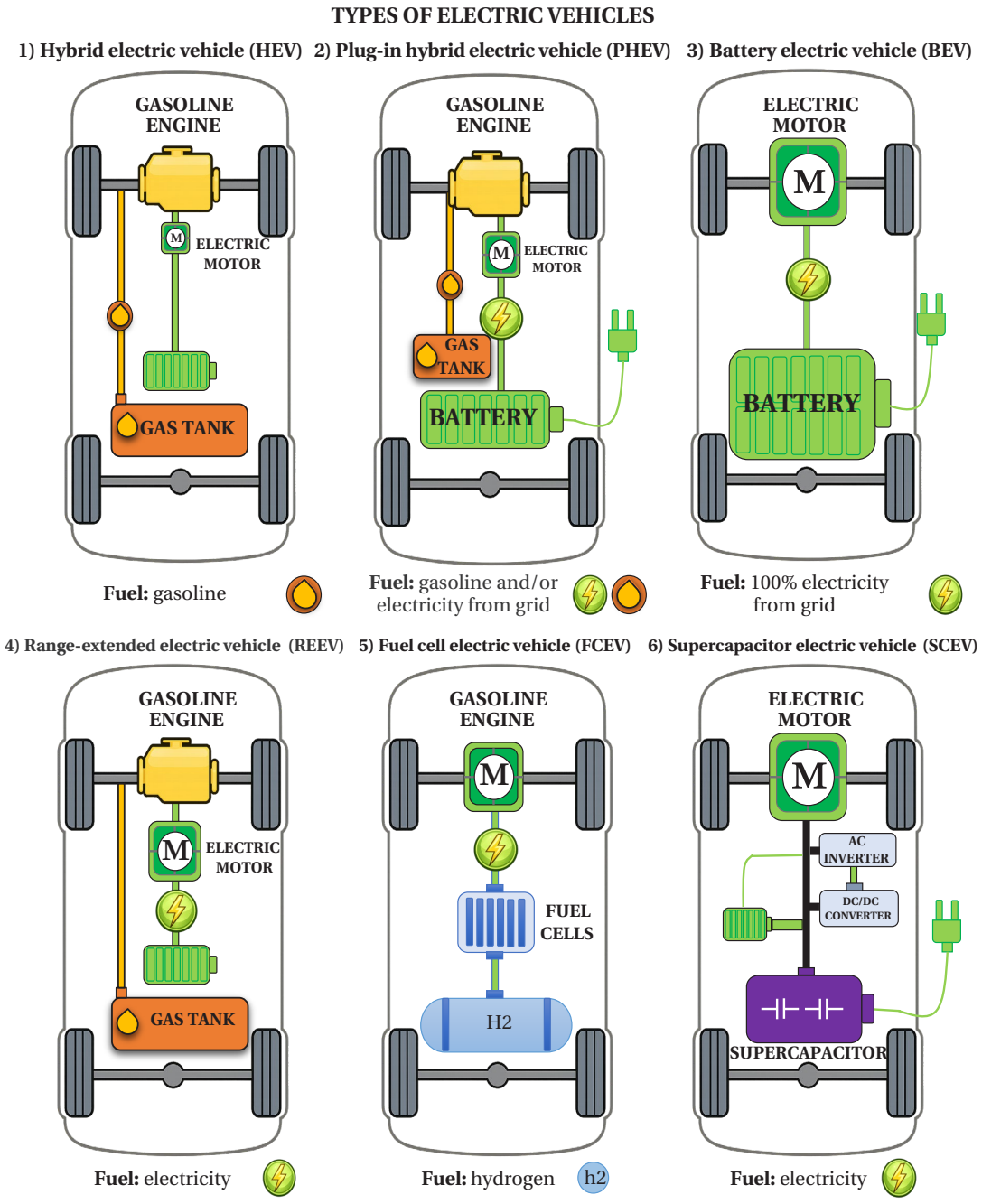


Figure 1. Block diagram of electric vehicle types

Source: compiled by the authors based on E-AUTO (2023), Encyclopedia (n.d.)

An HEV (Hybrid Electric Vehicle) is a type of hybrid system that uses a combination of an internal combustion engine and an electric motor; the battery is charged whilst the internal combustion engine is running via a generator, which reduces fuel consumption compared to vehicles powered solely by an internal combustion engine. A PHEV (Plug-in Hybrid Electric Vehicle) differs in that the battery can be charged from an external power supply, which increases the proportion of driving in electric mode and extends the range provided that charging is available. A BEV (Battery Electric Vehicle) is a fully electric vehicle without an internal combustion engine and operates exclusively on battery power; its range is determined by the battery capacity and operating conditions. A REEV (Range-Extended Electric Vehicle) combines an electric drive with an internal combustion engine (ICE) range extender: the electric motor plays the primary role, whilst the ICE is used to generate electricity when the battery charge level drops. FCEV (Fuel Cell Electric Vehicle) uses an electric motor, with electricity generated by fuel cells through the conversion of hydrogen and oxygen. SCEV (Supercapacitor Electric Vehicle) stores energy in supercapacitors, which ensures very fast charging and high cycle durability; however, the low energy density of supercapacitors compared to lithium-ion batteries limits the range and makes them suitable primarily for routes with frequent stops and the possibility of regular recharging (Encyclopedia, n.d.).

In commercial operation, electric transport is viewed as an alternative to traditional vehicles given the potential to reduce energy costs and certain service costs; however, the economic viability of the transition is not universal. The main factor of uncertainty is the higher initial investment in vehicles and charging infrastructure. Additional constraints include range and charging time, which affect the continuity of the transport process and the operating schedule: for commercial electric trucks, a typical range is between 150 and 350 km, depending on battery capacity and operating conditions, whilst charging can take approximately 4-12 hours with slow alternating current (AC) charging or around 30-60 minutes with fast direct current (DC) charging. Alongside these limitations, decisions regarding electrification are influenced by regulatory and economic factors, as set out in Regulation (EU) No. 851… (2023) of the European Parliament and of the Council. For businesses, potential differences in energy and maintenance costs are of additional significance, as is the reduction in local emissions during operation, which may be relevant for urban logistics and service operations in areas with environmental restrictions.

In many countries, financial incentives for the transition to electric transport are created through a combination of subsidies, tax breaks and reductions in certain fees associated with vehicle registration and operation. Additional incentives may include discounted or free access to parking in cities and tiered charging tariffs. The practice of supporting electric mobility in Ukraine has included exemption from value-added tax on imports, the absence of excise duty and import duties, as well as reduced registration fees; at the local level, specific measures were implemented regarding parking and the use of public transport lanes, whilst programmes supporting investment in electric transport and charging infrastructure were available for legal entities. The validity of certain preferential schemes was time-limited and specified as remaining in force until 2026. Despite the technological advantages and incentives, the economic viability of investments in the electrification of the commercial vehicle fleet requires a quantitative financial justification, taking into account the operational profile, electricity tariffs and assumptions regarding residual value. In the context of further analysis, such justification is provided by the calculation of the break-even annual mileage and the marginal purchase price of an electric vehicle, at which the levelised cost of ownership is equal to that of a comparable vehicle equipped with an internal combustion engine.

The break-even annual mileage of an electric commercial vehicle is determined by formula (3) as the threshold value of annual mileage at which the discounted ownership costs of the electric van equal the discounted ownership costs of a diesel counterpart. The threshold value is interpreted as the limit beyond which the electric van provides a lower total cost of ownership compared to a vehicle equipped with an internal combustion engine, under fixed assumptions regarding service life, discount rate, cost structure and residual value. To demonstrate the application of this approach, a model scenario comparing a diesel van and a similar electric van is considered. The FORD TRANSIT VAN 350 TREND is taken as the base vehicle with an internal combustion engine, and the FORD E-TRANSIT VAN 350 as the electric alternative; the gross vehicle weight is 3,500 kg. The initial prices and technical parameters are based on the manufacturer's price lists, and the numerical cost values are used as illustrative input parameters for the model example, fixed as of 2025. The annual mileage in the model example is assumed to be 60,000 km, the useful life is 10 years, and the discount rate is 5%. There is no single discount rate for all enterprises in Ukraine, as it is determined individually for a specific project, asset or company. In the model example, a discount rate of 5% is adopted as a standard assumption for discounting costs over time; in practical calculations, the discount rate may vary depending on the cost of capital and the level of risk.

To standardise subsequent calculations, costs are divided into the capital (investment) component of ownership, fixed annual costs and variable costs per 1 km of mileage. Capital costs include the initial cost of the vehicle and an assumption regarding the residual value at the end of the operating period. In the model parameters, the initial cost of a diesel van is UAH 1,935,734, and that of an electric van is UAH 3,316,615 (Ford, n.d.). Different residual value rates have been applied, as the depreciation patterns for internal combustion engine vans and electric vans differ. For the diesel van, the residual value ratio is set at 35% as a generalised assumption based on a review

of market offers for similar vehicles with a service life of around 10 years on the AUTO.RIA website. For electric vans of a comparable class, long-term resale statistics are less certain, and the risk of additional depreciation is linked to the potential degradation of the battery after prolonged use; in view of this, a more conservative residual value of 25% of the original price has been adopted in the model example.

Annual fixed costs include insurance and the driver's salary. In this example, the average cost of van insurance, based on quotes from leading insurance companies in Kyiv, is assumed to be UAH 10,486.17 per year. The driver's salary is set at UAH 360,000 per year; the total annual fixed costs amount to UAH 370,486.17. The uniformity of these fixed costs in the model example is due to the fact that the driver's salary does not depend on the type of power plant, whilst insurance costs for vans are determined primarily by the vehicle category and insurance terms, rather than the type of fuel. Variable costs per 1 km are calculated as the sum of energy costs, maintenance costs and associated operating costs, which depend on mileage. According to the FORD TRANSIT VAN 350 TREND price list, diesel fuel consumption can be up to 10.5 litres per 100 km; for the purposes of this calculation, 11 litres per 100 km has been used as a conservative estimate. For the FORD E-TRANSIT VAN 350, the price list specifies an electricity consumption range of 26-38 kWh per 100 km; in the model example, an average value of 32 kWh per 100 km has been adopted. The price of diesel fuel is set at UAH 58.99 per litre as the baseline parameter for the model example, based on pricing from a large network of petrol stations. The cost of electricity is differentiated depending on the charging scenario: for the on-site charging scenario, two indicative tariffs of 6 and UAH 10 per 1 kWh are used, and for commercial charging infrastructure – UAH 13.50 per 1 kWh for the slow alternating current (AC) charging scenario and UAH 18.50/kWh for the fast direct current (DC) charging scenario (Ford, n.d..).

Maintenance costs are calculated based on scheduled intervals. For a diesel van, the indicative cost of a single service is set at UAH 8,000 for a 15,000 km interval. For the electric van, maintenance costs are assumed to be 50% lower, or UAH 4,000 for the same interval, in line with general findings regarding lower maintenance costs for electric transport compared to fossil fuel-powered transport (Heisel, 2020; Denzadnem, 2025). Variable costs also include washing costs of UAH 300 per 1,000 km of mileage and tyre costs: the average cost of a set of tyres is assumed to be UAH 21,494 for an expected mileage of 60,000 km. A separate environmental tax on CO_2 emissions for a diesel van is not itemised in the company's costs, as the relevant fiscal components are factored into the final fuel price. Based on these assumptions, the aggregated values for capital costs, variable costs per 1 km and fixed costs are presented in Table 1 and used to further determine the threshold mileage for the charging scenarios.

Table 1. Data used for the break-even model calculation

Cost category	Diesel van (ICE)	Typical electric van (EV)
Initial purchase cost (P)	UAH 1,935,734	UAH 3,316,615
Residual value (α)	UAH 677,506.90 (35%)	UAH 829,153.75 (25%)
Service life (T)	10 years	10 years
***Annual fixed costs (annual insurance, annual driver salary) (F)**	UAH 10,486.17 + UAH 360,000 = **UAH 370,486.17**	UAH 10,486.17 + UAH 360,000 = **UAH 370,486.17**
Variable costs per kilometre (V):		
Fuel/electricity	UAH 6.49/km (11 L/100 km × UAH 59/L)	UAH 1.92/km (32 kWh/100 km × UAH 6/kWh) UAH 3.20/km (32 kWh/100 km × UAH 10/kWh) UAH 4.32/km (32 kWh/100 km × UAH 13.50/kWh) UAH 5.92/km (32 kWh/100 km × UAH 18.50/kWh)
Maintenance and repairs	UAH 0.53/km	UAH 0.27/km
Other costs (washing, tyres)	UAH 0.30/km UAH 0.36/km	UAH 0.30/km UAH 0.36/km
Total variable costs per kilometre	**UAH 7.68/km**	**UAH 2.85/km (UAH 6/kWh)** **UAH 4.13/km (UAH 10/kWh)** **UAH 5.25/km (AC charging)** **UAH 6.85/km (DC charging)**

Source: compiled by the authors

The parameters presented in Table 1 were used to determine the break-even annual mileage threshold for an electric van using the approach proposed in this study. The calculations were performed using a scenario-based framework, as the charging tariff represents the principal source of uncertainty affecting the electric van and directly influences its variable costs per kilometre travelled. Given fixed assumptions regarding service life, discount rate, initial purchase prices, and residual value percentages, only the energy component of the electric van's variable costs changes across scenarios. For the diesel van, the assumptions relating to fuel price and fuel consumption remain unchanged. The results confirm that an increase in the charging tariff reduces the difference

between the variable costs of the electric van and its diesel counterpart. Under the scenario of charging at the company at a tariff of UAH 6/kWh, the variable costs of the electric van amount to UAH 2.85/km, whereas for the diesel van they amount to UAH 7.68/km; under the scenario of charging at the company premises at a rate of UAH 10/kWh, the variable costs of the electric van rise to UAH 4.13/km. The switch to commercial charging rates further increases the variable costs of the electric van to 5.25 UAH/km under the scenario of charging at a slow charging station (AC) and to UAH 6.85/km when charging at a fast charging station (DC), which brings the electric van's cost profile closer to that of its diesel counterpart and increases the break-even mileage required to offset the higher initial cost of electric transport under the model's assumptions.

The resulting break-even annual mileage thresholds demonstrate a pronounced dependence on the charging tariff. Under the scenario of charging at company premises at UAH 6/kWh, the break-even annual mileage is 34,529 km per year. Under the scenario of charging at company premises at UAH 10/kWh, the threshold increases to 46,979 km per year, reflecting the reduction in savings from lower variable costs. For commercial charging modes, the break-even points increase significantly: 68,631 km/year for the slow charging station (AC) scenario and 200,932 km/year for the fast charging station (DC) scenario. This trend is explained by the fact that, at high charging tariffs, the difference in variable costs between an electric van and a diesel van becomes insufficient to offset the capital component of ownership within the scope of practically typical operating modes for a commercial van. The practical interpretation of the results is that achieving economic parity based on the criterion of levelised cost of ownership requires a combination of sufficient usage intensity and an affordable charging tariff. Under the given parameters of the model example, lower corporate charging tariffs significantly reduce the threshold mileage, whilst commercial charging infrastructure tariffs shift the threshold value into the high annual mileage range. A graphical representation of the obtained threshold values is shown in Figure 2.

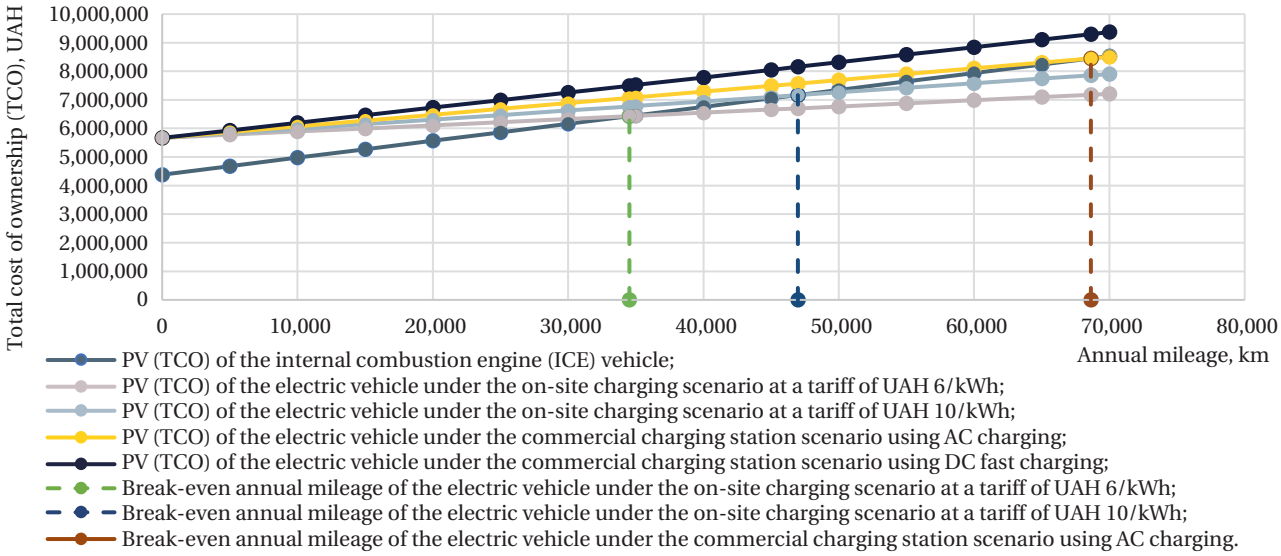


Figure 2. Break-even range graph for an electric vehicle

Source: compiled by the authors

The break-even annual mileage chart provides a visual representation of the threshold at which the use of an electric van becomes economically viable compared with a diesel equivalent under different charging scenarios. Its interpretation is based on identifying the mileage threshold beyond which the lower variable operating costs of the electric vehicle offset its higher initial purchase cost. The results indicate that the economic performance of the electric van is highly dependent on both the charging tariff and the intensity of vehicle utilisation. As electricity prices increase, the break-even mileage also rises, reducing the economic attractiveness of electric vehicles for businesses with relatively low annual mileage. Determining the threshold, or maximum acceptable, purchase price (initial cost) of an electric van involves identifying the acquisition price at which the present value of total ownership costs of the electric van, for a given service life and expected annual mileage, reaches parity with the corresponding value for a diesel equivalent. When the purchase price falls below this threshold, the electric van gains an economic advantage according to the criterion of discounted ownership costs, taking residual value into account. The calculations were performed using the approach presented in Equation (4), applying the same assumptions regarding service life, discount rate, capital cost component, annual fixed costs, and variable costs per kilometre as those used in the previous model example. The only unknown variable is the initial purchase price of the electric van, which is determined as the threshold value. The input parameters used in the analysis are summarised in Table 2.

Table 2. Data used for calculating the maximum initial purchase price of an electric vehicle below which its purchase is economically advantageous

Cost category	Diesel van	Typical electric van
Initial purchase cost (P)	UAH 1,935,734	Maximum purchase price to be determined
Residual value (α)	UAH 677,506.90 (35%)	Residual value of the electric vehicle: 25%
Service life (T)	10 years	10 years
Annual fixed costs (insurance, annual driver's salary) (F)	UAH 10,486.17 + UAH 360,000 = **UAH 370,486.17**	UAH 10,486.17 + UAH 360,000 = **UAH 370,486.17**
Variable costs per kilometre (V):		
Fuel/electricity	UAH 6.49/km (11 L/100 km × UAH 59/L)	UAH 1.92/km (32 kWh/100 km × UAH 6/kWh) UAH 3.20/km 32 kWh/100 km × UAH 10/kWh) UAH 4.32/km (32 kWh/100 km × UAH 13.50/kWh) UAH 5.92/km (32 kWh/100 km × UAH 18.50/kWh)
Maintenance and repairs	UAH 0.53/km	UAH 0.27/km
Other costs (washing, tyres)	UAH 0.30/km UAH 0.36/km	UAH 0.30/km UAH 0.36/km
Total variable costs per kilometre	**UAH 7.68/km (based on a fuel consumption rate of 11 L/100 km)**	**UAH 2.85/km (based on electricity consumption of 32 kWh/100 km and charging at the indicative minimum commercial tariff)** **UAH 4.13/km (based on electricity consumption of 32 kWh/100 km and charging at the maximum commercial tariff)** **UAH 5.25/km (based on electricity consumption of 32 kWh/100 km and charging at a commercial charging station using AC charging)** **UAH 6.85/km (based on electricity consumption of 32 kWh/100 km and charging at a commercial charging station using DC fast charging)**

Source: compiled by the authors

The results obtained demonstrate that the threshold purchase price of an electric van is scenario-dependent and determined primarily by the charging tariff, which directly influences the variable cost per kilometre travelled. Assuming an expected annual mileage of 60,000 km and all other parameters of the model example remaining unchanged, the maximum initial purchase price of the electric van amounts to UAH 4,438,825.82 under the scenario of charging at company premises at a tariff of UAH 6/kWh and UAH 3,738,277.62 under the scenario of charging at company premises at a tariff of UAH 10/kWh. For commercial charging scenarios, the threshold values decrease to UAH 3,125,297.94 when using alternating current (AC) charging at a tariff of UAH 13.50/kWh and to UAH 2,249,612.70 when using direct current (DC) fast charging at a tariff of UAH 18.50/kWh. The decline in the threshold purchase price as charging tariffs increase is explained by the reduction in the difference between the variable costs of the electric van and those of the diesel equivalent. As a result, achieving parity in discounted ownership costs requires a lower permissible initial purchase price for the electric van.

Comparing these threshold values with the dealer price of the FORD E-TRANSIT VAN 350 used in the model example allows the practical viability of the purchase decision to be assessed. Under the scenarios of charging at company premises at tariffs of UAH 6/kWh and UAH 10/kWh, the actual purchase price of the electric van remains below the corresponding threshold values, indicating that the investment is economically justified according to the criterion of discounted ownership costs. Under the commercial charging scenarios (AC and DC), however, the actual purchase price exceeds the threshold values, indicating that the electric van does not provide an economic advantage within the assumptions adopted in the model. The validity of the calculated threshold values is confirmed through a parity verification procedure. Substituting the calculated threshold purchase price into the expression for the present value of total cost of ownership of the electric van yields equality between the discounted ownership costs of the electric van and those of the diesel equivalent, subject only to rounding differences. The present value of total cost of ownership for both the electric van and the comparable internal combustion engine vehicle amounts to UAH 7,938,774.99. A graphical representation of the relationship between the threshold purchase price and annual mileage under the different charging scenarios is presented in Figure 3.

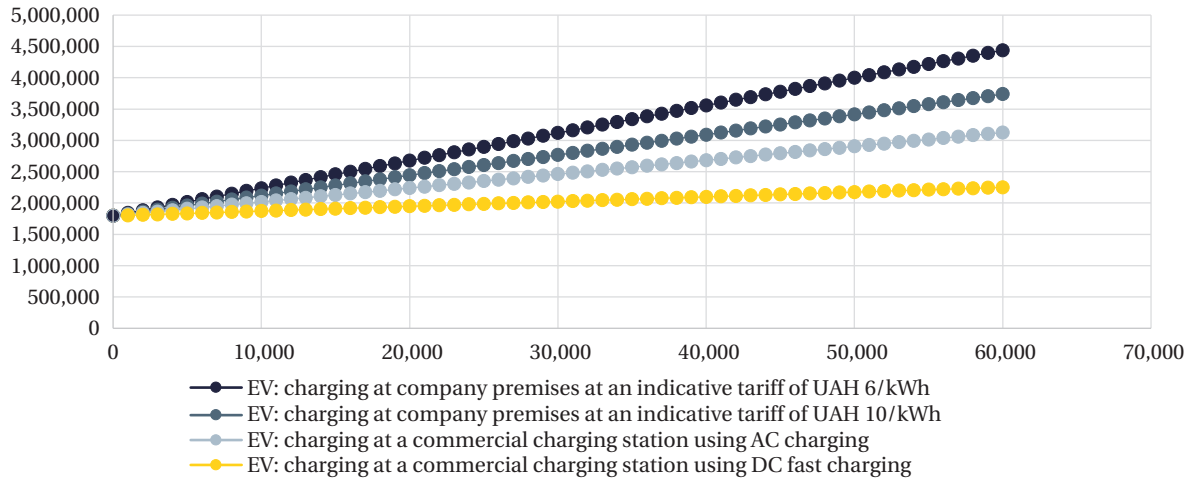


Figure 3. Maximum initial purchase price of a new electric vehicle below which its purchase is economically advantageous

Source: compiled by the authors

Thus, the relationship shown in Figure 3 between the marginal (maximum permissible) purchase price of an electric van and annual mileage reflects the threshold conditions for parity in terms of the levelised cost of ownership compared to an equivalent model equipped with an internal combustion engine, under various charging scenarios. As annual mileage increases, the acceptable purchase price of an electric vehicle rises, as savings on variable costs are realised to a greater extent, whilst an increase in the charging tariff reduces the acceptable price due to rising operating costs. The practical application of the resulting diagram lies in a quick feasibility check: if the actual market price of an electric van is lower than the corresponding curve for a given mileage and charging scenario, then economic parity or the advantage of electric transport is achieved based on the criterion of the discounted total cost of ownership.

A considerable number of studies have been devoted to this topic; for instance, E. Figenbaum's (2022) study focuses on a retrospective assessment of the total cost of ownership of battery electric vehicles using Norway as a case study. The study shows that conclusions regarding the economic viability of electric transport depend significantly on market conditions and incentive policies, as it is the combination of initial investment, operating costs and tax incentive mechanisms that determines the final level of ownership costs. In this context, electric vehicles may prove competitive; however, the outcome is scenario-dependent and requires consideration of local parameters. In the public transport segment, H. Sistig *et al.* (2025) point out that the electrification of bus fleets is linked not only to costs but also to operational parameters, including the need for charging capacity.

K. Shepurov (2025) investigated various methods of charging batteries and their impact on the feasibility of using electric buses, demonstrating that the choice of charging strategies for electric buses and the location of charging infrastructure influence operational organisation and cost components. The study by C. Gil Ribeiro & S. Silveira (2024) aims to assess the impact of financial incentives on the total cost of ownership of electric light commercial vehicles in EU countries. The study emphasises that support mechanisms can significantly alter the cost parity between electric and conventional vehicles by reducing the investment component, and that the effect of incentives varies across different countries and commercial usage segments. The study's conclusions confirm that assessments of the economic viability of fleet electrification must take into account institutional conditions, cost structures and operating profiles.

The study by J. Bauer *et al.* (2025) analyses how energy prices affect the total cost of ownership of battery electric vehicles. The results of the study emphasise that the energy component of operating costs is the key source of variability in conclusions regarding subsidies and charging profiles, and that different charging profiles and electricity pricing regimes can alter the comparative attractiveness of electric transport. This conclusion is consistent with the threshold values obtained by the authors in a model example, where the charging tariff influences the break-even mileage and the maximum acceptable purchase price. P. Miązek & L. Zhang (2025) compared the total cost of ownership of electric and conventional lorries in the Polish context. The study emphasises that for the freight segment, the critical factors are operating intensity, infrastructure conditions and cost structure, and that conclusions regarding the viability of electric lorries depend on a combination of capital investment and variable costs. Consequently, the economic viability of freight transport electrification is evident only under certain mileage and energy supply conditions, which correlates with the concept of threshold criteria used in this article. The study by M. Woody *et al.* (2024) aims to compare the total cost of ownership of

electric and petrol-powered vehicles in various US cities. The study shows that even with the same vehicle technology, the final economic assessment varies depending on the local environment, in particular the structure of tariffs, energy prices and operating conditions. The study by L.-I. Dulău (2024), conducted using Romania as a case study, also demonstrates that TCO assessment results are sensitive to the set of initial assumptions and the usage profile. Taken together, these publications confirm that a numerical conclusion regarding the cost-effectiveness of electric transport should be interpreted not as universal, but as a result for a specific set of conditions.

Unlike the cited works, in which total cost of ownership is mostly used to compare alternatives in specific markets or under given scenarios, this article focuses on developing an applied analytical toolkit for operational decisions. The proposed approach allows break-even to be determined in two complementary ways: via the minimum annual mileage threshold and via the maximum permissible purchase price of an electric vehicle, at which the present value of ownership costs is equal to that of an internal combustion engine equivalent. This formulation establishes a decision-making algorithm for commercial use: under specified operating conditions and tariffs, it is possible to determine threshold values that distinguish the zone of economic advantage for electric transport from the zone in which traditional transport remains the more economically justified option.

Conclusions

Electric vehicles are not always economically advantageous in business operations, as their viability is determined not only by environmental benefits but primarily by the cost structure and operating conditions. Decisions regarding the replacement of commercial vehicle fleets with electric vehicles or comparable internal combustion engine (ICE) vehicles are highly context-dependent and influenced by annual mileage, energy and charging tariffs, maintenance and servicing costs, service life, assumptions concerning residual value, and the presence or absence of financial incentives. This article proposes an analytical approach based on the concept of total cost of ownership (TCO) and the break-even principle, enabling the economic feasibility of transitioning to electric transport to be formalised. The study presents formulas for calculating the break-even annual mileage of an electric vehicle, above which its use becomes economically preferable to an ICE alternative, as well as a formula for determining the maximum initial purchase price of an electric vehicle below which its acquisition is economically justified. These formulas provide business owners with clear and practical decision-making criteria. Such an approach makes it possible not only to determine whether an electric vehicle is economically advantageous but also to identify the threshold values of key operating parameters at which it enters the zone of economic superiority. The proposed formulas and the economic calculations based upon them confirm the hypothesis that there are specific conditions under which the operation of electric vehicles can be profitable and that these conditions should be met to ensure economic viability.

Within the model example (10-year horizon, 5% discount rate), the threshold indicators vary significantly depending on the charging tariff. The break-even annual mileage amounts to 34,529 km per year under the scenario of charging the electric van at company premises at UAH 6/kWh and 46,979 km per year under the scenario of charging at UAH 10/kWh. For commercial charging, however, the thresholds increase to 68,631 km per year when using AC charging (UAH 13.50/kWh) and to 200,932 km per year when relying exclusively on DC fast charging (UAH 18.50/kWh). For an annual mileage of 60,000 km, the maximum initial purchase price of an electric van that ensures parity in discounted ownership costs with a diesel equivalent amounts to UAH 4,438,825.82; UAH 3,738,277.62; UAH 3,125,297.94; and UAH 2,249,612.70, respectively, for the charging scenarios considered. The corresponding PV(TCO) value at the parity point equals UAH 7,938,774.99. These calculations reflect only the economic dimension of the transition to electric transport and do not account for the positive environmental and social benefits associated with the adoption of electric vehicles. If national or municipal authorities seek to promote a cleaner and safer environment, financial resources should be allocated to support this objective through subsidies and substantial incentives that reduce the financial burden of purchasing and operating electric vehicles.

In conclusion, the proposed set of formulas and the procedure for their application can serve as a universal decision-support tool for business owners. Using their own operational data, firms can perform tailored calculations, compare alternative technologies (electric vehicles versus ICE vehicles), and justify fleet renewal decisions according to their specific business circumstances. Further research into the application and operation of electric vehicles should focus on improving the profitability and economic viability of their commercial use, as well as increasing the distance that electric vehicles can travel between charges, reducing battery charging time and cost, and creating the conditions and capabilities necessary for the use of electric vehicles in international and intercity transport. This may be achieved through the implementation of a modular principle based on standardised and interchangeable battery packs, the rapid and cost-effective replacement of which would allow operators to avoid the lengthy charging process currently associated with electric vehicles.

Acknowledgements

None.

Funding

The study received no funding.

Conflict of Interest

None.

References

[1] APS Smart. (2025). *When price is not the main thing: How to calculate costs like a pro using TCO*. Retrieved from https://www.aps-smart.com/koli-tsina-ne-golovne-yak-rahuvati-po-doroslomu-za-dopomogoyu-tco.

[2] Bauer, J., Letmathe, P., & Woeste, R. (2025). Total cost of ownership for battery electric vehicles: The role of energy prices. *Applied Energy*, 389, article number 125764. doi: 10.1016/j.apenergy.2025.125764.

[3] Delina, L.L., & Shi, L. (2025). Sustainable mobility transitions in developing states: A comparison of Southeast Asia's electric mobility policies and aspirations. *Sustainable Futures*, 9, article number 100751. doi: 10.1016/j.sftr.2025.100751.

[4] Denzadnem. (2025). *Is it profitable to buy an electric car in 2025? A detailed breakdown*. Retrieved from https://denzadnem.com.ua/blogy/korysni-porady/199652.

[5] Dixon, J., Zhou, Z., Phommachanh, S., Kythavone, S., Inthavongsa, P., & Hirmer, S.A. (2023). Plugging into green growth: Towards e-mobility and renewable energy integration in Lao PDR. *Energy Strategy Reviews*, 48, article number 101099. doi: 10.1016/j.esr.2023.101099.

[6] Dulău, L.-I. (2024). Study of the total ownership cost of electric vehicles in Romania. *World Electric Vehicle Journal*, 15(12), article number 569. doi: 10.3390/wevj15120569.

[7] E-AUTO. (2023). *Types of electric vehicles (BEV, HEV, PHEV, FCEV)*. Retrieved from https://e-auto.in.ua/vidi-elektromobiliv-bev-hev-phev-fcev/.

[8] Encyclopedia. (n.d.). *Capa vehicle*. Retrieved from https://encyclopedia.pub/entry/37079.

[9] Figenbaum, E. (2022). Retrospective total cost of ownership analysis of battery electric vehicles in Norway. *Transportation Research Part D: Transport and Environment*, 105, article number 103246. doi: 10.1016/j.trd.2022.103246.

[10] Ford. (n.d.). Retrieved from https://ford.ua/.

[11] Gil Ribeiro, C., & Silveira, S. (2024). The impact of financial incentives on the total cost of ownership of electric light commercial vehicles in EU countries. *Transportation Research Part A: Policy and Practice*, 179, article number 103936. doi: 10.1016/j.tra.2023.103936.

[12] Hafsah, H., Dianti, D.V., Priandana, E.R., Chandrasa, G.T., Rianjani, D.A., & Aryono, N.A. (2024). Break-even analysis of battery electric vehicles and internal combustion engine vehicles in the Indonesian market. *Evergreen*, 11(3), 2415-2426. doi: 10.5109/7236884.

[13] Heisel, R. (2020). *Consumer reports study finds electric vehicle maintenance costs are 50% less than gas-powered cars*. Retrieved from https://surl.li/cyodxd.

[14] Kostenko, H. (2023). Situation analysis of electric transport development prospects and its integration into Ukraine's power system. *Energy: Economics, Technology, Ecology*, 1, 117-124. doi: 10.20535/1813-5420.1.2023.276185.

[15] Li, Y., Zhu, F., Li, L., & Ouyang, M. (2024). Electrifying heavy-duty truck through battery swapping. *Joule*, 8(6), 1556-1561. doi: 10.1016/j.joule.2024.04.008.

[16] Matusiak, S.K., & Romaniuta, E.E. (2025). Impact of government incentives on the BEV market in Europe and a forecast for Ukraine after 2026. *Kyiv Economic Scientific Journal*, 9, 196-200. doi: 10.32782/2786-765X/2025-9-26.

[17] Miązek, P., & Zhang, L.L. (2025). Analysis of the total cost of ownership of electric and combustion engine trucks used in Poland. *European Research Studies Journal*, 28(3), 1280-1289. doi: 10.35808/ersj/4226.

[18] Pamidimukkala, A., Kermanshachi, S., Rosenberger, J.M., & Hladik, G. (2023). Evaluation of barriers to electric vehicle adoption: A study of technological, environmental, financial, and infrastructure factors. *Transportation Research Interdisciplinary Perspectives*, 22, article number 100962. doi: 10.1016/j.trip.2023.100962.

[19] Porfirenko, V.I., & Kudin, Y.R. (2024). International transportation by electric vehicles: Advantages of using the modular principle of sectional release and battery replacement. *Automobile Roads and Road Construction*, 116(1), 294-313. doi: 10.33744/0365-8171-2024-116.1-294-313.

[20] Prushkivska, E.V., Prushkivsky, V.G., Maksymenko, I.Y., & Prushkivska, V.V. (2024). Global electric vehicle market and prospects for Ukraine's contribution to its development. *Academy Review*, 1(60), 258-271. doi: 10.32342/2074-5354-2024-1-60-19.

[21] Regulation of the European Parliament and of the Council of the European Union No. 851 "As Regards Strengthening the CO_2 Emission Performance Standards for New Passenger Cars and New Light Commercial Vehicles in Line with the Union's Increased Climate Ambition". (2023, April). Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32023R0851.

[22] Romeral, P.A. de A.F., & Zancul, E. (2025). Total cost of ownership of electric vehicles: A synthesis of critical factors. *The Journal of Engineering*, 2025(1), article number e70113. doi: 10.1049/tje2.70113.

[23] Scherrer, A., Lockwood, M., Burghard, U., & Rogge, K.S. (2026). Institutional barriers to dynamic truck charging: Why electric road systems struggle in Europe. *Transportation Research Part D: Transport and Environment*, 153, article number 105154. doi: 10.1016/j.trd.2025.105154.

[24] Shepurov, K.O. (2025). Features of charging infrastructure placement and electric bus charging strategies. *Bulletin of Kharkiv National Automobile and Highway University*, 110, 167-174. doi: 10.30977/BUL.2219-5548.2025.110.0.167.

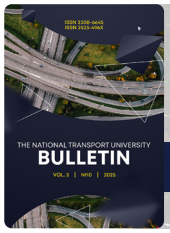
[25] Sistig, H.M., Sinhuber, P., Rogge, M., & Sauer, D.U. (2025). Evaluating costs and operations of public bus fleet electrification. *Npj Sustainable Mobility and Transport*, 2, article number 15. doi: 10.1038/s44333-025-00030-y.
[26] Stetsiuk, O., Lozynskyi, R., Skliarska, O., & Labinska, H. (2024). Electromobility in Ukraine: Development realities, European context, and the impact of martial law. *Scientific Innovations and Advanced Technologies*, 9(37), 771-795. doi: 10.52058/2786-5274-2024-9(37)-770-795.
[27] Twin, A. (2025). *Total cost of ownership: How it's calculated with example*. Retrieved from https://www.investopedia.com/terms/t/totalcostofownership.asp.
[28] Woody, M., Adderly, S.A., Bohra, R., & Keoleian, G.A. (2024). Electric and gasoline vehicle total cost of ownership across US cities. *Journal of Industrial Ecology*, 28(2), 194-215. doi: 10.1111/jiec.13463.

Дослідження точки беззбитковості електромобілів у бізнес-процесах підприємницької діяльності

Володимир Порфіренко
Кандидат економічних наук, доцент
Національний транспортний університет
01010, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
https://orcid.org/0000-0003-0329-6217
Антон Луговцов
Студент
Національний транспортний університет
01010, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
https://orcid.org/0009-0004-1342-706X

Анотація. Електрифікація комерційного транспорту розглядається як перспективний напрям зниження експлуатаційних витрат і локальних викидів, однак економічна вигода електротранспорту не є універсальною та залежить від умов використання. Актуальність дослідження зумовлена потребою підприємств мати кількісні критерії вибору між електричним комерційним транспортним засобом і аналогом на викопному паливі за різних режимів експлуатації та тарифів енергопостачання. Мета роботи полягала у формуванні розрахункового підходу для визначення беззбиткового річного пробігу, понад який використання електротранспорту стає економічно доцільним, а також граничної, максимально допустимої ціни придбання електричного транспортного засобу, нижче якої його придбання є економічно виправданим. Методи дослідження включали порівняльний аналіз економічної доцільності альтернатив; аналіз вторинних даних щодо цін, тарифів і витрат на обслуговування для формування вхідних параметрів моделі; економіко-математичне моделювання на основі сукупної вартості володіння; аналітичний метод для виведення формул беззбитковості; сценарний аналіз різних варіантів заряджання електромобіля; врахування часової вартості грошей через дисконтну ставку та коефіцієнт приведення ануїтету. У межах модельного прикладу (горизонт 10 років, ставка дисконту 5 %) встановлено, що беззбитковий річний пробіг електрофургона коливається від 34 529 до 200 932 км залежно від тарифу та способу заряджання, а за пробігу 60 000 км/рік гранична економічно доцільна ціна його придбання становить від 2,25 до 4,44 млн грн. У статті проведено аналіз факторів, що визначають доцільність переходу на електромобілі, оцінено вплив початкових інвестицій, операційних витрат та існуючих механізмів підтримки на загальну економічну доцільність використання електромобілів у підприємницькій діяльності. А також запропоновано формули для розрахунку беззбиткового пробігу електромобілів та максимальної первісної вартості електромобілів нижче котрої їх купувати вигідно для різних видів комерційного використання. Практична цінність роботи полягає в можливості застосування запропонованих формул підприємствами транспортно-логістичного сектору та власниками комерційних автопарків для обґрунтування рішень щодо оновлення парку на основі приведених витрат володіння

Ключові слова: сукупна вартість володіння; річний пробіг; експлуатаційні витрати; порогова ціна придбання; двигуни внутрішнього згоряння; економічна доцільність



BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 30 | №2 | 2026
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X

Received: 08.02.2026. Revised: 25.05.2026. Accepted: 25.06.2026. Published: 06.07.2026.

UDC 656.13:656.078:658.7 DOI: 10.33744/2308-6645-2026-2-30-65-72

Mechanism for balancing freight flows between international road border crossing points under conditions of uneven border infrastructure utilisation

Yelyzaveta Danileiko*
Postgraduate Student
National Transport University
01010, 1 M. Omelianovych-Pavlenko Str., Kyiv, Ukraine
https://orcid.org/0009-0005-0399-5976

Abstract. The structural transformation of international transport flows after 2022 resulted in a disproportionate distribution of transport demand across Ukraine's international road border crossing points (IRBCPs), leading to congestion at certain crossing points and prolonged queues. The aim of this article was to substantiate a mechanism for balancing freight flows between international road border crossing points in order to improve the efficiency of international freight transport under conditions of uneven utilisation of border infrastructure. The methodological framework of the study was based on queueing theory (a multi-channel M/G/s system with the Allen-Cunneen approximation), combined with scenario analysis and normalised multi-criteria assessment methods. To ensure the reproducibility of the results, a separate methodological section was included to justify the procedure for determining all key model parameters (λ, μ, s, c_a, c_s). The article investigated the problem of uneven utilisation of Ukraine's international road border crossing points under conditions of the structural transformation of international transport flows. It has been established that changes in the geography of foreign trade routes have led to an imbalance in the utilisation of border infrastructure, resulting in the systematic overloading of certain border crossing points. An adaptive mechanism for balancing freight flows between IRBCPs based on an integral efficiency criterion has been developed. A dedicated methodology section has been introduced to justify the procedure for obtaining the model parameters. The results of the scenario modelling confirmed the effectiveness of the proposed approach, reducing the utilisation factor (ρ) of the Krakovets-Korczowa IRBCP from 1.05 to 0.63-0.74 and decreasing the average queue waiting time (W_q) from more than 72 hours to 2.3-7.2 hours. The proposed mechanism enables the prompt redistribution of freight flows between IRBCPs without requiring capital investment in border infrastructure, thereby significantly reducing the economic losses incurred by freight carriers as a result of prolonged delays at the border

Keywords: transport and technological process; M/G/s; queueing theory; logistics; e-Queue; digitalisation

Introduction

Following 2022, Ukraine's international freight transport system underwent a substantial transformation driven by changes in the structure of foreign trade flows, the reorientation of logistics routes, and a sharp increase in the utilisation of international road border crossing points (IRBCPs). According to The State Border Guard Service (2024) and Solidarity Lanes: Latest Figures (2025a), restrictions on the capacity of maritime and rail transport corridors resulted in a significant proportion of export and import freight being redirected to road transport, leading to a systematic increase in traffic intensity at Ukraine's western border crossings. According to Solidarity Lanes: Latest Figures (2025b), the Polish corridor experienced the highest level of demand, accounting for approximately 48%

Suggested Citation: Danileiko, Ye. (2026). Mechanism for balancing freight flows between international road border crossing points under conditions of uneven border infrastructure utilisation. *Bulletin of the National Transport University*, 30(2), 65-72. doi: 10.33744/2308-6645-2026-2-30-65-72.

*Corresponding author (*lizadanil@gmail.com*)

Copyright © The Author(s). This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/)

of Ukraine's international road freight transport in 2025. This asymmetry in freight flows resulted in the persistent overloading of several IRBCPs, particularly Krakovets-Korczowa, Rava-Ruska-Hrebenne, and Yahodyn-Dorohusk, while the Hungarian and Slovak corridors retained substantial spare capacity. During peak periods, the average waiting time for vehicles at certain IRBCPs exceeds 60-72 hours, with maximum waiting times surpassing 240 hours (Solidarity Lanes: Latest Figures, 2025b). As noted by the European Commission (2025) and K. Prytula *et al.* (2022), conventional approaches to alleviating congestion at IRBCPs, such as reconstructing border infrastructure or increasing the number of service channels, require considerable capital investment and long implementation periods of five to ten years. Consequently, the development of a freight flow balancing mechanism between IRBCPs using digital decision-support systems has become particularly relevant.

Numerous contemporary studies have examined the operation of international transport and technological systems and the management of transport flows under conditions of congested border infrastructure. In particular, the studies by M. Golnar & B. Beškovnik (2022), and B. Stewart *et al.* (2023), explored the application of queueing theory and multi-criteria decision-making methods to evaluate the performance of border crossing points. A.K. Jain *et al.* (2023) analysed approaches to optimising multimodal transport networks under conditions of stochastic demand, the digital transformation of supply chains, inter-organisational integration of information systems, enhancing the resilience of transport and logistics networks to external disruptions, developing intermodal freight transport between Ukraine and Poland, forecasting waiting times at border crossings using machine learning techniques, and modelling and optimising border service systems using a simulation-based multi-criteria decision analysis approach. D. Ivanov & A. Dolgui (2021) introduced the concept of the ripple effect, explaining how congestion at a single IRBCP propagates disruption throughout the entire transport corridor. The freight flow balancing mechanism proposed in this study effectively implements the principle of structural resilience through route diversification, consistent with the recommendations of these authors. Its distinguishing feature lies in adapting this concept to the specific characteristics of border logistics, where traffic redistribution is constrained by the fixed geographical distribution of IRBCPs and customs regulations. The study by I. Jacyna-Gołda *et al.* (2024) confirmed that the development of intermodal transport routes between Ukraine and Poland is essential for reducing the utilisation of road border crossing points. The integration of a border logistics hub proposed in the present study represents a specific organisational and technological mechanism for implementing this approach, complementing the strategic recommendations of that research with an operational decision-making framework.

Nevertheless, the majority of existing studies focus primarily on the local optimisation of individual transport nodes without comprehensively addressing the asymmetry of international freight flows between border corridors. Adaptive freight flow balancing between alternative IRBCPs, taking into account an integral efficiency criterion for the transport and technological process, remains insufficiently investigated, thereby highlighting the relevance of the present research. The aim of this study was to develop a mechanism for balancing freight flows between international road border crossing points under conditions of uneven utilisation of border infrastructure in order to improve the efficiency of the transport and technological process of international freight transport. To achieve this aim, the following objectives were defined: (1) to analyse the current operation of Ukraine's IRBCPs under conditions of structural asymmetry in transport flows; (2) to formalise and parameterise a mathematical model of an IRBCP as a multi-channel M/G/s queueing system, including the procedure for obtaining the required input data; and (3) to develop and validate an adaptive freight flow balancing mechanism between IRBCPs using an integral efficiency criterion for the transport and technological process.

Materials and Methods

The study was conducted as an applied modelling investigation of transport and logistics systems. The methodological framework was based on queueing theory, specifically the theory of multi-channel M/G/s systems and the Allen-Cunneen approximation for estimating the average waiting time. In addition, scenario analysis and normalised multi-criteria assessment methods were employed to evaluate alternative transport routes. The object of the study was the operational system of Ukraine's international road border crossing points. The subject of the study was an adaptive mechanism for balancing freight flows between IRBCPs under conditions of uneven utilisation of border infrastructure. The empirical basis comprised data provided by the Ministry for Development of Communities and Territories of Ukraine (n.d.) on traffic intensity at IRBCPs during 2024-2025, together with analytical materials published by the United Nations Economic Commission for Europe (2025). Data sources were selected according to the following criteria: (a) timeliness, covering the period 2024-2025; (b) reliability, including only official governmental and scientific sources; and (c) relevance, with direct applicability to IRBCPs located on the Ukrainian-Polish and Ukrainian-Hungarian border corridors.

The vehicle arrival rate (λ) was determined as the average number of freight vehicles per hour during peak operating hours (07:00-19:00) based on data from the State Border Guard Service of Ukraine for 2024-2025; for the Krakovets-Korczowa IRBCP, $\lambda = 22.6$ vehicles/h. The service rate (μ) was calculated as the reciprocal of the average service time per vehicle, taking into account customs and border control procedures; the baseline value was $\mu = 2.15$ vehicles/h/channel. The number of service channels ($s = 10$) corresponded to the number of operational inspection lanes at the IRBCP during the study period. The coefficients of variation for the arrival process (c_a)

and service time (c_s) were determined from statistical data describing the variability of inter-arrival intervals and service times. IRBCPs were classified according to threshold values of the utilisation factor (ρ): $\rho > 1$ indicated an overloaded operating regime (donor IRBCP); $0.85 \le \rho \le 1$ indicated a critically loaded regime; and $\rho < 0.85$ indicated a stable operating regime with reserve service capacity (recipient IRBCP). The critical threshold value of $\rho_{crit} = 0.85$ was selected to preserve sufficient spare capacity for compensating stochastic fluctuations in the arrival rate. The average waiting time for vehicles in the M/G/s system was estimated using the following relationship (Allen-Cunneen approximation):

$$W_q \approx [\rho^s / (s!(1-\rho))] \cdot [(c_a^2 + c_s^2)/2] \cdot (1/\mu), \quad (1)$$

where W_q – the average vehicle waiting time in the queue; ρ – the system utilisation factor; c_a – the coefficient of variation of the inter-arrival times; c_s – the coefficient of variation of the service times; s – the number of service channels; μ – the service rate of a single channel.

System utilisation factor:

$$\rho = \lambda / (s \cdot \mu), \quad (2)$$

where, for $\rho < 1$, the system operates under stable conditions. As $\rho \to 1$ a nonlinear increase in W_q is observed, whereas for $\rho \le 1$ the system enters an overloaded regime characterised by unlimited queue growth.

Results and Discussion

The operation of IRBCPs was modelled as a multi-channel M/G/s queueing system. Based on the analysis of materials published by the Ministry for Development of Communities and Territories of Ukraine (n.d.) concerning the operation of international transport corridors, it was established that the Polish corridor experienced the most critical level of utilisation during 2024-2025. At the Krakovets-Korczowa IRBCP, the system utilisation factor reached a value corresponding to an overloaded operating regime:

$$\rho_{\text{Krakovets}} = \frac{22{,}6}{10 \cdot 2.15} \approx 1.05.$$

Figure 1 illustrates the relationship between W_q and ρ for an M/G/s system with parameters $c_a = 1.0$ and $c_s = 0.6$.

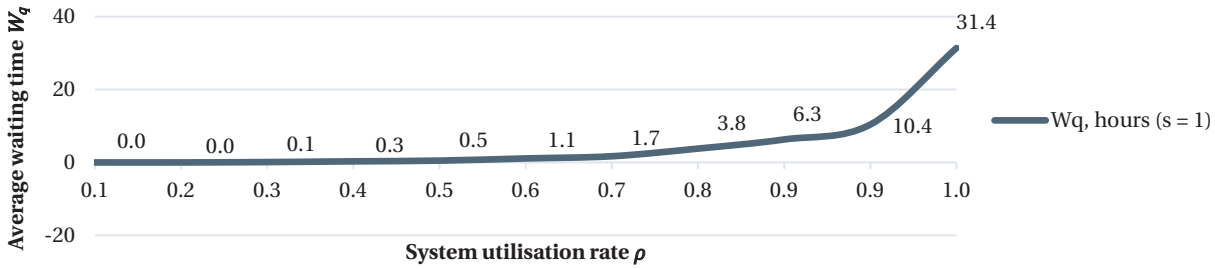


Figure 1. Relationship between the average waiting time for vehicles and the system utilisation factor M/G/s
Source: compiled by the author

Analysis of Figure 1 demonstrates the nonlinear nature of this relationship. Within the range $\rho < 0.7$, the average waiting time does not exceed 2 hours and increases gradually. In the interval $0.7 \le \rho < 0.9$, queue accumulation accelerates significantly, while as $\rho \to 1$ W_q tends towards infinity. The practical region of stable system operation corresponds to $\rho \le 0.85$, which justifies selecting this value as the threshold for activating the freight flow balancing mechanism. Practical evidence supporting this theoretical relationship is provided by the operation of the e-Queue system. At most IRBCPs, digital slot allocation reduced W_q by 24-70% through a reduction in service time variability (c_s) (Ministry for Development of Communities and Territories of Ukraine, 2025). However, no substantial improvement was observed at the Krakovets-Korczowa IRBCP. When $\rho < 1$, even a considerable reduction in service time variability cannot stabilise the system because the arrival rate exceeds the total service capacity. This finding is consistent with the conclusions of I. Badi *et al.* (2026), who argued that the digitalisation of border procedures is a necessary but insufficient condition for resolving congestion problems. Within the framework of this study, an adaptive mechanism for balancing freight flows between IRBCPs is proposed. A continuous monitoring system records the current values of λ, μ, and s and calculates the utilisation factor (ρ) for each IRBCP in real time. When the critical threshold $\rho_{crit} = 0.85$ is reached or when $\rho > 1$, the decision-support module initiates the balancing procedure by assessing the available capacity of recipient IRBCPs and generating a recommendation to redirect part of the freight traffic. The criterion for initiating freight flow balancing is:

$$\rho \ge \rho_{crit} = 0.85.$$

Figure 2 shows a structural diagram of the proposed mechanism.

The proposed framework comprises four functional modules: a monitoring module (collecting real-time data on λ, μ, and ρ from all IRBCPs), an analysis module (classifying IRBCPs according to threshold values of ρ and identifying donor and recipient IRBCPs), a decision-support module (calculating the integral efficiency indicator, , for each alternative route and selecting the optimal option), and an implementation module (generating recommendations for freight carriers through integration with

the e-Queue system and logistics platforms). Feedback between the implementation module and the monitoring module enables the effects of traffic redirection to be monitored continuously and recommendations to be adjusted promptly as operating conditions change. The optimal route is selected on the basis of the integral efficiency indicator of the transport and technological process:

$$I_e = w_1 \cdot T_n + w_2 \cdot C_n + w3 \cdot R + w_4 \cdot S + w_5 \cdot E, \quad (3)$$

where T_n – the normalised delivery time indicator; C_n – the normalised transport cost indicator; R – the delivery reliability indicator; S – the service quality indicator; E – the environmental indicator; w_i – the weighting coefficients ($\Sigma w_i = 1$).

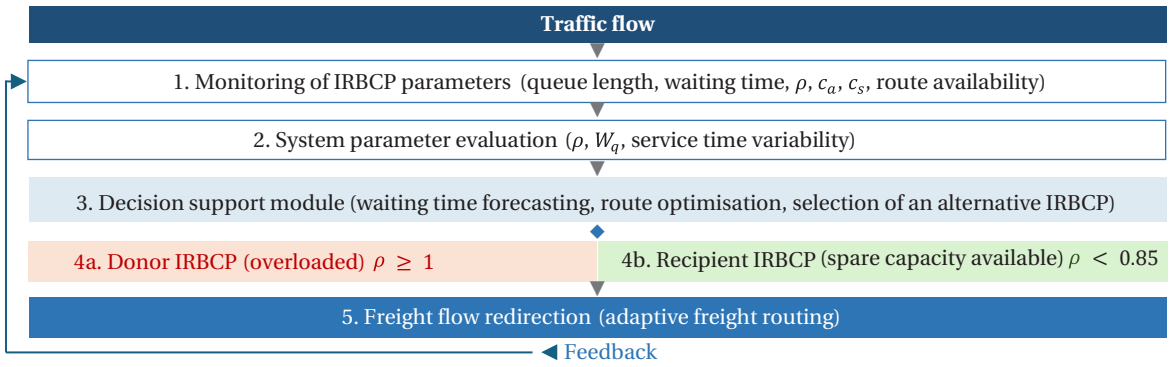


Figure 2. Structural diagram of the adaptive freight flow balancing mechanism between international road border crossing points

Source: developed by the author

Normalisation is performed using linear scaling within the range [0, 1]. The weighting coefficients are determined using the AHP, taking into account the priorities of the individual freight carrier. To evaluate the effectiveness of the proposed mechanism, three scenarios were considered: S0 (baseline scenario – no freight flow balancing), S1 (conservative scenario – partial traffic redirection combined with digital slot allocation), and S2 (optimistic scenario – full adaptive freight flow balancing supported by a border logistics hub). Table 1 presents a comparison of the baseline, conservative, and optimistic scenarios for the operation of the Krakovets-Korczowa IRBCP in terms of arrival rate, service channel utilisation, and average vehicle waiting time.

Table 1. Impact of the freight flow balancing mechanism on the operational parameters of the Krakovets-Korczowa IRBCP

Parameter	Baseline scenario	Conservative scenario	Optimistic scenario
Arrival rate, λ (vehicles/h)	22.6	18.9	15.9
Number of service channels, s	10	10	10
Service rate, μ (vehicles/h/channel)	2.15	2.54	2.54
Service time coefficient of variation, c_s	0.60	0.25	0.25
Arrival process coefficient of variation, c_a	1.00	0.35	0.30
Utilisation factor, ρ (–)	1.05	0.74	0.63
Average waiting time, W_q (h)	≥ 72	4.8-7.2	2.3-4.1

Source: compiled by the author based on Ministry for Development of Communities and Territories of Ukraine (n.d.)

Analysis of Table 1 reveals several fundamentally important patterns. In the conservative scenario (S1), reducing the λ from 22.6 to 18.9 vehicles/h is achieved by redirecting approximately 16% of the freight traffic to alternative IRBCPs (Rava-Ruska-Hrebenne and Yahodyn-Dorohusk). With the number of service channels remaining unchanged ($s = 10$), this reduces the utilisation factor (ρ) from an overloaded operating regime (1.05) to a stable level (0.74). At the same time, the increase in the service rate (μ) to 2.54 vehicles/h/channel results from the introduction of digital slot allocation, which standardises vehicle arrival intervals and reduces organisational delays. The reduction in the coefficients of variation (c_s from 0.60 to 0.25 and c_a from 1.00 to 0.35) reflects the positive effect of the digitalisation of border service procedures. Consequently, decreases to 4.8-7.2 hours, representing a ten- to fifteen-fold reduction compared with the baseline scenario. In the optimistic scenario (S2), the further reduction of the arrival rate (λ) to 15.9 vehicles/h is achieved through the active use of a border logistics hub and intermodal transport routes, reducing the ρ to 0.63 and the to 2.3-4.1 hours. The difference between the baseline scenario (S0) and the conservative scenario (S1) exceeds 65 hours, corresponding to a reduction of more than 90%, thereby confirming the practical effectiveness of the proposed mechanism. Table 2 specifies the application of the proposed mechanism to actual international road border crossing points.

Table 2. Classification of IRBCP by service system utilisation level

IRBCP category	Characteristics	Value ρ	Recommended action
Donor IRBCP (overloaded)	Exceeds service capacity; persistent growth in vehicle queues and waiting times	$\rho > 1$	Redirection of part of the freight flow to reserve IRBCPs
Critically loaded	High utilisation level; close to critical operating conditions; periodic congestion and delays may occur	$0.85 \le \rho \le 1$	Partial balancing of freight flows and stricter monitoring
Recipient IRBCP (reserve)	Available reserve service capacity; capable of accommodating additional traffic flow without the risk of congestion	$\rho < 0.85$	Acceptance of additional freight flow

Source: compiled by the author based on Solidarity lanes: Latest figures… (2025a; 2025b; 2025c), Ministry for Development of Communities and Territories of Ukraine (n.d.)

Table 2 presents the classification of IRBCPs according to the level of service system utilisation, establishing threshold values of the utilisation factor (ρ), the characteristics of each category of border crossing point, and the corresponding management measures: redirecting part of the freight flow to reserve IRBCPs, partial freight flow balancing with enhanced monitoring, or accommodating additional freight traffic. The Krakovets-Korczowa IRBCP, with $\rho \approx 1.05$, represents the highest priority for traffic redistribution. The Rava-Ruska-Hrebenne and Yahodyn-Dorohusk IRBCPs operate within the critically loaded range ($\rho \approx 0.88$-0.95). For these crossing points, enhanced monitoring involves increasing the frequency of data updates to once per hour and automatically generating an alert for the traffic management centre whenever ρ increases by 0.05 compared with the previous measurement. The recipient IRBCPs on the Hungarian corridor – Luzhanka-Beregsurány, Chop-Záhony, and Uzhhorod-Vyšné Nemecké – operated with average utilisation factors of approximately $\rho \approx 0.55$-0.70, indicating substantial reserve service capacity for accommodating redirected freight flows. A comparison of the principal system performance indicators under the three scenarios (S0, S1, and S2) is presented in Figure 3.

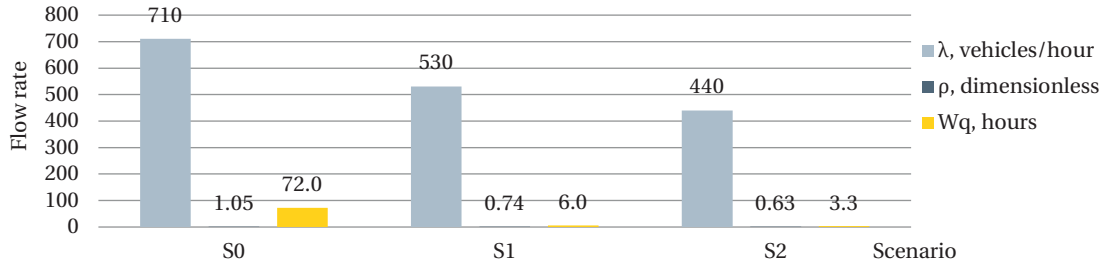


Figure 3. Graphical comparison of key performance indicators for the IRBCPs

Source: compiled by the author

Figure 3 demonstrates that freight flow balancing reduces traffic intensity from 710 to 530 and 440 vehicles/h under scenarios S1 and S2, respectively. This is accompanied by a reduction in the utilisation factor from 1.05 to 0.74 and 0.63, together with a decrease in the average waiting time from 72.0 hours to 6.0 and 3.3 hours, indicating a substantial improvement in the operational stability of IRBCPs. The practical implementation of the proposed balancing mechanism involves integrating digital traffic monitoring systems, the e-Queue system, the e-CMR electronic consignment note system, and a decision-support module into a unified information and analytical platform for managing international freight transport (Regulation (EU) 2020/1056, 2020; United Nations Economic Commission for Europe, 2025). The border logistics hub represents the key organisational and technological component of the proposed mechanism. Rather than constructing a new dedicated facility, the concept involves the functional repurposing of existing infrastructure, including warehouse complexes, customs terminals, and temporary storage facilities located within 20-50 km of an IRBCP. The adaptive vehicle redirection algorithm implemented at the logistics hub operates as follows. Upon vehicle arrival, the system retrieves the current ρ for all available IRBCPs, calculates the for each alternative route, and provides the driver with a recommendation specifying the optimal IRBCP, the estimated average , and the recommended route. Synchronisation of border-crossing time slots is achieved through integration between the logistics hub and the e-Queue system, allowing vehicles to receive a confirmed crossing slot at the selected IRBCP while still at the hub, thereby eliminating unproductive waiting near the border. The intermodal capability of the hub is ensured through the availability of railway sidings or the organisation of road-to-rail transhipment operations for freight that can be redirected to rail border crossings with lower utilisation levels (Solidarity Lanes: Latest Figures, 2025c; Ministry for Development of Communities and Territories of Ukraine, n.d.). A practical example is the rerouting of freight from the Krakovets-Korczowa crossing to the Luzhanka-Beregsurány IRBCP. The additional detour cost is approximately EUR 216, corresponding to more than 300 km of additional travel. The economic benefit of freight flow balancing is:

$$\Delta E_b = C_{delay} - C_{detour}, \quad (4)$$

where ΔE_b – the economic benefit of balancing, EUR; C_{delay} – the cost of vehicle delay while queuing; C_{detour} – the additional cost incurred when travelling via an alternative IRBCP.

With the average daily cost of freight vehicle downtime estimated at EUR 400-600 and $W_q \geq 72$ hours, the total losses associated with vehicle delays amount to EUR 1,200-1,800, which is five to eight times greater than the additional detour costs. A similar effect is observed for the Rava-Ruska-Yahodyn and Uzhhorod-Chop routes. These findings should be considered in the context of related research in order to assess the contribution of the proposed mechanism and identify promising directions for further development. The approach proposed in this study is conceptually consistent with the work of I. Badi *et al.* (2026), in which queueing theory is combined with MCDM to optimise border crossing operations. The principal distinction is that the cited study focuses on the static evaluation of the configuration of a single border crossing point, whereas the mechanism proposed here provides dynamic, real-time management of a system of interconnected IRBCPs. R.S. Sakhare *et al.* (2024) proposed a methodology for monitoring delays at road border crossing points using connected vehicle data, enabling the estimation of waiting times, the ranking of IRBCPs according to their utilisation levels, and the support of operational decision-making for border traffic management. The application of the , rather than relying solely on the minimisation of travel time, makes it possible to incorporate economic, reliability, and environmental considerations that are particularly relevant to international freight transport. The results of the scenario analysis, which reduced from more than 72 hours to 2.3-7.2 hours, are comparable with the benefits of adaptive optimisation in hub-and-spoke transport networks reported by M. Karimi-Mamaghan *et al.* (2020), M.H. Akyüz *et al.* (2023), and J. Zhang *et al.* (2024). However, as noted by W. Xu *et al.* (2021) and J. Wu *et al.* (2023), the specific characteristics of border service systems, where ρ may exceed 1 and the system therefore operates beyond the assumptions of conventional optimisation models, require the application of queueing theory. This constitutes a methodological advantage of the present study over approaches based exclusively on optimisation techniques. The findings concerning digitalisation, specifically the reduction of the service time coefficient of variation (c_s) from 0.60 to 0.25 in Scenario S1, are consistent with the conclusions of H.S. Sternberg *et al.* (2021), who emphasised the critical role of inter-organisational integration. Their research demonstrated that digital solutions achieve maximum effectiveness only when customs authorities, freight carriers, and IRBCP operators are fully synchronised. The practical experience of the e-Queue system fully supports this conclusion: its limited effectiveness at the Krakovets-Korczowa IRBCP is attributable primarily to insufficient organisational integration rather than to technical limitations of the digital platform itself (Ministry for Development of Communities and Territories of Ukraine, n.d.). The results regarding carriers' willingness to use alternative routes when the economic benefit ranges from EUR 550 to EUR 1,600 (the difference between C_{delay} and C_{detour}) are consistent with the findings of S. Sharma *et al.* (2021) and G. Cole *et al.* (2023). Forecasting W_q, provided by the decision-support module, is precisely the tool that enables freight carriers to make informed routing decisions before commencing their journey, as highlighted by these authors. Consequently, the proposed mechanism not only addresses the local problem of congestion at individual IRBCPs but also implements a system-wide approach to managing freight flows across border infrastructure, consistent with current trends in the development of adaptive logistics systems reported in the contemporary scientific literature.

Conclusions

As a result of the study, it was established that one of the principal causes of congestion at Ukraine's IRBCPs is the uneven distribution of freight flows across international transport corridors, causing queueing systems to enter an unstable operating regime. The operation of IRBCPs was formalised as multi-channel M/G/s queueing systems, and the influence of the utilisation factor ρ, arrival rate, and service time variability on the average queue waiting time (W_q) was substantiated. It was found that when $\rho \geq 1$, even the digitalisation of border crossing procedures is insufficient to stabilise traffic flow. An adaptive freight flow balancing mechanism between IRBCPs was developed, based on continuous monitoring of ρ, forecasting of W_q, digital decision-support systems, and adaptive traffic redirection using an integral efficiency criterion (I_e) that incorporates time, economic, reliability, service quality, and environmental delivery parameters. The results of the scenario modelling confirmed the effectiveness of the proposed mechanism, reducing the utilisation factor (ρ) of the Krakovets-Korczowa IRBCP from 1.05 to 0.63-0.74 and decreasing W_q from more than 72 hours to 2.3-7.2 hours, depending on the scenario. The economic benefits of traffic redirection exceed the additional detour costs by a factor of five to eight under the current level of congestion. Practical implementation through the establishment of a border logistics hub and adaptive routing does not require large-scale infrastructure reconstruction and could be implemented within 12-18 months. Future research should focus on the development of a dynamic model for forecasting the arrival rate (λ) using machine learning techniques to improve the accuracy of preventive freight flow balancing and to assess the risk of overloading recipient IRBCPs following traffic redistribution. Particular attention should also be given to investigating the behavioural factors influencing carriers' decisions when selecting alternative routes, as well as to developing regulatory mechanisms that encourage the voluntary redistribution of transport flows between alternative corridors.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Akyüz, M.H., Dekker, R., & Sharif Azadeh, S. (2023). Partial and complete replanning of an intermodal logistic system under disruptions. *Transportation Research Part E: Logistics and Transportation Review*, 169, article number 102968. doi: 10.1016/j.tre.2022.102968.

[2] Badi, I., Baryannis, G., & Bouraima, M.B. (2026). Integrating queueing theory and multi-criteria decision-making for optimizing border crossing operations. In Ž. Stević, O. Prentkovskis, M. Kostadinović, & A. Danilevičius (Eds.), *New horizons of transport and communications 2025: TransportaCom 2025* (pp. 563-575). Cham: Springer. doi: 10.1007/978-3-032-14078-4_49.

[3] Cole, G., Wolshon, B., & Schmidt, J. (2023). Incident diversionary routing: Survey of influences and decisions. *Transportation Research Record: Journal of the Transportation Research Board*, 2677(12), 830-839. doi: 10.1177/03611981231170009.

[4] European Commission. (2025). *Results of the 2024 connecting Europe facility transport calls for proposals*. Retrieved from https://surl.li/iugbhh.

[5] Golnar, M., & Beškovnik, B. (2022). A Multi-criteria approach for evaluating a sustainable intermodal transport chain affected by the COVID-19 pandemic. *Journal of Marine Science and Engineering*, 10(11), article number 1644. doi: 10.3390/jmse10111644.

[6] Ivanov, D., & Dolgui, A. (2021). OR-methods for coping with the ripple effect in supply chains during COVID-19 pandemic: Managerial insights and research implications. *International Journal of Production Economics*, 232, article number 107921. doi: 10.1016/j.ijpe.2020.107921.

[7] Jacyna-Gołda, I., Shmygol, N., Gavkalova, N., & Salwin, M. (2024). Sustainable development of intermodal freight transportation – through the integration of logistics flows in Ukraine and Poland. *Sustainability*, 16(1), article number 267. doi: 10.3390/su16010267.

[8] Jain, A.K., de Ruiter, J., Häring, I., Fehling-Kaschek, M., & Stolz, A. (2023). Design, simulation and performance evaluation of a risk-based border management system. *Sustainability*, 15(17), article number 12991. doi: 10.3390/su151712991.

[9] Karimi-Mamaghan, M., Mohammadi, M., Pirayesh, A., Karimi-Mamaghan, A.M., & Irani, H. (2020). Hub-and-spoke network design under congestion: A learning based metaheuristic. *Transportation Research Part E: Logistics and Transportation Review*, 142, article number 102069. doi: 10.1016/j.tre.2020.102069.

[10] Ministry for Development of Communities and Territories of Ukraine. (n.d.). *eCherha: Electronic border crossing queue. Statistics*. Retrieved from https://echerha.gov.ua/statistics.

[11] Ministry for Development of Communities and Territories of Ukraine. (2025). *Three years of eCherha: Key results of the digital system for border crossing*. Retrieved from https://mindev.gov.ua/news/try-roky-iecherhy-kliuchovi-rezultaty-roboty-tsyfrovoi-systemy-dlia-peretynu-kordonu.

[12] Prytula, K., Maksymenko, A., Demedyuk, O., Kalat, Y., & Kyryk, I. (2022). Methodology for assessing the prospects for developing the border crossing point network of Ukraine. *Science and Innovation*, 18(3), 37-48. doi: 10.15407/scine18.03.037.

[13] Regulation (EU) 2020/1056 of the European Parliament and of the Council of 15 July 2020 on electronic freight transport information. (2020). Retrieved from https://eur-lex.europa.eu/eli/reg/2020/1056/oj.

[14] Sakhare, R.S., Desai, J., Saldivar-Carranza, E.D., & Bullock, D.M. (2024). Methodology for monitoring border crossing delays with connected vehicle data: United States and Mexico land crossings case study. *Future Transportation*, 4(1), 107-129. doi: 10.3390/futuretransp4010007.

[15] Sharma, S., Kang, D.H., Montes de Oca, J.R., & Mudgal, A. (2021). Machine learning methods for commercial vehicle wait time prediction at a border crossing. *Research in Transportation Economics*, 89, article number 101034. doi: 10.1016/j.retrec.2021.101034.

[16] Solidarity lanes: Latest figures – February 2025. (2025a). Retrieved from https://transport.ec.europa.eu/news-events/news/solidarity-lanes-latest-figures-february-2025-2025-03-20_en.

[17] Solidarity lanes: Latest figures – March 2025. (2025b). Retrieved from https://transport.ec.europa.eu/news-events/news/solidarity-lanes-latest-figures-march-2025-2025-04-24_en.

[18] Solidarity lanes: Latest figures – May 2025. (2025c). Retrieved from https://transport.ec.europa.eu/news-events/news/solidarity-lanes-latest-figures-may-2025-2025-06-24_en.

[19] Sternberg, H.S., Hofmann, E., & Roeck, D. (2021). The struggle is real: Insights from a supply chain blockchain case. *Journal of Business Logistics*, 42(1), 71-87. doi: 10.1111/jbl.12240.

[20] Stewart, B., Moya, H., Raysoni, A.U., Mendez, E., & Vechione, M. (2023). Port-of-entry simulation model for potential wait time reduction and air quality improvement: A case study at the gateway international bridge in Brownsville, Texas, USA. *CivilEng*, 4(1), 345-358. doi: 10.3390/civileng4010020.

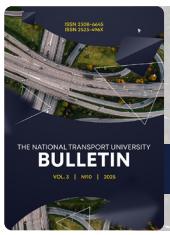
[21] The State Border Guard Service summed up the results of 2023 and identified further priority areas. (2024). Retrieved from https://dpsu.gov.ua/uk/news/40660-U-Derzhprikordonsluzhbi-pidbili-pidsumki-2023-roku-ta-viznachili-podalshi-prioritetni-napryamki.
[22] United Nations Economic Commission for Europe. (2025). *Handbook on digitalization and automation in intermodal freight transport*. Geneva: United Nations.
[23] Wu, J., Ba, X., & He, H. (2023). Optimization model of hybrid hub-and-spoke transportation network of road less-than-truckload cargo with different transportation time limits. *Journal of Engineering Science and Technology Review*, 16(6), 98-107. doi: 10.25103/jestr.166.12.
[24] Xu, W., Huang, J., & Qiu, Y. (2021). Study on the optimization of hub-and-spoke logistics network regarding traffic congestion. *Journal of Advanced Transportation*, 2021, article number 8711964. doi: 10.1155/2021/8711964.
[25] Zhang, J., Li, H., Han, W., & Li, Y. (2024). Research on optimization of multimodal hub-and-spoke transport network under uncertain demand. *Archives of Transport*, 70(2), 137-157. doi: 10.61089/aot2024.1g17bx18.

Механізм балансування вантажопотоків між міжнародними автомобільними пунктами пропуску в умовах нерівномірного навантаження прикордонної інфраструктури

Єлизавета Данілейко
Аспірант
Національний транспортний університет
01010, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
https://orcid.org/0009-0005-0399-5976

Анотація. Структурна трансформація міжнародних транспортних потоків після 2022 року зумовила диспропорційний розподіл транспортного навантаження на міжнародні автомобільні пункти пропуску (МАПП) України, наслідком чого стали перевантаження окремих пунктів пропуску та тривалі черги. Метою статті стало обґрунтування механізму балансування вантажопотоків між міжнародними автомобільними пунктами пропуску з метою підвищення ефективності міжнародної доставки вантажів за умов нерівномірного навантаження прикордонної інфраструктури. Методологічну основу дослідження складав апарат теорії масового обслуговування (багатоканальна система типу M/G/s з апроксимацією Аллена-Куніна) у поєднанні з методами сценарного аналізу та нормалізованої багатокритеріальної оцінки, причому для забезпечення відтворюваності результатів введено окремий розділ з обґрунтуванням порядку отримання всіх ключових параметрів моделі (λ, μ, s, c_a, c_s). У статті досліджено проблему нерівномірного навантаження міжнародних автомобільних пунктів пропуску України в умовах структурної трансформації міжнародних транспортних потоків. Встановлено, що зміна географії зовнішньоторговельних маршрутів призвела до дисбалансу у використанні прикордонної інфраструктури, наслідком чого стало систематичне перевантаження окремих пунктів пропуску. Розроблено механізм адаптивного балансування вантажопотоків між МАПП на основі інтегрального критерію ефективності. Введено окремий розділ методології з обґрунтуванням порядку отримання параметрів моделі. Результати сценарного моделювання підтвердили ефективність: зниження ρ МАПП Краківець-Корчова з 1,05 до 0,63-0,74 та скорочення W_q із понад 72 до 2,3-7,2 години. Розроблений механізм дає змогу оперативно перерозподіляти вантажопотоки між МАПП без капітальних інвестицій в інфраструктуру, що суттєво знижує економічні втрати перевізників від тривалих простоїв на кордоні

Ключові слова: транспортно-технологічний процес; M/G/s; теорія масового обслуговування; логістика; єЧерга; цифровізація



BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 30 | №2 | 2026
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X

Received: 27.01.2026. Revised: 02.06.2026. Accepted: 25.06.2026. Published: 06.07.2026.

UDC 656.13 DOI: 10.33744/2308-6645-2026-2-30-73-82

Criterion for reducing traffic delays at a roundabout exit in the presence of a public transport stop

Dmytro Tkachenko
Postgraduate Student
National Transport University
01010, 1 M. Omelyanovych-Pavlenko Str., Kyiv, Ukraine
https://orcid.org/0009-0001-0788-5927

Inna Vyhovska*
PhD in Technical Sciences, Associate Professor
National Transport University
01010, 1 M. Omelyanovych-Pavlenko Str., Kyiv, Ukraine
https://orcid.org/0000-0003-1426-9863

Abstract. The efficiency of roundabout intersections largely depends on traffic conditions at their exit sections, in particular the location of public transport stops immediately after the exit or in its vicinity, which reduces capacity and increases delays due to forced lane-changing manoeuvres and a shortage of acceptable gaps in the traffic stream. The aim of the study was to develop criteria for reducing traffic delays at the exit of a roundabout in the presence of a public transport stop, taking into account vehicle lane-changing processes and the critical gap in the adjacent traffic lane. The study was conducted using principles of traffic flow theory, methods for evaluating intersection capacity, and approaches for determining critical gaps; it was also shown that delays at roundabout exits are caused by right-lane blockage by public transport, demand for lane changing, and insufficient acceptable gaps in the adjacent stream within a local critical zone. A system of delay-reduction criteria is proposed, based on minimising total delay in the local critical zone, ensuring consistency between traffic demand and effective exit capacity, and matching lane-changing demand with the possibility of its execution under existing traffic conditions. Conditions for the transition of the traffic stream to a critical operating regime were also defined in terms of speed, density, and capacity indicators. To validate the proposed methodological approach, a computational scenario of a two-lane roundabout exit was considered. With an exit traffic flow of 1,000 veh/h, adjacent lane flow of 900 veh/h, and an average right-lane blocking time by public transport of 25 s, a lane occupancy coefficient of $\varphi = 0.125$ was obtained, resulting in a reduction of effective capacity to 1,575 veh/h. Under these conditions, traffic demand does not exceed the effective exit capacity, ensuring stable traffic operation and enabling lane-changing manoeuvres without the formation of critical delays. The obtained results may be used to justify the location of urban public transport stops, determine the length of weaving sections, and select organisational and technical measures aimed at improving the efficiency of roundabout operation and reducing traffic delays

Keywords: traffic management; lane-changing manoeuvres; critical gap; lane blockage; bottlenecks

Introduction

Roundabouts are widely recognised as one of the most effective traffic control solutions in urban transportation systems due to their ability to improve road safety, reduce the number of conflict points, and maintain continuous traffic movement. However, the operational efficiency of roundabouts is strongly influenced by traffic conditions at their exit sections, particularly when public transport stops are located directly at or immediately downstream of the exit area. Under such conditions, traffic delays may increase significantly due to the combined effects of lane

Suggested Citation: Tkachenko, D., & Vyhovska, I. (2026). Criterion for reducing traffic delays at a roundabout exit in the presence of a public transport stop. *Bulletin of the National Transport University*, 30(2), 73-82. doi: 10.33744/2308-6645-2026-2-30-73-82.

*Corresponding author (*i.vyhovska2609@gmail.com*)

Copyright © The Author(s). This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/)

blockage, lane-changing manoeuvres, and limited availability of acceptable gaps in adjacent traffic streams. Recent research has increasingly focused on the operational performance of roundabouts under varying traffic conditions. M. Guerrieri (2024) proposed a methodology for assessing sustainable traffic levels at urban roundabouts using a macroscopic fundamental diagram approach. The study demonstrated the importance of traffic density and speed relationships in determining operational efficiency and identifying the transition from stable to congested traffic conditions. H. Jiang *et al.* (2024) conducted a comprehensive review of traffic behaviour and intelligent driving at roundabouts from a microscopic perspective. The authors emphasised that traffic delays and travel times are strongly affected by lane-selection behaviour, lane-changing decisions, traffic demand, and geometric characteristics of roundabouts. E. Campi *et al.* (2024) analysed the application of traffic simulation models for evaluating the operation of connected and automated vehicles at roundabouts. Their findings confirmed the importance of microscopic modelling approaches for investigating vehicle interactions and traffic flow dynamics within roundabout influence areas. F. Abu Hamad *et al.* (2024) investigated driver behaviour at roundabouts operating under mixed traffic conditions using machine learning techniques. The study demonstrated that lane selection, gap acceptance behaviour, and driver decision-making processes significantly influence traffic performance and the occurrence of conflicts within roundabout influence areas. The authors emphasised the importance of considering vehicle interactions and lane-changing behaviour when assessing operational efficiency at roundabouts.

Y. Liang *et al.* (2024) developed a three-stage cellular automata model for analysing traffic operations at complex multilane roundabouts. Their findings showed that vehicle interactions occurring during entering, circulating, and exiting manoeuvres substantially affect traffic stability, delay formation, and overall operational performance. The study confirmed the importance of considering localised traffic disturbances and lane-changing processes when evaluating roundabout efficiency. K. Čulík *et al.* (2025) compared the operational performance of conventional and turbo roundabouts using field observations and calibrated simulation models. The results demonstrated that traffic delays and capacity utilisation are highly sensitive to lane allocation and vehicle weaving processes. E. Zadobrischi (2025) investigated intelligent traffic management systems for roundabouts based on advanced vehicle communication technologies. The study highlighted the significance of traffic flow organisation and conflict reduction measures for improving operational efficiency and reducing vehicle delays. The influence of public transport stops on traffic performance has also attracted considerable attention. I. Medvediev & S. Soroka (2020) proposed a methodology for evaluating the impact of public transport stop placement on the capacity of urban road networks. Their results confirmed that stop location may substantially affect traffic performance and capacity utilisation. E.B. Lieberthal *et al.* (2024) examined traffic conditions on urban road sections with reduced capacity and demonstrated the necessity of considering localised bottlenecks when assessing traffic performance and delay formation processes.

Recent studies addressing public transport stop operations and lane-changing processes indicate that the interaction between temporary lane blockage, lane-changing demand, and traffic flow characteristics plays a significant role in determining local traffic conditions. Nevertheless, existing studies primarily investigate these factors separately. The combined influence of public transport stop operations, lane-changing demand, and the availability of acceptable gaps within the roundabout exit area remains insufficiently explored. The aim of this study was to establish criteria for reducing traffic delays at roundabout exits where a public transport stop is present, considering vehicle lane-changing behaviour and the critical gap in the adjacent traffic stream.

Literature Review

The issue of determining capacity and traffic delays at roundabouts is predominantly addressed in the scientific literature through gap-acceptance models, critical gap estimation, and analyses of traffic flow interactions within roundabout entry and exit areas. A. Polus *et al.* (2003) found that the critical gap is dependent on drivers' waiting time, which directly affects roundabout capacity. O. Hagring (2001) proposed an approach for estimating roundabout entry capacity while accounting for mixed circulating and exiting traffic flows. O. Giuffrè *et al.* (2016) systematised the gap-acceptance parameters commonly applied in the evaluation of roundabout performance. K. Shaaban & H. Hamad (2020) investigated variations in critical gap values for single-, two-, and three-lane roundabouts. A separate group of studies focuses on the impact of public transport stops on traffic conditions. D. Cvitanić (2017) demonstrated that the location and configuration of a public transport stop significantly affect vehicle delays and the operational performance of intersections. X. Yang *et al.* (2013) developed a model for evaluating vehicle delays in the vicinity of public transport stops under mixed traffic conditions. H. Jin *et al.* (2019) found that curbside stops cause periodic lane blockages, aggressive lane-changing manoeuvres, reduced roadway capacity, and increased traffic delays. In recent studies, increasing attention has been devoted to microscopic traffic flow modelling, driver behaviour in lane-selection decisions, and the evaluation of traffic management measures. H. Jiang *et al.* (2024) noted that travel time and delays at roundabouts depend on drivers' lane-changing behaviour, the geometric characteristics of the intersection, traffic demand, and local traffic control regulations. K. Čulík *et al.* (2025), in a comparison of conventional and turbo roundabouts, employed field observations, origin-destination traffic matrices, and a calibrated microscopic simulation model. E. Zadobrischi (2025) investigated opportunities for improving traffic flow efficiency

at roundabouts, particularly through the implementation of public transport priority measures. M. Riaz *et al.* (2023) highlighted the effectiveness of microscopic traffic simulation techniques for evaluating traffic management strategies in urban transportation systems. The authors demonstrated that microsimulation models can successfully reproduce lane-changing behaviour, traffic delays, and congestion formation, providing valuable support for the assessment of traffic control measures and infrastructure design alternatives.

Despite the considerable progress achieved in the fields of roundabout capacity assessment, lane-changing behaviour analysis, traffic microsimulation, and public transport stop evaluation, the combined influence of temporary lane blockage, lane-changing demand, and acceptable gap availability at roundabout exits remains insufficiently investigated. Existing studies primarily address these factors separately, whereas their simultaneous interaction may significantly affect traffic delays and traffic flow stability within the exit influence area. Recent studies have increasingly focused on the behavioural and operational aspects of traffic flow at roundabouts. F. Abu Hamad *et al.* (2024) and Y. Liang *et al.* (2024) demonstrated the importance of lane-changing processes and vehicle interactions for traffic performance, whereas M. Riaz *et al.* (2023) confirmed the usefulness of microscopic simulation approaches for evaluating traffic management strategies. However, the integration of these factors into a unified analytical framework for assessing traffic delays at roundabout exits has received limited attention in previous research. At the same time, the literature review indicates that most studies examine either roundabout capacity, the impact of public transport stops, or vehicle lane-changing processes as separate components. Their combined effect at roundabout exits remains insufficiently explored, despite the fact that three interrelated factors occur simultaneously in this area: temporary blockage of the outer lane by public transport vehicles, increased lane-changing demand, and a shortage of acceptable gaps in the adjacent traffic stream. This research gap justifies the need to develop criteria for reducing traffic delays within the critical exit zone of a roundabout. Although numerous studies have addressed roundabout capacity, the effects of public transport stops on traffic conditions, and vehicle lane-changing processes separately, their combined impact within the roundabout exit area has received limited attention. In particular, the mechanism of traffic delay formation under the simultaneous influence of outer-lane blockage, lane-changing demand, and the limited availability of acceptable gaps in the adjacent traffic stream requires further investigation (Yang *et al.*, 2013; Cvitanić, 2017; Jin *et al.*, 2019). An analysis of the current regulatory framework indicates that the requirements governing the location and design of public transport stops in Ukraine are primarily established by GBN V.2.3-37641918-550:2018 (2018) and DBN V.2.3-5:2018 (2018). GBN V.2.3-37641918-550:2018 defines the general requirements for the design of public transport stops, while DBN V.2.3-5:2018 serves as the principal regulatory document governing the design and construction of urban streets and roads in populated areas. When addressing traffic control devices and traffic management measures, reference should also be made to DSTU 4100:2021 (2021) and DSTU 2587:2021 (2021).

However, the aforementioned regulatory documents do not provide an analytical framework for assessing the impact of a public transport stop on traffic delays specifically within the exit area of a roundabout. Furthermore, they do not account for the process of forced lane-changing manoeuvres undertaken by vehicles, nor do they relate the feasibility of such manoeuvres to the critical gap available in the adjacent traffic stream. This constitutes the principal distinction and scientific value of the proposed study. The conducted review demonstrates that previous studies have significantly contributed to the understanding of roundabout capacity, critical gap acceptance, traffic flow dynamics, and the operational effects of public transport stops. However, the majority of existing research examines these factors independently. Insufficient attention has been paid to the combined influence of temporary lane blockage caused by public transport stops, lane-changing demand, and the availability of acceptable gaps within adjacent traffic streams at roundabout exits. Consequently, there remains a need for a comprehensive methodological approach capable of simultaneously accounting for these interacting factors when assessing delay formation and developing traffic management measures at urban roundabouts.

Materials and Methods

The study was conducted based on the principles of traffic flow theory, methods for assessing the capacity of transportation facilities, and approaches to determining the critical gap required for vehicle lane-changing manoeuvres. The object of the study was the process of traffic delay formation at a roundabout exit in the presence of a public transport stop. The subject of the study comprised the interaction patterns of traffic flows within the roundabout exit area, which were determined by the influence of the public transport stop, traffic demand, lane-changing demand, and the availability of acceptable gaps in the adjacent traffic stream. A schematic representation of vehicle lane-changing manoeuvres within the influence area of the public transport stop is shown in Figure 1. The dynamics of vehicle departures from a roundabout are characterised by pronounced traffic flow heterogeneity in terms of speed profiles, headways, and the spatial distribution of vehicles across roadway lanes. The operation of a public transport stop located in close proximity to the roundabout exit creates conditions for temporary lane blockage, which not only directly reduces roadway capacity but also generates additional conflict areas associated with vehicle lane-changing manoeuvres. For the subsequent analysis of traffic delay formation, it was proposed to distinguish functional zones representing the influence of a public transport stop on traffic flow, as illustrated in

Figure 2. As vehicles move away from the roundabout, the traffic stream naturally disperses both longitudinally along the roadway segment and laterally across its width. However, the presence of a public transport stop modifies this process. In particular, it shifts the traffic stabilisation zone further downstream while simultaneously affecting key traffic performance measures, including average travel speed, the distribution of vehicles across lanes due to overtaking and lane-changing manoeuvres, and the overall travel time along the roadway segment.

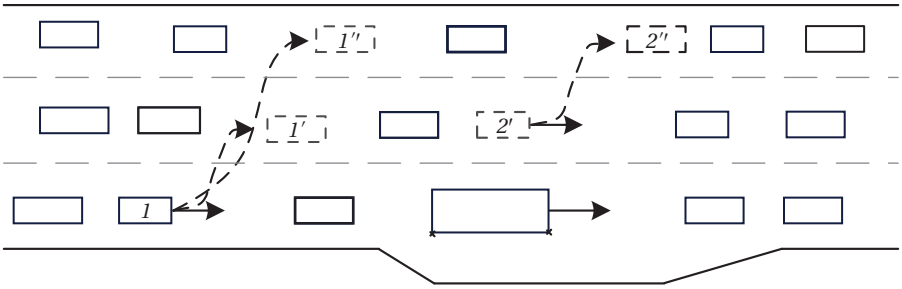


Figure 1. Schematic representation of a vehicle lane-changing manoeuvre
Source: developed by the authors

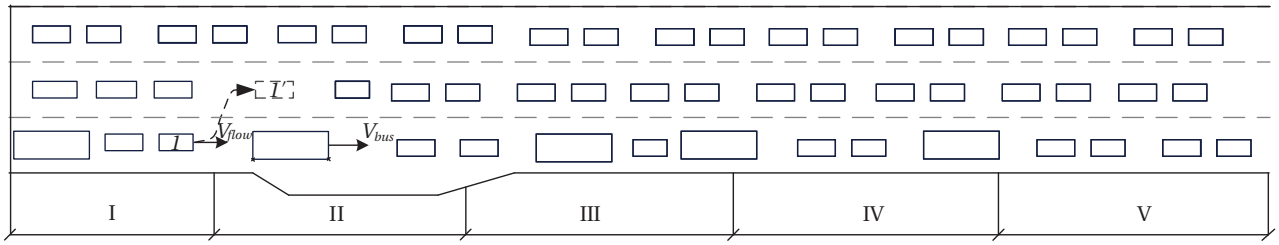


Figure 2. Functional zones of public transport stop influence on traffic flow
Source: developed by the authors

The structural decomposition of the public transport stop influence area (Fig. 2) made it possible to identify five consecutive sections whose characteristics are variable parameters: the approach zone (I), the manoeuvring zone during entry into the bus bay (II), the exit zone from the bus bay (III), the zone of direct merging of public transport vehicles into the main traffic stream (IV), and the traffic stabilisation zone (V). For the purposes of this study, the local critical zone is defined as the road section extending from the roundabout exit line to the point where traffic flow parameters return to stable operating conditions. The upstream boundary of the zone coincides with the beginning of the exit section, whereas the downstream boundary was determined by the completion of lane-changing manoeuvres and the stabilisation of traffic flow speed, density, and headway distribution. Consequently, the length of the local critical zone is not constant and depends on traffic demand, public transport stop operation characteristics, and the geometric parameters of the road section. The length of the approach section is determined by the time required to reach the lower speed threshold, which is constrained by the dynamic envelope characteristics of the specific vehicle type. In turn, the parameters of the entry section are governed by the geometric characteristics of the bus bay and the presence of a queue of public transport vehicles. To evaluate the operating conditions of the local critical zone, the following indicators are employed: traffic flow rate, vehicle speed, traffic density, effective lane capacity, and the critical gap available in the adjacent lane.

The critical gap represents one of the key parameters governing the feasibility of lane-changing manoeuvres. In practical applications, its value may be estimated from accepted and rejected gaps obtained through field observations within the influence area of a public transport stop. The performance criterion for the local critical zone is defined as the minimisation of total vehicle delay while ensuring the required exit capacity and maintaining the feasibility of lane-changing manoeuvres without causing the traffic stream to enter a critical operating state. The study was based on a theoretical and analytical framework developed using the principles of traffic flow theory and capacity analysis. Illustrative traffic scenarios with representative parameters of urban roundabout exits were used to demonstrate the application of the proposed criteria. The illustrative scenarios were developed using parameter ranges reported in previous studies on roundabout capacity, gap acceptance, and public transport stop impacts, such as K. Shaaban & H. Hamad (2020), H. Jin *et al.* (2019) and National Academies of Sciences, Engineering, and Medicine (2010). Field observations are considered as a future stage of research intended for model calibration and validation. Based on the proposed methodological framework, functional relationships were established among traffic flow rate, effective lane capacity, lane-changing demand, and the number of acceptable gaps in the adjacent

traffic stream. These relationships provided the basis for developing a system of criteria aimed at reducing traffic delays at roundabout exits.

Results and Discussion

To investigate traffic conditions at roundabout exits, it is proposed to define a local critical zone comprising the following components: the immediate roundabout exit zone, the influence area of the public transport stop, the lane-changing section where vehicles merge into the adjacent lane, and the traffic stabilisation zone located downstream of the stop. It is within this zone that the most significant reductions in vehicle speed, changes in traffic density, and the formation of additional travel delays occur. The proposed analytical framework is based on several simplifying assumptions. Traffic arrivals in the adjacent lane are assumed to follow a Poisson process. Traffic flow characteristics within the local critical zone are considered homogeneous over short observation intervals. Public transport vehicles are assumed to occupy the curb lane for the average dwell time at the stop. Lane-changing demand is represented by the proportion of vehicles affected by temporary lane blockage. These assumptions allow the derivation of analytical relationships suitable for preliminary traffic engineering assessments. The total traffic delay within the local critical zone can be determined as the difference between the actual and normative travel times required to traverse the individual exit segments:

$$T_{\text{delay}} = \sum_{r=1}^{m} q_r \left(\frac{L_r}{v_r} - \frac{L_r}{v_{0r}}\right), \quad (1)$$

where q_r – traffic flow rate in the r-th zone, veh/h; L_r – length of the r-th zone, m; v_r – actual average travel speed, m/s; v_{0r} – average travel speed under normal operating conditions, m/s.

The obtained relationship makes it possible to quantify the contribution of each functional zone within the local critical area to the formation of total traffic delay and provides a basis for the subsequent development of performance criteria for roundabout exit operations. The performance criterion for roundabout exit operations is defined by the equation:

$$T_{\text{delay}} \rightarrow min. \quad (2)$$

The presence of a public transport stop at a roundabout exit reduces the capacity of the outer lane due to its periodic occupation by public transport vehicles. The magnitude of this effect is proposed to be assessed using the lane occupancy factor given by the equation:

$$\varphi_{ps} = \frac{q_b \cdot t_d}{3600}, \quad (3)$$

where q_b – arrival rate of public transport vehicles at the stop, veh/h; t_d – average dwell time of a public transport vehicle at the stop, s.

Accordingly, the effective lane capacity within the stop influence area can be expressed by the equation:

$$C_{ps} = C_0(1 - \varphi_{ps}), \quad (4)$$

where C_0 – lane capacity in the absence of a public transport stop, veh/h.

Based on the equation (4), the first condition for reducing traffic delays is expressed by the equation:

$$q_{ex} \leq C_{ps}, \quad (5)$$

where q_{ex} – traffic flow rate at the roundabout exit, veh/h.

If this condition is not satisfied, a portion of vehicles is forced to merge into the adjacent lane. The lane-changing demand can then be determined according to the equation:

$$q_{lc} = p_{lc} \cdot q_{ex}, \quad (6)$$

where q_{lc} – flow rate of vehicles requiring a lane change, veh/h; p_{lc} – proportion of vehicles compelled to change lanes.

However, the existence of lane-changing demand alone does not guarantee the feasibility of executing the manoeuvre. For a lane change to occur, sufficiently large temporal gaps must be available in the adjacent lane. Such a gap may be characterised by the critical gap t_{cr}, which may be estimated from field observations according to the equation:

$$t_{cr} = \frac{\bar{h}_{\text{rej}} + \bar{h}_{\text{acc}}}{2}, \quad (7)$$

where $\bar{h}_{\text{rej}}$ – mean value of the gaps rejected by drivers; $\bar{h}_{\text{acc}}$ – mean value of the gaps accepted for performing the lane-changing manoeuvre.

The critical gap is considered as one of the key parameters affecting lane-changing feasibility. In practical applications, it may be estimated using established approaches such as the Raff method based on accepted and rejected gap observations. For the illustrative scenario presented in this study, a representative critical gap value of $t_c = 4.0$ s was adopted. This value lies within the range of critical gap values reported in the literature and applied in roundabout capacity assessment and traffic operations analysis and was selected to demonstrate the application of the proposed methodology (National Academies of Sciences, Engineering, and Medicine, 2010; Austroads, 2017). According to the Raff method, the critical gap corresponds to the intersection point of the cumulative distribution functions of accepted and rejected gaps. This approach enables the identification of the minimum acceptable time interval required for a driver to perform a lane-changing manoeuvre under prevailing traffic conditions. Future studies should estimate the critical gap using field observations collected at urban roundabout exits. Assuming a Poisson arrival process of vehicles in the adjacent lane, the probability of observing a gap not smaller than t_{cr} is determined by the equation:

$$P_{\text{cr}} = exp\left(-\frac{q_{adj} \cdot t_{\text{cr}}}{3600}\right), \quad (8)$$

where q_{adj} – traffic flow rate in the adjacent lane, veh/h.

Accordingly, the number of gaps suitable for lane-changing manoeuvres per unit time can be calculated using the equation:

$$n_{\text{cr}} = q_{adj} \cdot exp\left(-\frac{q_{adj} \cdot t_{\text{cr}}}{3600}\right). \quad (9)$$

The second principal condition for reducing traffic delays is represented by the equation:

$$q_{lc} \leq n_{cr}. \quad (10)$$

To demonstrate the application of the proposed criteria, a hypothetical urban roundabout exit with a two-lane downstream section was considered. The following input parameters were adopted: exit flow rate q_{ex} = 1,000 veh/h, adjacent lane flow rate q_{adj} = 900 veh/h, base lane capacity C_0 = 1,800 veh/h, public transport arrival rate λ_{bus} = 18 veh/h, average dwell time t_d = 25 s, and critical gap t_c = 4.0 s, and weaving section length Lr = 120 m. The calculated lane occupancy factor was φ = 0.125, resulting in an effective lane capacity of C_{ps} = 1,575 veh/h. Since $q_{ex} < C_{ps}$, the capacity criterion was satisfied. The probability of observing an acceptable gap was P = 0.368, corresponding to approximately 331 acceptable gaps per hour. Under these conditions, the traffic stream remains within a stable operating regime and no critical congestion effects are expected. The scenarios summarised in Table 1 represent generalised operating conditions developed for comparative assessment of public transport stop placement alternatives, whereas the numerical example presented in the text corresponds to a specific illustrative calculation scenario.

Table 1. Scenario analysis of roundabout exit operation

Scenario	Stop position (m)	Lane occupancy factor φ	Effective capacity (veh/h)	Lane-changing demand	Traffic regime
No public transport stop	–	0.00	1,800	Low	Stable
Stop located at roundabout exit	0	0.125	1,575	High	Transitional
Stop relocated downstream	120	0.06	1,692	Moderate	Stable

Source: developed by the authors

Traffic regimes were classified according to the conceptual thresholds presented in Figure 3: stable operation (q < 1,100 veh/h), transitional operation (1,100 ≤ q ≤ 1,400 veh/h), and oversaturated operation (q > 1,400 veh/h). Lane-changing demand was qualitatively assessed based on the proportion of vehicles affected by temporary lane blockage and required to merge into the adjacent lane, where low, moderate, and high demand levels correspond to increasing proportions of affected vehicles. The scenario analysis demonstrates that the operational regime of the roundabout exit is highly sensitive to the location of the public transport stop. The most unfavourable conditions are observed when the stop is located directly within the exit influence area, resulting in reduced effective capacity and increased lane-changing demand. Relocating the stop further downstream improves operating conditions by reducing lane blockage duration and increasing the availability of acceptable gaps for lane-changing manoeuvres. The obtained results indicate that the location of a public transport stop relative to the roundabout exit constitutes one of the key factors affecting traffic performance. Stops located within the immediate influence area of the exit increase lane-changing demand and reduce the availability of acceptable gaps for manoeuvre execution. Consequently, the proposed criteria may serve as a practical tool for evaluating alternative stop locations and identifying configurations that minimise traffic delays while maintaining adequate operational conditions. If the condition defined by the equation is satisfied, a portion of vehicles is unable to complete the lane-changing manoeuvre within the available weaving section:

$$q_{lc} > n_{cr}. \quad (11)$$

A portion of vehicles is unable to complete the lane-changing manoeuvre within the available weaving section. As a result, localised vehicle accumulation occurs, traffic speed decreases, and delays increase.

To assess the transition of the roundabout exit into a critical operating state, it is also necessary to consider the critical speed v_{cr} and the critical traffic density λ_{cr}. The critical density may be determined according to the equation:

$$\lambda_{\text{cr}} = \frac{q_r}{v_{\text{cr}}}. \quad (12)$$

The local critical zone is considered to operate under critical conditions when at least one of the criteria expressed by the equations is satisfied:

$$v_r < v_{cr}; \quad (13)$$
$$\lambda_r > \lambda_{cr}; \quad (14)$$
$$q_{ex} > C_{ps}; \quad (15)$$
$$q_{lc} > n_{cr}. \quad (16)$$

Thus, traffic delay at a roundabout exit is not caused by a single factor but rather by the combined influence of three interrelated mechanisms: periodic blockage of the outer lane by public transport vehicles serving the stop, the forced redistribution of vehicles between lanes, and an insufficient number of acceptable gaps in the adjacent traffic stream. Considering the above, the proposed system of criteria for reducing traffic delays at roundabout exits includes the following conditions:

- the traffic flow rate at the exit should not exceed the effective lane capacity within the public transport stop influence area;

- lane-changing demand should not exceed the number of acceptable critical gaps available in the adjacent lane;
- traffic speed within the local critical zone should not fall below the critical speed;
- actual traffic density should not exceed the critical density;
- total delay within the local critical zone should be minimised.

Based on the proposed system of criteria, a conceptual relationship between traffic delay and traffic flow rate can be established. When both the capacity criterion and the lane-changing feasibility criterion are satisfied, the traffic stream operates under stable conditions. As traffic demand approaches the effective capacity of the local critical zone, the system gradually transitions to an unstable operating regime. Further increases in traffic flow rate result in system oversaturation, leading to a sharp increase in traffic delays (Fig. 3). Figure 3 illustrates the impact of a public transport stop on vehicle delays as a function of traffic flow rate, comparing scenarios with and without a public transport stop located at the exit of a roundabout. The threshold values shown in the figure are illustrative and intended to demonstrate the qualitative behaviour of the proposed criteria rather than represent a specific field case. Analysis of the graph indicates that under low and moderate traffic demand levels (up to 1,100 veh/h), the traffic stream operates in a stable regime. Within this range, traffic delay increases gradually, while the difference between scenarios with and without a public transport stop remains relatively small. This can be explained by the availability of a sufficient number of acceptable gaps for lane-changing manoeuvres and the absence of lane oversaturation. For traffic flow rates ranging from 1,100 to 1,400 veh/h, a transitional operating regime is observed. Traffic delays begin to increase more rapidly, particularly in the presence of a public transport stop. During this phase, lane-changing demand increases, whereas the number of acceptable gaps available in the adjacent lane gradually decreases. When traffic demand exceeds 1,400 veh/h, the traffic stream enters an oversaturated regime. Traffic conditions are characterised by a sharp increase in delays, with the presence of a public transport stop significantly amplifying the negative effect. This phenomenon is attributable to the simultaneous action of three factors: the reduction in effective lane capacity caused by periodic occupation of the outer lane by public transport vehicles, the increase in the number of forced lane-changing manoeuvres, and the shortage of acceptable gaps required for their execution.

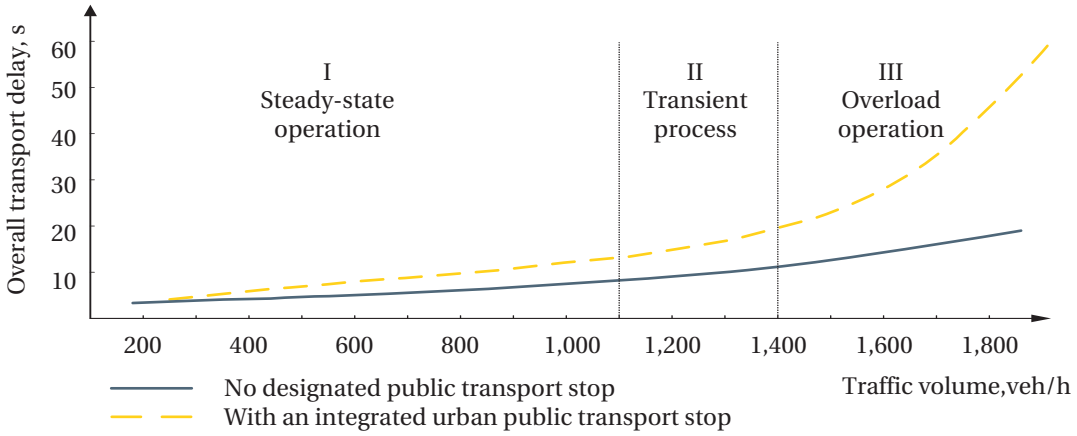


Figure 3. Conceptual relationship between traffic delays and traffic flow rate in the presence of a public transport stop
Source: developed by the authors

The obtained results demonstrate that the impact of a public transport stop on traffic delays is nonlinear and becomes particularly significant under high traffic demand conditions, when the system approaches a critical operating state. From a practical perspective, traffic delays may be reduced through the appropriate placement of public transport stops relative to the roundabout exit, increasing the length of the weaving section, reducing the duration of outer-lane blockage, and implementing traffic management measures aimed at decreasing forced lane-changing demand. The findings support previous studies emphasising the critical role of gap acceptance and lane-changing processes in determining roundabout capacity, such as K. Shaaban & H. Hamad (2020) and A. Polus *et al.* (2003). However, unlike existing approaches, the proposed system of criteria incorporates the combined effects of public transport stop operations, lane-changing demand, and the shortage of acceptable gaps in the adjacent traffic stream. This makes it possible to provide a more comprehensive description of the mechanisms responsible for traffic delay formation at roundabout exits and expands the opportunities for developing and justifying traffic management and engineering measures aimed at mitigating such delays. The proposed approach may be applied both to the evaluation of existing traffic management schemes at urban roundabouts and to the design of new transportation facilities. Its application enables the assessment of the suitability of locating a public transport stop within the roundabout exit area, the determination of the required weaving section length, and the

justification of traffic management measures intended to reduce delays and improve the operational performance of the intersection. The proposed methodology consists of the following sequential stages:

1. Determination of traffic flow characteristics within the local critical zone.

2. Estimation of the lane occupancy factor caused by public transport stop operations.

3. Calculation of the effective lane capacity.

4. Assessment of lane-changing demand generated by temporary lane blockage.

5. Determination of the critical gap and the number of acceptable gaps available for manoeuvre execution.

6. Verification of the proposed delay-reduction criteria.

7. Identification of stable, transitional, or critical traffic operating conditions.

The obtained results indicate that traffic delays at roundabout exits are determined not only by traffic demand and available capacity but also by the interaction between lane-changing demand and the availability of acceptable gaps in the adjacent traffic stream. The analysis demonstrates that even when the effective lane capacity remains sufficient, traffic performance may deteriorate if the number of available gaps becomes inadequate for the execution of mandatory lane-changing manoeuvres. The obtained findings are generally consistent with previous studies addressing roundabout operations and public transport stop impacts. Similar conclusions regarding the influence of public transport stop placement on traffic performance were reported by I. Medvediev & S. Soroka (2020) and H. Jin *et al.* (2019). Furthermore, the importance of gap acceptance and driver decision-making processes identified in the present study is in agreement with the findings of K. Shaaban & H. Hamad (2020) and H. Jiang *et al.* (2024). However, unlike previous research, the proposed approach simultaneously considers effective lane capacity, lane-changing demand, and acceptable gap availability within a unified analytical framework. The principal contribution of the proposed methodology lies in the introduction of the concept of a local critical zone at roundabout exits affected by public transport stop operations. The developed criteria make it possible to identify traffic conditions under which the combined influence of lane blockage, lane-changing demand, and limited gap availability may result in unstable traffic operation and increased delays. From a practical perspective, the proposed criteria may assist traffic engineers in evaluating alternative locations of public transport stops, determining appropriate weaving section lengths, and identifying traffic conditions requiring operational improvements. The methodology may also support decision-making during the design and reconstruction of urban roundabouts by providing a simple analytical tool for preliminary traffic performance assessment. Several limitations of the proposed approach should be acknowledged. The presented methodology is based on simplified assumptions regarding traffic arrival distributions and average public transport dwell times. Furthermore, the proposed framework does not explicitly account for variations in driver behaviour, heavy vehicle composition, weather conditions, or traffic signal interactions. The threshold values presented in the illustrative example are scenario-specific and should not be interpreted as universal design values. Future research should focus on model calibration and validation using field observations collected at urban roundabouts with different geometric and traffic characteristics.

Conclusions

The rationale for treating the exit section of a roundabout located adjacent to a public transport stop as a local critical zone had been established, as this was the area where primary additional vehicle delays were formed. Theoretical analysis had shown that delay formation within this local critical zone was driven by the combined influence of three interrelated factors: a temporary decrease in the capacity of the right-hand lane caused by public transport stop operations, an increase in the intensity of mandatory lane-changing manoeuvres, and a lack of suitable gaps in the adjacent traffic stream. The research objective was achieved by developing a set of criteria for mitigating traffic delays at roundabout exits. The proposed framework was founded on three key principles: minimising total delay experienced by the traffic stream, maintaining consistency between traffic demand and effective lane capacity within the stop influence area, and balancing lane-changing demand with the availability of acceptable gaps in the adjacent traffic stream. The practical value of the findings lay in their applicability to the justification of public transport stop placement, the determination of the required length of weaving sections, and the selection of traffic management and engineering measures intended to enhance the operational performance of roundabouts. The obtained results confirmed that the location of a public transport stop within the roundabout exit influence area significantly affected traffic performance. Relocating the stop beyond the local critical zone could reduce lane-changing demand and improve traffic operating conditions. The illustrative scenario demonstrated the practical applicability of the proposed criteria. For an exit flow rate of 1,000 veh/h and a public transport stop occupancy factor of 0.125, the effective lane capacity was estimated at 1575 veh/h, while approximately 331 acceptable gaps per hour were available for lane-changing manoeuvres. Under these conditions, the traffic stream remained within a stable operating regime. Future research should focus on validating the proposed models through field observations and on identifying the threshold operating conditions of the local critical zone for various traffic control schemes, public transport stop configurations, and numbers of traffic lanes.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Abu Hamad, F., Hasiba, R., Shahwan, D., & Ashqar, H.I. (2024). Driver behavior at roundabouts in mixed traffic: A case study using machine learning. *Journal of Transportation Engineering, Part A: Systems*, 150(12). doi: 10.1061/JTEPBS.TEENG-8325.

[2] Austroads. (2017). *Guide to traffic management, part 3: Traffic studies and analysis*. Sydney: Austroads.

[3] Campi, E., Mastinu, G., Previati, G., Studer, L., & Uccello, L. (2024). Roundabouts: Traffic simulations of connected and automated vehicles – a state of the art. *IEEE Transactions on Intelligent Transportation Systems*, 25(5), 3305-3325. doi: 10.1109/TITS.2023.3325000.

[4] Čulík, K., Kalašová, A., Fabian, P., & Ondruš, J. (2025). Enhancing intersection efficiency: A comparative analysis of converting single-lane roundabout to turbo roundabout. *Sensors*, 25(22), article number 7002. doi: 10.3390/s25227002.

[5] Cvitanić, D. (2017). Joint impact of bus stop location and configuration on intersection performance. *Promet – Traffic & Transportation*, 29(4), 443-454. doi: 10.7307/ptt.v29i4.2338.

[6] DBN V.2.3-5:2018. (2018). *Streets and roads of settlements*. Retrieved from https://e-construction.gov.ua/laws_detail/3199686959802877315?doc_type=2.

[7] DSTU 2587:2021. (2021). *Road traffic safety. Road markings. General technical specifications. Test methods. Rules of application*. Retrieved from https://zakon.isu.net.ua/sites/default/files/normdocs/dstu_2587_2021.pdf.

[8] DSTU 4100:2021. (2021). *Road traffic safety. Traffic signs. General technical specifications. Rules of application*. Retrieved from https://zakon.isu.net.ua/sites/default/files/normdocs/dstu_4100_2021.pdf.

[9] GBN V.2.3-37641918-550:2018. (2018). *Automobile roads. Public transport stops. General design requirements*. Retrieved from https://surl.li/ptkkhf.

[10] Giuffrè, O., Granà, A., & Tumminello, M.L. (2016). Gap-acceptance parameters for roundabouts: A systematic review. *European Transport Research Review*, 8, article number 2. doi: 10.1007/s12544-015-0190-4.

[11] Guerrieri, M. (2024). A practical method for assessing sustainable traffic levels of roundabouts in urban areas using the macroscopic fundamental diagram. *Sustainable Futures*, 7, article number 100157. doi: 10.1016/j.sftr.2024.100157.

[12] Hagring, O. (2001). Derivation of capacity equation for roundabout entry with mixed circulating and exiting flows. *Transportation Research Record: Journal of the Transportation Research Board*, 1776, 91-99. doi: 10.3141/1776-12.

[13] Jiang, H., Shen, Q., Li, A., & Yin, C. (2024). A review of traffic behaviour and intelligent driving at roundabouts based on a microscopic perspective. *Transportation Safety and Environment*, 6(3), article number tdad031. doi: 10.1093/tse/tdad031.

[14] Jin, H., Yu, J., & Yang, X. (2019). Impact of curbside bus stop locations on mixed traffic dynamics: A bus route perspective. *Transportmetrica A: Transport Science*, 15(2), 1419-1439. doi: 10.1080/23249935.2019.1601789.

[15] Liang, Y., Wang, X., Zhang, H., & Liu, Y. (2024). A three-stage cellular automata model of complex large roundabouts. *Sensors*, 24(23), article number 7672. doi: 10.3390/s24237672.

[16] Lieberthal, E.B., Serok, N., Duan, J., Zeng, G., & Havlin, S. (2024). Addressing the urban congestion challenge based on traffic bottlenecks. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 382(2285), article number 20240095. doi: 10.1098/rsta.2024.0095.

[17] Medvediev, I., & Soroka, S. (2020). The road network traffic capacity taking into account public transport stops layout method. *Transport Technologies*, 1(2), 13-22. doi: 10.23939/tt2020.02.013.

[18] National Academies of Sciences, Engineering, and Medicine. (2010). *Roundabouts: An informational guide* (2nd ed.). Washington, DC: National Academies Press. doi: 10.17226/22914.

[19] Polus, A., Shmueli Lazar, S., & Livneh, M. (2003). Critical gap as a function of waiting time in determining roundabout capacity. *Journal of Transportation Engineering*, 129(5), 504-509. doi: 10.1061/(ASCE)0733-947X(2003)129:5(504).

[20] Riaz, M., Khan, S., Ahmad, M., & Ullah, N. (2023). Strategic utilization of microsimulation for sustainable traffic management. *The Open Transportation Journal*, 17, article number e26671212281061. doi: 10.2174/0118744443266712122810 61.

[21] Shaaban, K., & Hamad, H. (2020). Critical gap comparison between one-, two-, and three-lane roundabouts in Qatar. *Sustainability*, 12(10), article number 4232. doi: 10.3390/su12104232.

[22] Yang, X., Mei, H., & Gao, Z. (2013). Car delay model near bus stops with mixed traffic flow. *Journal of Applied Mathematics*, 2013, article number 437637. doi: 10.1155/2013/437637.

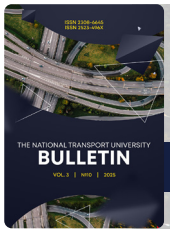
[23] Zadobrischi, E. (2025). Traffic and vehicle management in roundabouts through systems based on dedicated short-range communications and visible light communications. *Electronics*, 14(2), article number 317. doi: 10.3390/electronics14020317.

Критерій зменшення затримок руху на виїзді з кільцевого перехрестя за наявності зупинки міського транспорту

Дмитро Ткаченко
Аспірант
Національний транспортний університет
01010, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
https://orcid.org/0009-0001-0788-5927
Інна Виговська
Кандидат технічних наук, доцент
Національний транспортний університет
01010, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
https://orcid.org/0000-0003-1426-9863

Анотація. Ефективність кільцевих перехресть значною мірою залежить від умов руху на вихідних ділянках, зокрема розташування зупинок громадського транспорту одразу після виїзду з кільця або поблизу нього, що знижує пропускну здатність і підвищує затримки через вимушені маневри та дефіцит прийнятних інтервалів у потоці. Мета роботи полягала у розробленні критеріїв зменшення затримок руху на виїзді з кільцевого перехрестя за наявності зупинки міського транспорту з урахуванням процесів перешикування транспортних засобів та величини граничного інтервалу в суміжній смузі руху. Дослідження виконано з використанням положень теорії транспортних потоків, методів оцінювання пропускної здатності та визначення критичних інтервалів, а також показано, що затримки на виїзді з кільцевого перехрестя зумовлені блокуванням правої смуги громадським транспортом, попитом на перешикування та нестачею придатних інтервалів у суміжному потоці в межах локальної критичної зони. Запропоновано систему критеріїв зменшення затримок, що ґрунтується на мінімізації сумарної затримки в локальній критичній зоні, забезпеченні відповідності інтенсивності транспортного потоку ефективній пропускній здатності виїзду та узгодженні попиту на перешикування з можливістю його реалізації в наявних умовах руху. Також визначено умови переходу транспортного потоку в критичний режим функціонування за показниками швидкості, щільності та пропускної здатності. Для апробації запропонованого методичного підходу розглянуто розрахунковий сценарій функціонування двосмугового виїзду з кільцевого перехрестя. За інтенсивності транспортного потоку на виїзді 1000 авт/год, інтенсивності руху в суміжній смузі 900 авт/год та середній тривалості блокування правої смуги маршрутним транспортом 25 с отримано значення коефіцієнта зайнятості смуги $\varphi = 0{,}125$, що обумовлює зниження її ефективної пропускної здатності до 1575 авт/год. За цих умов інтенсивність руху не перевищує ефективної пропускної здатності виїзду, що забезпечує функціонування транспортного потоку у стабільному режимі та створює передумови для виконання маневрів перешикування без формування критичних затримок. Отримані результати можуть бути використані для обґрунтування розташування зупинок міського транспорту, визначення довжини ділянок перешикування та вибору організаційно-технічних заходів для підвищення ефективності функціонування кільцевих перехресть і зменшення затримок руху

Ключові слова: організація дорожнього руху; транспортний потік; перешикування транспортних засобів; граничний інтервал; пропускна здатність



BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 30 | №2 | 2026
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X

Received: 19.01.2026. Revised: 21.05.2026. Accepted: 25.06.2026. Published: 06.07.2026.

UDC 656.13:629.3:504.06 DOI: 10.33744/2308-6645-2026-2-30-83-92

Operational efficiency of cargo vehicles in terms of energy and environmental criteria

Roman Lovha*
Postgraduate Student
National Transport University
01010, 1 M. Omelyanovych-Pavlenko Str., Kyiv, Ukraine
https://orcid.org/0000-0001-9051-6550

Abstract. Rising fuel costs, stricter decarbonisation requirements for freight transport, and the increasing use of telematics monitoring call for a shift from assessing freight vehicles solely based on average fuel consumption to a mode-specific assessment of their performance on specific routes. The purpose of the study was to substantiate and formalise the model of operational efficiency of vehicles of category N3, which combines fuel, environmental, route, regime, and information indicators. The source base was formed from peer-reviewed publications from 2020-2025, selected based on direct relevance to heavy trucks, real route conditions, telematics or on-board data, eco-management, and emissions. System, comparative, and structural and functional analysis, formalisation of indicators, and scenario modelling were applied. The information of the smart tachograph, Global Positioning System-telematics, Controller Area Network/Fleet Management System/On-Board Diagnostics and fuel sensors was differentiated; equations for fuel consumption per 100 km and tonne-kilometre, weight CO_2, idle and Eco-Roll fractions, average acceleration, speed stability, and integral index were proposed. An analysis of the factors showed that the route and the weight of the road train determine the base load, whilst the most readily controllable factors are the duration of idling, the frequency of acceleration, speed stability, the use of coasting, and the carrier's organisational decisions. Practical operation of the model was demonstrated on a conditional 100-kilometre route of a road train with a gross weight of 36 tonnes with a load of 20 tonnes. Reducing idle speed from 24 to 12 minutes, forming an Eco-Roll share of 6.9% of driving time, and speed stabilisation reduced estimated fuel consumption from 32.4 to 31.1 litres, and direct CO_2 emissions from 85.54 to 82.10 kg; the integral index increased from 0.804 to 0.933. The above scenario is a demonstration scenario and requires further verification based on actual route data. The practical value lies in the ability to use the model to compare trips, identify the causes of cost overruns, and provide recommendations to the driver and dispatcher under specific route and operational conditions

Keywords: fuel efficiency; route profile; Eco-Roll; smart tachograph; telematics; Controller Area Network; Fleet Management System

Introduction

Freight road transport provides a significant part of domestic and international commodity flows, but its operational effectiveness is increasingly linked to energy consumption and environmental impact. For vehicles of category N3, this issue is aggravated due to the large gross weight of the road train, long routes, variable longitudinal road profile, and a high share of engine performance under load. The average fuel consumption per route characterises the final result, but does not explain how much of the overspending occurred as a result of idling, heavy acceleration, unstable speed, unfavourable slope, underloading, or technical deviations. Therefore, it is advisable to interpret operational efficiency as the result of interaction between the vehicle, route, cargo, driver, and

Suggested Citation: Lovha, R. (2026). Operational efficiency of cargo vehicles in terms of energy and environmental criteria. *Bulletin of the National Transport University*, 30(2), 83-92. doi: 10.33744/2308-6645-2026-2-30-83-92.

*Corresponding author (*roman.lovga@gmail.com*)

Copyright © The Author(s). This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/)

information control system. The transition to real-world evaluation requires reliable measurements. J. Pavlovic *et al.* (2021) showed that the accuracy of determining actual fuel consumption depends not only on on-board fuel metering, but also on the correctness of measuring the distance travelled and matching On-Board Diagnostics (OBD) and Global Positioning System (GPS) data. J.I. Huertas *et al.* (2022) and F. Jelti & R. Saadani (2024) confirmed on the material of the logistics corridor with variable topography that the route profile significantly changes the actual fuel consumption compared to standard estimates. These results suggest that the energy indicator should be formed after synchronisation of spatial, temporal, and fuel data, and not by a single final value.

A separate area is related to the use of on-board and telematics parameters. H. Abediasl *et al.* (2024) proved the possibility of estimating instantaneous flow from OBD parameters coming from an electronic control unit. J.J. Posada-Henao *et al.* (2023) found a statistically significant effect of total weight and road slope on truck fuel consumption. L. Fang *et al.* (2025) proposed segmentation of time series of speed, acceleration, and other sensory parameters to recognise driver behaviour and generate targeted recommendations for eco-driving. The combination of these approaches creates grounds to consider individual driving modes as independent objects of assessment. The environmental result of exploitation should be considered together with the energy result, but not reduced to it. A. Magnino *et al.* (2024) showed that the choice of a power unit for heavy fleets should consider both efficiency and sustainability of operation. Systematic review by G. Gentilucci *et al.* (2025) showed significant variability in the life cycle estimates of diesel and non-emission trucks depending on the boundaries of the system and energy source. P.D. Larson *et al.* (2024) identified the infrastructure and logistics barriers of emission-free mainline transport, whereas M. Penchev *et al.* (2025) emphasised the need to use real-world data in a full life assessment. Therefore, for the existing diesel fleet, reducing unproductive fuel consumption remains a practically significant means of reducing direct CO_2 emissions.

Available studies reveal individual elements of the problem in detail, but less often combine the origin of operational data, mode segmentation, energy formulas, environmental indicators, and control output in one transparent procedure. For Ukrainian carriers, this is of additional importance due to the heterogeneity of the fleet: vehicles of different brands and generations may have a smart tachograph, GPS terminal, access to the Controller Area Network (CAN)/Fleet Management System (FMS) or only a limited set of parameters. Uncertainty of the indicator source creates a risk of misinterpretation: the tachographic speed does not characterise the engine load, the GPS coordinate does not determine fuel consumption, and the value with CAN/FMS needs to be checked by an independent measuring channel. The purpose of the study was to develop a formalised structure for evaluating the operational efficiency of cargo vehicles based on energy and environmental criteria, considering driving modes, route conditions, Eco-Roll, and digital monitoring. To achieve this objective, the following measures were established:

1. To differentiate the information capabilities of the smart tachograph, telematics platforms and on-board vehicle systems and formalise key indicators necessary for assessing traffic, load, fuel consumption, and operational efficiency;

2. To identify and rank the main factors affecting the fuel efficiency of heavy cargo transport, considering their influence, handling, and connection with the Eco-Roll mode and the logic of the structural model;

3. To demonstrate the practical application of the proposed approach to the calculated route scenario and compare the results obtained with the provisions of contemporary research on modelling the fuel efficiency of cargo vehicles.

Materials and Methods

The object of the study was the operational efficiency of cargo vehicles of category N3 in domestic and international transportation, and the subject was the relationship between driving modes, fuel efficiency, direct CO_2 emissions, and information completeness of monitoring. The source database was formed in May-June 2025 among peer-reviewed publications of 2020-2025. The final sample included papers that simultaneously met at least two criteria: examined heavy cargo vehicles or road trains; used real route, telematics, OBD/CAN/FMS, or fuel data; analysed idle speed, acceleration, steady motion, coasting, or predictive control; contained energy or environmental indicators and DOI. Duplicates, materials without a description of the methodology, studies only of passenger cars, and papers in which the route context was not separated from the design characteristics were excluded. As a result, 22 sources were selected. The theoretical basis for formalisation consisted of studies by A. Hamednia *et al.* (2022) and G.R. Gonçalves Da Silva & M. Lazar (2022) on eco-management, H.I. Ashqar *et al.* (2024) on behavioural parameters. The study had a theoretically-analytical and computationally applied design. System analysis was used to build the "vehicle – route – driver – data – energy result – environmental result" contour. Comparative analysis was used to establish common and distinctive positions in models of real fuel consumption, telematics control, and eco-control. Structural and functional analysis provided a distribution of factors by origin, influence, manageability, and information needs. Scenario modelling was used to demonstrate a practical sequence of calculations without presenting a conditional example as a field experiment.

The operational profile of the route was divided into idle, acceleration, steady motion, inertia/Eco-Roll, and braking. Idling was identified by zero speed and engine running; acceleration – by positive acceleration; steady motion – by deviation of speed and acceleration within the specified limits; Eco-Roll – by movement of a vehicle without traction load with a confirmed transmission

condition or the corresponding on-board flag; braking – by negative acceleration in combination with the state of the service braking system, retarder, or engine braking. This segmentation provided a separate calculation of duration, distance, and fuel consumption for each mode.

Operational data sources were differentiated by their actual function. The smart tachograph provided timestamps, speed and distance travelled, driver identification, work and rest modes, events, malfunctions, and GNSS positions; it did not measure engine load or actual fuel consumption. GPS telematics provided continuous data on coordinates, route, speed, stops, geofences, and estimated acceleration. CAN/FMS/OBD was the source of engine speed and load, accelerator pedal position, selected gear, cruise control status, retarder, operating hours, and available fuel consumption values. Independent fuel probes or flow meters were used to detect changes in fuel reserve, refueling/draining events, and cross-check on-board accounting. The choice of approach was based on synchronising these channels on a single timeline, rather than attributing all metrics to a single device. The evaluation criteria were grouped into energy, environmental, regime, and information blocks. The energy block contained route and specific fuel consumption; environmental – direct CO_2 emissions and the context of NOx and PM generation; mode – idle and Eco-Roll fractions, average acceleration and speed stability; information – the presence and consistency of tachographic, GPS, and on-board parameters. To compare routes, the indicators were normalised to the interval 0-1 and combined into a weighted integral index:

$$q_{100} = 100 \cdot Q^f / L, \quad (1)$$

where q_{100} – fuel consumption per 100 km, L/100 km; Q^f – fuel volume per route, l; L – route length, km.

$$q_{tkm} = Q^f / (m^c \cdot L), \quad (2)$$

where q_{tkm} – specific fuel consumption, L/(t·km); mc – cargo weight, t.

$$MCO_2 = k_{CO_2} \cdot Q^f, \quad (3)$$

where MCO_2 – direct CO_2 emissions, kg; k_{CO_2} – accepted conversion factor for a specific type of fuel, kg/L.

$$k_{id} = t_{id} / t_{eng} \cdot 100\%, \quad (4)$$

where k_{id} – idle speed share; t_{id} – its duration; t_{eng} – total engine operating time.

$$k_{ER} = t_{ER} / t_{mov} \cdot 100\%, \quad (5)$$

where k_{ER} – share of Eco-Roll; t_{ER} – duration of the mode; t_{mov} – vehicle travel time.

$$\bar{a} = (1/n) \cdot \Sigma[(v_{2,i} - v_{1,i}) / \Delta t_i], \quad (6)$$

where $\bar{a}$ – average acceleration in the selected overclocking events; n – number of events.

$$I_v = \max[0; 1 - \sigma_v / \bar{v}], \quad (7)$$

where I_v – speed stability index; σ_v – standard deviation; v – average speed on a homogeneous area.

$$I_{eff} = w_Q \cdot I_Q + w_{CO_2} \cdot I_{CO_2} + w_{id} \cdot I_{id} + w_{ER} \cdot I_{ER} + w_v \cdot I_v; \Sigma w_j = 1, \quad (8)$$

where I_{eff} – integral index; I_j – normalised partial indicators; w_j – weighting coefficients set in accordance with the evaluation purpose.

Results and Discussion

The formalisation results showed that the operational efficiency of the vehicle has a hierarchical structure. The first level consists of parameters that are only loosely controlled within the context of a single route – the vehicle's design, gross vehicle weight, body type, and road profile. The second level comprises the driving modes that can be controlled in real time – idle, acceleration intensity, speed stability, coasting, and the use of braking systems. The third level covers the carrier's organisational decisions: loading, route planning, maintenance, and driver control. Digital monitoring performs an end-to-end function, as it converts the listed factors into measurable parameters and provides their comparison between routes.

Table 1. Factors of operational efficiency of cargo vehicles by energy and environmental criteria

Group of factors	Content	Impact on energy efficiency	Impact on environmental efficiency
Vehicle-related factors	Engine type, transmission, environmental standard, vehicle weight, technical condition	Determine the basic fuel requirement and power loss	Affect the level of emissions under real operating conditions
Route factors	Road profile, slope, traffic density, speed limit, route length	Change the proportion of acceleration, steady-state movement, and inertia movement	Affect CO_2 emissions and pollutant generation
Operating modes	Idling, acceleration, steady motion, inertia motion, engine braking	Determine instantaneous and average fuel consumption	Form the intensity of emissions under different engine loads
Driver behaviour	Choice of speed, acceleration intensity, braking style, use of cruise control	Can increase or decrease fuel consumption under comparable route conditions	Affects excessive fuel combustion and associated emissions
Digital monitoring	Smart tachograph, telematics, event recording, mileage and speed data	Provides data for detecting inefficient use	Supports monitoring of violations and deviations in environmental indicators
Organisational factors	Maintenance, route planning, loading planning, compliance monitoring	Reduce avoided fuel losses and unproductive mileage	Provide a systematic reduction of harmful effects on the environment

Source: developed by the author

The data in Table 1 allowed ranking factors based on two characteristics – the strength of impact and the possibility of operational adjustment. The gross weight, slope, and speed of the road train have the greatest basic impact, as they determine the need for traction. J.J. Posada-Henao *et al.* (2023) attributed weight and slope to factors whose influence exceeded that of velocity under the studied conditions. However, these parameters may not always be changed by the driver during the route. Idle time, acceleration amplitude, speed selection, and the moment of transition to coasting have the highest operational handling. Their adjustment does not require vehicle replacement but does require reliable time series of speed, acceleration, and powertrain operating status. Technical factors are divided into constructive and state-dependent ones. The type of engine and transmission determines potential efficiency, while tyre pressure, condition of injectors, transmission supports, and operation of neutralisation systems can be improved by maintenance. Monitoring study by M.A. Costagliola *et al.* (2025) showed that the effect of technical measures depends on the initial condition of the vehicle: older or polluted power systems have the greatest reserve. Thus, technical modernisation is a capital-intensive area, and maintenance is a managed medium-term factor. Route and organisational factors require different data. Slope, curvature, speed limit, and traffic density are determined by GPS tracking and a digital map; loading is determined by documents or weight estimation; idling and acceleration are determined by telematics; speed, transmission, cruise control, and braking modes are determined by CAN/FMS. Backload planning, reducing empty mileage, and agreeing on arrival times mostly depend on dispatching decisions. Therefore, digital monitoring itself does not reduce fuel consumption, but provides an evidence-based basis for choosing technical, security or organisational intervention. Figure 1 shows a generalised logic of the relationship between route conditions, operating modes, energy and environmental indicators of a cargo vehicle of N3 category.

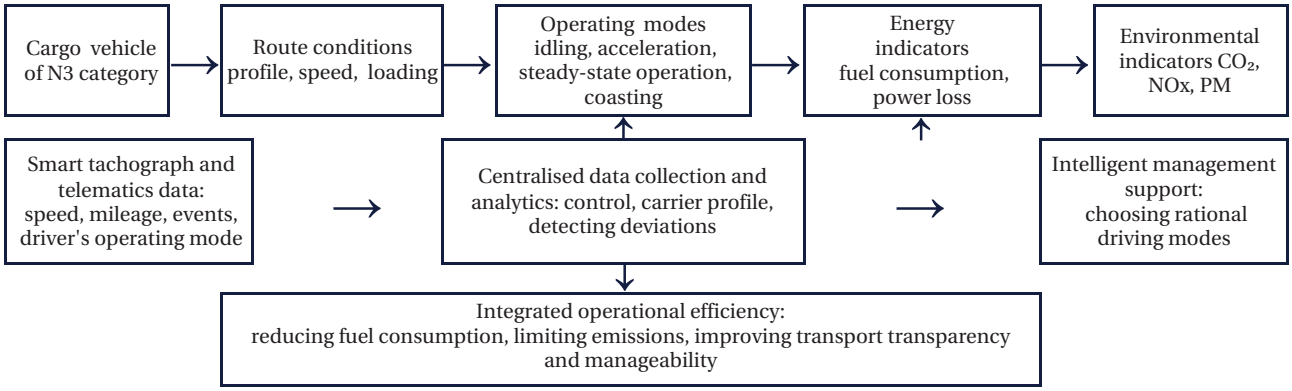


Figure 1. Structural model for evaluating the operational efficiency of cargo vehicles
Source: compiled by the author

The logic of Figure 1 starts with four groups of input data. Static parameters include category, mass, engine type, transmission and emissions standard; route-related parameters include coordinates, gradient, length, speed limits and load; dynamic parameters include speed, acceleration, revs, engine load, gear selection and the condition of the braking systems; organisational parameters include driver identification, working hours, stops and deviations from the schedule. The smart tachograph provides normatively significant time and mode recordings, telematics provides a detailed route profile, and CAN/FMS/OBD provides the state of the power unit. After synchronisation, the data is segmented into driving modes. The energy block of the model calculates q_{100}, q_{tkm}, the proportion of unproductive idle speed, mode flow rate, and speed stability. The environmental unit determines direct CO_2 emissions by the amount of fuel burned, and interprets NOx and PM only if appropriate on-board or measurement data is available, as they depend on the temperature, load, and operation of neutralisation systems. This separation prevents methodological errors when tachographic or GPS data is attributed to indicators that are actually generated by an electronic control unit or an external meter. At the output, partial indexes are normalised and combined into I_{eff}. The integral value does not replace individual indicators, but is used to rank comparable trips under the same cargo and route conditions. Low I_{eff} must be decomposed into the following components: excess k_{id} indicates an organisational or behavioural problem; low I_v – on unstable management; and insufficient k_{ER} with a favourable profile – on the unused reserve of kinetic energy. It is this schedule that forms the management recommendation, and not just states the final fuel consumption. The sequence of making control decisions on the choice of rational driving modes on a section of a route with a complex profile, in particular using Eco-Roll, is summarised in Figure 2.

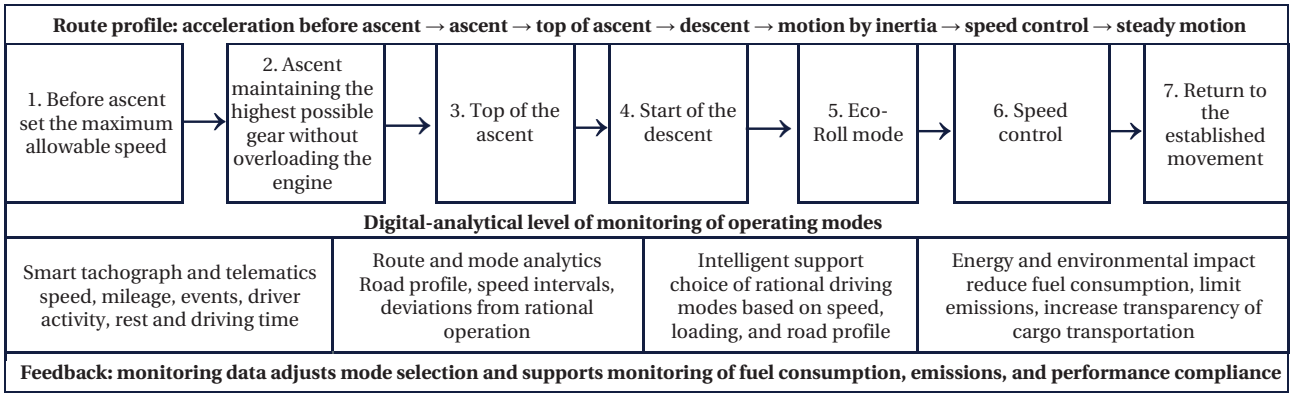


Figure 2. Road train driving modes on a route section with a complex profile

Source: compiled by the author

Figure 2 shows a sequence in which the decision on Eco-Roll is made not after the appearance of a descent, but after predicting the speed at its end. The mode is suitable when the longitudinal slope and accumulated kinetic energy allow maintaining traction without traction, the predicted speed remains below the limit with a safe reserve, and the transmission structurally supports automatic disconnection. For the conditional scenario, descents of 2-4% are accepted, the initial speed is 5-10 km/h lower than the permissible and the total weight of 36 tonnes; these limits are the parameters of the example, and in the real system should be calculated by drag forces, weight, curvature, pavement, and road situation. The effect of driving by inertia is reduced if the driver accumulates excessive speed in advance and is forced to actively apply a retarder, engine braking, or service brakes. In this case, some of the kinetic energy that was supposed to be used to overcome the next section is converted into heat in the braking mechanisms. The transition to braking should occur after reaching the calculated speed threshold, and not immediately after the start of descent. The proposed logic is consistent with approach of G.R. Gonçalves Da Silva & M. Lazar (2022), where mode control is related to previous slope information and the result by J. Hong *et al.* (2025), which received savings of 5.73% for their coordinated predictive cruise control and coasting strategy. This value characterises specific research conditions and is not automatically transferred to other routes. At least the GPS/tachograph speed and time, longitudinal profile, transmission status or on-board designation, engine speed, instantaneous/accumulated fuel consumption, and retarder and brake signals are required to record the Eco-Roll duration and performance. Temperature, wind, tyre pressure, and traffic density are auxiliary factors. Without confirming the condition of the transmission, normal downhill driving should not be automatically classified as Eco-Roll. The regime structure determines not only the average consumption, but also the reason for it. Idling has the worst fuel-transport ratio, since the denominator of useful work is zero. Acceleration generates the highest short-term costs due to the need for inertial force, especially with a large weight. Steady-state driving is the basic economy mode when the engine is running in an efficient zone, and Eco-Roll has the greatest conditional savings potential on suitable descents. Braking provides safety, but its excessive frequency indicates a loss of previously stored energy. Table 2 shows the dependence of energy and environmental indicators of cargo vehicles on operating modes.

Table 2. Impact of operating regimes on the energy and environmental performance of cargo vehicles

Operating mode	Technical characteristics	Energy effect	Environmental impact	Monitoring parameter
Idle speed	Engine runs without performing useful transport work	Unproductive fuel consumption	Emissions without moving cargo	Idle time, engine operating time
Overclocking	Increased speed with a high tractive effort requirement	Increased instantaneous fuel consumption	Increased intensity of emissions under load	Speed gradient, acceleration, engine load
Steady motion	Driving at a relatively stable speed and gear ratio	Potentially efficient mode at rational speed	Stable emissions when the engine is running in the efficient zone	Speed stability, route section, fuel consumption
Motion by inertia/ Eco-Roll	Vehicle is moved by kinetic energy; the power unit can be disconnected from the transmission	Reduction of engine load and fuel requirements	Reduction of CO_2 in proportion to fuel economy	Duration of movement by inertia, road slope, speed limit
Engine/retarder braking	Controlled speed reduction on descents	Prevents speeding, but reduces the effect of driving by inertia	Supports traffic safety; has an indirect impact on emissions	Braking events, descent sections, speed limit compliance

Source: compiled by the author

According to Table 2, the most problematic in the specific dimension is idling, and in the instantaneous – intensive acceleration. Cuts have the greatest potential without constructive modernisation of k_{id}, decrease in average acceleration, speed stabilisation, and increase of k_{ER} in safe areas. Mandatory analysis parameters are time, speed, distance travelled, engine condition, fuel volume, and identified mode. Acceleration requires additional acceleration and load, while Eco-Roll requires slope, transmission/transmission condition, and brake signals. Temperature, wind, and coating conditions increase accuracy, but are auxiliary in the absence of appropriate sensors. Quantitative interpretation involves calculating the idle speed fraction as a percentage of engine running time, Eco-Roll duration and distance, the average and 95th acceleration percentile, the number of decelerations per 100 km, the speed range and fuel consumption for each mode. Approach of A. Liu *et al.* (2025) confirmed the significance of engine parameters, driver behaviour, and weight, and A. Schoen *et al.* (2019) showed the suitability of telematics data for modelling the flow rate of heavy trucks. The proposed model differs in that it preserves the transparent origin of each indicator and allows it to be used even for a fleet with different digital equipment. The resulting system of priorities showed that the average route consumption should be analysed after rationing for cargo and separating the regime components. For two routes with the same q_{100} the reasons can be different: in one case – prolonged idling, in the second – high weight and lifting. Therefore, the comparison was performed first in homogeneous groups by vehicle, weight, route, and weather conditions, and then by k_{id}, k_{ER}, $\bar{a}$ and I_v.

The results also confirmed the need for cross-testing of fuel. The CAN/FMS value is suitable for high-frequency mode analysis, but it is advisable to compare the trip result with a calibrated fuel probe, flow meter, or refuelling documents. Channel divergence should be considered as an indicator of data quality, and not hidden by averaging. In the absence of a reliable fuel channel, the model can evaluate the operating profile, but should not claim accurate savings. The smart tachograph in the proposed structure performs a regulatory and temporal function. It confirms the driver's identity, speed, mileage, activity, and events, but does not replace CAN/FMS for RPM, load, gear, accelerator pedal, or fuel consumption. The telematics platform combines these channels, performs time synchronisation, and binds them to coordinates. This distribution ensures reproducibility of the calculation and allows specifying which indicator is measured and which is derived. Energy and environmental criteria remain interrelated, but functionally different. Reducing Qf directly reduces MCO_2, while NOx and PM can change non-linearly due to temperature, transient loads, and the operation of cleaning systems. Therefore, in the absence of PEMS or validated on-board data, the environmental section of the paper is limited to direct CO_2 measurements and a qualitative analysis of the conditions under which other components are formed. The practical application of the structure involves the sequence "conditions – segmentation – calculation – diagnosis – recommendation". First, the route profile is generated, then the synchronised data is distributed by mode, after which partial and integral indicators are calculated. The deviation is decomposed into factors, and only then the action is selected: reducing downtime, changing the acceleration profile, adjusting the speed, using Eco-Roll, technical verification, or changing the route organisation. The sequence of practical use of the model is presented in Table 3.

Table 3. Stages of evaluating the operational efficiency of cargo vehicles

Stage	Analytical content	Expected result
Route characteristics	determining route length, slope, speed limits, traffic conditions, and stops	description of external operating conditions
Characteristics of the vehicle and cargo	identification of category, weight, engine, transmission, and environmental standard	technical basis for evaluation
Segmentation of driving modes	selection of idle, acceleration, steady state, inertia, and braking modes	operational profile of the route
Assessment of energy indicators	analysis of fuel consumption, idle speed, driving duration by inertia, and speed stability	energy efficiency profile
Assessment of environmental indicators	interpretation of CO_2 emissions and harmful substances according to fuel consumption and engine operating modes	environmental efficiency profile
Digital feedback	use of tachograph and telematics data to detect deviations and select rational modes	basis for intelligent control algorithms

Source: compiled by the author

A fundamental feature of Table 3 is the prohibition of switching to integral evaluation until quality control and data segmentation are completed: an error in time binding or incorrect classification of the descent as Eco-Roll directly distorts the result. At the first stage, the dispatcher or researcher sets a homogeneous comparison group for the car, cargo, and route. On the second stage, passes, refuelling events, GPS, and on-board time consistency are checked. On the third stage, the route is segmented by mode, and then calculated q_{100}, q_{tkm}, MCO_2, k_{id}, k_{ER}, $\bar{a}$, and I_v. The fifth stage is compared to the reference trip or target limits. The final step turns the detected deviation into a specific recommendation and involves repeated measurement after its implementation. For the demonstration, a conditional route with a length of 100 km with 6 km of ascents with a slope of 3-5%, 8 km of descents with a slope

of 2-4%, and 86 km of flat and mixed sections was used. The gross weight of the road train was 36 tonnes, the cargo weight was 20 tonnes, and the driving time was 105 minutes. The baseline scenario provided for 24 minutes of idle time, no confirmed Eco-Roll, a standard speed deviation of 9.0 km/h and a flow rate of 32.4 litres. The rational scenario provided for 12 minutes of idle time, 7.2 minutes of Eco-Roll, a standard deviation of 6.2 km/h and a flow rate of 31.1 litres. For the demonstration recalculation of CO_2, it is accepted that $k_{CO_2} = 2.64$ kg/L.

Table 4. Calculated example of estimating a 100-kilometre trip

Indicator	Basic scenario	Rational scenario	Change / interpretation
Route length; cargo; gross weight	100 km; 20 t; 36 t	100 km; 20 t; 36 t	Comparison conditions are the same
Idle speed	24 min; $k_{id} = 18.60\%$	12 min; $k_{id} = 10.26\%$	-8.34 pp
Eco-Roll	0 min; $k_{ER} = 0\%$	7.2 min; $k_{ER} = 6.86\%$	8 km of suitable descents were used
Fuel consumption Qf	32.4 L	31.1 L	-1.3 l; -4.01%
q_{100}	32.4 L/100 km	31.1 L/100 km	–4.01%
q_{tkm}	0.01620 L/(t·km)	0.01555 L/(t·km)	-0.00065 L/(t·km)
Direct CO_2 emissions	85.54 kg	82.10 kg	-3.44 kg; -4.01%
Speed stability I_v	0.842	0.891	+0.049
Integral index I_{eff}	0.804	0.933	+0.129; +16.0%

Note: these figures are for illustrative purposes only
Source: compiled by the author

The calculation showed that reducing idle speed and rational use of coasting reduced Qf and MCO_2 by 4.01%. Since the load and length remained unchanged, the same relative improvement was obtained for q_{tkm}. The integral index is calculated with weights wQ = 0.35; $wCO_2 = 0.25$; wid = 0.15; wER = 0.10; wv = 0.15, a reference flow rate of 30 L/100 km and a target share of Eco-Roll of 8%. The 16.0% increase in the I_{eff} exceeds the relative reduction in fuel consumption, as the index considers idling discipline, speed stability, and the use of suitable downhill gradients. The example demonstrates how the model works, but is not proof of universal savings of 4%. Its purpose is to show how scenarios that are identical in route and cargo are compared by regime structure. Field validation requires repeated trips, uncertainty assessment, weather monitoring, traffic, tyres, technical condition, and CAN/FMS verification via an independent fuel channel.

The proposed model is consistent with conclusions of A. Hamednia *et al.* (2022) that the economy mode should be determined not by an isolated driver response, but by a forecast over a longer horizon. Their algorithm optimises the velocity trajectory, while this study focuses on a transparent structure of metrics and data sources suitable for a heterogeneous park. Therefore, the result obtained does not replace the optimisation controller, but forms the measurement and criterion level necessary for its further application. The findings of G.R. Gonçalves Da Silva & M. Lazar (2022) confirmed the key role of preliminary slope information in driving trunk modes. The logic proposed in Figure 2 corresponds to the following approach: Eco-Roll is chosen after predicting the final speed, and not just based on descent. The difference is that data origin, weight control, transmission status, and brake signals have been added to the road profile, without which the actual mode can be classified incorrectly. The conclusion about high manageability of behavioural factors corresponds to H.I. Ashqar *et al.* (2024), who showed the feasibility of including driving style in fuel forecasting. A.S. Mane *et al.* (2021) also used telematics data to identify behavioural parameters associated with overspending. In this paper, the behavioural block was specified through k_{id}, $\bar{a}$, I_v, and the number of brakes, but its impact is separated from the weight and route. This is important because without rationing, the driver of a heavier road train on a more complex profile may get an unreasonably lower rating. Z. Zhang *et al.* (2023) found a significant association between truck driver behaviour, fuel consumption, and CO_2 emissions. The proposed model confirms this relationship for direct CO_2 emissions, since they are proportional to the volume of fuel burned. Simultaneously, it restricts the interpretation of NOx and PM in the absence of PEMS or a validated on-board channel. This precaution narrows down the environmental conclusion, but increases its validity and prevents fuel reduction from being identified with the same change in all pollutants. A. Schoen *et al.* (2019) and A. Liu *et al.* (2025) demonstrated the capabilities of telematics and explicable machine models for predicting the flow rate of heavy trucks. The advantage of such methods is their high predictive power, but they require a representative training sample. Proposed index I_{eff} has another function: it provides an interpreted trip comparison to the accumulation of a large data set. In the future, formalised metrics can be used as attributes for machine learning, and model results can be used as controls for logical consistency of the forecast. The estimated cost reduction of 4.01% does not contradict the result of J. Hong *et al.* (2025), who received 5.73% for coordinated predictive cruise control and coasting under their own simulation conditions. The lower value in the above scenario is explained by the fact that Eco-Roll covered only 6.86% of the driving time, and part of the effect was formed by reducing idle speed. Thus, the model demonstrates a valid directional response: an increase in the proportion of rational coasting and a decrease in unproductive modes improve the energy and CO_2 result. The limitations of this study include the hypothetical nature

of the scenario, the lack of field replicates, and the need to calibrate the I_{eff} weights for a specific carrier. The practical significance of the model lies in the transition from rating cars by one average consumption to diagnosing the causes of the result. For the carrier, the source document can be a route profile with the share of modes, data quality, comparison with the standard, and a list of recommended actions. Recommendations should be checked by a repeat trip, which turns the model into a closed cycle of improvement. For the existing diesel fleet, this cycle complements long-term decarbonisation with short-term measures: reducing idle speed, stabilising speed, monitoring technical condition and rational use of kinetic energy. It does not replace the upgrade of power units, but it allows quantifying reserves until the fleet is updated.

Conclusions

The study formalised an evaluation model for the operational efficiency of category N3 vehicles, integrating data acquisition, operating mode segmentation, and the calculation of energy and environmental performance indicators. It was established that the smart tachograph provides time, speed, and mode recordings of the driver; GPS-telematics – route and stops; CAN/FMS/OBD – parameters of the engine, transmission, and available fuel consumption; independent fuel channel – control of the actual stock change. This distinction defines the validity limits of each conclusion. The analysis of factors showed that the weight and profile of the road have a high basic impact, but limited operational handling. The most accessible adjustments without replacing the vehicle are the idle speed ratio, acceleration intensity, speed stability, rational coasting, and organisational decisions of the carrier. Eco-Roll is recommended only if the predicted compliance with speed and safety limits, the presence of a suitable slope and a confirmed condition of the transmission; excessive braking reduces its effect due to kinetic energy dissipation. Eight basic dependencies were proposed for q_{100}, q_{tkm}, MCO_2, k_{id}, k_{ER}, average acceleration, speed stability, and I_{eff}. On the conditional route of 100 km, reducing idle speed from 24 to 12 minutes, using Eco-Roll for 6.86% of the driving time and stabilising the speed reduced the estimated flow rate from 32.4 to 31.1 litres and direct CO_2 emissions from 85.54 to 82.10 kg; I_{eff} increased from 0.804 to 0.933. The result obtained confirmed the operability of the proposed model, but it cannot be considered a full-fledged field validation. Practical application of the model involves the formation of homogeneous trip groups, data quality control, regime segmentation, calculation of partial indicators, diagnosis of the causes of deviations, and re-verification after the implementation of recommendations. Further research should be aimed at analysing the series of repeated trips, calibrating fuel channels, assessing the uncertainty of results, and adapting the scales of the integral index to the operating conditions of a particular fleet.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Abediasl, H., Ansari, A., Hosseini, V., Koch, C.R., & Shahbakhti, M. (2024). Real-time vehicular fuel consumption estimation using machine learning and on-board diagnostics data. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 238(12), 3779-3793. doi: 10.1177/09544070231185609.

[2] Ashqar, H.I., Obaid, M., Jaber, A., Ashqar, R., Khanfar, N.O., & Elhenawy, M. (2024). Incorporating driving behavior into vehicle fuel consumption prediction: Methodology development and testing. *Discover Sustainability*, 5, article number 344. doi: 10.1007/s43621-024-00511-z.

[3] Costagliola, M.A., Marchitto, L., Piras, M., & Berra, A. (2025). Effect of performance packages on fuel consumption optimization in heavy-duty diesel vehicles: A real-world fleet monitoring study. *Energies*, 18(20), article number 5542. doi: 10.3390/en18205542.

[4] Du, K., Shi, Q., Song, J., Chen, D., & Liu, W. (2025). Prediction of truck fuel consumption based on Crossformer-LSTM characteristic distillation. *Applied Sciences*, 15(1), article number 283. doi: 10.3390/app15010283.

[5] Fang, L., Li, H., Zheng, Y., & Luo, X. (2025). Driving behavior recognition and fuel economy evaluation for heavy-duty vehicles. *Research in Transportation Business & Management*, 60, article number 101371. doi: 10.1016/j.rtbm.2025.101371.

[6] Gentilucci, G., Accardo, A., & Spessa, E. (2025). Life cycle greenhouse gas emissions of diesel oil and zero-emission trucks: Systematic review of status and perspectives. *Transportation Research Interdisciplinary Perspectives*, 32, article number 101563. doi: 10.1016/j.trip.2025.101563.

[7] Gonçalves da Silva, G.R., & Lazar, M. (2022). Long hauling eco-driving: Heavy-duty trucks operational modes control with integrated road slope preview. In *2022 European control conference (ECC)* (pp. 1752-1758). Piscataway, NJ: IEEE. doi: 10.23919/ECC55457.2022.9837981.

[8] Hamednia, A., Sharma, N., Murgovski, N., & Fredriksson, J. (2022). Computationally efficient algorithm for eco-driving over long look-ahead horizons. *IEEE Transactions on Intelligent Transportation Systems*, 23(7), 6556-6570. doi: 10.1109/TITS.2021.3058418.

[9] Hong, J., Liu, Y., Li, M., Zhu, J., Tian, M., & Na, X. (2025). Coordinated predictive cruise and coasting control for energy saving in heavy-duty trucks. *Advances in Mechanical Engineering*, 17(12). doi: 10.1177/16878132251403630.
[10] Huertas, J.I., Serrano-Guevara, O., Díaz-Ramírez, J., Prato, D., & Tabares, L. (2022). Real vehicle fuel consumption in logistic corridors. *Applied Energy*, 314, article number 118921. doi: 10.1016/j.apenergy.2022.118921.
[11] Jelti, F., & Saadani, R. (2024). Energy efficiency analysis of heavy goods vehicles in road transportation: The case of Morocco. *Case Studies on Transport Policy*, 17, article number 101260. doi: 10.1016/j.cstp.2024.101260.
[12] Larson, P.D., Parsons, R.V., & Kalluri, D. (2024). Zero-emission heavy-duty, long-haul trucking: Obstacles and opportunities for logistics in North America. *Logistics*, 8(3), article number 64. doi: 10.3390/logistics8030064.
[13] Liu, A., Fan, P., He, X., Lu, H., Yu, L., & Song, G. (2025). CatBoost-based fuel consumption modeling and explainable analysis for heavy-duty diesel trucks: Impact of engine, driving behavior, and vehicle weight. *Energy*, 333, article number 137485. doi: 10.1016/j.energy.2025.137485.
[14] Magnino, A., Marocco, P., Saarikoski, A., Ihonen, J., Rautanen, M., & Gandiglio, M. (2024). Total cost of ownership analysis for hydrogen and battery powertrains: A comparative study in Finnish heavy-duty transport. *Journal of Energy Storage*, 99, article number 113215. doi: 10.1016/j.est.2024.113215.
[15] Mane, A.S., Djordjevic, B., & Ghosh, B. (2021). A data-driven framework for incentivising fuel-efficient driving behaviour in heavy-duty vehicles. *Transportation Research Part D: Transport and Environment*, 95, article number 102845. doi: 10.1016/j.trd.2021.102845.
[16] Pavlovic, J., Fontaras, G., Broekaert, S., Ciuffo, B., Ktistakis, M., & Grigoratos, T. (2021). How accurately can we measure vehicle fuel consumption in real world operation? *Transportation Research Part D: Transport and Environment*, 90, article number 102666. doi: 10.1016/j.trd.2020.102666.
[17] Penchev, M., Johnson, K.C., Raju, A.S.K., & Akinci, T.C. (2025). Comprehensive well-to-wheel life cycle assessment of battery electric heavy-duty trucks using real-world data: A case study in Southern California. *Vehicles*, 7(4), article number 162. doi: 10.3390/vehicles7040162.
[18] Posada-Henao, J.J., Sarmiento-Ordosgoitia, I., & Correa-Espinal, A.A. (2023). Effects of road slope and vehicle weight on truck fuel consumption. *Sustainability*, 15(1), article number 724. doi: 10.3390/su15010724.
[19] Schoen, A., Byerly, A., Hendrix, B., Bagwe, R.M., dos Santos, E.C., & Miled, Z.B. (2019). A machine learning model for average fuel consumption in heavy vehicles. *IEEE Transactions on Vehicular Technology*, 68(7), 6343-6351. doi: 10.1109/TVT.2019.2916299.
[20] Serrano-Guevara, Ó.S., Huertas, J.I., & Giraldo, M. (2025). Real energy efficiency of road vehicles. *Energies*, 18(8), article number 1933. doi: 10.3390/en18081933.
[21] Zhang, Z., Demir, E., Mason, R., & Di Cairano-Gilfedder, C. (2023). Understanding freight drivers' behavior and the impact on vehicles' fuel consumption and CO_2e emissions. *Operational Research*, 23(4), article number 59. doi: 10.1007/s12351-023-00798-2.

Експлуатаційна ефективність вантажних транспортних засобів за енергетичними та екологічними критеріями

Роман Ловга
Аспірант
Національний транспортний університет
01010, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
https://orcid.org/0000-0001-9051-6550

Анотація. Зростання вартості палива, посилення вимог до декарбонізації вантажних перевезень і поширення телематичного контролю потребують переходу від оцінювання вантажного транспортного засобу лише за середньою витратою палива до режимно-орієнтованої оцінки його роботи на маршруті. Метою дослідження було обґрунтувати й формалізувати модель експлуатаційної ефективності транспортних засобів категорії N3, яка поєднує паливні, екологічні, маршрутні, режимні та інформаційні показники. Джерельну базу сформовано з рецензованих публікацій 2020-2025 років, відібраних за безпосередньою релевантністю важким вантажним автомобілям, реальним маршрутним умовам, телематичним або бортовим даним, еко-керуванню та викидам. Застосовано системний, порівняльний і структурно-функціональний аналіз, формалізацію показників та сценарне моделювання. Розмежовано інформацію смарт-тахографа, Global Positioning System-телематики, Controller Area Network/Fleet Management System/On-Board Diagnostics і паливних датчиків; запропоновано формули витрати палива на 100 км і тонно-кілометр, маси CO_2, часток холостого ходу та Eco-Roll, середнього прискорення, стабільності швидкості й інтегрального індексу. Аналіз чинників показав, що маршрут і маса автопоїзда визначають базове навантаження, тоді як найбільш оперативно керованими є тривалість холостого ходу, інтенсивність розгонів, стабільність швидкості, використання вибігу та організаційні рішення перевізника. Практичну роботу моделі продемонстровано на умовному 100-кілометровому маршруті автопоїзда повною масою 36 т із вантажем 20 т. Скорочення холостого ходу з 24 до 12 хв, формування частки Eco-Roll 6,9 % часу руху та стабілізація швидкості зменшили розрахункову витрату палива з 32,4 до 31,1 л, а прямі викиди CO_2 – з 85,54 до 82,10 кг; інтегральний індекс зріс з 0,804 до 0,933. Наведений сценарій є демонстраційним і потребує подальшої перевірки за фактичними маршрутними даними. Практична цінність полягає у можливості використовувати модель для порівняння рейсів, виявлення причин перевитрати та формування рекомендацій водієві й диспетчеру за конкретних маршрутних та експлуатаційних умов

Ключові слова: паливна економічність; маршрутний профіль; Eco-Roll; смарт-тахограф; телематика; Controller Area Network; Fleet Management System

ВІСНИК

НАЦІОНАЛЬНОГО ТРАНСПОРТНОГО УНІВЕРСИТЕТУ

VOL. 30 | № 2 | 2026

Відповідальний редактор:
Олексій Шумейко

Підписано до друку 25.06.2026
Формат 60*84/8
Ум. друк. арк. 11
Наклад 100 прим.

Видавництво:
Національний транспортний університет
01010, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
E-mail: ntu@ntu-bulletin.com
https://ntu-bulletin.com/uk

BULLETIN

THE NATIONAL TRANSPORT UNIVERSITY

TOM 30 | No. 2 | 2026

Managing Editor:
Oleksii Shumeiko

Approved for publication 25.06.2026
Format 60*84/8
Conventional Printed Sheet 11
Circulation 100 copies

Publisher:
National Transport University
01010, 1 M. Omelianovych-Pavlenko Str., Kyiv, Ukraine
E-mail: ntu@ntu-bulletin.com
https://ntu-bulletin.com/en