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CONTENT

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OPTIMIZATION OF TRAFFIC SIGNAL CONTROL AT ROAD INTERSECTIONS

From a functional perspective, intersections are the most complex elements of road networks. This is where paths of traffic from different directions intersect, leading to various maneuvers. This underscores the importance of efficient traffic regulation, especially at intersections, in enhancing safety and improving efficiency. The article investigates the complex relationship between transportation infrastructure and the quality of public life, emphasizing the significance of effective traffic control, particularly at intersections, in enhancing safety and increasing efficiency. The research is aimed at optimizing traffic light management at congested four-way intersections in cities, with the goal of reducing congestion, increasing safety, and improving traffic flow. In most intersections with heavy traffic, traffic movement is regulated by traffic lights, and inefficient settings can lead to unjustified long waiting periods and increased overall traffic delays. For simulation modeling of traffic conditions at this intersection, PTV Vissim software was used. Observations of traffic flows, their distribution by direction, and parameters of traffic light regulation were used as input data for intersection modeling. The results of the modeling identified various approaches to optimizing traffic light management, including adjusting cycle times and considering passenger flows, with a particular emphasis on adaptive systems that respond to real-time traffic parameters. The study identifies challenges such as variable traffic flow and proposes solutions such as extending green phases and introducing pedestrian phases. It concludes by emphasizing the importance of collecting and interpreting dynamic traffic movement parameters for effective traffic light regulation, particularly in the implementation of automated traffic management systems.

Keywords: intersection, vehicle, traffic flow, traffic signal control, road conditions modeling.

INTRODUCTION

Transport and the quality of public life are inextricably related. This connection is greatly influenced by the role that highways, streets, and sidewalks play in our lives. Excellent transport connections are crucial for the development of the national economy.

From the functional point of view, the intersection is the most complex element of the road network. It is here that the traffic flows in different directions cross, and various maneuvers take place. This indicates that the intersection is a place with an increased concentration of conflict situations and an increased risk of traffic accidents.

At most of the high-flow intersections, traffic is controlled by traffic lights, and their inefficient operation can lead to unnecessarily long wait times and overall increase in traffic delays.

Therefore, it is extremely important to properly regulate road traffic in order to ensure the rational use of the intersection's potential, the increase in the throughput of all its elements, safety driving and efficiency [1, 2].

ANALYSIS OF LITERATURE DATA.

Traffic management in large cities is a complex and not always solved process, especially when it comes to managing intense traffic flows through regulated intersections. One of the primary tools for traffic management is traffic signalization, designed to organize the sequential movement of road users through intersections or specific street segments, as well as to mark hazardous zones on the road.

The optimization of traffic signal control regimes has attracted the attention of researchers in both domestic and foreign literature. Among them, studies by scholars such as V. P. Polishchuk, V. I. Eresov, M. P. Pechersky, Ye.Yu. Fornalchyk,, I. A. Mohyla, B. M. Chetverukhin, V. T. Kapitanov, Ye. O. Pidkhody, as proposed by [11-20], allow identifying the advantages of simulation modeling in the study of intersection functioning, applying various tools and mechanisms in adaptive control algorithms, and organizing traffic considering the needs of pedestrians and public transport. Scientific research by Reitzen, F. Webster, H. Inose, T. Hamada [22-25], and others.

Scientific works dedicated to various aspects of traffic management at regulated intersections in cities are studied by foreign scientists. Specifically, issues under investigation include analyzing the reliability of pedestrian crossings in urban conditions (Guo H.), determining current road and intersection capacities (Highway Capacity Manual), improving public transport priority systems at intersections (Kim W.), developing control algorithms based on fuzzy logic and simulation modeling (Kosonen I., Madhavan Nair B., Murat Y. Sazi), as well as optimizing response time to changes in traffic flow (Newell G., Noland R.).

Some studies explore the establishment and effectiveness of fixed and adaptive traffic signal control cycles (Miller A. J., Pappis C., Sosin J. A.) [11,13]. Possibilities of using basic knowledge for developing intersection control algorithms (Pranevicius H.) [17] and developing controllers based on fuzzy logic in the VISSIM environment are also investigated (Staniek M., Stotsko Z.) [12-14].

Thus, literary sources cover a wide range of problems related to traffic management at regulated intersections in cities, from pedestrian safety to the development of complex control algorithms.

Some aspects of traffic management at regulated intersections remain insufficiently researched or require further study. For example, integration with other transport systems, which could improve management efficiency and enhance safety, is often overlooked. Less attention is paid to environmental aspects and adaptive management, which could contribute to emissions reduction and energy consumption. Also important is considering the needs of pedestrians and cyclists, which significantly impacts safety and comfort in urban mobility.

FORMULATION OF THE PROBLEM.

The most significant issue at most existing traffic light installations is the constant increase in the number of vehicles, requiring continuous monitoring and timely response. The purpose of the research is to optimize traffic light control at a four-way intersection, adapting to road conditions, aimed at reducing congestion, improving safety and traffic flow, as well as enhancing the overall productivity of the transportation system.

The research analyzed a regulated intersection at the crossing of Stepana Bandery and Viacheslava Chornovola main streets in the city of Rivne. This intersection is characterized by constant significant traffic jams.

PURPOSE AND OBJECTIVES OF THE STUDY.

The main role of traffic lights, i.e. light signals for regulating traffic at intersections, is to separate (reduce) conflict situations between vehicles, pedestrians and other traffic participants at the intersections. Light signals regulate traffic flows in such a way as to allow vehicles from one flow group (non-conflicting or conflicting) to pass in a given time interval (phase), while vehicles from the other flow group are paused at the same time.

The regulation of vehicles is carried out based on a signal plan, which uniformly takes into account all flows grouped within phases. The main problem that needs to be solved when it comes to a signalized intersection is the calculation and optimization of the signal plan, which involves determining the length of the cycle, the number of phases, as well as the calculation of the distribution of green signal intervals for each phase (short cycles of 60-90 seconds are ideal for urban areas [3]). Traffic lights can operate in a fixed mode, when the signal plans are determined based on the pre-collected traffic data, and as adaptive systems, when the traffic lights operate depending on changes in traffic parameters, such as flow, speed, density and others.

Optimization of traffic light control at road intersections is a process aimed at improving the efficiency of the traffic light system to ensure the safety and smooth flow of vehicular traffic. This process may involve various aspects such as optimizing the timing of traffic light cycles, considering passenger flow, and installing sensors for automatic regulation (Figure. 1).

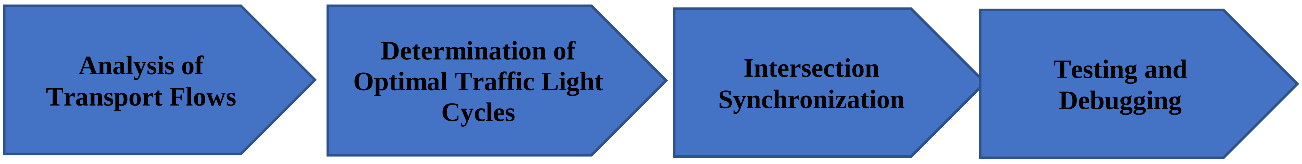


Figure. 1. Key Steps in Traffic Light Control Optimization

To model traffic conditions at the studied intersection with traffic light regulation, the research used PTV Vissim multimodal traffic simulation software [4].

RESEARCH RESULT.

An intersection, also known as a node, denotes the point where two or more road segments intersect, excluding access roads, and is delineated by the edges of the roads or, if absent, by the lateral boundary lines of the roadway.

Selecting the appropriate type of intersection for a given scenario can be a multifaceted and contentious decision. Regardless of the circumstances, the primary objective is to establish the safest feasible configuration of the intersection while ensuring an acceptable level of mobility, with the aim of optimizing traffic safety. The safety and requirements of all road users, including pedestrians and cyclists, especially those with disabilities or limited mobility, must be considered, as their needs can significantly influence decisions regarding traffic organization and management strategies.

Intersections are structured based on urban design principles, tailored to their specific location and the nature of present or anticipated regional development. This process considers the potential necessity for revised traffic organization, implementation of traffic light controls, projected traffic volume, and vehicle size considerations.The constructive elements of the studied intersection are shown in Figure. 2.

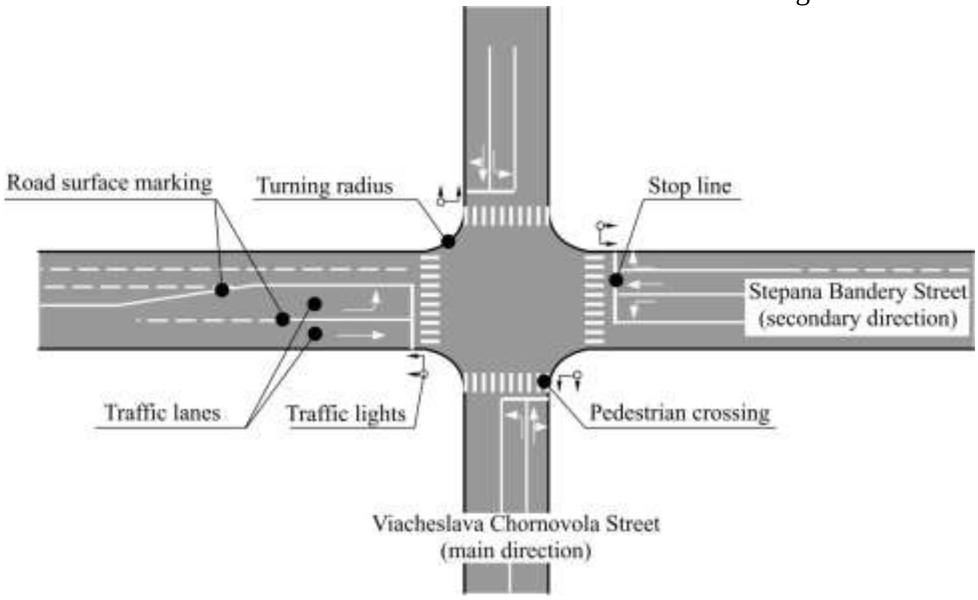


Figure. 2. Basic elements of the studied four-way intersection in the city of Rivne

The organization of the traffic at the intersection is mainly determined by the intensity of the traffic flow. At a low traffic intensity, the intersection can function as an unregulated one, and as the flow increases, the organization of traffic at the intersection becomes possible only with the use of traffic signals (Figure. 3).

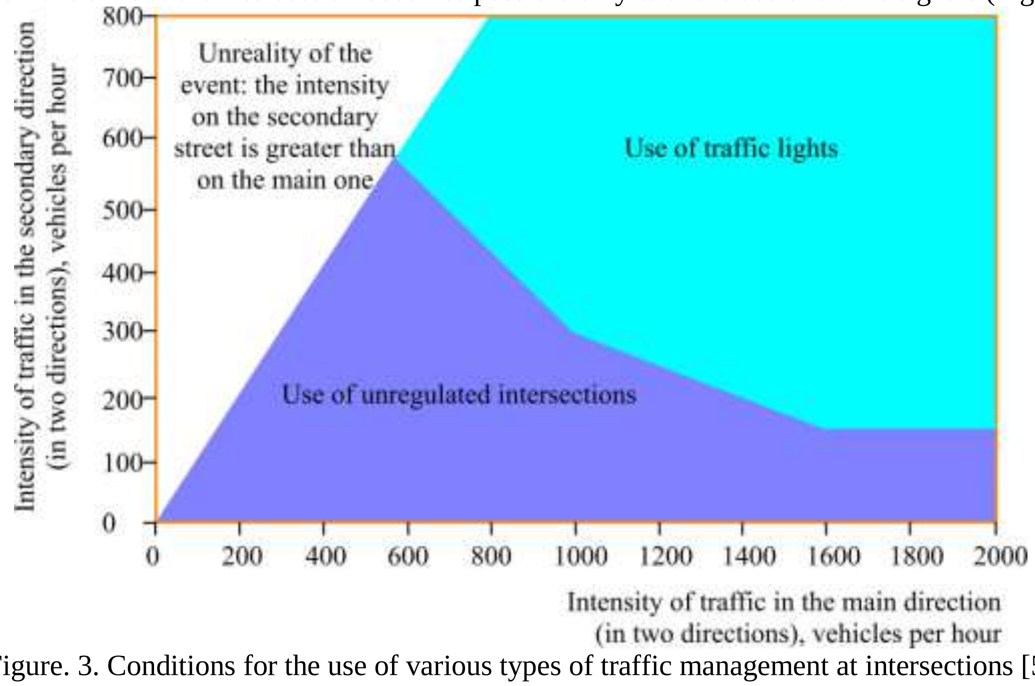


Figure. 3. Conditions for the use of various types of traffic management at intersections [5]

Traffic light regulation is one of the measures commonly used at intersections to minimize travel time and delays for vehicles and/or pedestrians. Traffic light regulation at intersections allows traffic control by allocating time slots during which separate traffic flows at each approach to the intersection can use the available road space [6].

DISCUSSION OF THE RESULTS OF THE STUDY.

Regulated with traffic lights intersections in the city of Rivne are controlled using a fixed time (all signal parameters are calculated in advance and kept constant based on the traffic data). This method usually shows good results under normal traffic conditions, but it sometimes fails to cope with complex time-varying traffic conditions.

From the point of view of planning, systems with a fixed mode are most often implemented as static, with a constant cycle length during the day, and dynamic, which take into account the non-stationarity of the traffic flow during the day. In dynamic systems, the day is divided into a number of time intervals, assuming that for each separate time interval, traffic flows are constant [7].

There are three main concepts that describe the sequence of traffic signals – cycle, phase and duration: cycle (the total time required to complete one sequence of signals for all movements at the intersection), phase (unit of controller time associated with one or more movements) and duration (the amount of time the signal is displayed in each phase) [8]. Furthermore, a traffic flow group is defined as one or more compatible movements of road users, and each phase has a set of time slots for each traffic flow group.

The main problem that must be solved when considering isolated traffic light intersections is the calculation and optimization of the signal plan, which involves: determining the number of phases; determining cycle duration; distribution, i.e. determining parts of available green time for each phase; modeling of traffic situations that may arise due to the passage of priority vehicles, congestion of vehicles in intersection areas during peak periods or other situations. At the same time, it is necessary to achieve the best possible characteristics of the intersection functioning.

At the studied intersection, two-phase traffic light regulation with fixed cycles for the main direction (Viacheslava Chornovola Street, 30 seconds) and the secondary direction (Stepana Bandery Street, 30 seconds) is used (Figure. 4).

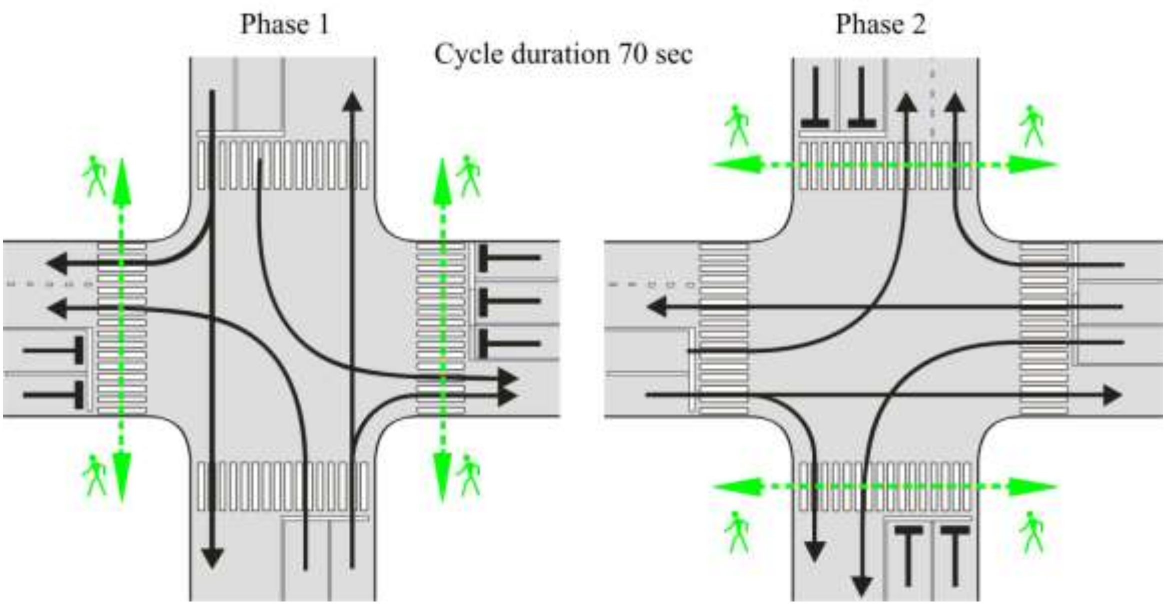
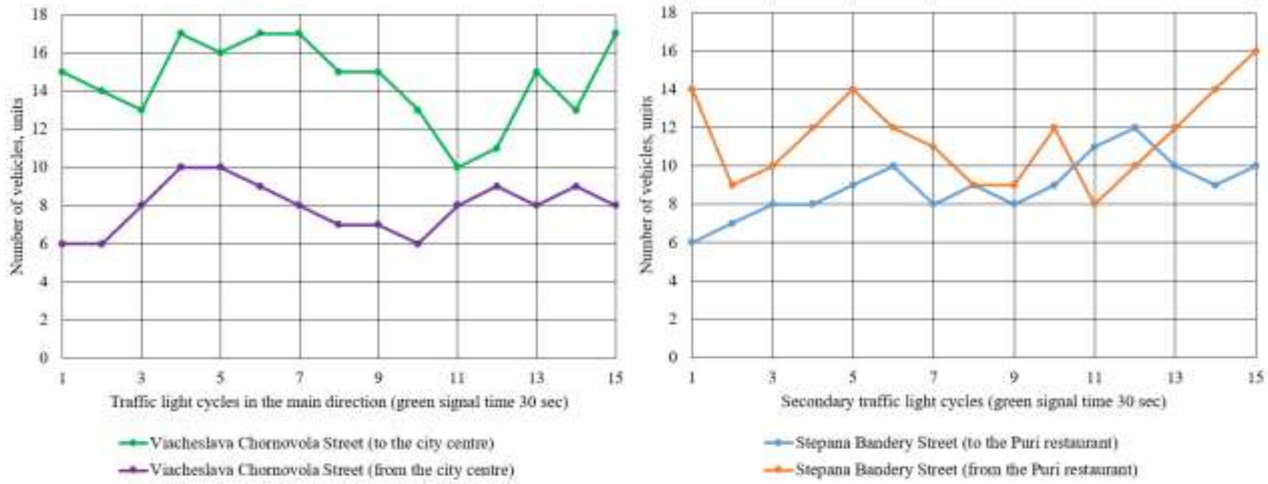


Figure. 4. Traffic light regulation at the Viacheslava Chornovola and Stepana Bandery streets intersection, city of Rivne

The flow of vehicles that pass through the intersection during one cycle of the traffic light signal is uneven, ranging from 17 to 6 vehicles and depends on the time period. The traffic flow reaches its peak during the commuting time (Figure. 5).



а) *б)*

Figure. 5. Number of vehicles that pass through the intersection during one cycle of the traffic light signal for the main (a) and secondary (b) direction

An increase in the number of trucks and buses in the traffic flow is accompanied by a decrease in the number of vehicles that pass the intersection, which is explained by their lower speed, more time spent on the start of movement and other factors (Figure. 6).

The maximum throughput of the intersection is determined by the theoretical possibility of the traffic flow to pass the selected node at the most probable speed within one hour.

The saturation flow is the flow of vehicles from the queue in front of the stop line, which move according to the permissive signal of the traffic light [8]. In its essence, it is a traffic flow that exists when the roadway (traffic lane) is operating at throughput capacity.

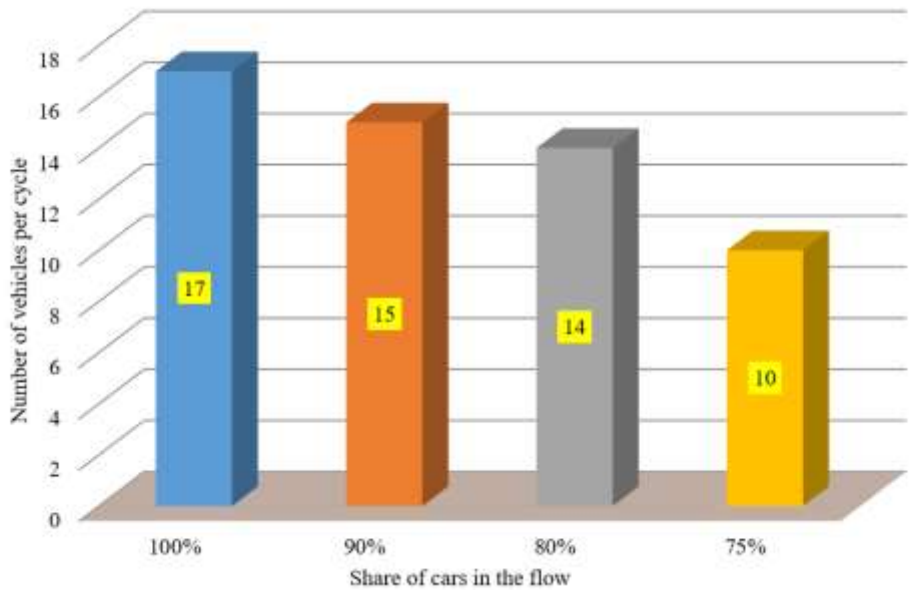


Figure. 6. Throughput capacity of the intersection for one cycle of traffic light regulation depending on the composition of the traffic flow

An important assessment indicator, which characterizes the functioning of the intersection and depends primarily on its geometric parameters, is the degree of saturation of traffic directions, that is, the maximum intensity of vehicles per hour through the intersection. The average value is 724 cars, which indicates overloading of the studied intersection and requires its redesigning by changing the duration of traffic light regulation (Figure. 7).

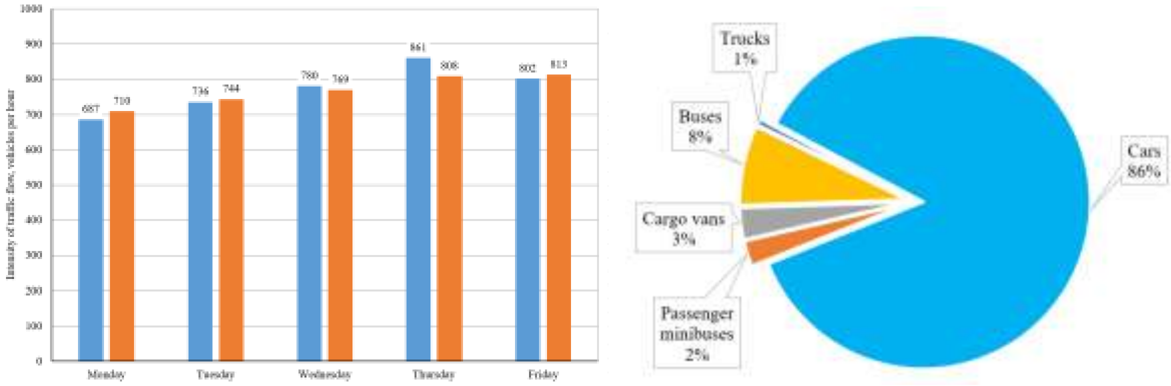


Figure. 7. Structure of the traffic flow in the main direction – Viacheslava Chornovola street (8:00-9:00 a.m.)

The studied intersection uses to 60-70% of its throughput capacity according to the selected cycles of the traffic light regulation and needs their optimization or significant changes in the organization of the traffic flow (Figure. 8).

The number of vehicles in the queue affects the throughput capacity of the intersection and the speed of the flow. In particular, when the queue of vehicles increases to 20 units, the throughput capacity of the lane decreases by 1.5-2 times.

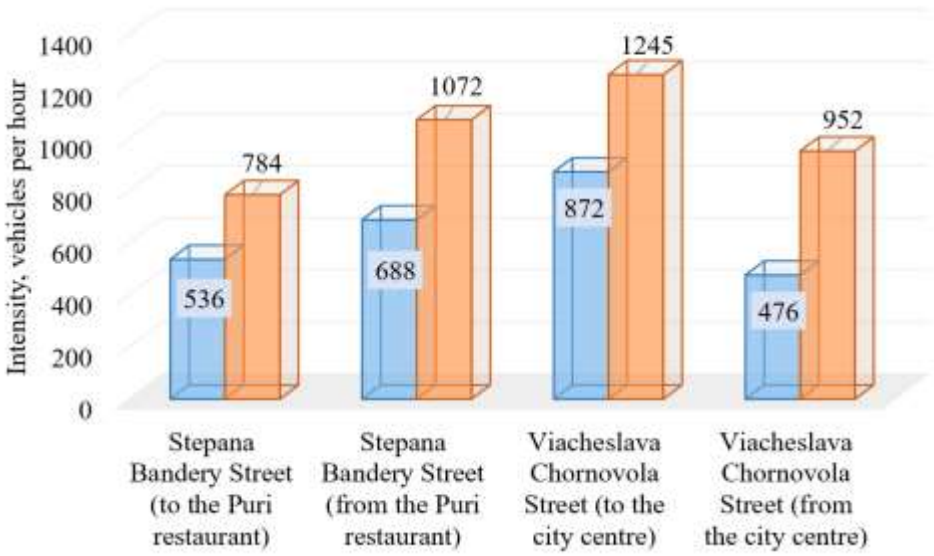


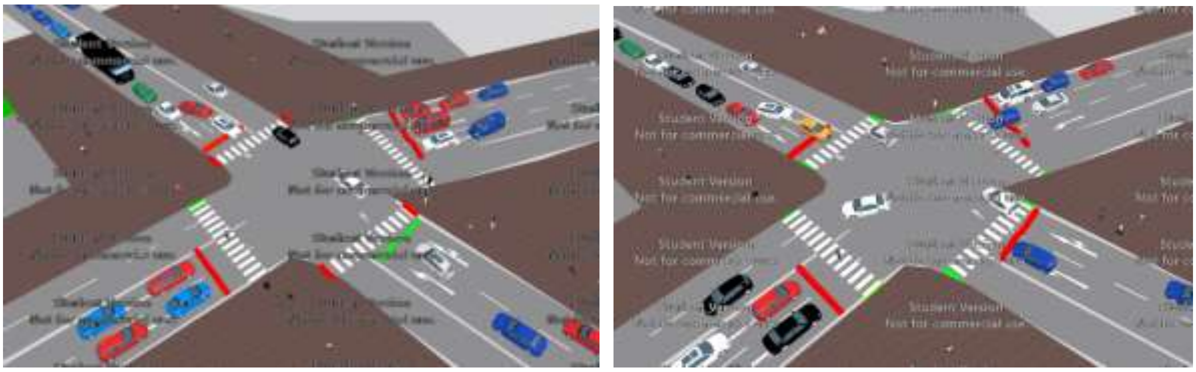
Figure. 8. Actual and estimated indicators of the traffic flow by direction (averaged values)

According to the research results, the road conditions were modeled and the signal plan was optimized with the use of PTV Vissim software. Simulation modeling of the intersection included drawing a road network, installing traffic lights (signal controllers) with a description of their work (choosing the type of light signaling devices, creating signal groups and traffic light signals, parameters for coordinating signals), forming pedestrian zones and a node, performing calculations with subsequent analysis of the received data.

In order to improve the efficiency of the intersection, two options for the operation of the traffic light controllers are offered (Figure. 9):

1. Lengthening of the "green" phase, for the convenience of turning to the left (by reducing the phase of oncoming traffic in one direction by 5 seconds). The total duration of the cycle of 70 seconds will not change;

2. Implementation of the third phase – fully pedestrian in all directions, lasting 20 seconds. The total duration of the cycle will increase to 90 seconds.



а) *б)*

Figure. 9. Options for modeling traffic light regulation modes by extending the “green” phase (a) and implementing the third pedestrian phase (b)

Such changes are needed because it is quite difficult to make a left turn at the intersection. Although the studied intersection has two (in one direction – three) traffic lanes, the extreme one of which is intended for making a left turn, the number of vehicles that can perform such a maneuver at the permissive traffic light signal remains low and, in the best case, makes 3-4 vehicles.

In addition, the close location of another regulated intersection 500 m away for both the main and secondary directions, from which the queue of vehicles quite often reaches the studied intersection, reduces the capacity of the studied intersection with the frequent formation of traffic jams (Figure. 10). Therefore, the disruption of the traffic flow in all directions at the same time will be an effective measure, which can be implemented during peak periods of traffic accumulation.

Figure. 10. Formation of a traffic jam at the intersection due to a significant accumulation of vehicles at the exit

A more progressive measure can be the introduction of adaptive systems, which are based on new traffic monitoring technologies and allow obtaining accurate data on traffic flows in real time and performing adaptive control of traffic lights, that is, adapting the signal plan in real time to changes in traffic flows (Figure. 11).

The solution based on the proposed algorithm simplifies the use of the system, and also requires significantly lower costs for its implementation and maintenance [9,10].

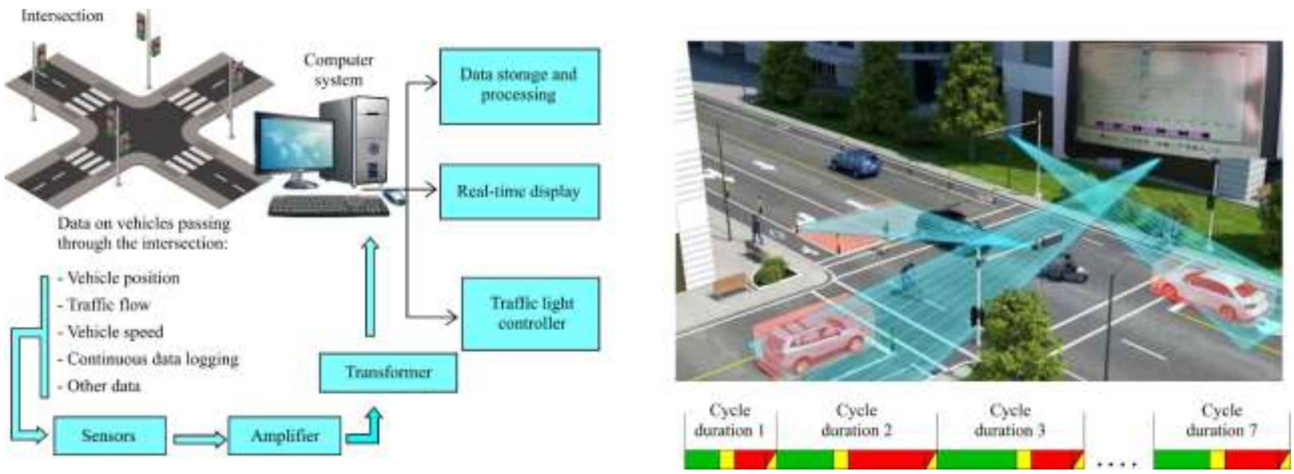


Figure. 11. Adaptive traffic light control system

One of the main requirements for the successful deployment of an effective, city-wide, automated traffic control system is an accurate estimation of the number of vehicles on the roads (this can be achieved in various ways, such as the use of inductive loops, magnetic sensors, magnetometers or even cameras).

SUMMARY

Thus, a successful solution to the effective operation of the traffic light regulation of the intersection requires the collection and interpretation of dynamic parameters of traffic flows; elimination or minimization of the possibility of traffic jams by changing the duration of both a separate phase and the entire traffic light cycle; determining the relationship between the parameters of the queue of outgoing vehicles and the throughput capacity of the intersection.

In the case of using an automatic system when receiving dynamic data about the traffic flow, the obtained data can serve as a basis for developing an algorithm for controlled regulation of the duration of the permissive traffic interval for the formation of a queue of vehicles entering the intersection.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

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CASE STUDY ON IMPLEMENTING TRAFFIC CALMING DEVICES: AN EXAMPLE FROM THE STREET AND ROAD NETWORK IN KHARKIV

The continuous growth of the car fleet and the underdevelopment of city streets and road networks require constant improvement in traffic management. The article suggests considering modern means, such as traffic calming, an essential component of strategies for ensuring road safety and creating a comfortable public area.

The analysis of existing traffic calming devices and their application practice abroad have proved the need for their widespread implementation to reduce vehicle average speeds to a safer level, reduce the number of road accidents and the severity of their consequences, and improve the conditions for movement on the street and road network for all road users.

The article analyses the implementation of three schemes of traffic management at a pedestrian crossing, namely, with the use of road signs and road markings only; with the provision of an elevated pedestrian crossing, road signs and road markings; with the use of road humps, road signs and road markings. The dependences of the average length of the traffic jam, the average delay time, and the average number of stops of one vehicle on the intensity of traffic and pedestrian flows when arranging a pedestrian crossing under the three options are obtained, which can be used for a preliminary assessment of their arrangement at pedestrian crossings.

It is substantiated that the average value of the traffic jam length, the average number of stops, and the average delay per vehicle are influenced by the traffic flow intensity, where the estimated indicators increase with their increase. As the area of influence of traffic calming devices and their geometric characteristics increases, the evaluation indicators also increase, i.e., since an elevated pedestrian crossing has smaller geometric parameters than a complex of pedestrian crossings with road humps, we have lower values of the evaluation indicators.

Keywords: traffic calming devices, pedestrian crossing, intersection, road hill, markings, transport modelling, criterion, analysis.

INTRODUCTION

Traffic calming is a set of measures and strategies to reduce vehicle speeds and create a safe and comfortable public space for all road users. These measures may include various engineering, educational and legal aspects. The main objective of road calming is to reduce the risk of road traffic accidents (RTAs) and the severity of their consequences, as well as to improve safety for pedestrians, cyclists, and other road users. Around the world, traffic calming is an essential component of road safety and public realm strategies that have been widely adopted, including the "three E's" (engineering, education, enforcement), and help create a safer and more harmonious environment for all road users. It also reflects a modern approach to urban planning and infrastructure.

Adequately applied traffic calming measures reduce vehicle average speeds to a safer level, reduce the number of RTAs and the severity of their consequences, improve conditions for pedestrians, cyclists, and public transport, and reduce transit traffic [1]. This type of measure has rarely been considered in the national urban planning literature and has not been applied in our country.

ANALYSIS OF LITERATURE DATA AND FORMULATION OF THE PROBLEM

Traffic calming is achieved by street and road network (SRN) changes and technical measures.

First, when creating traffic calming zones, transit traffic through the city centre is eliminated by turning through streets into loop streets, dead-ends, etc. In addition, vehicle speed limits are imposed, which can dramatically reduce the number of conflicts between traffic and pedestrian flows [2]. We want to emphasise that when designing calming zones, street landscaping and space design play a vital role and are considered as a means of influencing traffic modes. The zones are often serviced by public transport, which is given priority in the city. Therefore, it is possible to combine, for example, pedestrian traffic and tram lines (Strasbourg, Saint-Etienne) or pedestrian traffic and bus routes (Dijon). The organisation of street space, landscaping, and design ensure the priority of pedestrian and cyclist movement and stimulate a reduction in vehicle speed. In particular, it allows the capacity of the SRN or some of its sections to be reduced [3].

The range of techniques and means of traffic calming is extensive: organisation of parking zones; sewerage, lane separation; use of sharp turns; deviation of the trajectory at the intersection; use of road humps (speed bumps); narrowing of streets; restriction of access; use of roadway elevations with a change in road surface texture; application of restrictions on the size of vehicles; use of dead-end streets; redevelopment of streets; use of roundabouts; use of traffic control elements [4].

When determining the effectiveness of traffic calming, the following main results are achieved by this method: reduction in the number and severity of road accidents in cities at intersections and crossings, reduction in vehicle speed, and reduction in transit traffic in the city.

The specific results of a successful traffic calming policy can be illustrated by the example of Bruges [3], where traffic calming was introduced in the historic city centre in 1992. The following results were achieved: a 30% reduction in traffic intensity in the city centre; an increase in bus speed from 19 to 22 km/h; a 10% reduction in the number of vehicles arriving in the city centre (by 600 vehicles/h); a 33% increase in the number of residents using the bus; a 20% increase in the number of residents using bicycles; a 36% reduction in the number of road accidents in the city centre.

Data on the implementation of traffic calming in Graz (Austria) also indicate positive results: in particular, speed limits significantly impacted traffic safety and contributed to a positive assessment of traffic calming measures by residents and drivers.

In the United States, the first major experiment to implement a calming zone was the Stevens Neighbourhood in Seattle. The project, completed in early 1973, resulted in a 56% reduction in traffic intensity and a 0% reduction in road accidents.

Traffic calming is used to redistribute traffic to the SRN. It should be noted that using calming and speed limit zones implies that maintaining vehicles is performed by other sections and elements of the SRN. This is well confirmed by the data from surveys carried out in the places where these measures are implemented. According to the literature, namely [5], data analysis from 43 international studies showed that using traffic calming measures in cities reduces road accidents by 8-100%. At the same time, there was not a single case of road accidents increasing after introducing these devices, i.e., positive results and feedback were obtained in all cases.

According to [6], there are three groups of traffic calming devices:

1. Arrangement of obstacles on the carriageway (implemented using road humps, elevated pedestrian crossings and elevated intersections);
2. Change the trajectory of traffic (implemented using chicanes, mini-roundabouts, sewerage, and blocking traffic flows).
3. Change the width of the carriageway (implemented using chokers and inserts along the road axis).

Foreign studies in this area are aimed at comparing the number of accidents before and after the introduction of means of traffic calming. So, in [7], an analysis of data on road accidents with fatal consequences and injured on road sections showed that the introduction of means of vertical deceleration reduces the number of dead and injured by 60%; placement of safety islands with horizontal marking and flexible reflective poles - by 72.7%; and the placement of safety islands on the main road - by 35.7%. Interesting developments in [8], where the best measures for slowing down traffic are marked - a raised pedestrian crossing and narrowing of the lane. At the same time, the authors insist that even better results can be obtained when more than one means is used along the street to limit movement, the distance between which is not too large. In [9], the same authors compare the speed reduction from the introduction of increased pedestrian crossings and narrowing of traffic lanes. But it should take into account the effect of the driver's memory, which is stored along the entire length of the narrowed carriageway (for example, due to parking zones), when after the passage of an increased pedestrian crossing the driver does not save slow speed.

A number of other studies highlight the positive impact of using traffic calming techniques on roads, in which the authors see them as an effective tool for achieving peace, ensuring safety and improving the situation on the roads [10], a combination of strategies to reduce the negative impact on the environment, improving the safety and separation of the impact of the vehicle to assess the impact on the individual and society as a whole [11], a combination of predominantly physical measures to reduce the negative impact of vehicle, correct driving style and create better conditions for other road users, including pedestrians and cyclists [12]. Analysis of these sources revealed that traffic calming measures could be classified into 13 broad categories and take the form of diverse combinations or additional applications to existing SRN.

Analysis of domestic theoretical studies on the use of means of traffic calming shows that they mainly have a recommendatory nature of their use in Ukraine, based on the effectiveness of their use abroad. For example, in [13] it is indicated that raised pedestrian crossings contribute to the safe movement of pedestrians through the carriageway and should be common in our country, despite the high cost of their arrangement. The work [14] points out the spread of the use of means of traffic calming in some cities of Ukraine, an important advantage of which is the possibility of simultaneous speed control and restriction of transit traffic. Much attention is paid to the effectiveness of introducing mini-rings [15], but the authors note the need to study the design features of mini-roundabouts with the establishment of design parameters for use in domestic design practice, as well as the need for a detailed study of methods for determining the throughput at the junction entrance, since this issue is poorly studied in our country. To assess the level of safety and service efficiency at the design stage of mini-roundabouts, it is recommended to use transport simulation packages.

That is why, as part of this work, we will study implementing traffic calming measures for group 1 road traffic using transport modelling.

PURPOSE AND OBJECTIVES OF THE STUDY

The study aims to evaluate the effectiveness of traffic calming measures, namely, the introduction of various forms of pedestrian crossing organisation, using the example of the SRN in Kharkiv.

Road conditions and traffic and pedestrian flow parameters must be studied to achieve this goal. Based on this, simulation transport models of intersections in the PTV Vision VISSIM software environment can be developed.

RESEARCH RESULT

Fig. 1 shows typical pedestrian crossings near secondary education institutions in Kharkiv, where one can see typical conditions: a residential street (Vasyl Melnykov Street) and a main street of district importance (Oshchepkov Street, Biblik Street, Hromadianska Street) have one lane in each direction of traffic with a width of 3.0 to 4.0 m each. A pedestrian crossing is arranged opposite the main entrance to the educational institution. Due to tree plantations, the visibility of road signs 5.38.1 and 5.38.2 – Pedestrian crossing is limited. There are no road markings indicating a pedestrian crossing. The straight section of the street provokes vehicles to drive at high speeds. Public transport routes are organised on Oshchepkov Street and Biblik Street (before the war): trolleybus and bus routes. In the morning and evening, when children are brought and picked up, many vehicles are parked near educational institutions, further limiting the visibility of the pedestrian crossing.

Secondary school No. 11 (Vasyl Melnykov Street)

Secondary school No. 24 (Oshchepkov Street

Secondary school No. 80 (Biblik Street)

Technological Lyceum No. 9 (Hromadyanska Street)

Figure 1 – Organisation of pedestrian crossings near secondary schools in Kharkiv

DSTU (State Standards) 4123:2020 has arranged traffic calming measures near educational institutions, such as road humps or elevated pedestrian crossings, to improve road safety. To pass these artificial road bumps, drivers must slow down regardless of whether pedestrians are on or in the pedestrian crossing zone. Here, the question of studying the impact of traffic calming devices on the functioning of the transport network arises.

The following indicators will be used as criteria for assessing the effectiveness of traffic calming devices

[16-18]: the average delay per vehicle, s ($\overline{T_{zup}} \to \min$), the average length of the traffic jam, m ($\overline{L_{zat}} \to \min$), and the average number of vehicle stops, units ($\overline{N_{zup}} \to \min$). To evaluate the effectiveness of traffic calming devices at a pedestrian crossing, the model analysis was set up in the PTV Vision Vissim software (see Table 1).

Table 1 – Analysis parameters

Parameter name	Parameter description
1. Length of traffic jam	The average length of traffic jam, m
2. Length of traffic jam (max)	The maximum length of the traffic jam during the simulation, m
3. Vehicles (all)	The number of vehicles travelling in a given direction, vehicles.
4. Service level (traffic quality) (all)	Traffic quality level (A...F) according to the assigned service levels
5. Vehicle delay time (average value) (all)	Average vehicle delay time, s
6. Idle time (average) (all)	Average idle time of each vehicle, s
7. Stops (all)	Number of vehicle stops, excluding stops on car parks and units.

The pedestrian crossing in front of the Technological Lyceum No. 9 on Hromadyanska Street was taken as a prototype for studying traffic and pedestrian flows. A model of a pedestrian crossing was developed for three options: option 1 – organisation of a pedestrian crossing using road signs and road markings; option 2 – organisation of a pedestrian crossing using an elevated pedestrian crossing, road signs and road markings; option 3 – organisation of a pedestrian crossing using road humps, road signs and road markings.

When analysing the methods of traffic calming and the use of traffic calming devices for this purpose, it was determined that the parameters for assessing the SRN functioning, namely pedestrian crossings, are influenced by such input characteristics as the input intensity of the traffic flow and the input intensity of the pedestrian flow. It is also known that the values of these intensities change significantly during the hours of the day. Therefore, to vary the model's input parameters, the following indicators were determined in this study: traffic flow intensity and pedestrian flow intensity.

It is determined that the intensity of the traffic flow will vary in the range from 150 vehicles per hour to 750 c vehicles per hour in increments of 150 vehicles per hour, and the intensity of the pedestrian flow will vary from 150 pedestrians per hour to 550 pedestrians per hour in increments of 100 pedestrians per hour. By searching for possible variations in intensity, we find the number of modelling options: 5 variants for changing traffic flows and five variants for changing pedestrian flows; thus, 25 variants of input intensity parameters for each of the three modelling scenarios should be modelled. For example, Fig. 2 shows changes in estimated indicators depending on the intensity of traffic for the proposed study options, which indicate the feasibility of using a particular means of traffic calming.

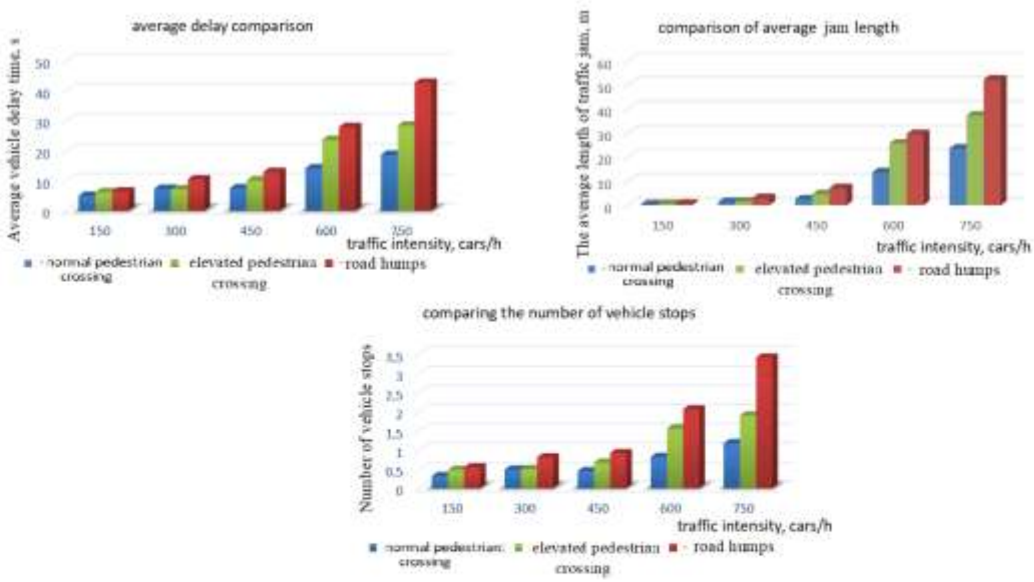


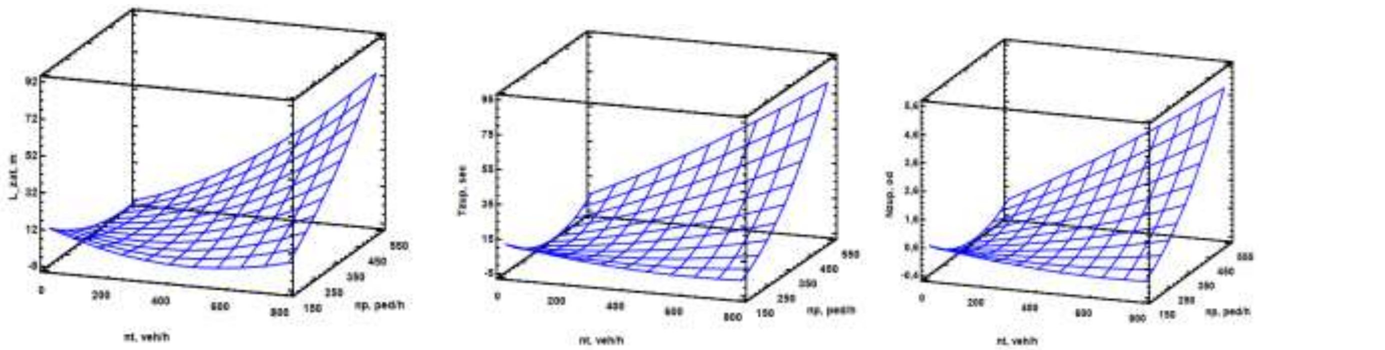
Figure 2 – Comparison of proposed options by estimated indicators

DISCUSSION OF THE RESULTS OF THE STUDY

The analysis of the impact of traffic and pedestrian flows on the indicators of assessing the SRN section functioning on the example of a pedestrian crossing using traffic calming devices can be seen in Figures 3-5. Using the statistical analysis package Statgraphics Centurion, the dependencies of the average value of the traffic jam length, the average number of stops and the average delay on the intensity of traffic and pedestrian flows in different scenarios were found (see Table 2).

Table 2 - Dependencies of the average value of the traffic jam length, the average number of stops and the average delay on the intensity of traffic and pedestrian flows in different scenarios

Scenario number	The resulting dependency
1	$\overline{L_{zat}^{var1}} = 33 - 0.1\cdot N_t - 0.15\cdot N_p + 0.00007\cdot N_t^2 + 0.0003\cdot N_t\cdot N_p + 0.0002\cdot N_p^2$
	$\overline{T_{zup}^{var1}} = 40.4 - 0.07\cdot N_t - 0.25\cdot N_p + 0.00003N_t^2 + 0.0003\cdot N_t\cdot N_p + 0.0003\cdot N_p^2$
	$\overline{N_{zup}^{var1}} = 2.24 - 0.039\cdot N_t - 0.013461N_p + 0.000001\cdot N_t^2 + 0.00002\cdot N_t\cdot N_p + 0.00002\cdot N_p^2$
2	$\overline{L_{zat}^{var2}} = 21.6 - 0.0948819N_t - 0.1001\cdot N_p + 0.00009\cdot N_t^2 + 0.00022\cdot Nt\cdot Np + 0.000099\cdot N_p^2$
	$\overline{T_{zup}^{var2}} = 35.41 - 0.0718174N_t - 0.208\cdot N_p + 0.000044\cdot N_t^2 + 0.00025\cdot N_t\cdot N_p + 0.0003\cdot N_p^2$
	$\overline{N_{zup}^{var2}} = 1.95 - 0.00402004N_t - 0.01\cdot N_p + 0.0000025\cdot N_t^2 + 0.000015\cdot N_t\cdot N_p + 0.000015\cdot N_p^2$
3	$\overline{L_{zat}^{var3}} = 14.7 - 0.0901034N_t - 0.069\cdot N_p + 0.00011\cdot N_t^2 + 0.00022\cdot N_t\cdot N_p + 0.000064\cdot N_p^2$
	$\overline{T_{zup}^{var3}} = 41.7 - 0.087\cdot N_t - 0.44\cdot N_p + 0.00005\cdot N_t^2 + 0.0003\cdot N_t\cdot N_p + 0.00033\cdot N_p^2$
	$\overline{N_{zup}^{var3}} = 1.7 - 0.00501171N_t - 0.00941\cdot N_p + 0.000004\cdot N_t^2 + 0.000017\cdot N_t\cdot N_p + 0.00001\cdot N_p^2$



average length of traffic jam — average delay time — average number of stops per vehicle

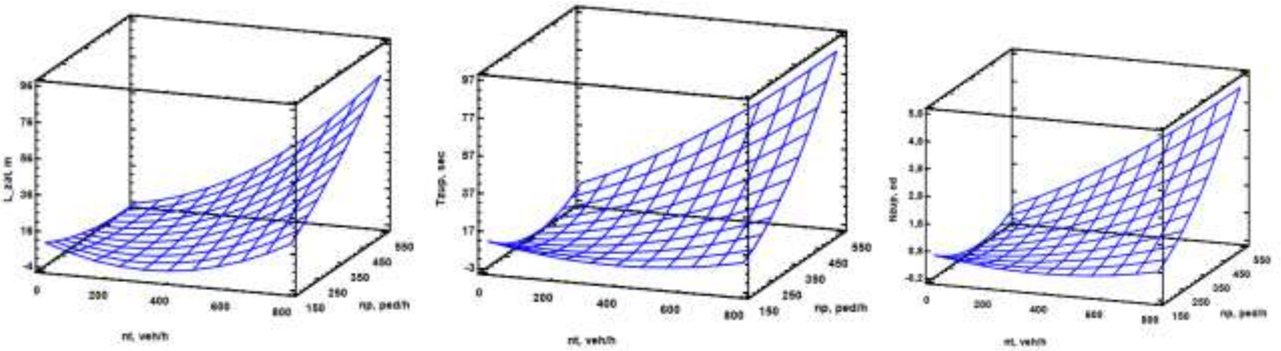
Figure 3 – Dependence of indicators on the intensity of traffic and pedestrian flows when organising a pedestrian crossing with the use of road signs and road markings (scenario No 1)

These dependencies describe accurate indicators with a 91-96% reliability, meaning we can state that the obtained models are adequate.

SUMMARY

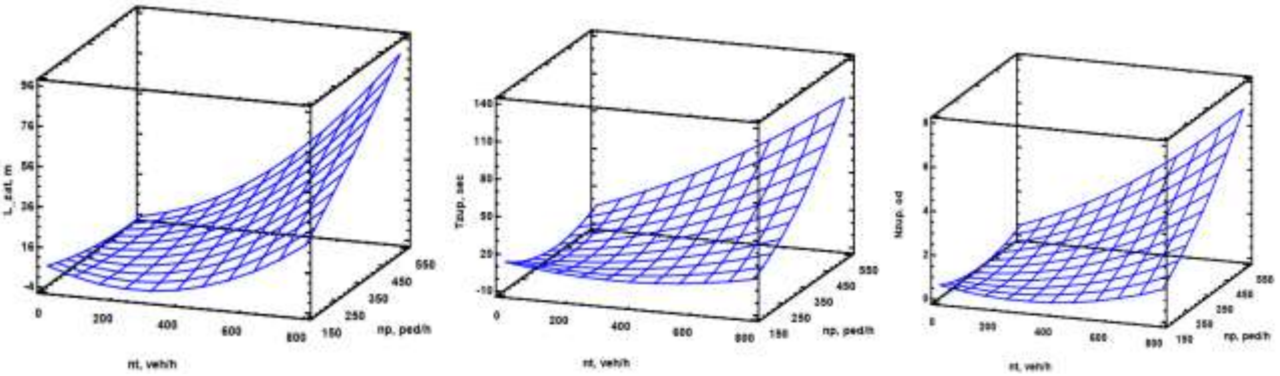
It has been proved that the availability of traffic calming devices affects indicators of the SRN section functioning at a pedestrian crossing, such as the average value of the traffic jam length, the average number of stops, and the average delay per vehicle. The intensity of traffic flows also impacts—as they increase, the estimated indicators also increase.

As the area of influence of the traffic calming devices and their geometric characteristics increase, the values of the evaluation indicators also increase. In other words, an elevated pedestrian crossing has smaller geometric parameters than a complex of a regular pedestrian crossing and road humps on both sides and, accordingly, has smaller values of the evaluation indicators, i.e. the average length of the traffic jam, the average number of stops and the average delay per vehicle.



average length of traffic jam　　average delay time　　average number of stops per vehicle

Figure 4 – Dependence of indicators on the intensity of traffic and pedestrian flows when organising a pedestrian crossing using an elevated pedestrian crossing, road signs and road markings (scenario No 2)



average length of traffic jam　　average delay time　　average number of stops per vehicle

Figure 5 – Dependence of indicators on the intensity of traffic and pedestrian flows when organising a pedestrian crossing using road humps, road signs and road markings signs and road markings (scenario No 3)

As the area of influence of the traffic calming devices and their geometric characteristics increase, the values of the evaluation indicators also increase. In other words, an elevated pedestrian crossing has smaller geometric parameters than a complex of a regular pedestrian crossing and road humps on both sides and, accordingly, has smaller values of the evaluation indicators, i.e. the average length of the traffic jam, the average number of stops and the average delay per vehicle.

The obtained dependencies can be used in a preliminary assessment of installing specific traffic calming devices at pedestrian crossings. In this case, the possibility of introducing an indicator into the model that will take into account the road safety should be considered. The studies conducted provide a useful basis for future, broader research in this area, which is planned to be directed to the use of combinations of traffic calming measures on SRN cities in order to promote the creation of safe, healthy and pleasant urban environments.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

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ON THE QUESTION REGARDING THE USE OF THREE-LINK ROAD TRAINS IN UKRAINE

Carrying out cargo transportation in intercity and international transportation by three-link road trains, compared to single vehicles, has a number of advantages, which ensure an increase in the productivity of rolling stock, a decrease in the cost of road transportation, a decrease in the total cost of cargo transportation, etc. Ukraine does not have its own production of tractor vehicles that can be used to work with trailers or semi-trailers with a large load capacity. Therefore, when choosing rolling stock for three-link road trains, its necessery to focusation on the products of leading automobile companies.

It was established by researches that the generalizing indicator of traction-speed properties of a motor vehicle is the average speed of movement, because it affects its productivity and determines the efficiency of its use. In the work, this speed is determined according to the developed algorithm. It was established that the average speeds of road trains consisting of tractors of the N3 category (MAN TGA, Iveco Magirus, Scania R-series, DAF XF 105, Volvo FH16) with semi-trailers and O4 trailers of the KRONE brand in given road conditions differ little from each other. The maximum deviation of the average speed of movement, which has the largest value 22.99 m/s (for Volvo FH16+KRONE SDP-27), from the smallest value 21.05 m/s (for DAF XF 105+KRONE SDP-27), does not exceed 8.5%, i.e. further comparison of road trains should be fulfilled according to other criteria, in particular according to maneuverability when moving on a route.

It is shown that the considered three-link road trains do not satisfy the requirements of Directive 2002/7/EC regarding maneuverability. For three-link road trains with unguided trailing links, the minimum external overall turning radius with an internal overall radius of 5.3 m varies from 12.63 m for a trailed road train to 14.9 m for a "B-Double" type road train. This is explained by the fact that the length of the three-link road train lies within 26.0...27.0 m. Therefore, for the practical use of three-link road trains in Ukraine, changes should be made both in the transport legislation and in the construction of road trains, in particular, the introduction of controlled trailer links into their structure and the determination of their placement in the road train.

Keywords: transport system, technical and operational indicators, load capacity, three-link road train, tractor vehicle, semi-trailer, trailer, average speed, maneuverability.

INTRODUCTION

An integral part of the functioning of the country's transport system is the cargo delivery by rolling stock of the road transport, in particular, by three-link road trains of increased load capacity. These road trains are widely application in the countries of the European Union, the USA and Canada, where they are used to execution of transportation of industrial, agricultural and construction cargo.

The using of three-link road trains in intercity freight transportation has a number of advantages compared to single vehicles, which affect to increase mileage utilization rate, to reduce of idle time during load-unload operations, to increase the speed and decrease of cargo delivery time, to decrease the number of trips and the total mileage of vehicles, and, as a result, to increase of the productivity of the rolling stock, to reduce the cost price of road transportation, to decrease of the total cost of cargo transportation, and reducing the number of harmful emissions into the environment. This gives reason to believe that for Ukraine in the conditions of martial law, with the increase in the volume of road freight transportation and the presence of an almost unchanged road network, the issue of the use of three-link road trains becomes relevant.

ANALYSIS OF LITERATURE DATA AND FORMULATION OF THE PROBLEM

The use of road trains is an effective method of increasing productivity and reducing the cost price of transportation [1]. Ukraine, unfortunately, does not have its own production of tractor vehicles that can be used to work with trailers or semi-trailers with a large load capacity. It is obvious that the purchase of foreign-made wheeled vehicles (tractors, trailers and semi-trailers) for the purpose of creating a new type of rolling stock must be preceded by a detailed comparative analysis of their technical characteristics in order to ensure of meeting to requirements, which established by national and international legislation, as well as customers (consumers) of these products regarding such technical and operational properties of road trains as active and passive safety, traction-speed properties, fuel efficiency, environmental indicators, controllability, stability. The choice of the type of tractor and its towing links for execution of cargo transportation must be carried out taking into account the safety of their constructions, compliance of their operational characteristics with the conditions under which transportation is planned and the goals set by the organizers of transportation.

Increasing of the quality of vehicles, including improving traction-speed properties, should be carried out at the expense of market competition. Thus, EU legislation, in particular EU Directive 92/6/EEC [2], provides requirements for the construction of vehicles in relation to only one indicator - the maximum speed. The implementation of Directive 92/6/EEC into the national legislation of Ukraine is provided for by the Ukraine-EU Association Agreement. In addition, Ukraine joined the UN Regulations No. 89 [2] regarding the limitation of the maximum speed of vehicles, which are also included in the list of mandatory requirements that apply to vehicles put into circulation, according to the "Procedure for approval of the design of vehicles, their parts and equipment" [2].

The mentioned measures to limit the maximum speed of vehicles are introduced with the aim of increasing road safety. They do not change the potential maximum speed, but only artificially limit the speed by adjusting the fuel supply to the engine when the vehicle is reached the given speed. Therefore, the average speed of traffic, as well as the quality of vehicles in general, should not "suffer" from the implementation of such regulatory measures.

Since the average speed of a freight vehicle is a factor that, together with the load capacity, determines its productivity and provides the most complete idea concerning traction-speed properties, this evaluation indicator is undoubtedly gaining weight among the criteria by which it is advisable to conduct comparative analyzes of road trains [1]. The average speed of movement depends on the interaction of the main elements of the "Vehicle - road - driver - environment" system. The first two elements are defining, the last two are limiting, since their influence always reduces the speed of movement, which could be developed by this or that road train at full use of its technical capabilities on the given path of its movement [1,2].

Increasing the operational characteristics of the road network and its development is, without a doubt, one of the powerful measures for solving the problem of road safety. At the same time, reducing the number of vehicles and drivers on the road network when putting the three-link road trains into operation will significantly improve the situation with accidents [3-6]. Therefore, simultaneously with the development of the transport infrastructure, it is advisable to focus attention on measures to possibilities of unloading the road network due to process improving of cargo transportation organizing.

In the modern automobile industry, when creating three-link road trains, the issue of choosing towing links is relevant and is actively discussed in the scientific literature. There are two main schemes of three-link road trains - trailer and semi-trailer. In the trailing scheme, each link rests on its axles, and in the semi-trailer - as on its axles and on the axis of the previous link.

In Ukraine, intercity and international cargo transportation is carried out by road trains consisting of MAN, DAF, IVECO, VOLVO and other similar tractors, and of Krone, Schmitz, Fliegle and other similar semi-trailers. The selection of the best combination of the road train in the composition with the specified tractors and semi-trailers (trailers) are carried out according to the indicators of traction-speed properties (high-speed driving mode) and maneuverability (road restrictions).

If a road train has more than three links, difficulties arise in that the study of the movement of such a multi-link vehicles is significantly complicated due to the need to take into account the influence of a considerable amount of factors on the nature of the movement of all links. The interaction of neighboring links during the movement of the road train eventually spreads to the entire vehicle and causes certain deviations of the components of the road train (modules) from the direction of movement set by the leading link (tractor). Taking into account the fact that the road train as an vehicle is a means of increased danger, when solving problems regarding the possibility of operating three- and multi-link road trains, the first steps should be taken in the direction of theoretical studiying of their maneuverability and stability of movement, the results of which will be the basis for answering many questions of technical, of an organizational and legal nature [7-9]. Thus, in [10], a simplified analysis of the maneuverability and stability of combinations of vehicles, such as a tractor in combination with one or two semi-trailers, or a truck and a full trailer, was carried out. Combinations of tractor vehicles with trailers and semi-trailers are considered as linear dynamic systems with two degrees of freedom for each module. The model of the road train with 31 degrees of freedom is built using the AutoSim package. At the same time, it is shown that the maneuverability and stability of the road train can be significantly improved with the help of an inerter, which is considered effective for increasing the stability and productivity of multi-track road trains. However, as practice shows, determining the nature of the behavior of the system in the area of instability and identifying the causes of its occurrence has not lost its relevance until now.

Since the curvilinear movement of the vehicle determines the construction of the control systems of the towing links, at the first stage it is necessary to decide with parameters of vehicle during circular movement and its execution of various maneuvers [7]. At the second stage, the previously obtained parameters are checked for the satisfaction of stability indicators both in a rectilinear movement and when execution various maneuvers. Selection and optimization of vehicle parameters for the entire range of operational speeds and loads requires availability of differential equations of motion. Such equations of varying degrees of complexity for two- and three-link road trains are given in works [7,10,11] and others. Combinations of vehicle are considered as linear dynamic systems with two degrees of freedom for each block. In work [12], the equations of vertical and lateral dynamics of a road vehicle with 6 degrees of freedom are reduced to matrix form. The movement of such vehicle in the vertical and lateral planes was studied. It is shown that the developed method can be applied to the analysis of traffic stability, in particular passenger road trains. In [13], a multivariate extension of the D2-IBC (Data Driven - Inversion Based Control) method is considered and its application to control the stability of the traffic of road trains is discussed in detail. Work [14] shows that freight vehicles with lots of trailers (MTAHV: multi-trailer articulated heavy vehicle) exhibit unstable modes of movement at high speeds, including folding of links, swinging of the trailer, and overturning. These unstable, adverse traffic modes can lead to traffic accidents.On the other hand, these vehicles have poor maneuverability at low speeds. This requires research and their analysis in order to find a compromise between the maneuverability of the vehicles at low speeds and its lateral stability at high speeds.

PURPOSE AND OBJECTIVES OF THE STUDY

The characteristics of maneuverability and stability of the vehicle movement, as is known, are determined by a combination of operational, mass-geometric and constructural parameters of its modules and their control systems. In general, the desired combination of the specified parameters from the point of view of maneuverability and stability even for the same vehicle in the range of operating loads and speeds are different. As a result, it is difficult to obtain accurate constructural parameters and quantitative indicators in the early stages of the creation of vehicle based on the criteria of maneuverability and stability of its movement. Success in solving such problems depends on how successfully the mathematical model and its essential parameters describing the behavior of the dynamic system in different modes of motion will be chosen. In work [10], differential equations of plane-parallel motion were compiled to determine the motion stability indicators. However, these equations can characterize the stability of vehicle only in rectilinear motion. Using them to assess maneuverability can lead to significant errors. In this regard, the aim of the work is a comparative evaluation of three-link road trains of different layout schemes according to the indicators of traction-speed properties and maneuverability.

To achieve the goal of the research, the following tasks are solved:

- the comparative evaluation of three-link road trains of different layout schemes according to traction-speed properties, selection of the best option;
- the comparative analysis of three-link road trains of different layout schemes in terms of maneuverability, selection of the best option.

The materials of the research are the technical characteristics and constructual features of tractors MAN TGA, Iveco Magirus, Scania R-series, DAF XF 105 and Volvo FH16, and Krone semi-trailers and trailers.

By methods of research of traction-speed properties and maneuverability of three-link road trains of various layout schemes was expected:

- development of a methodology for determining the traction-speed properties of three-link road trains consisting of MAN TGA, Iveco Magirus, Scania R-series, DAF XF 105 and Volvo FH16 tractors with Krone semi-trailers and trailers for choosing the best option;
- simulation of the movement of road trains along curves of highways to assess the influence of the layout scheme of a three-link road train on maneuverability indicators and its compliance with the requirements of regulatory documents.

RESEARCH RESULT

By previously conducted studies [1,2,15] it were established that the general indicator of the traction-speed properties of a single car and road train is the average speed of movement, as it determines its productivity and efficiency of use.

The average speed is determined by the driving conditions of the road train and the capabilities of the tractor in each of the gears [15]. In this regard, the solution to the task of determining the average speed of the vehicle can be sought on the basis of the comparison of the forces of movement resistance and the traction forces that the vehicle can develop on the drive wheels.

Depending on the initial data on the road resistance coefficient of vehicle [16], it is possible to use discrete or probabilistic methods of calculating the average speed of the vehicle.

Considering the traffic conditions of three-link road trains, preference should be given to the probabilistic method. At the same time, movement resistance values are determined on the basis of data about route and described by the normal law of the distribution of the road resistance coefficient along the length of the route [15], i.e

$$f(\psi) = \frac{1}{\sigma_{\psi} \times \sqrt{2\pi}} \times e^{-\frac{(\psi - m_{\psi})^2}{2\sigma_{\psi}^2}}, \quad (1)$$

where m_{ψ} and σ_{ψ} - the mathematical expectation and average square deviation of the road resistance coefficient ψ.

The average speed of vehicle under the probabilistic distribution of road resistance on a given route was determined by the algorithm presented in the table 1 [15].

Table 1

Basic calculation formulas for determining indicators of traction-speed properties of a vehicle

Parameter	Calculation formula
1	2
Equation of motion during acceleration	$\frac{dV}{dt} \times m_a \times \delta_i = a \times V^2 + b \times V + c$, (2) where V - the speed of the road train, m/s; m_a - the mass of the road train, kg; a, b, c - the coefficients of the polynomial that approximates the external speed characteristics of the tractor engine; δ_i - the coefficient that takes into account the increase in the inertia forces of the rolling masses of the road train due to its rotating masses, which is defined as $\delta_i = 1 + \sigma_1 \times u_{ki}^2 + \sigma_2$; (3) σ_1 - the coefficient that takes into account the rotating masses of the engine and transmission of the tractor; σ_2 - the coefficient that takes into account the rotating masses of the wheels of the tractor and the towing links; u_{ki} - the transmission ratio of the tractor gearbox on the i-th gear.
Acceleration time on the i-th gear, s	$\tau_i = m_a \times \delta_i \times \int_{V_{Hi}}^{V_{Ki}} \frac{dV}{a \times V^2 + b \times V + c}$, (4) where V_{Hi} - the initial speed on the i-th gear in the acceleration process, s; V_{Ki} - the final speed on the i-th gear in the acceleration process, s.
The time of acceleration of the road train, s	$T = \Sigma\tau_i$. (5)
Acceleration path on the i-th gear, m	$S_i = m_a \times \delta_i \times$ $\times \left\{ \frac{1}{2 \times a_i} \times ln\|a \times V^2 + b \times V + c\|\Big\|_{V_{Hi}}^{V_{Ki}} - \frac{b}{2 \times a} \times \times \int_{V_{Hi}}^{V_{Ki}} \frac{dV}{a \times V^2 + b \times V + c} \right\}$. (6)

Continuation of table 1

1	2
Dispersal path of the road train, m	$S = \Sigma S_i$. (7)
Equation of motion when running out	$\frac{dV}{dt} \times m_a \times \delta_0' = -m_a \times g \times (f_0 \times K_f \times V) - K_B \times F \times V^2 - P_{fx}$, (8) where δ_0' - the coefficient that takes into account the increase in the inertia forces of the translational masses of the road train due to the rotating masses of only the wheels; g - the acceleration of free fall, m/s^2; f_0 - the coefficient of rolling resistance at a speed of 1 m/s; K_f - the coefficient that takes into account the increase in the rolling resistance coefficient f from the speed of movement; K_B - the coefficient of air resistance of the road train, N×s^2/ m^4; F - the Midel area, m^2 (taken to be equal to the area of the projection of the road train on the plane perpendicular to its longitudinal axis) and is defined as $F = B \times H$; (9) B - the tractor track, m; H - the height of the road train, m; P_{fx} - the force of resistance to motion when the engine is idling, N, which is defined as $P_{fx} = (2 + 0{,}025 \times V) \times m_a \times g \times 10^{-3}$. (10)
Minimum steady speed, m/s	$Vmin_y = -\frac{m_a \times g \times f_0 \times A_i - K_B \times F \times C_i}{m_a \times g \times K_f \times A_i - K_B \times F \times B_i} + \sqrt{\left(\frac{m_a \times g \times f_0 \times A_i - K_B \times F \times C_i}{m_a \times g \times K_f \times A_i - K_B \times F \times B_i}\right)^2 - \frac{m_a \times g \times (f_0 \times B_i - K_f \times C_i)}{m_a \times g \times K_f \times A_i - K_B \times F \times B_i}}$, (11) where A_i, B_i, C_i - the constant coefficients determined by the car's engine and transmission parameters.
Maximum speed, m/s	$V_{max} = \frac{-b_i - \sqrt{b_i^2 - 4 \times a_i \times c_i}}{2 \times a_i}$. (12)
Maximum acceleration during acceleration, m/s^2	$j_{max} = \frac{1}{G_a \times \delta_i} \times \left(c_i - \frac{b_i^2}{4 \times a_i}\right)$, (13) where G_a - the gravitational force from the full mass of the road train, N.
Average acceleration during acceleration, m/s^2	$j_{cp} = \frac{1}{G_a \times \delta_i} \times \left[\frac{a_i}{3} \times (V_K^2 + V_K \times V_H + V_H^2) + \frac{b_i}{2} \times (V_K + V_H) + c_i\right]$. (14)
The maximum climb that can be overcome	$\sin \alpha_{max} = \frac{1}{G_a \times \delta} \times \left(C_i - G_a \times g \times f_0 \times \cos\alpha - \frac{(B_i - G_a \times g \times K_f \times \cos\alpha)^2}{4 \times A_i}\right)$, (15) where α - the angle of elevation of the road.
Speed on rise, m/s	$V_{уст} = \frac{-b_i - \sqrt{b_i^2 - 4 \times a_i \times c_i}}{2 \times a_i}$. (16)

Continuation of table 1

1	2
Maximum traction force on the hook, N	$$P_{KPmax} = \frac{b_i^2}{4 \times a_i}. \quad (17)$$
Average speed on the route, m/s	$$V_c = \frac{0{,}27 \times N_{уд} \times \eta_m \sum_{i=1}^{n} K_i \times d_i}{\frac{\gamma_{piN} \times \sum K_i \times d_i}{l_i}}, \quad (18)$$ where $N_{уд}$ - the specific power of the road train, kW/t; η_m - the efficiency factor of the transmission of the tractor; K_i - the relative path of the road train in the i-th gear; γ_{piN} - the specific traction force of the road train in the i-th gear when the engine is operating in the maximum power mode; l_i - the coefficient that takes into account the type of speed distribution law on the transmission; d_i - the calculation coefficient, which is defined as $$d_i = \frac{V_i}{V_{i-1}}; \quad (19)$$ V_i, V_{i-1} - the maximum speeds on i-th and i -1 gears, m/s.
Coefficients of equations	$$a_{\text{i}} = A_{\text{i}} - K_B \times F. \qquad b_{\text{i}} = B_{\text{i}} - K_f \times m_a \times g. \qquad c_{\text{i}} = C_{\text{i}} - f_a \times m_a \times g \quad (20)$$ $$A_i = a \times \frac{U_i^3 \times \eta_м}{r_д \times r_к^2}, \quad B_i = b \times \frac{U_i^2 \times \eta_м}{r_д \times r_к}, \quad C_i = c \times \frac{U_i \times \eta_м}{r_д} \quad (21)$$ where U_i - the gear ratio of the transmission of the tractor in the i-th gear; $r_д$ - the dynamic radius of the wheel, m; $r_к$ - the rolling radius of the wheel, m.

In accordance with the given algorithm, the average speed of road trains carrying out intercity and international transportation on paved roads in flat terrain is determined. For such roads, the parameters of the normal distribution law of the road resistance coefficient along the length of the path are [14]: m_ψ=0.022, σ_ψ=0.012.

In the table 2 shows the results of calculating the average speed of road trains consisting of tractors MAN TGA, Iveco Magirus, Scania R-series, DAF XF 105 and Volvo FH16 with Krone semi-trailers and trailers.

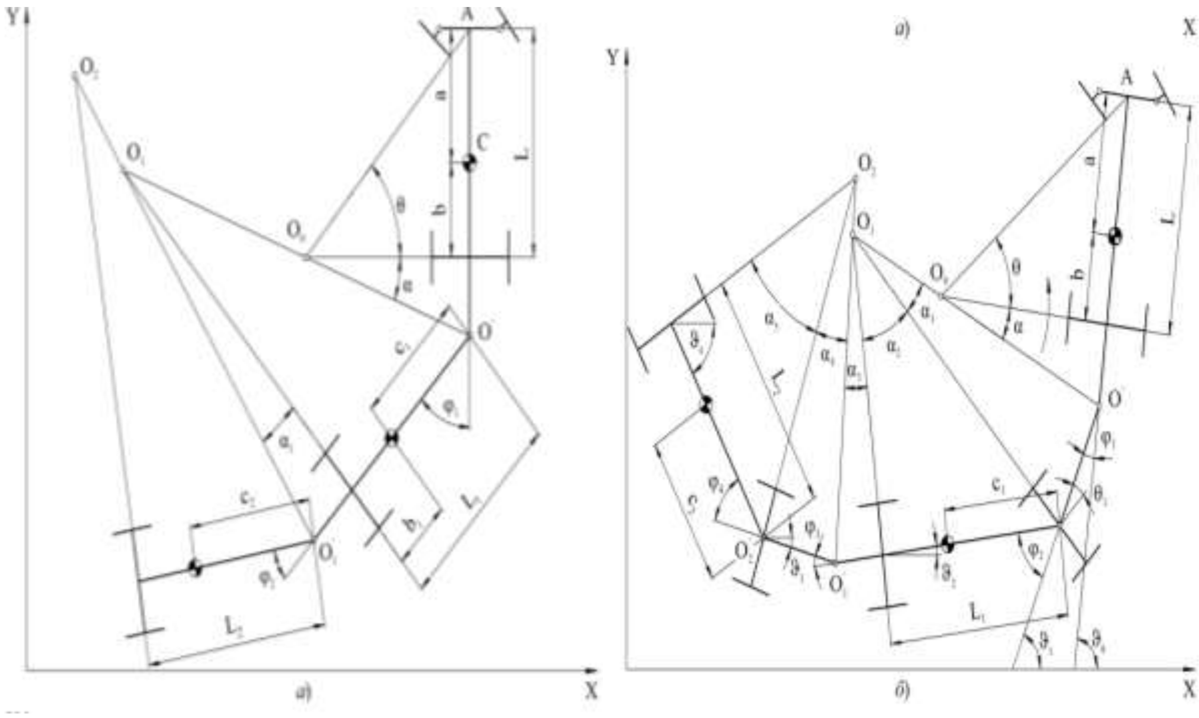
Table 2

The average speed of a road train consisting of different tractors

Tractor	MAN TGA	Iveco Magirus	Scania R-series	DAF XF 105	Volvo FH16
Average speed, m/s	22.13	21.57	22.68	21.05	22.99

As follows from the table 2, the average speeds of road trains consisting of tractors of category N3 (MAN TGA, Iveco Magirus, Scania R-series, DAF XF 105, Volvo FH16) with semi-trailers of category O4 in given road conditions differ little from each other. The maximum deviation of the average speed of movement, which has the largest value (for Volvo FH16+KRONE SDP-27 – 22.99 m/s), from the smallest value (for DAF XF105+KRONE SDP-27 – 21.05 m/s) does not exceed 8.5%, that is, further comparison of road trains should be executed according to other criteria, in particular, according to maneuverability when moving on a given route.

In the paper [7], in which the issues of maneuverability of three-link vehicles trailed and semi-trailer layout schemes were considered, the modular construction of the road train was adopted. Under this condition, the road train was presented in the form of three modules - a tractor and two towing links (Fig. 1).



а) - according to the semi-trailer scheme; *б)* - according to the trailer scheme.
Figure 1. Calculation scheme of a three-link road train

With the modular construction of the road train, the tractor is presented in the form of one module - a skeleton with front steerable wheels and one or two axles with non-rotating wheels (axles). For further calculations, it was assumed that the turning angles of the left $\theta_л$ and right $\theta_п$ of the steered wheels of the tractor are equal to their average turning angle θ, i.e. $\theta_л=\theta_п=\theta$. The towing links were also presented in the form of either one module - a skeleton with non-rotating wheels (axles) under the semi-trailer layout scheme, or from two kinematically independent elements - a platform with a non-rotating rear axle and a rotating axle with a drawbar, in which the angles of rotation of the first and second trailers - θ_1 and θ_2, moreover, there is a hinge connection between them.

Determining the maneuverability indicators of the road train with sufficient accuracy for practical calculations can be carried out on rigid in the lateral direction wheels at the angles of assembly and rotation of the links of the road train.

These angles for a towed road train (Fig. 1) are defined as follows [7]:

$$\frac{d\varphi_1}{dt} + \frac{v_A}{L \times \frac{\sin(\pi/2-\varphi_2-\alpha_1)}{\sin(\varphi_1+\varphi_2+\alpha_1)}} - \frac{v_C \times tg\theta}{a+b-d} = 0, \qquad (22)$$

where φ_1 - the first folding angle (the angle between the longitudinal axis of the tractor and the drawbar of the first trailer);

φ_2 - the second folding angle (the angle between the longitudinal axis of the first trailer and its drawbar);

v_A - the speed of point A (the middle of the steered axle of the tractor);

v_C - the speed of point C (center of mass of the tractor);

L - tractor base;

a - the distance from the center of mass to the front axle of the tractor;

b - the distance from the center of mass to the rear axle of the tractor (to the middle of the paired axles of a three-axle vehicle);

d - the distance from the center of mass of the tractor to the point of towd with the first towing link;

α_1 - the auxiliary angle, which is defined as

$$\alpha_1 = arctg\left(\frac{d_1-c_1}{a_1+b_1} \times tg\theta\right), \qquad (23)$$

c_1 - the distance from the center of mass of the first trailer to the point of towd with the tractor;
a_1 - the distance from the center of mass of the first trailer to its front axle;
b_1 - the distance from the center of mass of the first trailer to its rear axle;
d_1 - the distance from the center of mass of the first towing link to the point of towd with the second towing link;

$$\frac{d\varphi_2}{dt} - \frac{v_{C1} \times sin(\pi/2-\varphi_1)}{\frac{a_1+b_1}{tg\theta_0} \times sin(\pi/2-\varphi_2-\alpha_1) \times \sqrt{1+\left(\frac{L_1-c_1}{a_1+b_1} \times tg\theta_1\right)^2}} - \frac{v_A \times sin(\varphi_1+\varphi_2+\alpha_1)}{L_1 \times sin(\pi/2-\varphi_1-\alpha_1)} = 0, \tag{24}$$

where L_1 - base of the first trailer.

$$\frac{d\varphi_1}{dt} - \frac{v_{C1} \times sin(\varphi_1+\varphi_2+\alpha_1) \times L^2{}_1 \times sin(\gamma_1+\varphi_3+\alpha_2)}{L_2 \times L_3 \times sin\varphi_2\, sin(\pi/2-\varphi_3-\alpha_2)} \times$$
$$\times \frac{sin\left(\frac{\pi}{2}-\varphi_2-\alpha_1\right) \times ctg\gamma_1}{\frac{a_2+b_2}{tg\varphi_2} \times \sqrt{1+\left(\frac{d_2-c_2}{a_2+b_2} \times tg\varphi_2\right)^2 + L_2 \times \frac{cos\varphi_1}{sin(\varphi_1+\varphi_2+\alpha_1)} - L_3 \times sin(\pi/2-\varphi_2-\alpha_1) \times ctg\gamma_1}} -$$
$$- \frac{v_{C1} \times L_1 \times sin(\varphi_1+\varphi_2+\alpha_2)}{L_2 \times L_3 \times sin(\pi/2-\varphi_2-\alpha_2)} = 0, \tag{25}$$

where φ_3 , φ_4 - the third and fourth folding angles;
α_2 - the auxiliary angle, which is defined as

$$\alpha_2 = arctg\left(\frac{d_2-c_2}{a_2+b_2} \times tg\varphi_2\right), \tag{26}$$

where d_2 - the distance from the center of mass of the second towing link to the point of towd with the third towing link;
c_2 - the distance from the center of mass of the second trailer to the point of its towd with the first trailer;
a_2 - the distance from the center of mass of the second trailer to its front axle;
b_2 - the distance from the center of mass of the second trailer to its rear axle;
ϕ_1, ϕ_2 - the auxiliary angles, which are defined as

$$\phi_1 = arctg\left[\begin{array}{c}\frac{l_1 \times sin(\varphi_2+\varphi_1+\alpha_1)}{L_1 \times sin(\pi/2-\varphi_2-\alpha_1)} \times \\ \times \frac{1}{\sqrt{1-\left\{\frac{\left[\frac{sin(\pi/2-\varphi_2-\alpha_1)}{sin(\varphi_2+\varphi_1+\alpha_1)}\right]^2+1-\left[\frac{sin(\pi/2-\varphi_1)}{sin(\varphi_2+\varphi_1+\alpha_1)}\right]^2}{2 \times \frac{sin(\pi/2-\varphi_2-\alpha_1)}{sin(\varphi_2+\varphi_1+\alpha_1)}}\right\}^2}}\end{array}\right], \tag{27}$$

$$\phi_2 = arctg\left[\begin{array}{c}\frac{L_2 \times sin(\varphi_4+\varphi_3+\alpha_2)}{d_2 \times sin(\pi/2-\varphi_4-\alpha_2)} \times \\ \times \frac{1}{\sqrt{1-\left\{\frac{\left[\frac{sin(\pi/2-\varphi_4-\alpha_2}{sin(\varphi_4+\varphi_3+\alpha_2}\right]^2+1-\left[\frac{sin(\pi/2-\varphi_3)}{sin(\varphi_4+\varphi_3+\alpha_2)}\right]^2}{2 \times \frac{sin(\pi/2-\varphi_4-\alpha_2)}{sin(\varphi_4+\varphi_3+\alpha_2)}}\right\}^2}}\end{array}\right] \tag{28}$$

where L_2 - base of the second trailer.

$$\frac{d\varphi_4}{dt} - \frac{v_{C1} \times tg\phi_1 \times sin(\varphi_1+\varphi_2+\alpha_1)}{\frac{a_2+b_2}{tg\theta_2} \times sin(\pi/2-\varphi_2-\alpha_2) \times \sqrt{1+\left(\frac{l_2-c_2}{a_2+b_2} \times tg\theta_2\right)^2}} - \frac{v_{C1} \times sin(\varphi_1+\varphi_2+\alpha_1) \times sin(\phi_1+\varphi_4+\alpha_2)}{d_2 \times sin\,\varphi_2 \times sin(\pi/2-\varphi_4-\alpha_2)} = 0. \tag{29}$$

In the case of a semi-trailer truck, the first and second folding angles are marked as γ_1 and γ_2 (Fig. 1, a).

It is advisable to determine the angles of assembly of the links and rotation of the steered axles of the trailers during the circular motion of the road train. In this case, the calculation formulas for determining the folding angles and angles of rotation of the steered axles of the second and third trailers are determined by the geometric parameters of the links and the setting parameter - the angle of rotation of the steered wheels of the tractor. So, if the turning angle of the steered wheels of the tractor is taken as a defining parameter for the road train, then the turning angles and folding angles are determined as follows:

$$\varphi_1 = arcsin\frac{L_1^2+c_1^2-b^2}{2\times L_1\times\sqrt{L_1^2\times ctg^2\theta\ \ +c_1^2}} - arctg\frac{c_1}{L_1\times ctg\theta}, \quad (30)$$

$$\varphi_2 = arcsin\frac{L_1^2-c_1^2+b^2}{2\times L_1\times\sqrt{L_2^2\times ctg^2\theta\ \ +b^2}} + arctg\frac{b}{L_2\times ctg\theta}, \quad (31)$$

$$\varphi_3 = arcsin\frac{L_2^2+c_2^2-{b_1}^2}{2\times L_2\times\sqrt{L_1^2\times ctg^2\theta_1+c_2^2}} - arctg\frac{c_2}{L_1\times ctg\theta_1}, \quad (32)$$

$$\varphi_4 = arcsin\frac{L_2^2-c_1^2+{b_1}^2}{2\times L_2\times\sqrt{L_1^2\times ctg^2\theta_2+{b_1}^2}} + arctg\frac{b_1}{L_1\times ctg\theta_2}, \quad (33)$$

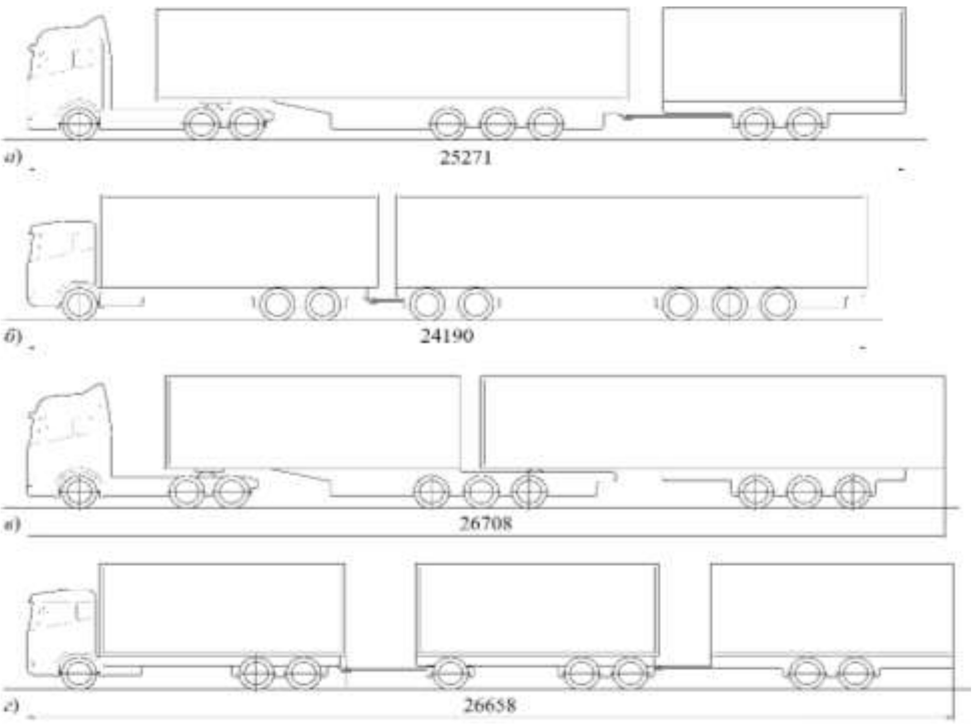
$$\theta_1 = arctg\frac{L_1}{L_2\times ctg\theta_1}, \quad (34)$$

$$\theta_2 = arctg\frac{L_2}{L_1\times ctg\theta_2}. \quad (35)$$

The constructural differences of freight trains are determined by the number of axles of the driving link (tractor) and trailing links (trailer or semi-trailer), by the number of controlled axles and their location. At the same time, from the proposed general scheme of a three-link road train (Fig. 1, b), it is possible to obtain any other one by equating to zero either the mass and the moment of inertia of the axis, or the angle of rotation of the axis, or the corresponding composition parameters.

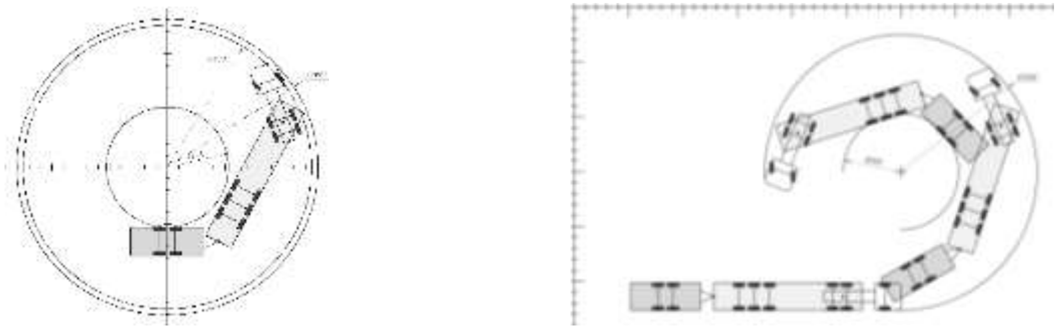
The overall turning radii of the road train and the generalizing indicator of maneuverability - the dimensional traffic lane - are determined by the found angles of assembly of the links of the road train.

In fig. 2 shows the layout schemes of typical road trains.



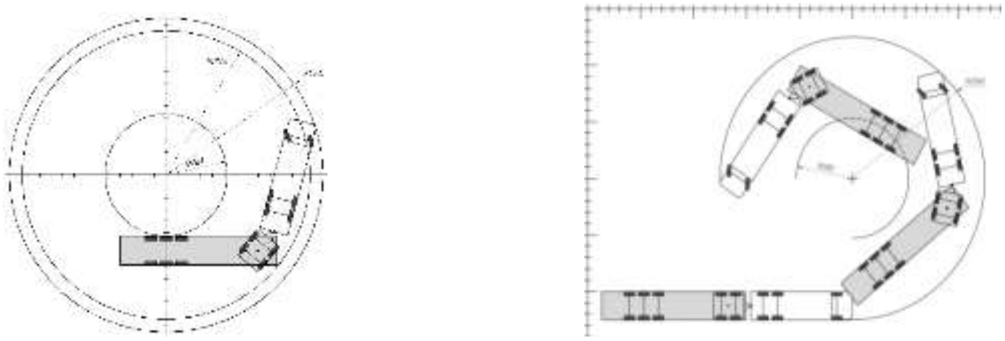
а) - a saddle-coupled three-link road train; *б)* - a three-link road train on a “Dolly” trolley;
в) - "B-Double" type three-link road train; *г)* - trailer three-link road train.
Figure 2. Layout schemes of typical road trains

In fig. 3-6 it is shows a graphic representation of the determination of the dimensional traffic lane of typical road trains during circular motion and when entering a turn.



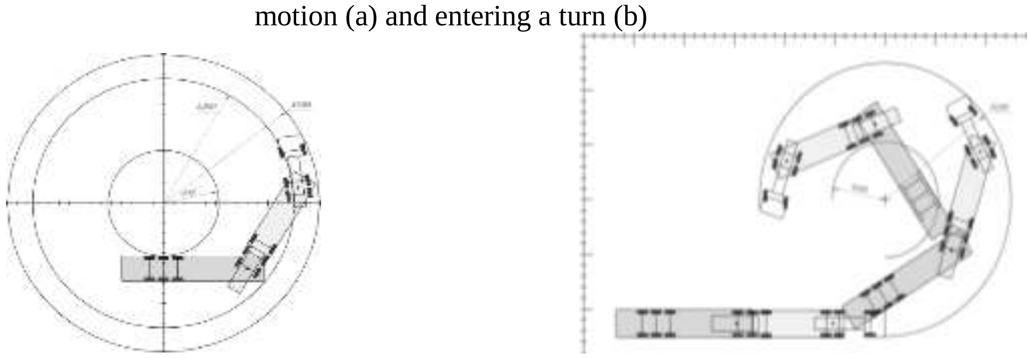
a) б)

Figure 3. The dimensional traffic lane of a saddle-coupled three-link road train at circular motion (a) and entering a turn (b)



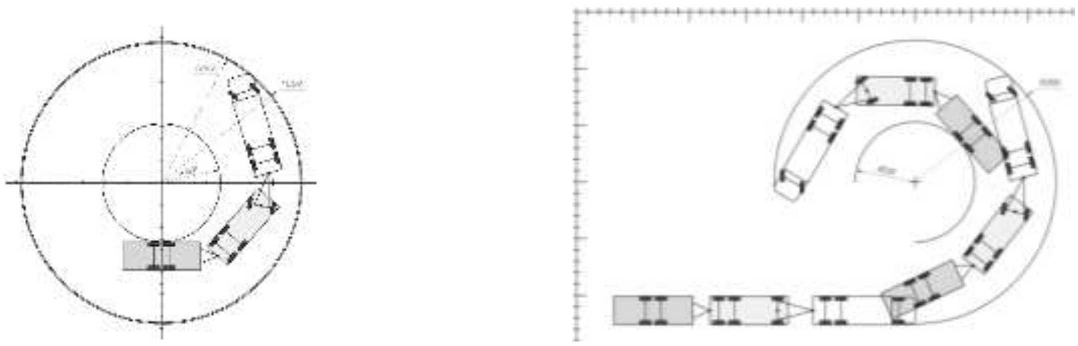
a) б)

Figure 4. The dimensional traffic lane of the trailer three-link road train on a “Dolly” trolley at circular motion (a) and entering a turn (b)



a) б)

Figure 5. The dimensional traffic lane of a three-link road train of the "B-Double" type at circular motion (a) and entering a turn (b)



a) б)

Figure. 6. The dimensional traffic lane of the trailer three-link road train at circular motion (a) and entering a turn (b)

Data analysis of fig. 3-6 shows that three-link road trains do not saticfy the requirements of Directive 2002/7/EC on maneuverability [17]. For three-link road trains with unguided towing links, the minimum external overall turning radius with an internal overall radius of 5.3 m changes within from 12.63 m for a trailed road train to 14.9 m - for a "B-Double" type road train. This is explained by the fact that the length of the three-link road train lies within 26.0...27.0 m. Therefore, for the practical use of three-link road trains in Ukraine, changes should be made both in the transport legislation and in the construction of tractor and in the construction of towing links, in particular, the introduction of controlled towing links into their composition and the determination of their placement in the composition of road train.

DISCUSSION OF THE RESULTS OF THE STUDY

As shown by the calculations of the generalizing indicator of traction-speed properties, the average speed of a road train consisting of tractors of category N3 (MAN TGA, Iveco Magirus, Scania R-series, DAF XF 105, Volvo FH16) with semi-trailers and trailers of category O4 of the KRONE brand in given road conditions differ little from each other, despite the fact that the power of the Volvo FH16 tractor engine (Ne=449 kW) exceeds the power of the DAF XF 105 engine (Ne=375 kW) by 16.5%. From this, it can be concluded that choosing a tractor for a three-link road train based on the power of the engine of the tractor is not appropriate. The selection of the layout scheme of a three-link road train should be based on such indicators as maneuverability and stability of movement.

Conducted studies of the maneuverability of road trains of various layout schemes showed that none of them not saticfy the requirements of Directive 2002/7/EC on maneuverability [17]. Therefore, the issues of maneuverability and stability of three-link road trains with controlled towing links can become directions of further research.

SUMMARY

1. It was established that the average speeds of road trains consisting of tractors of the N3 category (MAN TGA, Iveco Magirus, Scania R-series, DAF XF 105, Volvo FH16) with semi-trailers and trailers of the KRONE brand of the O4 category differ little from each other in the given road conditions. The maximum deviation of the average speed of movement, which has the largest value (for Volvo FH16+ KRONE SDP-27) 22.99 m/s, from the smallest value (for DAF XF 105+KRONE SDP-27) 21.05 m/s, do not exceed 8,5%, i.e. further comparison of road trains should be execute according to other criteria, in particular, according to maneuverability, when moving on a given route.

2. It is shown that the considered three-link road trains do not saticfy the requirements of Directive 2002/7/EC regarding maneuverability. For three-link road trains with unguided towing links, the minimum external dimensional turning radius with an internal dimensional radius of 5.3 m varies from 12.63 m for a trailer road train to 14.9 m for a "B-Double" type road train. This is explained by the fact that the length of the three-link road train lies within 26.0...27.0 m. Therefore, for the practical use of three-link road trains in Ukraine, changes should be made both in the transport legislation and in the construction of tractor, in particular, the introduction of controlled towing links into their composition and the determination of their placement in the composition of road train.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

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SYSTEMATIC ANALYSIS OF FACTORS INFLUENCING THE EFFICIENCY OF MULTIMODAL TRANSPORT

The transport policy of many developed countries is based on the development and implementation of multimodal transport systems. They are an effective means of solving urgent problems of social development, globalisation of internal and external relations between states. The wide coverage of the problems of functioning and developing multimodal transport systems by the world scientific community shows that multimodal transport systems are currently considered as one of the means of solving the most pressing problems of the economy, transport, mobility, etc.

The authors have analysed existing research and found that there are no holistic approaches to analysing, designing, planning and managing different types of multimodal transport systems. The direct application of mathematical methods alone is insufficient and inefficient for such large technical systems as multimodal transport systems (MMTS). The reason for this is the uncertainty of a large number of factors and situations. Therefore, this paper uses the logical foundations of systems analysis. This has allowed the authors to gain a much deeper understanding of the nature of multimodal transport systems, their structure, organisation, tasks, regularities of functioning, optimal ways of development and management methods. The most important factors influencing the efficiency of international multimodal transport were identified using the method of expert evaluation. The content of the most influential factors identified by the experts was systematised. The systematic procedure allowed analysing possible alternative methods and means of achieving the goals, identifying effective solutions for improving the efficiency of MMTS, identifying the largest possible number of organisational and subjective factors affecting the object of study and considering how they affect each other.

Keywords: multimodal transport system, system analysis, influence factors, automation, efficiency.

INTRODUCTION

Multimodal transport systems are integrated systems in which different transport modes work closely together to make moving people and goods convenient and efficient. These systems combine the use of cars, bicycles, pedestrians, public transport and air travel, creating the conditions for the optimisation of traffic flows. The main benefits are improvements in accessibility, reductions in travel time and reductions in carbon dioxide emissions. Multimodality allows travellers to choose the mode of transport that is most appropriate for them.

The terminology of multimodal transport has been laid down in international law. The first document introducing the multimodal concept was the 1980 UN Convention on International Multimodal Freight Transport (Geneva Convention) [1]. In 1995, the United Nations Conference on Trade and Development (UNCTAD) developed a set of rules for multimodal transport. The International Chamber of Commerce (ICC) has made an important contribution to the development of legal regulation of multimodal transport. Under its auspices the “Package of Rules on Multimodal Transport” has been adopted.

In the European Union, multimodal transport systems are regulated by Council Directive 92/106/EEC of 7 December 1992 establishing common rules for certain types of combined transport of goods between Member States, which has to be implemented by all Member States by 2022. This Directive aims to reduce road transport by developing multimodal rail, inland waterway and maritime systems. [2].

Much attention is given to developing and improving multimodal transport in Ukraine, which is served by road, rail, air and water. The country occupies 603,550 sq km. The shape of the country is complex, stretched in the latitudinal direction, the maximum distance from east to west is 1316 km, from north to south – 893 km.

The geographical location of Ukraine allows it to control land and air transport routes between Eastern and Central Europe, sea transport routes in the Black and Azov seas, transport corridors along inland waterways between the Baltic and the Black Sea (Dnipro-Bug channel of the Vistula-Dnipro water system), and pipeline transport of hydrocarbons to European countries from the East (Druzhba, Soyuz, Urengoy-Pomary-Uzhhorod [3]). Rail and waterways played a leading role in multimodal freight transport, which was significantly reduced due to hostilities.

Developing multimodal transport systems (MMTS) is an important process whose successful implementation can solve the country’s security problems and increase investment in its economy.

ANALYSIS OF LITERATURE DATA AND FORMULATION OF THE PROBLEM

The strong interest of the scientific community in the development of this topic confirms the importance of the introduction and development of multimodal transport systems.

The essence of the "multimodal transport" concept, its development prospects and multimodal transport infrastructure are considered in [4-10].

In particular, Petrenko O.I. and Derepovska T.V. [4] substantiated the factors that have a negative impact on the development of multimodal transport in Ukraine; outlined the basic principles of the multimodal system and the main reasons that hinder the development of multimodal transport in Ukraine.

The problem of multimodal transport development from the point of view of ensuring its safety and reliability was addressed by Cherednichenko K., Ivankikova V. et al [5]. The authors have proposed a methodology for the evaluation and selection of the optimal safe transport route. The issue of reliability is important for the effective organisation and functioning of multimodal transport systems. This is shown by the analysis of existing studies [5, 6, 11]. According to the authors, the complexity of multimodal transport systems and the involvement of different types of vehicles explain the importance of this criterion for the evaluation of multimodal transport systems. The complexity of ensuring the safety of such integrated transport systems lies in the need for adaptation of their assessment methods and the main criteria that ensure reliability and safety for all modes of transport.

Methodological and methodical support of making management decisions in the system of multimodal freight transport and analysis of ways to improve the economic efficiency of making decisions is the subject of research by many authors [12, 13, 14, 15].

In order to organise the management process, management often uses graph models [12, 13, 14]. In our opinion, these models do not always take into account all the characteristics of a multimodal system in detail, in particular the time spent at freight or passenger transfer points, which does not always correspond to the plan. Researchers are developing modern software products for effective management and management methods which include the use of automated and digital control systems and artificial intelligence [16, 17, 18]. Such a management organisation meets the requirements of universality. It takes into account the multi-criteria choice under conditions of uncertainty from a discrete or continuous set of alternatives.

An analysis of recent research has shown that researchers have been developing new approaches to the solution of multimodal transport problems [19-21].

Zukhruf F., Frazila R. B. and others [19] proposed a comprehensive model for the restoration of a multimodal system destroyed by a natural disaster. The model includes measures to restore the road network and multimodal terminals, and also takes into account the interdependence of infrastructure and equipment in the system for the smooth distribution of humanitarian aid.

In this paper [20], the authors highlight the importance of travel time assessment in a multimodal freight transport network. This parameter is essential for the improvement of supply chain and logistics operations. Accurate travel time prediction is very important for freight transport and allows to improve logistics efficiency and quality. This paper develops a DLTTE-MFTN time estimation method that can be used to reduce dimensionality of multimodal transport data objects, significantly improving travel time prediction. The method has been tested by the authors and shows that using it gives superior performance compared to other models.

In order to justify the modes of transport for Japanese export containers, Dongxu Chen, Sufan Peng and others [21] used actual freight data. They developed a route selection model through data integration. This model is a theoretical basis for Japanese companies which are interested in the use of multimodal transport for the export of various goods to Europe or China. In addition, this approach helps to provide the operators with a more accurate assessment of the potential demand in the market.

Chuanzhong Yin, Ziang Zhang and others [22] have developed a comprehensive model for restoring a multimodal system that has been destroyed by a natural disaster. The model includes measures to restore the road network and multimodal terminals. It takes into account the interdependence of infrastructure and equipment in the system to ensure the smooth distribution of humanitarian aid.

The wide coverage of the functioning and development of multimodal transport systems by the global scientific community shows that the public policies of many countries are currently based on developing them, and MMTS are considered as one of the means to solve the most pressing economic, transport, mobility, etc. problems.

At the same time, an analysis of the literature showed that holistic approaches to the analysis, design, planning and management of different types of multimodal transport systems do not exist. The authors have used various methods of mathematical modelling, structural synthesis, optimal control, optimisation for load studies, description of the conditions for the safe operation of transport, capacity, etc.

The direct application of mathematical methods alone is insufficient and not very effective for such large technical systems as MMTS. The reason for this is the uncertainty of a great number of factors and situations. That is why we will not use mathematical methods, but the logical foundations of systems analysis, which will allow us to understand better the nature of multimodal transport systems, their structure, organisation, tasks, regularities of operation, optimal ways of development and management methods.

PURPOSE AND OBJECTIVES OF THE STUDY.

The purpose of the study is the systematic analysis of the factors which have an impact on the efficiency of multimodal transport. In order to achieve this goal, it was necessary to carry out the following tasks: an expert assessment to identify the most important factors influencing the efficiency of international multimodal transport; systematisation of the content of the most influential factors identified by the experts.

RESEARCH RESULT

Effective use of MMTS requires a systematic and scientific approach to the organisation of multimodal transport. All logistical and technological processes must be taken into account. This is particularly important in the case of international multimodal transport. In contrast to other formalised approaches, systems analysis makes it possible to:

- analyse all possible alternative methods and means of achieving objectives, combining them where necessary to solve the problem identified;
- find non-standard, but effective solutions;
- identify the maximum number of organisational and subjective factors influencing the studied problem and consider how they interact.

Multimodal international transport can be seen as a process based on the integration of production and transport that can lead to improvements in transport quality and reductions in resource costs. Transport efficiency is influenced by many factors, both internal and external. However, it should be understood that external factors are virtually impossible to change. However, on the basis of a systematic analysis they can be taken into account, predicted and controlled, which will allow timely adjustment of internal factors.

The first phase of the research was an expert assessment of the key factors that influence the efficiency of international multimodal transport.

According to the recommendations of [23], an expert group was formed. It consisted of 12 experts: 3 teachers, 6 representatives of transport companies (4 of them were specialised in international transport), 3 representatives of the Ukrzaliznytsia.

Several stages were involved in the technology of expert evaluation: Stage I – formulating the purpose of the expert analysis; Stage II – forming an expert group; Stage III – developing procedures and expert assessment; Stage IV – obtaining results; Stage V – processing the results and analysing the data obtained; Stage VI – determining the degree of achievement of the purpose of the expert assessment.

The experts were asked to analyse the following factors: automation of control systems, technical support, introduction of information technologies, meteorological conditions, availability of means of transport, social conditions, spatial planning and organisation of transport.

Generalised information about the object under investigation and the decision was obtained on the basis of the experts' assessments. A variety of quantitative and qualitative methods are available for the processing of individual expert opinions. The choice of the method depends on the complexity of the problem to be solved and on the form and the purpose of the expert opinion.

The experts used the ranking method. This is the arrangement of objects in ascending or descending order of some inherent characteristic. The ranking method makes it possible to select the most important of the set of factors or parameters that have been studied. The resulting ranked list is called the Ranked List. The rank of the most important indicator equals 1 and the rank of the least important indicator equals the number n. The advantage of the method is its simplicity. The responses of the experts are averaged to obtain a generalised assessment of a group of experts. Averages are most often used for this.

The arithmetic mean of the rankings assigned to the objects:

$$\bar{x} = \frac{\sum_{j=1}^{m} x_j}{m}, \tag{1}$$

where $\bar{x}$ is the arithmetic mean of the expert group scores;

x_j is the score of the j expert.

The accuracy of the experts' ratings was determined by the degree of concordance between the opinions of the experts. The coefficient of concordance was calculated by the formula

$$W = \frac{12S}{n^2(m^3-m)}, \quad (2)$$

where S is the sum of the squared deviations of the number of rankings or preferences of each factor from the mean; n is the number of experts; m is the number of factors to score.

Sum of the squares of the deviations from the arithmetic mean (P_{cep})

$$S = \sum_{i=1}^{n}\left(\sum_{j=1}^{m} x_{i,j} - \bar{x}\right)^2, \quad (3)$$

where $x_{i,j}$ is the number of ranks assigned by the j expert to the i factor;

$\bar{x}$ is the arithmetic mean of the rankings.

The results of the expert ranking are presented below.

The expert evaluation method showed that the main factors influencing transport are automation of control systems, introduction of information technologies, availability of modes and infrastructure (Table 1).

Table 1 – Results of the experts' assessment of the importance of the influencing factors

The factors	Scores of the experts												Sum of rankings	Deviation square $\Delta^2 = (x_j - \bar{x})^2$
	1	2	3	4	5	6	7	8	9	10	11	12		
the meteorological conditions	1	1	2	3	1	1	1	2	3	1	1	1	18	1296
the availability of transport and infrastructure	6	5	6	5	5	5	6	6	6	3	5	2	60	36
the social conditions	2	2	1	1	2	3	2	1	1	2	3	3	23	961
the automation of the control systems	8	7	8	8	8	6	8	7	7	8	7	8	90	1296
the technical support	5	4	5	4	6	7	5	3	5	4	6	4	58	16
the implementation of information technology	7	6	7	6	7	8	7	8	8	7	8	7	86	1024
spatial planning	3	3	4	7	4	2	3	4	2	5	2	6	45	81
the organisation of the transport operations	4	8	3	2	3	4	4	5	4	6	4	5	52	4
-	-	-	-	-	-	-	-	-	-	-	-	-	$\bar{x} = 54$	$\sum 56856$

The coefficient of concordance is the result of the formula (2): $W = 0{,}78$. The value of the concordance coefficient is close to 1, which indicates the consistency of the experts' opinions.

DISCUSSION OF THE RESULTS OF THE STUDY

Problem solving is the process of exploring different ways of finding an answer to a problem. The essence of problem solving is the presentation of the collected and processed information material in the form of a coherent, consistent and reasoned justification for the achievement of the objectives. Much time is often lost in finding the most effective way to achieve the end goal because of incomplete or inadequate information.

It is at this level that information needs are most active. Satisfying them can lead to significant savings in human, material and financial resources.

The expert analysis carried out by the authors of the article made it possible to identify the main factors influencing the transport process. This is the basis for finding ways to improve the efficiency of multimodal transport, including in Ukraine.

We want to systematise the content of the first three factors identified by experts as having the greatest impact on the efficiency of multimodal transport.

1. The automation of the control systems.

The infrastructure and management of transport systems are complex and require the implementation of automated systems at the current stage of development. The processes of traffic tracking and operational management of transport systems are greatly facilitated by automated systems. It is possible to react quickly to emerging dangerous situations through the use of automated systems. This can be achieved through automated tools that support the exchange of data between vehicles and systems, and between vehicles and infrastructure. At present, it is known that automated systems are built into the design of vehicles to ensure the safety of the driver: ABS (Anti-Lock Braking System); ESC (Electronic Stability Control); DBC (Dynamic Brake Control); TCS (Traction Control System); EBD (Electronic Brake Distribution); BAS (Brake Assist Systems); AEBS (Automatic Emergency Braking Systems); LDWS (Lane Departure Warning Systems); FCWS (Frontal Collision Warning Systems), etc. These functions are implemented using ultrasonic sensors, infrared sensors, radar and artificial vision.

The safety of road traffic is not only influenced by the reliability of the vehicle itself and its equipment, but also by the automation of road traffic equipment. In particular, automated meteorological systems based on using high-precision sensors to measure temperature, wind speed, direction, precipitation, etc. Detectors for the monitoring of traffic are a set of sensors placed under the surface of the road. Various sensors transmit information to control panels. The information is processed immediately.

Rail transport is an important component of the multimodal transport system of Ukraine. Mainly due to its ability to carry the majority of bulk freight over long distances throughout the year, rail is the backbone of the country's transport system. The loss of sea freight has also contributed to the growing importance of this mode of transport. Automation equipment has become a vital part of the railway's technical armoury, helping it to reliably perform its transport tasks, increase its capacity, ensure the safe movement of trains and provide seamless communication between all rail transport equipment.

Automation equipment includes: automation equipment that regulates the movement of trains on the tracks (semi-automatic and automatic blocking); control equipment for switches and signals in the station; door position sensors; automated systems for control of power supply to power equipment and their operation. The reliable operation of automated systems ensures the safety of people, goods and rolling stock, the speed of transport and the comfort of passengers and staff. Automated systems perform tasks of optimal process control, collection and processing of information, planning and prediction of technological processes and the state of equipment.

2. The implementation of information technology.

We now turn to the second influencing factor, namely the importance of information technology for the efficient organisation of multimodal transport. The concept of information is important for the systems and for the analysis of them. Therefore, there will be a formalisation of this concept. To organise the process of efficient information use for multimodal transport, high-bandwidth electromagnetic and optical channels are used. In particular, fibre optic information transmission networks are widely used in Ukraine. They enable information exchange, video surveillance and free access to Internet resources. Information systems make it possible to process information concerning the location, safety and environmental situation of transport. Railway transport uses fibre optic networks. Road transport uses wireless technologies such as GSM and DSRC. The monitoring and management of logistics processes is being improved by artificial intelligence and other technologies.

The number of devices that use GPS and GSM-R has now grown considerably and is continuing to develop in all modes of transport. This provides detailed information on passenger and freight movements to transport infrastructure operators.

The use of information technology enables rail and road companies to have access to each other's information and to communicate with customers.

The transfer of electronic texts between computers in management and transport eliminates the need for paper documentation. It greatly simplifies the management and planning of multimodal transport and reduces the time required for its implementation. In addition, according to UNECE experts [24], the development of electronic information systems saves on average 7-8% of the value of goods in international trade.

3. Accessibility of transport infrastructure.

Transport infrastructure is the fixed structures, facilities and networks that enable people and goods to move. Urban transport infrastructure is divided into five broad groups: roads, bridges and tunnels, rail and tram, water, and cycling and walking [25]. Underdeveloped transport infrastructure has a direct impact on the speed, safety and reliability of transport, including an insufficient number of vehicles, both road and rail.

For the creation of an efficient infrastructure for both domestic and international transport, it is necessary to develop the construction of logistics terminals that enable the interaction of different modes of transport, which in turn creates favourable conditions for the organisation of multimodal transport and integration into the international logistics system.

We are going to analyse how the infrastructure affects the efficiency of the MSEs. First of all, the basis for reducing negative environmental impacts is to solve the problem of organising modern high-tech infrastructure. Particularly in Ukraine, in view of the reduction in the number of waterways, it is advisable to build and technically develop existing railway lines and equip them with modern logistics centres. As a result, carbon dioxide emissions will be significantly lower in comparison with road transport.

Given the strategic importance of rail transport for the country, a major problem in developing it as a component of the multimodal transport system is the low level of organisation of high-speed rail transport. The solution to this problem will require a whole range of systemic research, which will result in a programme of scientific, technical and technological solutions.

The development of the transport infrastructure in Ukraine also requires the creation of multimodal transport and logistics hubs in the country. The current multimodal transport system in Ukraine, as revealed by the system analysis, requires the relocation of freight terminals from the eastern and southern parts of the country to the western part. An example of this is the organisation of a logistics centre in the Rivne region. This centre is used for both export and import of goods. Most of the staff are employees of sea freight terminals who have experience in the construction and maintenance of such terminals. The terminal offers cargo owners handling and storing, customs clearance, packing, insurance, etc.

An analysis of the organisation of production processes within the terminal allowed the authors to identify the main factors preventing the terminal from becoming more dynamic. The first is the increase in the cost of transporting goods due to the need to replace wagons, which is caused by the difference in track gauge between Ukraine and the EU. In addition, the MMTS of the partner countries does not have enough rolling stock, which hinders the growth of freight traffic from Ukraine.

SUMMARY

The study has carried out a systematic analysis of the problem of organising multimodal transport and of the factors that influence its efficiency.

The results of the study led to the following conclusions:

1. The scientific community pays considerable attention to the study of modern principles of operation of certain types of transport and multimodal transport. Researchers' attention is mainly focused on improving a particular mode of transport, certain stages of multimodal transport or solving problems in a particular geographical region. This approach does not meet the current development trends and problems of multimodal transport and innovative technologies.

2. Using expert assessment, the authors have established the main factors affecting the efficiency of multimodal transport systems, that is, determining the specifics of the multimodal freight transport system: automation of control systems, introduction of information technologies, availability of transport modes and infrastructure.

3. A systematic analysis of the content of the factors that primarily affect the efficiency of multimodal transport allows to identify the main unresolved problems of organising MMTS.

Regarding Ukraine, these are:

- low development of transport infrastructure, including insufficient number of vehicles, in particular in the field of rail transport, which directly affects the speed, cost, and reliability of transportation;

- poor development of innovative technologies.

4. In order to achieve significant progress in the field of multimodal transport system of Ukraine, a number of strategic tasks must be solved:

- to intensify the construction of logistics terminals that enable broad interaction between different modes of transport and create favourable conditions for organising multimodal transport, increase the efficiency of logistics processes and create conditions for successful integration into the international logistics system;

- to introduce transport innovations, including the digitalisation of the transport industry;
- to apply electronic document management, electronic data exchange, technologies and standards of EDIFACT, EDI and others.

In order to increase the efficiency of MMTS, the research should be continued in the following directions:

- development and implementation of adaptive systems for controlling motion parameters, including software and hardware solutions using artificial intelligence elements;
- development of a model for managing transport routes using information technologies, taking into account the peculiarities of the economic, social and political situation in Ukraine.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

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PECULIARITIES OF DETERMINATION THE SELF-ALIGNING TORQUE OF THE TIRE DURING MOVEMENT WITH SIDE SLIP

The movement of an elastic wheel with a side slip, which is determined by the angle between the velocity vector and the wheel disk, causes a lateral displacement of the disk relative to the tire contact patch. The displacement is formed during the time the point of the tire comes into contact with the support surface until it leaves it. During such movement, longitudinal and lateral reactions occur in the contact patch and reduce to the self-aligning torque and resultant force, applied in the centre of the contact patch. The self-aligning torque is developed if there are reactions in the plane of the tire contact patch and the displacement of their resultant relative to contact patch centre. At the same time, the forces and moments that developed in the contact patch depend on the state of the contact patch, which is characterized by the ratio of the adhesion and sliding zones in it. This contact patch state is determined by the values of the turning angles of the locked steered wheel during its static turn and depends on the coefficient of road adhesion and the type of tire. Analytical dependencies were obtained for determining the self-aligning torque depending on the slip angle in the range of zero to the slip angle at which the traction properties of the tire with the support surface are fully realized. When the traction properties are fully realized in the tire contact patch during the movement of the wheel with side slip, the self-aligning torque of the tire reaches zero, since the displacement of the resultant reactions relative to the centre of the contact patch goes to zero. At the same time, under the effect of longitudinal reactions, the self-aligning torque can acquire negative values at large slip angles.

Keywords: vehicle, elastic wheel, slip, tire, self-aligning torque, support surface.

INTRODUCTION

Modern scientific research in the automotive industry is aimed at creating a safe and efficient vehicle that will meet modern environmental and technological requirements.

The elastic wheel of the vehicle is considered as a complete mechanism, which transforms the rotational movement of the wheel relative to the axis of rotation into its translational movement [1, 3, 6]. At the same time, the elastic wheel includes a hard disk, an elastic body of the tire (pneumatic) and a tire contact patch, which belongs to both the elastic wheel and the support surface simultaneously. At the same time, the input link of this mechanism is the hard disk, and the output link is the tire contact patch.

If there is adhesion of the tire to the supporting surface the forces and moments applied to the wheel disc from the car frame, transmission, braking and steering systems, etc., passing through the body of the tire, cause to occur reactions in contact between the tire and the support surface, which ensure the movement of the car [1, 2]. Thus, during the rectilinear movement of an elastic wheel, a moment of rolling resistance occurs due to the displacement of the resultant of any normal reactions relative to the center of the tire contact patch. At the same time, during curvilinear movement of a car, additional wheel movement resistance occurs due to the simultaneous turning of the wheel disk and its lateral displacement relative to the contact patch, which give rise to the tire body twisting torque and lateral force, respectively [3-6].

Rolling of the wheel with toe-in and the action of the lateral force on the wheel occurs the lateral displacement of the wheel disk relative to the tire contact patch during the time the point of the tire comes into contact with the support surface and until the moment it leaves the contact, which causes the wheel to move with side slip [3, 6]. At the same time, lateral reactions develop in the contact patch, the resultant of which is shifted relative to the geometric center of the tire contact patch. This resultant is reduced to the self-aligning torque and the force applied at the center of the tire contact patch. Longitudinal reactions in the tire contact during motion with side slip also give rise a tire self-aligning torque. Since the value of this torque is significantly smaller than the value of the self-aligning torque from lateral forces, and the effect of longitudinal reactions on its value is taken into account by the appropriate coefficient [1, 6].

This work is considered peculiarities of determining the self-aligning torque of the tire during the movement of an elastic wheel with a side slip.

The aim of the study. Determine the peculiarities of calculating the self-aligning torque of the tire during the movement of the wheel with a side slip.

ANALYSIS OF LITERATURE DATA AND FORMULATION OF THE PROBLEM

The results of theoretical and experimental studies of the self-aligning torque of a wheel tire rolling with a side slip are given in the works of M. Keldysh [4], V. Knoroz [5], A. Lytvynov [7], R. Smiley and V. Gornom [8], H. Frondenstein [9], H. Pacejka [10] and others. In works [11-14] the results of the study of the self-aligning torque using the simulation of the operation of the car tire by the method of finite elements are presented.

From the analysis of the above-mentioned works, it is known that during the rolling of a wheel with a side slip, the self-aligning torque Mt of the tire increases with an increase in the slip angle δ, reaches its maximum value, and then decreases when $\delta > \delta_{Mtmax}$ [7–14]. For some tires, at large slip angles, the value of the self-aligning torque can be significantly affected by longitudinal reactions, which causes a change in the sign of this torque [7, 10].

Increasing the inflation pressure in the tire reduces the self-aligning torque. However, this decrease is all the more remarkable, the greater the normal load [7].

The coefficient of road adhesion, which is one of the main physical and mechanical characteristics of the supporting surface, significantly affects the value of this torque. As the road adhesion coefficient increases, the maximum self-aligning torque increases [7–9].

The maximum self-aligning torque for tires under rated load and inflation pressure during wheel rolling with a side slip in [7] is recommended to be determined empirically:

$$\mathrm{M_{tmax}} = (0{,}015...0{,}0225)G_w\ , \tag{1}$$

where M_{tmax} is the maximum self-aligning torque, N·m; G_w is the normal load on the tire, N.

This dependence is approximate and does not take into account the coefficient of road adhesion, inflation pressure, and design features of the tire.

Considering that the value of the self-aligning torque depends significantly on the slip angle, the self-aligning torque is determined as a function of the slip angle.

Analysis of the results of experimental studies of the dependence of self-aligning torque on slip angle for a tire size 6.45–13 mod. M130-A showed, that as the tire inflation pressure increases, both the current value of the tire self-aligning torque and their maximum values decrease [15].

Based on the analysis of experimental data on the dependence of tire self-aligning torque on slip angles, obtained by many researchers, in [15] an empirical dependence is proposed, which approximates the curve Mt = f(δ) in the slip angles range from zero to a value greater than 20–30 % of the slip angle corresponding to the maximum value of the self-aligning torque:

$$\frac{\mathrm{M}_t}{\mathrm{M}_{t\mathrm{max}}} = 2\frac{\delta}{\delta_{\mathrm{Mtmax}}} - \left(\frac{\delta}{\delta_{\mathrm{Mtmax}}}\right)^2, \tag{2}$$

where M_t is the self-aligning torque of the tire at the current value of the slip angle δ; M_{tmax} is the maximum value of the tire self-aligning torque; δ_{Mtmax} is the slip angle at which the self-aligning torque of the tire reaches its maximum value.

Values M_{tmax} and δ_{Mtmax} the author recommends to determine experimentally on the bench. However, during the research on the drum stand, the value of the torque Mt = f(δ) will be smaller than during determination on the plane [7, 15]. The difference between the experimental data will depend on the ratio of the drum and tire diameters. This is explained by the fact that as a result of testing tires on a drum, the pressure distribution over the contact area and its dimensions change. To obtain data on the self-aligning torque, it is necessary that the ratio of the drum diameter to the tire diameter should be at least 3.5.

In [8], it is recommended to determine the self-aligning torque of the tire according to empirical dependencies, dividing it into three zones, depending on the dimensionless value, which depends on the value of the road adhesion coefficient:

$$\text{at } \frac{k_{\text{во}}\delta}{\varphi R_N} \le 0{,}1 \quad M_ш = 0{,}4ak_{\text{во}}\delta\ , \tag{3}$$

$$\text{at } 0{,}1 \le \frac{k_{\text{во}}\delta}{\varphi R_N} \le 0{,}55 \quad M_ш = \frac{a}{2}\left[k_{\text{во}}\delta\left(1 - \frac{k_{\text{во}}\delta}{\varphi R_N}\right) - 0{,}01\varphi R_N\right], \tag{4}$$

$$\text{at } \frac{k_{\text{во}}\delta}{\varphi R_N} \ge 0{,}55 \quad M_ш = \frac{a}{2}\left[0{,}2925\,\varphi R_N - 0{,}1k_{\text{во}}\delta\right]. \tag{5}$$

where k_{s0} is the coefficient of lateral deflection at a small slip angle; R_N – vertical force acting on tire from ground; φ –coefficient of road adhesion; a is the contact patch length.

At the same time, in [8] recommend to determine the maximum value of the tire self-aligning torque by the expression:

$$M_{t\max} = 0{,}12a\varphi R_N. \quad (6)$$

In [11], a model of the Regional Haul Steer II, RHS 315/80 R22.5 truck tire was developed using the finite element method, and the Pam-Crash software, a study of the influence of some operating conditions on the characteristics of tires turning on a hard surface was carried out. The obtained dependences of the lateral force and the self-aligning torque of the tire on the slip angle for different values of the vertical load, inflation pressure, and speed of movement. It was concluded that the self-aligning torque of the tire increases parabolically at all values of the speed of movement, approaching the maximum at a slip angle of 4 degree, and then decreases at larger slip angles. In [12], [13], proposed several numerical methods for modeling the behavior of aircraft tires during cornering. The obtained dependences of the self-aligning torque on the slip angle, when the torque first increases, reaching the maximum value (at a slip angle of about 5 degree), then decreases. At the same time, the results of the simulation of the self-aligning torque of the tire and the coefficient of road adhesion sufficiently coincide with the experimental data, in particular, when the surface temperature changes.

Therefore, the self-aligning torque is formed by the displacement of the resultant of lateral and longitudinal reactions in the tire contact patch relative to the center of the contact patch during wheel rolling with side slip, and when the traction properties are fully realized in the tire contact patch during the movement of the wheel with side slip, the self-aligning torque of the tire approaches zero.

RESEARCH RESULT

The forces and moments acting on the elastic wheel when moving with side slip are determined by the reactions in the contact of the tire with the supporting surface and depend on the state of the contact patch. The state of the tire contact patch is characterized by the ratio of the adhesion and sliding zones. Depending on the ratio of the adhesion and sliding zones, three of its states are distinguished: in the contact patch there are only areas of adhesion, in the contact patch there are areas of adhesion and sliding; in the contact patch there are only sliding zones [1, 6, 15].

The state of the contact patch of the tire will be determined by the turning angle of the hard disk of the wheel relative to the tire contact patch during wheel static turn. The first state is possible at the turning angle of the disk $\theta \leq \theta_A$, where θ_A is the maximum turning angle of the wheel disk during wheel static turn at which it is considered that there are only adhesion zones in the contact patch. The second state is possible at the turning angle $\theta_A<\theta<\theta_B$, where θ_B is the minimum turning angle of the wheel during wheel static turn where it is considered that there are only sliding zones in the tire contact patch. When the angle θ varies in the range from θ_A to θ_B, the area of the sliding zones increases, and the area of the adhesion zones decreases accordingly. The third state occurs at the rotation angle $\theta \geq \theta_B$. The values of the angles θ_A and θ_B for a specific tire depend on the value of the coefficient of road adhesion, the maximum adhesion of which is achieved on a dry asphalt concrete surface, and is in range 0.6-0.8 [1].

Considering the above, the dependence of the self-aligning torque can be described by analytical expressions as a function of the slip angle.

The results of experimental studies conducted with a wide-profile tire of size 1300x530–533 mod. ВИ-3 and radial tire of size 9.00-20Р mod. И-Н142Б in driven mode showed that the self-aligning torque of the tire acquires a maximum value during rolling with side slip angle $\delta_{M t\max}$, which in absolute value is close to the angle of turning of the wheel during wheel static turn θ_A, in which conditionally linear dependence between the static tire steering resistance torque and the angle of turning of the wheel is maintained.

If we assume that the diagram of the distribution of lateral forces approaches a right triangle when $\delta \leq \theta_A$, and their resultant is applied at its mass center, located at a distance of a/3 from its base, then the self-aligning torque of the tire Mt is determined by the expression:

$$M_t = P_s \frac{a}{6}, \quad (7)$$

where a is the length of the tire contact patch; $a/6$ – the distance from the transverse axis of the tire contact patch to the mass center of the right-angled triangle of the side force plot P_s; P_s is the resultant of elementary lateral forces during wheel rolling with the slip angle $\delta \leq \theta_A$.

Expression (7) is valid if the diagram of lateral forces is a right triangle. Taking into account expression (7), the maximum self-aligning torque of the tire is determined as follows:

$$M_{\text{tmax}} = P_{M_{t\max}} \frac{a}{6}, \tag{8}$$

where M_{tmax} is the maximum tire self-aligning torque due to lateral force, N·m; P_{Mtmax} is the lateral force causing the maximum self-aligning torque, N.

If, with sufficient accuracy for practical calculations, it is considered that in the slip angles range $0<\delta\leq\theta_A$, the dependence between the lateral force and the slip angle is conditionally linear, then it is possible to write:

$$P_{\text{M}_{\text{tmax}}} = k_s \delta_{\text{M}_{\text{шmax}}}, \tag{9}$$

where k_s is the coefficient of lateral deflection, N/deg; $\delta_{\text{M}_{\text{tmax}}}$ is the slip angle, at which the self-aligning torque of the tire reaches its maximum, deg.

The cornering stiffness is determined under the condition [15] that the energy supplied to the wheel for the disk twisting and its lateral displacement during movement along a curved trajectory is distributed equally:

$$k_s = \frac{2C_\theta}{a}, \tag{10}$$

where C_θ – angular stiffness of the tire relative to the vertical axis, N·m/deg.

Taking into account dependencies (8)–(10) and the self-aligning torque of the tire reaches its maximum value at the slip angle $\delta_{M_{t\max}} = \theta_A$, the maximum self-aligning torque will be determined as follows:

$$M_{\text{tmax}} = \frac{C_\theta \theta_A}{3}. \tag{11}$$

Dependence (11) is obtained without taking into account the displacement of the resultant longitudinal reactions of the support surface relative to the longitudinal axis of the tire contact patch and under the condition that the specific pressure at each point of the contact patch and the road adhesion coefficient are the same. In real conditions, these parameters differ. At the same time, the value of this difference is significantly affected by the type of tire. The effect of the mentioned factors is recommended to be taken into account by the coefficient of proportionality of the self-aligning torque K_t. Then we have:

$$M_{\text{tmax}} = \frac{K_t C_\theta \theta_A}{3}, \tag{12}$$

where K_t. is the coefficient of proportionality of the self-aligning torque.

The value of K_t for high-pressure tires does not exceed 1.1, for low-pressure tires the value of this coefficient reaches 1.36. For any individual tire, the Kt coefficient must be determined experimentally.

The analysis of experimental data, obtained by many researchers using different methods, showed that under rated inflation pressures and loads, with a high coefficient of road adhesion for truck tires in the driven mode, the slip angle at which the self-aligning torque of the tire approaches zero is 13±2 degree.

The analysis of experimental data Mt = f(δ) showed that this dependence approaches a parabola, and therefore, in the slip angle range $0<\delta\leq\theta_B$, the self-aligning torque during rolling in the driven mode is determined by one of the dependencies:

at $0<\delta\leq\theta_A$
$$M_{\text{ш}} = \frac{K_{ш} C_\theta \theta_A}{3}\left[1-\left(\frac{\delta}{\theta_A}-1\right)^2\right], \tag{13}$$

when $\theta_A<\delta\leq\theta_B$
$$M_{\text{ш}} = \frac{K_{ш} C_\theta \theta_A}{3}\left[1-\left(\frac{\delta-\theta_A}{\theta_B-\theta_A}\right)^2\right], \tag{14}$$

Fig. 1 shows the effect of slip angle on the self-aligning torque for a wide-profile tire size 1300x530–533 mod. ВИ-3, calculated by expressions (2), (3)–(5) and (13), (14). Fig. 2 – the effect of slip angle on the self-aligning torque for the Regional Haul Steer II tire, RHS 315/80 R22.5, calculated by expressions (2), (13), (14) and obtained from the results of computer simulation using the finite element method [11]. Calculations by expressions were carried out with the coefficient of road adhesion φ = 0.7, coefficients proportionality of the self-aligning torque of the tire Kt = 1.1, angles θ_A = 5 degree, θ_B = 13 degree, in the slip angle range from 0 to 14 degrees. Other initial data for the calculation are given in the table. 1. The cornering stiffness was determined by expression (10). Calculations according to dependence (2) were carried out in the slip angle range from zero to a slip angle that is 20% greater than the angle δ_{Mtmax}. The results of the computer simulation are shown in slip angle the range from 0 to 6 degrees.

Table 1. Input Data Calculation

Indicator	1300x530–533 mod. ВИ-3	Regional Haul Steer II, RHS 315/80 R22.5 [11]
G_w, kN	27.0	53.4
r_t, MPa	0.4	0.4275
C_θ, N·m/deg	267.0	534.0

From the analysis of fig. 1, 2, it can be seen that the self-aligning torque of both tires increases with the increase in the slip angle, reaches its maximum value, and then decreases.

For tires 1300x530-533 mod. ВИ-3 calculations based on dependencies (2) and (13), (14) show that the self-aligning torque of the tire reaches its maximum value at the slip angle = 5 degree, which corresponds to the maximum angle at which only adhesion zones are present in the contact zone of the tire with the supporting surface. In the slip angle range from 0 to 5 degrees, the values of the self-aligning torque completely coincide. At δ =6 degree the difference is 2.4 %. According to dependencies (13), (14), the self-aligning torque of the tire approaches zero at the slip angle δ = 13 degree, which corresponds to the minimum angle at which the traction properties of the tire with the supporting surface are fully realized. Dependence (2) does not allow us to determine at what slip angle the self-aligning torque reaches zero.

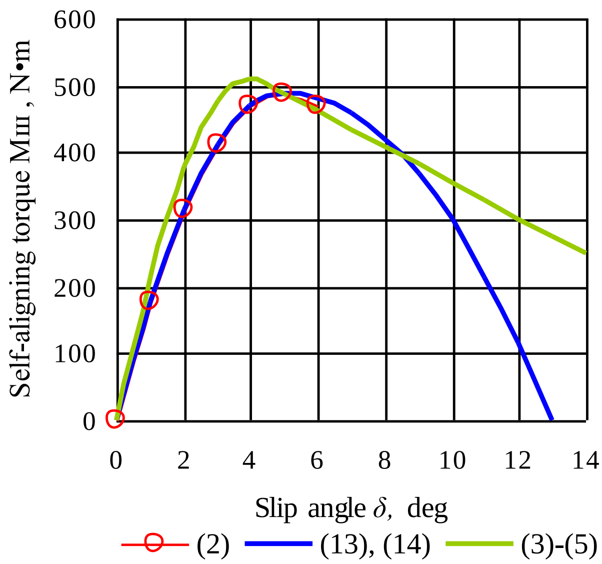

Fig1. Effect of slip angle on the self-aligning torque with 27 kN at 0.4 MPa

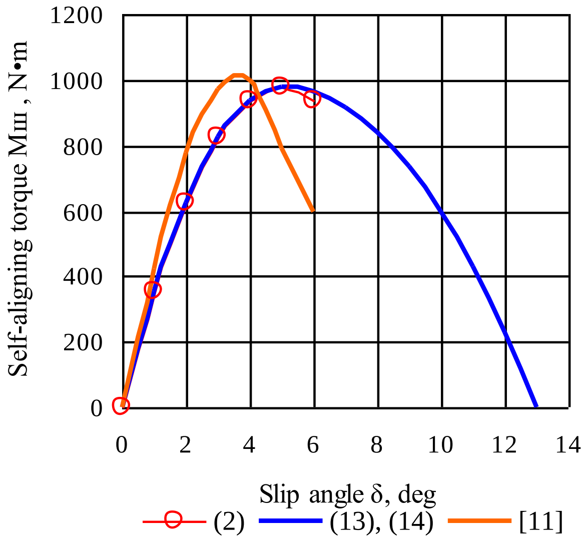

Fig2. Effect of slip angle on the self-aligning torque with 53.4 kN at 0.4275 Mpa

The results of calculations based on dependencies (6)–(8) show that the maximum value of the tire self-aligning torque is achieved at a smaller slip angle $\delta_{M_{t\max}}$ = 4 degree than determined by expressions (2) and (13), (14). In the slip angle range from 0 to 4 degrees, the difference in the values of the self-aligning torque does not exceed 8.5 %. In the case of a further increase in the slip angle δ>4 degree, the dependence $M_t = f(\delta)$ is almost linear. If the slip angles δ>9 degree, the calculation results differ significantly. The self-aligning torque of the tire reaches zero at the slip angle δ = 23.29 degree, which is significantly greater than according to dependencies (13), (14).

For the Regional Haul Steer II, RHS 315/80 R22.5 tire, calculated according to dependencies (2) and (13), (14), the values of the self-aligning torque of the tire when the slip angle changes from 0 to 5 degrees coincide. The maximum value of the self-aligning torque is reached at $\delta_{M_{t\max}}$ = 5 degree. At δ =6 degree the difference is 2.4 %. According to dependencies (13), (14), the self-aligning torque of the tire reaches zero at the slip angle δ = 13 degree.

The results of computer simulations in the slip angle range from 0 to 6 degrees show that the maximum value of the self-aligning torque is reached at a smaller slip angle = 3,8 degree than determined by expressions (2) and (13), (14). At a slip angle of 3.8 degree, the difference in the values of the self-aligning torque does not exceed 6.0 %. In the case of a further increase in the slip angle δ>4 degree, the calculation results differ significantly. At δ =6 degree the difference is 37.7 %.

Therefore, dependence (5) allows determining the self-aligning torque of the tire only in the slip angle range from zero to the slip angle at which the self-aligning torque reaches the maximum value, and dependencies (3)–(5), (13), (14) – from zero to the slip angle, at which traction properties are fully realized in the tire contact patch. At the same time, the analytically obtained dependencies (13), (14) with sufficient accuracy for practice reflect the physical phenomena that occur in the tire contact patch during wheel rolling with side slip, and allow determining the self-aligning torque of the tire in the slip angle range $0 \le \delta \le \theta_B$.

SUMMARY

1. The self-aligning torque of the tire occurs during the movement of the wheel with a side slip and is caused by lateral and longitudinal reactions, acting in the contact plane, and brought to the center of the contact patch of the tire. At the same time, the movement of the elastic wheel with side slip causes a lateral displacement of the disc relative to the tire contact patch, which is formed from the moment the point of the tire comes into contact with the support surface until the moment it leaves it.

2. Reactions that occur in the plane of the tire contact patch during the movement of the wheel with a side slip, depend on the state of the contact patch. This state of the contact patch is formed by the adhesion and sliding zones in it and is characterized by the values of the turning angles θ_A and θ_B of the locked steered wheel during wheel static turn. Their values depend on the coefficient of road adhesion and the type of tire. The obtained analytical dependences for determining the self-aligning torque of the tire during moving with side slip take into account the adhesion properties of the supporting surface and the tire.

3. When the traction properties are fully realized in the tire contact patch during the movement of the wheel with side slip, the self-aligning torque of the tire reaches zero, since the displacement of the resultant reactions relative to the center of the contact patch goes to zero. At the same time, under the effect of longitudinal reactions, the self-aligning torque can acquire negative values at large slip angles.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

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ELECTRIC VEHICLE BATTERIES AND CHARGING INFRASTRUCTURE: CHALLENGES AND OPPORTUNITIES

In today's world, as we move towards more sustainable and environmentally friendly transportation, electric vehicles are becoming a centerpiece. The article "Electric Vehicle Batteries and Charging Infrastructure: Challenges and Opportunities" analyzes the current state and prospects for the development of electric vehicle batteries and charging infrastructure.

The purpose of the article is to highlight the problems associated with charging infrastructure, the use of different types of batteries for the development of the electric vehicle sector and ways to solve them. The article explores the current battery technologies used in electric vehicles, in particular lithium-ion batteries, and points out the advantages and disadvantages of each type. By comparing energy density, charging speed, and service life, the article helps to understand which batteries may have advantages in the electric vehicle market in the future. The main motivations for the transition to electric vehicles are to reduce emissions of harmful gases, attract renewable energy sources and reduce dependence on oil resources. The research is based on key aspects of the introduction of electric vehicles: improvements in battery technology to ensure greater efficiency and durability; the need to develop an efficient and affordable charging infrastructure for electric vehicles; the importance of fast charging for convenience and efficiency, and to reduce charging waiting times, making electric vehicles more attractive to users; and the development of battery recycling and reuse systems.

The article examines the challenges associated with the development of charging infrastructure. It analyzes issues such as the limited availability of charging stations, different charging standards, and the efficiency of existing networks. In addition, the article highlights strategies that can be used to overcome these challenges, such as incentivizing infrastructure development and standardizing charging connectors. The economic and environmental benefits of the transition to electric transport and the need for joint efforts by governments, manufacturers, and infrastructure companies to overcome the challenges and ensure the sustainable development of this industry are discussed. Overall, the article provides an in-depth overview of the current state and prospects for the development of key components of electric vehicle infrastructure, contributing to the understanding and resolution of the challenges associated with the transition to more sustainable and environmentally friendly transportation.

As a result of further research, a conceptual approach to innovation and investment in the development of batteries for electric vehicles and charging infrastructure is proposed to overcome current challenges. The practical implications of the research findings for the transport industry are in the recommendations provided to facilitate cooperation between all stakeholders and are essential to achieving success.

Keywords: electric vehicle, charging infrastructure, electric vehicle battery, charging stations, electric energy.

INTRODUCTION

Electric vehicles have been the main trend in the growth of such vehicles in recent years. Most European countries have set the goal of switching to electric or hybrid vehicles and abandoning internal combustion engines. At the moment, the electric vehicle market is at the stage of active development. The number of electric vehicles on the road is growing, which indicates an increasing interest in this technology. The European Parliament voted in favour of a complete ban on new cars with internal combustion engines by 2035. The next step is approval from the EU Council [1].

The main advantage of electric vehicles is their environmental friendliness, as they do not emit harmful substances into the air and are therefore suitable for use in urban environments. They are also quieter, have a smoother ride and lower maintenance costs. However, at present, the high price and insufficient charging infrastructure are the main obstacles to the mass adoption of electric vehicles. The introduction of electric vehicles as an environmentally friendly alternative has significant potential to address environmental, energy and transport issues. However, the effective introduction of these vehicles requires government support, the development of charging infrastructure and further research into battery technology. The key aspects that explain their importance are: driving range and battery capacity, development of efficient and affordable charging infrastructure, charging speed, battery fire safety, and diversification of the energy mix.

The world is gradually moving towards the electric vehicle era, and battery production is becoming a priority for many countries [2]. Continuous improvements in battery technology are helping to increase battery capacity and improve driving range. The widespread distribution of charging stations in cities, car parks, public places and motorways is an attractive proposition for potential buyers. The availability of a sufficient number of charging stations provides convenience and reliability for EV owners, as they can charge their cars at a time and place that is convenient for them. The development of fast charging, which allows electric vehicle batteries to be charged in a short time, helps to reduce waiting times and makes electric vehicles more attractive to a wider audience.

Electric vehicle batteries can be used as a means of storing electricity and help to even out the load on the grid. Charged electric vehicles can serve as reservoirs of stored electricity that can be used during peak periods or during power outages. This contributes to the stability of the grid and the expansion of renewable energy sources.

The aim of the study is to investigate and describe the problems of charging station infrastructure and batteries for electric vehicles and consider ways to solve them. In this regard, it is necessary to analyse the results of testing and testing the fire resistance of the electric vehicle battery system and the safety of charging stations.

ANALYSIS OF LITERATURE DATA AND FORMULATION OF THE PROBLEM

Batteries are a key component of electric vehicle technology that provides electrical energy storage for propulsion. The main type of batteries used in electric vehicles is lithium-ion batteries. The choice of a specific battery type for an electric vehicle depends on various factors, such as driving range, charging time, cost and availability. Lithium-ion batteries are widely used due to their advantages in terms of energy density and weight, but other battery types also have their own unique advantages that may be considered in certain cases.

An important player in the battery technology market is A123 Systems, a company founded in 2001 that specializes in the development and production of batteries for electric vehicles, power sources, tools and other devices. One of A123 Systems' main products is lithium-ion batteries, in particular nano phosphate lithium iron phosphate (LiFePO4) batteries. These batteries are known for their high resistance to overheating, long service life and relatively safe operation compared to other types of lithium-ion batteries. A123 Systems manufactures batteries of various sizes and capacities that can be used in small electronic devices and large power systems. The company actively researches and develops new technologies to improve the performance, safety and durability of its batteries.

Based on the Bloomberg NEF lithium-ion battery supply chain ranking, Visual Capitalist has shown battery production capacity by country from 2022 and projected to 2027, highlighting China's dominance. Most of the parts and metals that make up a battery, such as lithium, electrolytes, separators, cathodes and anodes, are predominantly made in China. [2]. New battery materials and designs are being developed to increase energy density, extend driving range, reduce charging time, and improve overall life expectancy.

Other types of batteries are also used in electric vehicles, such as lithium-polymer batteries (Li-Po): These batteries have similar characteristics to lithium-ion batteries, but they are more flexible and can be made in different sizes and configurations. This allows them to be used in a wider variety of electric vehicle designs. The original type of batteries, called "lithium-polymer", were technologically a further development of conventional lithium-ion batteries and lithium batteries. The main difference was the use of a dense polymer electrolyte [3] .

Supercapacitors are another type of battery. Supercapacitors, also known as electric motors, have a high energy density and are capable of delivering a large energy flow. They are often used as additional energy sources to improve performance and to store energy during braking. Supercapacitors are electrochemical capacitors that differ significantly from conventional capacitors in their virtually unlimited durability, lower current losses and higher power density. At the same time, they are much smaller in size. In other words, this is a new generation battery that can open up numerous prospects in the energy sector and in electric vehicles [4]. The research and development of new battery materials, such as lithium-sulfur and lithium-metal batteries, opens up opportunities to increase energy density and improve capacity. These results bring Ukrainian technology much closer to being used in modern life. Globally, this development is unprecedented and exists only at the theoretical level, and the creation of a laboratory prototype is a significant breakthrough in the field of battery manufacturing [5]. The main advantages of lithium-sulfur (Li-S) batteries are their high energy density and potentially low cost. In addition, raw materials for lithium-sulfur batteries are cheaper and more readily available than those used in lithium-ion batteries. However, lithium-sulfur batteries have limited cyclic stability, which means that their efficiency decreases over time.

The use of new technologies such as nanomaterials and nanostructures can help improve the charge rate and battery life. "New bulk materials, film and powder technologies have made it possible to create rechargeable batteries and supercapacitors with high specific capacity, as well as high-quality permanent magnets. As a result, new efficient components have emerged: embedded electronic systems, sensors and mechanical drives (stepper, collector and brushless motors), galvanic cells and rechargeable batteries, etc. These components have become the basis for creating 3D printers, small aircraft (drones, etc.), electric vehicles, etc." [6].

However, there are several challenges to the widespread adoption of electric vehicles related to battery technology. Some of them include:

1. Cost: Batteries are expensive components of electric vehicles and represent a significant proportion of the total cost of the vehicle. Reducing the cost of batteries is considered an important step to increase the affordability of EVs for the general consumer.

2. Life cycle and disposal: Batteries have a limited life cycle, after which they lose their original energy density. Efficient disposal of used batteries is an important task to reduce the environmental impact and efficient use of renewable resources. The development of battery reuse programmers, as well as recycling and disposal technologies, are important steps in creating a sustainable and environmentally responsible infrastructure for battery systems.

3 Fire safety: Fire safety is an important aspect of electric vehicles because they use lithium-ion batteries, which can be potentially dangerous if misused or damaged. Batteries must be designed and manufactured to meet fire safety standards. The United Nations Economic Commission for Europe (UNECE) Resolution No. 100 "Specific requirements for the approval of vehicles with regard to specific requirements for electric drivetrains" (abbreviated as R100) has been significantly amended. New test requirements have been introduced in the approval process for motor vehicles and battery energy storage systems (REESS) to ensure safe operation of batteries and a higher level of safety for vehicle occupants. These new test requirements were adopted in July 2016 [7].

The deployment of an efficient charging infrastructure is a key element in the success of the electric vehicle industry. A convenient, accessible, and reliable network of charging stations is needed to increase the popularity of electric vehicles. Large cities, motorways and public places such as shopping centres and car parks should be equipped with charging stations [8]. Developing fast charging standards and standardising different types of charging connectors are also important aspects. Despite significant progress in the development of fast charging stations, the charging time for electric vehicles remains long compared to refueling a traditional car. The development of fast-charging technologies and the growth of the charging station network is an important aspect to ensure the convenient use of electric vehicles.

PURPOSE AND OBJECTIVES OF THE STUDY

At a time when the electric vehicle market is setting records, there is still no clarity on the standardisation of charging ports. How many and what types of chargers are needed now, in which regions do their customers live, where are there shortages, and where will this go in the future?

First, let's look at the types of charging stations for electric vehicles available in the world:

Level 1 is the lowest charging level and lowest connection security. . It usually takes about 12 hours to restore the vehicle's charge using this method. This process takes place without any special equipment, using a standard wall socket and a special AC adapter.

Level 2 is a standard AC charging station that can be installed at home or used at petrol stations. It is used for charging all types of electric vehicles with standard connection sockets and built-in protection. The charging time is approximately 6-8 hours for batteries with a capacity of 20-24 kWh.

Level 3 is the most powerful level, which uses AC stations. It is suitable for both single-phase and three-phase networks.

Level 4 - This type of charging station uses direct current. The power of these stations may be too high for some electric vehicles. However, cars that support this standard can charge their batteries up to 80% in 30 minutes. Such stations can be found in city car parks and highways, although they are quite rare in Ukraine, as they require a separate powerful power supply line. In addition, the cost of such charging stations is quite high.

Since the characteristics of levels 1-4 are constantly being amended, a classification of charging stations by charging power can be used: [9]

1. For household 230 V AC power supplies up to 16 A (3.7 kW), often referred to as cable power supplies.

2. For accelerated charging from 230 V/400 V AC power supplies from 16 A to 40 A (3.7 kW to 30 kW).

3. Fast charger or "Supercharger" - fast charging with direct current supplies power to the battery bypassing the inverter. This is a large stationary equipment with a capacity of 10 kW to 400 kW.

It is worth noting a separate type of Tesla Supercharger charging stations, which differ from the standards discussed above in their specificity of use. In practice, these are not even just charging stations, but energy pumps that can charge a car's batteries up to 50% in 20 minutes, up to 80% in 40 minutes and up to 100% in 75 minutes. Tesla Superchargers have an impressive charging capacity of 135 kW DC. The connectors of these stations vary depending on the region of use: in the US, they use three types of connectors, in Europe - five. This variety of connectors makes it much more difficult to operate Tesla vehicles that have been imported from the US to European countries.

Charging stations can also be classified according to the principle of use: - stations intended for stationary installation; - stations for portable use in one or more locations; - stations for portable and stationary use. [9]. The international standard IEC 62196-2 defines the types of electrical connectors and charging modes for electric vehicles. In May 2012, the eight largest European and American manufacturers (Audi, BMW, Chrysler, Daimler, Ford, General Motors, Porsche, Volkswagen) announced that a single Combined Charging System standard would be used for all their electric vehicles.

Rapid developments in high-power charging station technology, such as High-Power Charging (HPC), can significantly reduce charging times for electric vehicles. This includes the use of higher charging capacities, higher voltages and improved cooling systems, which allow batteries to be charged efficiently in a short time. Wireless charging technology, known as inductive charging, allows electric vehicle batteries to be charged without the need for wires. This can be a convenient and innovative solution that allows you to charge your car while it is parked at specially equipped sites or even while you are driving.

RESEARCH RESULT

Many countries in the European Union have set ambitious targets to reduce carbon emissions and promote a shift to non-conventional road transport systems. This includes banning the sale of new petrol and diesel cars in the future, as well as providing financial incentives for the purchase of electric vehicles, reducing taxes on them and providing charging infrastructure. The EU plans to set zero emissions for new cars from 2035. The US is committed to achieving a target of 50% of total electric vehicle sales by 2030. Of course, to achieve such goals, infrastructure needs to be developed in parallel.

In June 2023, more than 1.2 million new electric vehicles were registered worldwide, and one in five of them was electric. In total, electric vehicles, together with hybrid cars, account for a third of the global car market. In Ukraine, as of June 2023, according to the Institute of Research, 61,019 electric vehicles were registered, including 59,009 cars, 2,005 trucks and 5 buses.

However, there are still challenges related to battery technology for the large-scale deployment of electric vehicles. Today, there are several types of batteries that are considered promising for electric vehicles: lithium-ion, lithium-sulfur, lithium-polymer, solid-state, graphene, air-lithium and other batteries. Engineers developing batteries for electric vehicles continue to improve power systems to increase their energy capacity and, consequently, the range of electric vehicles. They strive to achieve performance that is on par with that of traditional cars.

The most common type of battery used in most modern electric vehicles is lithium-ion. They have a high energy capacity, long service life and a wide temperature range. Developers are trying to improve their efficiency and reduce their cost. It is important to note that at the current stage of industrial production, the use of electric vehicles in urban areas is becoming even more relevant due to the introduction of lithium-ion batteries to the market in recent years. These batteries can reduce the full charging time to 10-20 minutes due to their higher charging current and voltage.

When choosing a promising type of battery for an electric vehicle, manufacturers pay attention to factors such as energy efficiency, cost, environmental friendliness and the ability to integrate into the automotive infrastructure. Reducing the cost of an electric vehicle battery is a key factor in the growing popularity of electric vehicles. Optimising production processes and using more efficient technologies can significantly reduce the cost of battery production. The use of more economical and affordable materials, new assembly or wrapping methods can reduce the cost of a battery without sacrificing performance. Developing a second life for batteries: The use of used batteries from electric vehicles in renewable energy or other applications can extend their life cycle and reduce costs throughout the chain. Overall, reducing the cost of an electric vehicle battery requires a comprehensive approach, including technical innovation, manufacturing improvements, and collaboration across sectors.

To date, there are no unified approaches to determining the optimal operating modes of renewable energy sources depending on the capacity of electric vehicle batteries and charging methods, given the unpredictable nature of such electricity production. This, in turn, requires research into the operating modes of charging stations based on two or more renewable energy sources. One of the key tasks is to determine the capacity of the photovoltaic battery and wind turbine, as well as the storage devices, depending on the energy capacity of the electric vehicle battery and the duration of the required charge [11,12].

Forecasting the production of renewable energy, such as solar and wind, is an important aspect for the efficient management of charging stations that consume this energy. Various methods and approaches are used for this purpose. One of the main ways is to use meteorological data such as wind speed, solar radiation intensity, temperature, etc. This data can be used to calculate the expected production capacity from wind and solar installations. The use of statistical methods, such as regression analysis, allows for the development of forecasting models based on historical energy production data. Such models can take into account seasonal changes, daily fluctuations and other factors. For solar energy, cloud image analysis using satellite data can be used to determine cloud cover and predict solar radiation. Ensemble methods are a combination of several forecasting methods to obtain more accurate results. For example, both statistical methods and machine learning can be used. In addition to forecasting, adaptive control methods are used to adjust charging station operating modes in real time to the current energy production situation.

The most promising method of using renewable energy is artificial neural networks, which can be used to create complex forecasting models. They can take into account the multifactorial relationships between meteorological parameters and energy production. All of these methods are used to develop renewable energy production forecasting models that help to adapt charging station operating modes in a timely manner and optimise the use of available energy.

During the time a battery is used in a vehicle, it is charged and discharged. When batteries lose some of their capacity after prolonged use in electric vehicles, they can be used in a second life, for example as energy storage systems or backup power sources. Once batteries have lost their useful capacity, they must be disposed of properly. Recycling requires special attention to environmental aspects, as many of the materials used in batteries can be harmful to the environment. The development and improvement of recycling technologies is an important task to ensure sustainability and minimise the negative impact of batteries on the environment.

The use of mathematical models to predict the outcome of EV battery recycling can be an important tool for assessing the efficiency, cost-effectiveness and environmental impact of different recycling methods. Mathematical models can describe the kinetics of chemical and physical processes that occur during battery recycling. For example, the decomposition of materials at elevated temperatures or the dissolution of certain substances in liquid media. Mathematical models can include heat and mass balances to account for the heat energy released or absorbed during the recycling processes, as well as the transport of substances in the system. The models can describe the chemical reactions between different battery materials and the environment during the recycling process. This can help predict the products of the reactions and their environmental impact.

Mathematical models can estimate the cost of different disposal methods, including energy, equipment, materials and labour costs, as well as assess the efficiency of the process in terms of yields of useful products and waste, and can include an assessment of the environmental impact of different disposal methods, including emissions, water and air. Various numerical methods can be used to develop such mathematical models, as well as experimental data to validate and calibrate the models. As the recycling process can be quite complex and dependent on many factors, the development of accurate and reliable mathematical models is an important task to ensure the efficiency and sustainability of EV battery recycling [13].

Fire safety is indeed one of the most important aspects of electric vehicles. Due to their design, battery and electrical systems, it is important to take measures to prevent and control fires. The batteries in electric vehicles are highly energy intensive, so it is important to ensure that they are working and charging properly to avoid overheating. A fire can be caused by incorrect charging equipment connection, damage or poor quality components. Collision fire safety, where batteries or electrical systems can be damaged during accidents, which can lead to a fire. It is important to design the vehicle in a way that reduces the risk of fire after a collision.

Electric vehicles have control systems that monitor the condition of the batteries and electrical systems. These systems can detect elevated temperatures or other anomalies that may indicate a possible fire hazard. It is important to ensure that battery compartments are provided with adequate ventilation and cooling systems, which can prevent battery overheating and fire. Electric vehicles can be equipped with special extinguishing systems that are automatically activated in the event of a fire. In addition, fire extinguishers can be installed in electric vehicles to ensure a quick response to a fire.

There are safety standards that define the design requirements for electric vehicles and their components, including batteries, in order to prevent fires and minimise risk. Thus, the automotive industry is currently undergoing key changes, and these changes require the need to revise the relevant technical regulations. For example, changes to the United Nations Economic Commission for Europe (UNECE) Regulation No. 100 "Specific provisions relating to the approval of vehicles with regard to specific requirements for electric drivetrains" (abbreviated as R100). Significant changes have been made to the approval process for motor vehicles and battery energy storage systems (abbreviated as REESS). The test procedures, their list and a brief description are given in Table 1.

Table 1 - Stages of testing battery energy storage systems (REESS)

Appendix No.	Name of the test	Brief description
8A	Vibration testing	The objective is to test the safety of the EHS in a vibration environment to which the EHS may be exposed during normal vehicle operation. The equipment is subjected to a sinusoidal vibration with logarithmic transients for 15 minutes in the frequency range of 7 Hz to 50 Hz. This cycle is repeated 12 times within 3 hours.
8B	Thermal shock and cycling tests	The resistance to sudden changes in temperature must be assessed. The REESS is exposed to a temperature of 60 °C for at least 6 hours, followed by a temperature of 40 °C for a further 6 hours. The cycle is repeated 5 times.
8C	Mechanical impact	The safety under inertial loading, which can occur, for example, in the event of a road traffic accident, is tested. The REESS is accelerated or decelerated to the values given in R100.
8D	Mechanical integrity	Safety is tested under contact loads that may occur in the event of a road traffic accident. The REPS must be crushed between the pad and the impact plate at a specified force for a specified time.
8E	Fire resistance	The purpose is to test the resistance of the CEPBE to fire from outside the vehicle. The driver and passengers must have sufficient time to leave the vehicle in the event of a fire.
8F	External short-circuit protection	The operation of the short-circuit protection must be checked. This function must interrupt or limit the short-circuit current during use to protect the REESS from further accidents caused by short-circuit current.
8G	Overvoltage protection	Evaluation of the effectiveness of overcharge protection. The REESS should be charged until the charger stops charging, or limits the charging process, or the REESS charge reaches 2 times the battery capacity.
8H	Over-discharge protection	The performance parameters of the over-discharge protection must be checked. The REESS must be discharged until the device discharges itself or limits the discharge, or until it discharges to 25% of the rated voltage.
8I	Protection against overheating	Test the efficiency of the device against internal overheating during operation when the cooling system fails. During the test, the REESS is continuously charged and discharged with a constant current to raise the cell temperature. The REESS is then placed in an oven where the temperature is increased to the specified.

Fire resistance test - Annex 8E. The purpose of this test is to check the resistance of the REESS to fire originating outside the vehicle, for example due to a fuel leak (from the vehicle itself or another vehicle in the vicinity). The test is required for REESS containing a flammable electrolyte. It is not required if the lower surface of its casing is more than 1.5 m above the road. The test is performed either with the complete REESS system or with the associated subsystem, including the cells and their electrical connections. One sample is tested. At the manufacturer's discretion, the test is carried out on the vehicle or its structural parts. The device under test shall be placed on the structure. The device shall be driven by the flame of the fuel placed in the pan under the device.

Test conditions: ambient temperature min. 0°C, charge state at the upper 50 per cent of the normal operating charge state, at the beginning of the test all protective devices that affect the function of the test device and are relevant to the test result must be functional. The temperature behaviour of lithium-ion batteries is shown in Table 2.

Table 2 - Temperature behaviour of batteries

Temperature.	Behaviour of lithium-ion batteries
Up to 60°C	Normal operating and storage temperature (up to 85°C for some models)

Temperature.	Behaviour of lithium-ion batteries
70 - 90 °C	The graphite anode and electrolyte are self-heated. Self-ignition approx. 80 °C at 100% charge; 130 °C when discharged - Evaporation of electrolyte components => pressure increase => cell rupture
130-150 °C	Folding PE, PP or PE/PP separator closes the pores (shut-off)
>150 °C	The separator melts due to an internal short circuit => further heating => thermal discharge occurs in minutes
130-250 °C	The cathode material reacts exothermically with the electrolyte => small amount of oxygen is released => flammable gases escape at a pressure of approx. 13.8 bar (opening of the cell ventilation cover)
>660°C	Thermal discharge - Some cathode materials decompose and change their crystal structure => small amounts of oxygen are released - Heat leakage is a self-sustaining, continuous exothermic chemical reaction that is triggered by malfunctions or damage to the lithium-ion battery and leads to overheating => cannot be interrupted from the outside => results in a fire - Melting of an aluminium current conductor (cathode) - The release of graphite dust with a possible risk of fire, especially with large batteries in rooms, and damage to equipment due to short circuits.

Description of a real-life test of electric vehicle batteries [15]. The battery system (REESS) with the appropriate test fixtures was placed in the test shaft. Thermocouples were placed on the test equipment to provide an overview of the temperatures at different points during the test. In addition to temperature, the battery voltage was measured. The fuel used was petrol, which was ignited remotely by an electric igniter. The temperature of the petrol was higher than 20°C, so no preheating was performed. Direct exposure to the flame took place for a set period of 70 seconds. Then, for 60 seconds, the indirect flame with a screen was applied. After removing the flame tray, time was allowed for the battery temperature to drop to ambient temperature. During the test, no signs of explosion were recorded in any of the batteries. After the flame was removed, no spontaneous combustion was observed, and no significant voltage drop was recorded, meaning that the batteries were operable during and after the test.

The graphs (Figures 1, 2) showing the temperature and voltage curves during the traction battery test show that starting from the 25th second, the voltage measurement failed. The voltage of the traction battery was measured after the test and it was recorded that there was no voltage drop, the battery was operational (Fig. 3). The entire test process was recorded by a video camera.

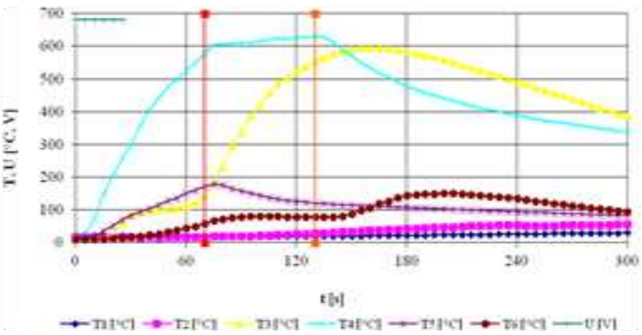

Figure 1 - Graph of the temperature measured during the fire resistance test of the battery system

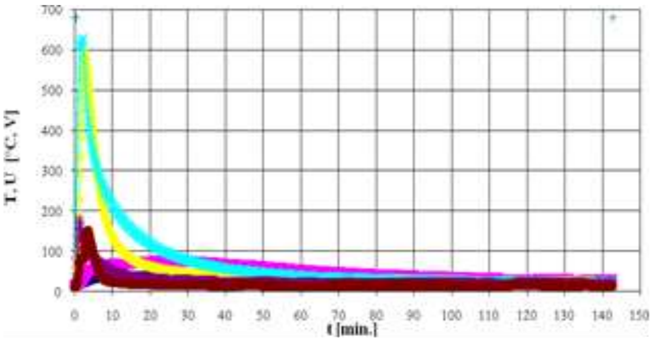

Figure 2 - Voltage plot measured during the battery system fire test (REESS)

Placement of thermal elements: T1 is the top of the battery from the inside; T2 - the side of the battery from the inside; T3 - the side of the shield - from the inside; T4 - casing temperature - bottom; T5 - temperature of the casing - top (lid); T6 - Temperature at the entrance to the test shaft at a height of 1.5 m from the floor;U - at the 25th second of the test, the insulation of the measuring wires burned out, followed by a short circuit of the bare wires.

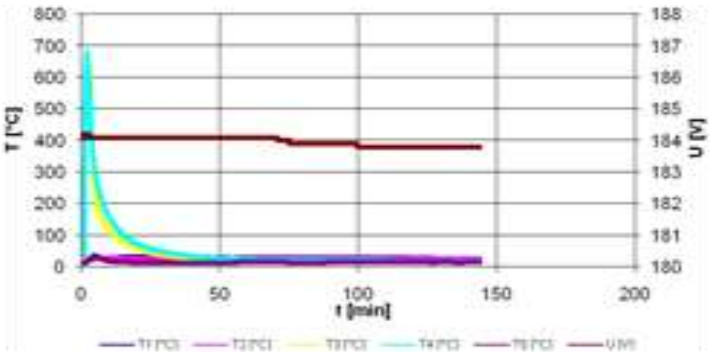

Figure 3 - Temperature and voltage graphs measured during the battery system fire test (REESS)

Placement of thermal elements: T1 - temperature inside the battery on the left side; T2 - temperature inside the battery on the right side; T3 - Surface temperature of the bottom of the battery on the left side; T4 - surface temperature of the bottom of the battery on the right side; T5 - Ambient temperature at the entrance to the test shaft; U is the voltage at the battery terminals.

Electric vehicles are environmentally friendly and do not emit CO2, SO2, NOx, which cause greenhouse effects and other health problems They operate using electrical energy, which can be generated from renewable energy sources such as solar and wind energy [14].

From the discussions on the impact of batteries on vehicle fire emissions, especially hydrogen fluoride (HF) and organic solvents (electrolytes), it was clear that despite many tests carried out, there is still disagreement among experts on measurement methods and effects. to be assessed. In particular, answers are awaited on the use of necessary protective equipment for rescuers.

Overall, fire safety is an integral part of the development and operation of electric vehicles. Engineers and researchers continue to improve technologies and standards to ensure that EVs are reliable and safe in relation to fire.

At a time when the electric vehicle market is reaching record levels, the issue of standardisation of charging stations and charging ports remains unresolved. Questions arise about the number and types of chargers needed at the moment, as well as the distribution of customers in different regions and the existing shortages. All of these aspects and their future solutions are being discussed with electromobility experts and representatives of authorised dealers.

Large investments may be required to build and deploy charging infrastructure. This may include government subsidies, partnerships with energy companies, or co-financing with third parties. Business models may include charging based on time, power or volume of electricity consumption. Within the European Union, projects are being developed to create international infrastructure networks of charging stations. This makes it easier for electric vehicles to travel across borders and ensures seamless charging.

The complexity of building and deploying charging infrastructure depends on various factors, such as project scale, grid availability, permitting procedures and financing. The location of charging stations should be strategically distributed, taking into account the needs of users and the possibility of increasing the number of stations in the future. One of the main challenges for the charging infrastructure is the insufficient number of stations compared to the growing number of electric vehicles. This can lead to queuing, a lack of accessible stations and reduced convenience for EV owners.

Different models of electric vehicles may use different charging standards, such as CHAdeMO, CCS, Tesla Supercharger, etc. This can pose challenges for EV owners who may be dependent on a particular standard. However, most new charging stations offer multifunctional connectors or adapters for compatible charging of different models.

Connecting charging stations to the electricity grid requires an adequate electrical connection and capacity. This may require upgrading the electrical infrastructure or installing additional equipment to provide the required capacity

Managing a network of charging stations. With a large-scale charging infrastructure, there may be a need to remotely monitor and manage charging stations. This may include a system for managing and monitoring stations, charging flows and charging factors.

DISCUSSION OF THE RESULTS OF THE STUDY

According to the ČSN EN 50604-1 Regulation for the Transport and Use of Lithium Batteries for Electric Vehicles and ISO 6469-1:2019 **-** Electric Road Vehicles, both tested batteries withstood the effects of fire during the test and there were no signs of explosion. The traction batteries have successfully passed the certification process due to the positive result of the fire test. The battery system (REESS) for trolleybuses is currently nearing the end of the approval process.

The results of previously published studies on this topic should be summarised and compared with the results of vehicle fires of conventional engines. Measurement methods and results of existing internationally available radio frequency and flue gas emission measurements on cell and electric vehicles. Reproducible, realistic measurement methods and, if necessary, recommendations for firefighters should be developed for fire emissions from electric vehicles and compared with conventionally powered vehicles.

In addition, it is necessary to determine the structure of the charging network, namely the types of charging stations and the required number of charging stations. Given the absence of standards for the required number of charging stations and charging network design rules established by the state, it was decided to adapt the standards for the number of petrol stations and use them for the infrastructure for charging batteries for electric vehicles, which faces several challenges that affect its development and efficiency.

The uneven distribution of charging stations across different regions and the lack of charging stations in some locations can create problems for EV owners and limit the use of EVs. Building and maintaining charging infrastructure requires investment. Securing funding can be a challenge, especially in regions with limited resources. Locating charging stations in urban areas where space is a limited resource can be challenging. The desire to use renewable energy for charging can be challenged by limited resources and fluctuations in renewable energy production.

SUMMARY

Electric vehicles (EVs) are environmentally friendly and do not emit CO2, SO2, NOx, which cause greenhouse effects and other health problems. They operate using electrical energy, which can be generated from renewable energy sources such as solar and wind power.

As electric vehicle batteries contain a significant amount of energy, following certain measures and protocols for fire safety is critical. Electric vehicle batteries are designed to withstand high temperatures and fire. They usually have built-in cooling and ventilation systems that control the temperature during charging and use. In addition, batteries are made of materials that have a high level of fire resistance and minimise the risk of fire.

Many electric vehicles are equipped with battery management systems that automatically monitor the temperature and charge of the battery. If anomalies or high temperatures are detected, the systems can take action to reduce the risk of fire by providing insulation and short-circuit protection. In the event of a battery fire, it is important to provide ventilation to help remove toxic gases and smoke. Additionally, drainage systems can be installed to ensure that water and other substances are removed in the event of a fire.

Modern charging infrastructure is constantly evolving and adapting to the growing demand for electric vehicles. Technological developments are aimed at improving the speed and availability of charging, making the use of electric vehicles more convenient and suitable for mass use. The proper design of charging infrastructure requires a comprehensive approach to determining the parameters of the charging station network. It is necessary to forecast the change in the electric vehicle fleet in the region under study. In the absence of long-term statistical data, it is proposed to use a sociological survey with the subsequent drawing up of a consumer portrait.

The absence of a single standard for charging ports across different electric vehicle models can lead to a complicated charging process, especially in public places. Advances in technology are increasing the capacity of charging stations. However, there is a challenge in providing enough power to quickly charge a large number of cars at the same time to avoid overloading the power grid.

Infrastructure development needs to be able to meet the growing demand for charging stations depending on the number of EVs on the road. Addressing these challenges requires cooperation between EV manufacturers, energy companies, government agencies and other stakeholders to ensure an efficient, reliable and convenient charging infrastructure. Many companies operate extensive networks of charging stations covering different regions. These networks can provide access to stations through mobile apps and charging cards.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

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EXPERIMENTAL STUDIES OF DIESEL ENGINE OPERATING ON DIESEL-TIRE PYROLYSIS OIL BLENDS

The article presents the experimental test results of diesel engine efficiency operating on diesel fuel and tire pyrolysis oil blends. The aim of the work was to study the performance efficiency and emissions of a diesel engine fuelled with blends of diesel fuel (DF) and tire pyrolysis oil (TPO) at a constant engine speed and various load modes. For experimental research diesel engine "ORUVA F1L 511" was used. Diesel fuel and its blends TPO10 and TPO20 with tire pyrolysis oil were used for the research. During the test, the engine's hourly fuel consumption, volumetric air consumption, engine torque, emissions and smoke opacity were measured. In the studies, it was found that the highest brake specific fuel consumption was obtained when the engine was running on a fuel blend TPO20 of diesel and tire pyrolysis oil. At full load, TPO10 and TPO20 fuel blends resulted in 3.6 % and 4% lower engine brake thermal efficiency compared to the diesel engine, respectively. In the same mode, using a blend of diesel fuel and tire pyrolysis oil TPO10, the engine generated the highest total emissions of nitrogen oxides. At full load, the highest carbon monoxide CO emissions were obtained with the TPO20 fuel blend (745 ppm), and the lowest with diesel fuel (646 ppm). When the engine was operating at full load, the TPO20 fuel blend, generated 25.5 % less smoke opacity than the diesel fuelled engine.

Key words: diesel fuel, tire pyrolysis oil, engine efficiency, emissions, smoke opacity.

INTRODUCTION

Currently, the world is facing a multitude of challenges related to energy. The most prominent issues include rapidly growing energy demand not only in developing but also in emerging countries, increasing dependence on fossil fuels in the global energy sector, and continuously rising concentration of greenhouse gases, leading to the universal impact on climate change. Tightening environmental regulations prompt the search for new ways to reduce the emission of these gases across various sectors. The expansion of transportation means increases the consumption of energy resources. In the European Union (EU), up to 26% of greenhouse gases are emitted in the transport sector. Considering these circumstances, scientists worldwide are actively searching for alternative and renewable energy sources that could be utilized in the transportation sector.

Converting waste into fuel holds immense potential as an alternative fuel, which could reduce the global waste burden. The disposal of used tire waste, by dumping it into landfills, poses a significant threat to the environment and human health. Every year, 1 billion used tires are discarded worldwide. Only 15 – 20 % of tires are reused, while the remaining tire waste becomes part of the environment [3]. Approximately 24 thousand tons of used tires are collected annually in Lithuania. Some of the used tires are left in the environment or in illegal landfills.

Recycling used tires is beneficial on several fronts: firstly, recycling reduces the amount of waste and protects nature from unnecessary landfilling; secondly, it increases the amount of secondary raw materials, contributing to the creation of a sustainable production and consumption model. Tires have high energy value, so they can be recycled into various aggregate state fuels: oil, carbon, and gas [4]. The waste of used tires are recycled into fuel by pyrolysis, which is burned in an inert atmosphere [1]. During the pyrolysis process of used tires, a liquid product is obtained: tire pyrolysis oil (TPO). Waste-based tire pyrolysis oil (TPO) can be a promising solution to replace the bio-proportion of diesel fuel. Since it is made from waste tires, it is also an optimal solution for recycling waste [8].

The physical and chemical characteristics of fuels, such as cetane number, viscosity, density, lower heating value, C/H ratio, oxygen content, influence the combustion process of diesel engines. The properties of fuels with different compositions effect on engine performance, emissions, and smoke opacity production differently. Although numerous chemical and physical properties of TPO closely resemble those of diesel fuel (Table 1), some differences significantly affect fuel injection, atomisation, the air-fuel mixing rate in the cylinder, combustion process, and consequently, emissions of harmful exhaust gases. Most scientists argue that TPO could be an excellent alternative fuel; however, using pure pyrolysis oil of used tires may pose challenges due to its low cetane number, high sulphur content, and high viscosity [3]. Nonetheless, the cetane number of TPO is lower at 39.94, compared to the 51.4 diesel fuel (DF). This disparity could potentially lead to autoignition issues, particularly when operating with blends of DF and TPO under light engine loads and speeds. A high sulphur content increases emission. More viscous fuels poorly atomize and distribute in the combustion chamber. Due to the influence of the physical and chemical properties of fuels, the comparative effective on fuel consumption, engine performance, emissions, and smoke production vary [2].

Pinto et al. [8] conducted analysis of blends containing traditional diesel, different amounts of pyrolysis oil from used tires and biodiesel from waste cooking oil has been proposed herein, with the aim of investigating the feasibility of using them in a diesel engine and analysing their emissions and power in comparison with traditional diesel fuel. Tests were carried out using a single-cylinder diesel engine with a maximum rated power of 5.6 kW and its emissions were measured with a gas analyser. The results revealed that using small amounts of tire pyrolysis oil in the blends (up to 5%) leads to a very small decrease in brake thermal efficiency (BTE) while emitting fewer CO and NOx pollutants, when compared to neat diesel. However, adding higher quantities of tire-pyrolysis oil causes a notable loss in BTE while increasing CO, decreasing NOx and emitting considerably more sulphur. Finally, replacing portions of diesel with biodiesel in diesel-tire pyrolysis oil blends decreased CO, but at the cost of increasing NOx emissions [8].

Kondor et al. [9] investigated different low-volume-percent tire pyrolyzed oil blended with diesel. The aim of research was to investigate the effect of low volume percentage TPO on performance and emissions on a light-duty diesel engine. Authors noted that until full engine load, the brake-specific fuel consumption increased. At low speed and low load, the TPO had a 16% higher emission value. With the increased engine loads, the HC emissions decreased. At 100% load, it was 42% lower than regular diesels. The NOx emissions increased. The reason for that might be the lack of oxygen. CO emissions increased in all investigated measuring points [9].

World scientists are extensively researching the possibilities to use alternative fuels, but there is no unanimous opinion how the physical and chemical properties of the different compositions fuels effect on the diesel engine performance, fuel system elements, and emission characteristics. The aim of the study is to investigate the performance and emission characteristics of a diesel engine fuelled by blends of diesel fuel and tyre pyrolysis oil.

OBJECTS, EXPERIMENTAL APPARATUS AND METHODOLOGY OF THE RESEARCH

The test results reflecting the comparative changes in the performance efficiency and emissions of the exhaust occurring due to its transition from diesel fuel to operation on diesel fuel-tyre pyrolysis oil blends prepared by mixing in various proportion (by volume). The fuel blends PPO10 and PPO20 were prepared by mixing 90 vol % DF/10 vol % TPO and 80 vol % DF/20 vol % TPO, respectively. The properties of the tested fuels are presented in Table 1.

Table 1 – Properties of the tested diesel fuel and tire pyrolysis oil

Property parameters	Fuel test methods	TPO	DF
Density at 15 C, kg/m^3	EN ISO 12185:1999	917	832,7
Kinematic viscosity, mm^2/s	EN ISO 3104+AC:2000 at 40 °C	3,77	2,13
Flash point (FP), °C	EN ISO 2719:2000	43	57
Stoichiometric air–fuel ratio, kg/kg	-	13,46	14,5
Low calorific value, MJ/kg	EN ISO 8217:2012	40,49	43
Cetane index	EN ISO 5165:1999	39,94	51,4
Carbon (%)		86,68	86,13
Hydrogen (%)		10,49	13,87
Oxygen (%)		1,29	–
Nitrogen (%)		0,48	–
Sulfur (%)		0,84	–

Experimental research was carried out in the fuel equipment-testing laboratory of the Department of Mechanical, Energy and Biotechnology Engineering at the Faculty of Engineering of Vytautas Magnus University - Agricultural Academy.

Table 2 – Engine FL 511 specifications

Type	Deutz F1L 511
Operating principle	4 strokes
Number of cylinders	one cylinder
Bore, mm	100
Stroke, mm	105
Swept volume, cm3	825
Compression ratio	17
Injection timing advance in CADs BTDC	24°
Maximum power (at 3000 rpm), kW	12.8 ±5%
Injection pressure, bar	175
Fuel consumption, g/kW·h	255 ±5%
Rated speed, rpm	3000
Engine weight, kg 135	135

For stroke, one-cylinder, direct injection, air cooled, "ORUVA FL 511" diesel engine was used for these experiments. Technical characteristics of the experimental engine are listed in Table 2. Load characteristics of an engine were taken when operating at gradually increasing load and constant engine speed of 2000 rpm at which an engine maximum torque develops.

Torque of an engine was measured with a magnetic powder brake dynamometer PT40M (0 – 60 N·m) with a definition rate of ±0.5 N·m and rotation speed with the mechanical tachometer (150 – 3000 rpm) with an accuracy of ±0.5% of the measured value. The air mass consumption was measured with the turbine type gas meter CGT-02 (10 – 100 m^3 /h) with an accuracy of ±1% of the measured value, and fuel mass consumption by using electronic scale SK - 1000 with an accuracy of ±0.5%.

Emissions of nitric oxide (NO), nitrogen dioxide (NO_2), carbon monoxide (CO) in parts per million (ppm) and carbon dioxide (CO_2) in vol% were measured with electrochemical cells installed in Testo 350 XL flue gas analyser. Total NO_x emissions were determined as a sum of both NO and NO_2 pollutants with an accuracy of ±5 ppm.

Exhaust smoke measured with a Bosch RTT 110 opacity meter with an accuracy of ±0.1% in a scale range of 0 – 100 %. The measuring rages of apparatus used, accuracies of the measured experimental data of engine performance and exhaust emission parameters and the uncertainties of the calculated test results (power, fuel consumption etc.) are listed in Table 3.

Table 3 – The accuracy of the measured engine performance and emission parameters and the uncertainty of the computed experimental results

Parameter	Measuring range	Accuracy
Torque	0 – 60 N·m	±1.5 %
Speed	150 – 3000 rpm	±0.5 %
NO	0 – 3000 ppm	5 %
NO_2	0 – 500 ppm	5 %
CO	0 – 10000 ppm	5 %
CO_2	0 – 50 %	1 %
Smoke density	0 – 100 %	1.5 %
Engine power output		±1
Fuel mass flow rate		±0.5
Brake specific fuel consumption		±1.5
Brake thermal efficiency		±1.5
Air flow rate		±1

To improve the reliability of the measured data the tests have been repeated no less than three times.

RESULTS AND DISCUSSION

Changes in the combustion process have influence on engine's economy parameters: brake specific fuel consumption (bsfc) and brake thermal efficiency (η_e). The dependency of brake specific fuel consumption on engine load when the engine operates on the tested fuel blends is presented in Figure 1. As seen, under the same engine operating conditions, the brake specific fuel consumption was higher when the engine operated on TPO blends. This can be explained by the lower calorific value of the tested fuel blends, which requires a larger fuel portion to produce the same engine power. At full load, when the engine operated on TPO10 and TPO20 fuel blends, the brake specific fuel consumption increased by 4.4 % and 5.5 %, respectively, compared to diesel fuel (DF).

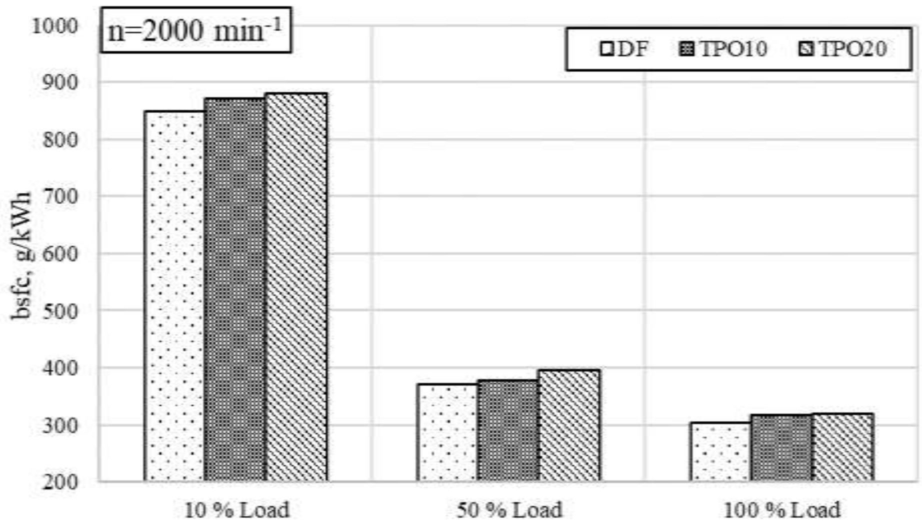

Fig.1 – Brake specific fuel consumption (bsfc) dependence on engine load when engine was running on diesel fuel and its blends with tire pyrolysis oil

Fig. 2 shows the dependency of the brake thermal efficiency on engine load when the engine operates on diesel fuel and its blends with tire pyrolysis oil. The graph shows that, across all load regimes, the highest brake thermal efficiency was obtained when the engine was fuelled on pure diesel fuel. At full 100 % engine load, using TPO10 and TPO20 fuel blends, the brake thermal efficiency decreased by 3.62 % and 4 % respectively, compared to the engine running on diesel fuel. The decrease of the brake thermal efficiency in this case can be explained by the fact that is the mostly affected by their reduced cetane number of TPO as the latter suppresses the auto ignition and combustion processes in the cylinder.

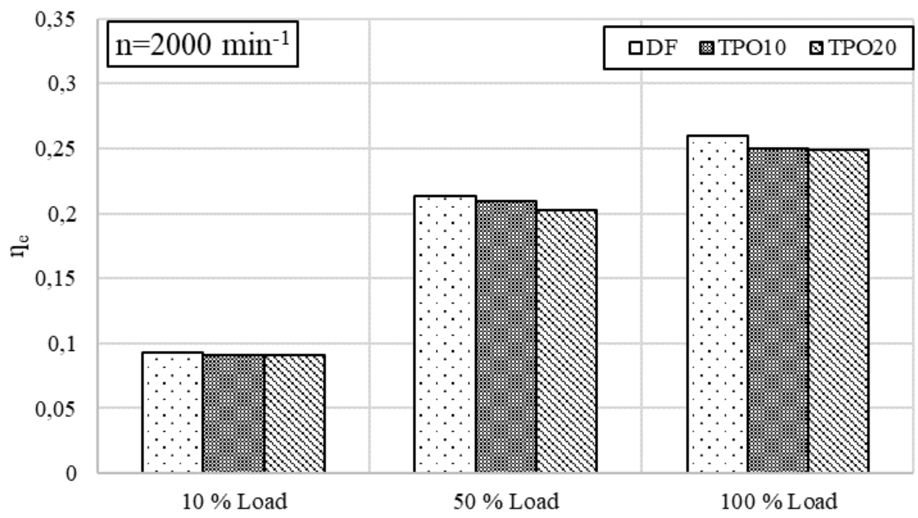

Fig. 2 – Brake thermal efficiency (η_e) dependence on engine load when engine was running on diesel fuel and its blends with tire pyrolysis oil

Nitrogen oxides are produced at elevated temperatures outside the flame front, where free nitrogen atoms react with excess oxygen in the combustion chamber through a complex chain reaction. The overall nitrogen oxides emissions during combustion are predominantly influenced by the maximum process temperature, as the reaction is endothermic and not directly associated with the combustion processes of the fuel mixture. As columns in |Fig. 3 show the amount of total nitrogen NOx emissions increased with increasing engine load for diesel fuels and the fuel blends tested. When the engine operated under low engine load, the highest amount of nitrogen oxides was generated when fuelled by diesel fuel. At the same engine load, using a TPO20 fuel blend resulted in a 6.8 % lower nitrogen oxide emission compared to using diesel fuel. From the graphs, it can be observed that at full load, the maximum nitrogen oxide emission value (2094 ppm) is obtained when the engine is running on TPO10 fuel blend. Significant influence on the formation of NOx emissions has two parameters a - high gas temperature in the cylinder and a longer duration of the self-ignition period. Fuels with a longer self-ignition delay period are characterized by a higher maximum of heat release rate. As a result, the temperature in the cylinder increases [7]. On the over hand a higher amount of aromatic substances increases the quantity of nitrogen oxides [6].

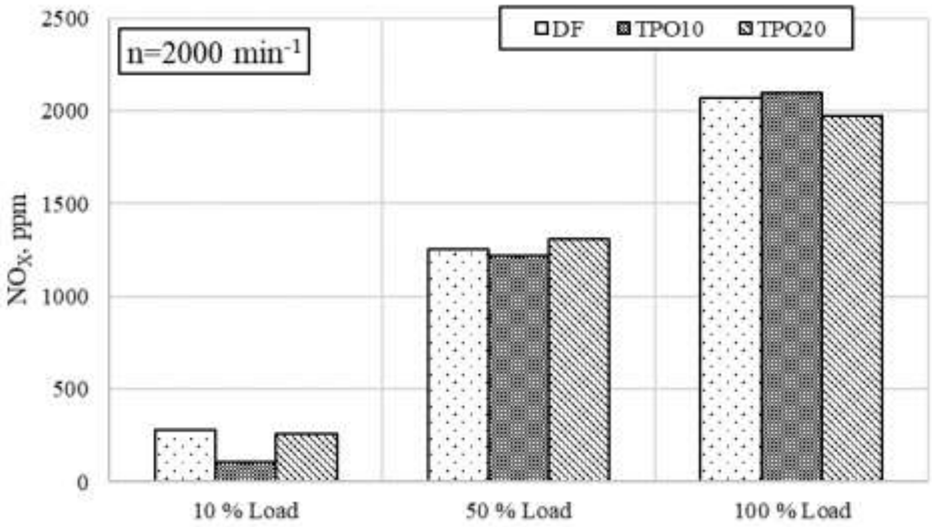

Fig. 3 – Nitrogen oxide emissions (NOX) dependence on engine load when engine was running on diesel fuel and its blends with tire pyrolysis oil

The dependencies of carbon monoxide (CO) emission on engine load are shown in Fig. 3.

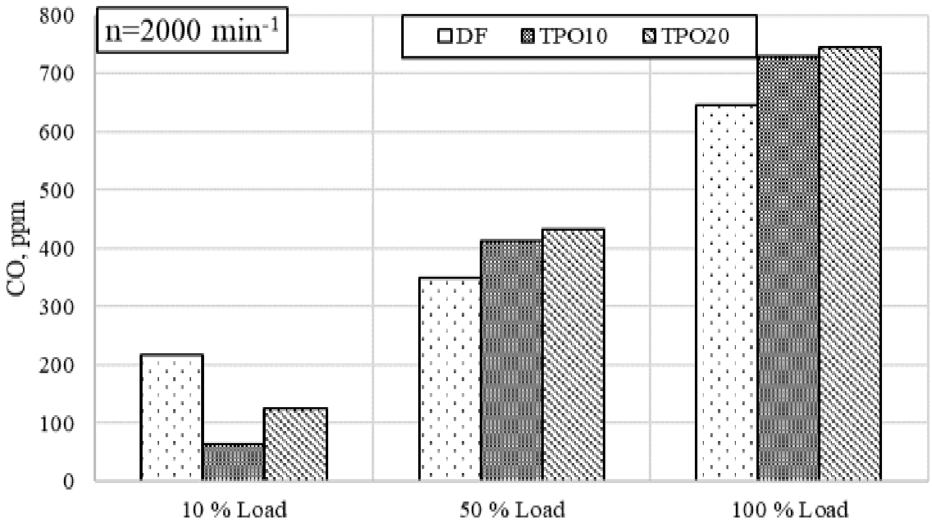

Fig.4 – Carbon monoxide (CO) emissions dependence of engine load when engine was running on diesel fuel and its blends with tire pyrolysis oil

When the engine operated under low load, the highest carbon monoxide (CO) emission was obtained when fuelled by diesel fuel. At average engine load, the carbon monoxide (CO) emission was higher when using a TPO20 fuel blend. At full engine load, using fuel blends of diesel fuel and tire pyrolysis oil (TPO10 and TPO20) carbon monoxide emissions increased in a 12.8 % and 15.3 % in, respectively, compared to the results obtained from testing diesel fuel (DD). The authors of other articles explain the increase of CO emissions by the lower cetane number in TPO fuel. For this reason, the combustion may be delayed and fuel may not burn completely in the combustion chamber [5].

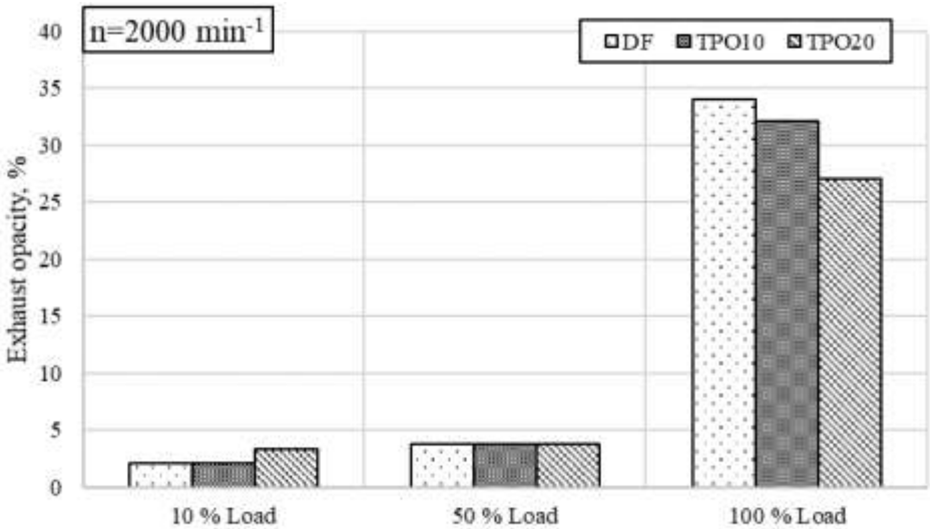

Fig.5 – Smoke dependence on engine load when engine was running on diesel fuel and its blends with tire pyrolysis oil

The soot formation is able to progress at local locations in the fuel-saturated combustion chamber during pyrolysis of hydrocarbons. The smoke opacity of diesel engines depends on the cetane number of the fuel, the chemical composition, the amount of aromatic hydrocarbons, the fuel injection and the quality of the combustible mixture, the diffusion process in the chamber and the complex mechanism of soot particle formation and their combustion burn reaction rate. The graphs in figure 5 show dependencies of smoke opacity on the exhaust of engine load when engine was running on diesel fuel and its blends with tire pyrolysis oil. It was observed that engine load has the most impact on smoke opacity. It can be seen that when the engine operates under low load, the lowest smoke opacity was obtained when the engine was fuelled on PPA20 fuel blend. At full load, using fuel PPA10 and PPA20 blends, smoke opacity decreased by 5.9 % and 25.5 % respectively, compared to an engine working on mineral diesel. It is evident that smoke opacity of the exhaust is influenced by the different physical and chemical properties of the fuels.

CONCLUSIONS

1. The lowest brake specific fuel consumption was obtained when the engine was running on diesel fuel and at a low (10 %) load. At full engine load (100 %), the highest (320.3 g/kW·h) brake specific fuel consumption was obtained with the engine running on the TPO20 fuel blend.

2. At an average engine load (50 %), using the TPO20 fuel blend resulted in a 5.4 % lower brake thermal efficiency compared to the engine running on diesel fuel.

3. At low engine load (10 %) and using the TPO20 fuel blend, the nitrogen oxide emissions were lower by 6.8 % compared to the diesel fuel.

4. When the engine is operating at the medium engine load (50 %), the highest carbon monoxide emissions were obtained from the engine running on the PPA20 fuel blend (433 ppm), and the lowest (349 ppm) from the diesel fuelled engine.

5. When using the PPA20 fuel blend at the full engine load (100 %), the smoke opacity was reduced by 25.5 %, compared to the diesel fuel.

The optimal ratio of the TPO blends on diesel fuel depends on many factors, such as the engine, injection system, injection pressure, the shape of the combustion chamber, the way the combustion mixture is prepared, and other factors. The influence of these factors can be determined by experimental studies, depending on the specific situation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

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MIXTURES OF ESSENTIAL OILS AND ALCOHOLS WITH DIESEL OIL USE AND IMPACT ON ENGINE PERFORMANCE AND POLLUTANT EMISSIONS. A REVIEW

Recent discoveries in the field of using blends of essential oil, alcohol and diesel in diesel engines open new perspectives for optimizing performance and reducing pollutant emissions. This work focuses on evaluating the combined effects of these blends on engine performance parameters and pollutant emission profiles, providing insight into the benefits and challenges associated with their use. The review of the literature and empirical data highlights the promising potential of steam extraction of biofuels, as well as the efficiency and cost-effectiveness of transesterification of oils in the production of biofuels. Also, mixing distilled alcohol with essential oil and diesel fuel is revealed as a viable strategy for improving the combustion characteristics and performance of the diesel engine. The results indicate a number of significant improvements in engine performance, including reduced specific fuel consumption, increased power and torque, as well as improved thermal efficiency and reduced smoke emissions. However, it is important to note that certain mixtures may lead to a slight increase in nitrogen oxide (NO_x) emissions, which requires further research to optimize the composition of the mixtures and minimize the environmental impact. Overall, this study highlights the promising potential of using blends of essential oil, alcohol and diesel in diesel engines, highlighting the importance of continued research in the field to develop sustainable and energy efficient solutions for road transport.

Keywords*:* essential oils, alcohols, diesel engine, engine performance, pollutant emissions.

INTRODUCTION

In the past three decades, road transport has undergone a significant transformation marked by a continual rise in the number of motor vehicles and an expansion of the road network (Mo, Wang, Zhang, & Zhuang, 2017), (Hassan, Amlan, Alias, Ab-Kadir, & Sukor, 2022; Mulholland & Feyen, 2021; Pažout, Brughmans, & de Soto, 2023; Schubert, Sys, Vanelslander, & Roumboutsos, 2022; Wu, Yu, & Zhang, 2023). This expansion has been accompanied by advances in vehicle technology and road safety, including the introduction of driver assistance systems and stricter safety regulations. However, the rapid growth in road traffic has also brought about environmental challenges, such as greenhouse gas emissions, noise pollution, and air pollution (Tasma, D. et al., 2011).

Looking ahead, the replacement of diesel fuel has become a pressing concern due to the adverse environmental impacts associated with fossil fuels and their limited resources. Substantial progress has been made in developing alternative fuels and enhancing electric and hybrid vehicle technologies. Nevertheless, challenges persist, particularly concerning the cost, availability, and infrastructure necessary for the widespread adoption of these technologies. Internal combustion engines, still widely used in vehicles today, present their own set of challenges. They emit greenhouse gases and pollutants affecting both human health and the environment. The ongoing energy crisis has made researchers turn their attention even more to oils as a potential source of renewable fuel. Oils derived from renewable sources, offer an alternative to finite fossil fuels. This paper delves into the utilization of pure essential oils or blends with diesel oil at varying proportions in diesel engine to investigate performance characteristics and pollutant emissions. Technologies of biofuels production are also revised. Biofuels, including essential oils, can be directly used in engines with minimal or no major modifications, contingent on the method of introduction into the fuel system (Chivu et al., 2023). The utilization of blends comprising alcohols, essential oils, and diesel fuel in engines stands as a promising avenue in contemporary research on alternative fuels. The study and development of these biofuel mixtures involve intricate analyses of their chemical properties, combustion efficiency, emission characteristics, and overall environmental footprint, further enriching the academic discourse on alternative energy sources.

In general, biofuels can be used directly in an engine without making constructive changes, or major constructive changes, this depends a lot on the method by which the biofuel is introduced into the fuel system.

PURPOSE AND OBJECTIVES OF THE STUDY

This study focuses on the overall objective of synthesizing existing literature and empirical data to provide an assessment of the use of essential oil and alcohol blends in diesel fuel, with an emphasis on their collective impact on both engine performance parameters and pollutant emission profiles. By elucidating the precise objectives of the study, including identifying key research questions and delineating methodological approaches, this study aims to provide a roadmap for further analysis and discussion. In addition, it highlights the importance of the study in the wider context of alternative fuel use and its potential implications for mitigating environmental impact and increasing engine efficiency without major modifications. By exploring these aspects, the aim is not only to understand the phenomenon in detail, but also to outline a robust framework to guide future research and technological development in the field of alternative fuel use and engine performance.

BIOFUEL PRODUCTION

Distillation (Mangalagiu, I., 2011), an essential separation technique in chemical engineering, involves the thermal separation of a liquid mixture into its constituent components by exploiting differences in their respective boiling points. This process entails subjecting the mixture to heat, causing it to vaporize; subsequently, the resulting vapours are then collected and condensed back into a liquid state for further processing (Figure 2).

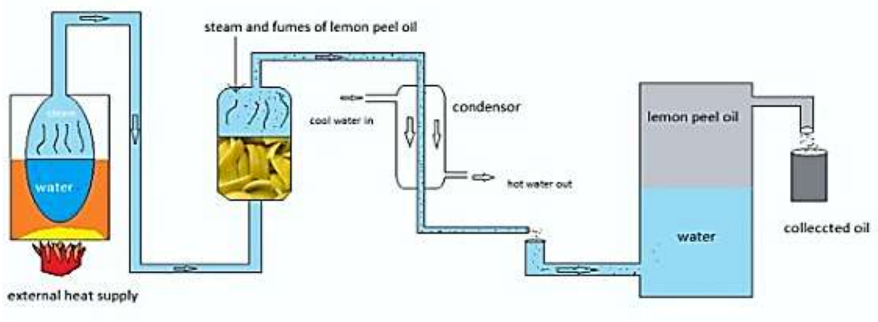

Figure 2– Distillation of lemon oil (Dhana Raju et al., 2022a).

Distillation constitutes a pivotal method in chemical engineering for the separation of liquid mixtures based on the disparities in their boiling points. In this process, components with lower boiling temperature volatilize more rapidly and are collected in advance, whereas those with higher boiling points remain in their liquid state and are subsequently gathered. Within the realm of biofuel production, particularly in the context of bioethanol extraction, distillation assumes a critical role in securing high-purity final products. Leveraging subtle differentials in boiling points among mixture constituents, distillation facilitates their efficacious segregation. Bioethanol, a prominent biofuel variant, is typically derived through fermentation processes, with distillation serving as the pivotal phase that transmutes it from a composite mixture into pristine ethanol fuel, primed for utilization in internal combustion engines. The utilization of distillation in bioethanol production offers salient advantages. Firstly, it embodies an environmentally benign approach, purging deleterious substances and contaminants from the mixture, thereby rendering the resultant biofuel cleaner and more ecologically sustainable. Moreover, distillation engenders the production of a high-calibre end product characterized by diminished impurity levels and consistent physicochemical attributes, rendering it apt for integration into contemporary engine systems. Nonetheless, ongoing research endeavours in the realm of distillation are directed toward enhancing process efficiency and curbing production outlays. Novel methodologies and technological innovations are continually being pioneered to render distillation more sustainable and cost-effective, thereby fostering the viability and accessibility of biofuels as a substitute for conventional fossil fuels. Consequently, distillation remains poised at the vanguard of innovation within the biofuel domain, charting a trajectory toward a cleaner and more sustainable energy landscape.

Bioethanol (Inderwildi & King, 2009) is a renewable fuel obtained by fermenting plant biomass. The bioethanol distillation process involves the following steps:

Fermentation (Partovinia, Salimi koochi, Talaeian, & Rasooly Garmaroody, 2022; Shen & Li, 2023; Šokarda Slavić et al., 2023) initiates this intricate journey, wherein plant biomass or starchy grains undergo a transformative process catalysed by microorganisms like yeast. This biological alchemy converts sugars into ethyl alcohol (ethanol), laying the foundation for subsequent stages;

Primary Distillation: Post-fermentation, the resultant mixture undergoes primary distillation, a fundamental step aimed at purging impurities such as water and non-alcoholic substances. Carried out within a still or a distillation column, this process yields a dilute ethyl alcohol solution;

Alcohol Concentration: The diluted ethyl alcohol solution then undergoes secondary distillation, a meticulous process where alcohol is concentrated. This phase entails the strategic evaporation of alcohol at precise temperatures, effectively separating water and other impurities and resulting in a higher alcohol concentration;
Dehydration (Zhu et al., 2016), (Silva et al., 2021) the final leg of this intricate journey involves dehydration, a critical step in obtaining pure bioethanol. This phase employs specific drying agents, including zeolites or reverse osmosis membranes, to meticulously eliminate any remaining traces of water and impurities;
Bioethanol utilization: Bioethanol obtained through this rigorous distillation process emerges as a versatile and eco-friendly resource. Its application as a motor vehicle fuel source serves a dual purpose: reducing greenhouse gas emissions while contributing to sustainable energy practices. The distillation process, with its ability to yield high-quality and pure bioethanol, paves the way for diverse applications, from automotive technology to renewable energy initiatives. In essence, the synergy between fermentation and distillation not only exemplifies the complexity of bioethanol production but also underscores the paramount importance of these processes. Through their integration, the scientific community continues to enhance the efficiency and sustainability of bioethanol production, offering a viable solution in the quest for cleaner energy alternatives.

Transesterification, as referenced in (Otera, 1993), involves the conversion of an ester into either another ester or an alcohol through its reaction with alcohol. Conversely, esterification, as explicated in (Araújo, Cardoso, Souza, Cardoso, & Pasa, 2021; Cannilla, Bonura, Costa, & Frusteri, 2018; Foukis et al., 2017; Rajabi & Luque, 2020; Wang et al., 2018; Zhang et al., 2023) entails the chemical reaction between an organic acid and an alcohol, resulting in the formation of an ester and water. Typically, acids or bases serve as catalysts in these reactions. In the esterification process, the hydroxyl groups (-OH) present in both the organic acid and alcohol are eliminated, leading to the formation of an ester bond (-COO-) between the respective acid and alcohol residues. This exothermic reaction is reversible through hydrolysis. The versatility of esterification is evident in its application across diverse domains, including the production of aromatic esters, essential oils, and plasticizers. Furthermore, esterification plays a crucial role in the production of biodiesel, as delineated in (Alfredo Quevedo-Amador, Elizabeth Reynel-Avila, Ileana Mendoza-Castillo, Badawi, & Bonilla-Petriciolet, 2022; Kingkam et al., 2022; Lee et al., 2022; Mahesha et al., 2022; Shrivastava et al., 2023). Biodiesel, a renewable biofuel, is generated through the transesterification of vegetable oils or animal fats. This involves combining the oil or fat with an alcohol (typically methanol) and a catalyst (e.g., sodium hydroxide) to yield fatty acid methyl esters and glycerol. The transesterification process replaces glycerol molecules with methanol in the fatty acids. Importantly, biodiesel derived from transesterification serves as a sustainable alternative to fossil fuels and can be seamlessly integrated into diesel engines without substantial modifications. Beyond the realm of biodiesel production, transesterification finds application in diverse sectors such as cosmetics production (Park & Kim, 2020) and other chemical synthesis processes. It is notably employed in organic synthesis within chemistry laboratories. In summary, both transesterification and esterification processes are integral to numerous industrial processes, contributing significantly to the synthesis of various products with applications ranging from biofuels to cosmetic formulations.

BLENDING BIOFUEL WITH REGULAR FUEL

This study delineates a strategy employed in the advancement of fuel properties through the blending of biofuels, as documented in references (Hoang et al., 2023; Martos, Doustdar, Zeraati-Rezaei, Herreros, & Tsolakis, 2023; Nagappan & Babu, 2023; Tsanaktsidis, Favvas, Tzilantonis, & Scaltsoyiannes, 2014) within the context of scientific discourse. The practice of blending, exemplified by the amalgamation of biodiesel with ethanol to formulate ethanol-diesel (Kharkwal, Kesharvani, Verma, Dwivedi, & Jain, 2023), represents an innovative approach aimed at enhancing the characteristics of extant fuels. This blending process is instrumental in ameliorating fuel quality by mitigating the flash point, enhancing fluidity at lower temperatures, and diminishing greenhouse gas emissions. The resultant ethanol-diesel blends exhibit the potential for seamless integration into existing diesel engines, obviating the necessity for substantial engine modifications. It is imperative to note, however, that ethanol, being an alcohol, is conventionally suited for utilization in spark ignition engines. Additionally, the strategic blending of ethanol with gasoline, as manifested in ethanol-gasoline formulations such as E10, E15, E85, etc. stands as another noteworthy practice. These blends, encompassing ethanol concentrations ranging from 10% to 85% serve the dual purpose of diminishing reliance on fossil fuels and mitigating environmental impact. Beyond the realm of blending established biofuels, ongoing research endeavours are focused on the development of novel renewable fuels, including those derived from algae or genetically modified bacteria-produced oils. The text underscores the emergence of essential oils as a subject of research interest, wherein their admixture with diesel, as expounded in references (Gad, He, El-Shafay, & El-Seesy, 2021; Gowthaman & Thangavel, 2022; R. Kumar, Kumar, Kumar, & Goga, 2023a; Sekar, Venkadesan, & Panithasan, 2022; Singh, Singh, & Kumar, 2020; Y. , Earnest, Raghavan, George Roy, & Koshy, 2022) manifests combustion behaviour akin to traditional diesel. The performance characteristics of such blends are contingent upon the specific composition, thereby offering a versatile approach to tailoring fuel properties, concomitant with a reduction in polluting emissions.

ANALYSIS OF LITERATURE DATA AND FORMULATION OF THE PROBLEM

This section initiates a methodical literature review relevant to the integration of essential oil and alcohol blends with diesel oil, scrutinizing their diverse effects on metrics related to engine performance and emissions of pollutants. Employing a rigorous synthesis of both empirical observations and theoretical frameworks, this chapter aspires to elucidate the fundamental mechanisms governing the interplay between these alternative fuel compositions and internal combustion engine configurations. Through the amalgamation of a comprehensive survey of existing research, this chapter establishes the foundational framework for subsequent analyses and deliberations, delineating the breadth and significance of the surveyed literature while identifying critical gaps in knowledge and articulating pertinent avenues for further investigation.

The impact of the mixtures on the performance and combustion characteristics

The paper (R. Kumar, Kumar, Kumar, & Goga, 2023b) investigates the performance characteristics of a compression ignition (C.I.) engine fuelled with distinct blends of eucalyptus biodiesel and conventional diesel fuel. The study focuses on the brake-specific fuel consumption (BSFC) and brake thermal efficiency (BTE) parameters across a range of loads (20 W to 100 W) for samples denoted as A and B. The results elucidate the variation in BSFC and BTE with respect to load for different biodiesel blends (Eu10-10% eucalyptus oil, 90% diesel to Eu100- 100% eucalyptus oil). The findings suggest a discernible impact of load on fuel consumption across all biodiesel blends, with a consistent increase in BSFC as load decreases. Notably, the BSFC for Eu100A (100% eucalyptus oil sample A) and Eu100B (100% eucalyptus oil sample B) exhibits a reduction of 8.18% and 4.05%, respectively, compared to diesel fuel at full load conditions. This implies a favourable performance of Eu100A and Eu100B in terms of fuel efficiency. Furthermore, this research reveals an inverse relationship between BTE and BSFC, indicating that the brake thermal efficiency of the C.I. engine is influenced by the fuel consumption rate. The BTE for Eu10-10% eucalyptus oil, 90% diesel, Eu30-30% eucalyptus oil, 70% diesel, Eu50-50% eucalyptus oil, 50% diesel, and Eu70-70% eucalyptus oil, 30% diesel in both samples (A and B) is observed to be lower than diesel fuel, suggesting a potential trade-off between fuel efficiency and biodiesel content. However, Eu100A and Eu100B exhibit higher BTE compared to diesel fuel, with an impressive 9.63% and 4.88% increase at full load conditions. This notable improvement in BTE is attributed to the effective vaporization and blend preparation of eucalyptus oil, resulting in an enhanced heat release rate. The comparison between sample A and sample B suggests that, in terms of engine performance, sample A, particularly Eu100A, outperforms sample B. The study contributes valuable insights into the impact of biodiesel blends on the fuel consumption and efficiency of C.I. engines, emphasizing the potential benefits of higher biodiesel content, specifically in the case of Eu100A and Eu100B. Other studies on the use of eucalyptus oil as fuel have shown similar trends in terms of engine performance (Liazid, Naima, Tazerout, Tarabet, & Bousbaa, 2019), (Suryawanshi & Ladekar, 2017), (Naima et al., 2022), (Kommana, Naik Banoth, & Radha Kadavakollu, 2015). Another research (Devan & Mahalakshmi, 2009a) investigates the performance characteristics of a methyl ester (Me) and eucalyptus oil (Eu) blend in comparison to other biodiesel blends and standard diesel fuel. The study focuses on BSEC, BTE, cylinder pressure variations, and heat release rates across different load conditions. The Me50–Eu50 blend stands out by exhibiting lower BSEC compared to other blends and methyl ester. This is attributed to improved combustion and increased energy content, as evidenced in Figure 3. The enhanced BTE observed in the Me50–Eu50 blend, as depicted in Figure 3, is associated with reduced viscosity leading to improved atomization, fuel vaporization, and combustion. The blend's closer ignition delay time to diesel contributes to faster burning of eucalyptus oil, further enhancing thermal efficiency, a phenomenon elucidated in subsequent heat release curves. As the concentration of eucalyptus oil increases in the mixture, the ignition delay increases and the release of heat is greater (Devan & Mahalakshmi, 2009b). The efficiency of Me50–Eu50 at full load is reported as 31.42%. Examining cylinder pressure variations, the high eucalyptus oil blends generate higher cylinder pressure compared to standard diesel, owing to the lower cetane number of eucalyptus in the blend. The addition of an ignition improver (methyl ester of paradise oil) decreases peak pressure and ignition delay, aligning the cylinder pressure trend of the 50% blend closer to that of standard diesel fuel. Analysing the heat release rates, Figure 3 reveals that the Me50–Eu50 blend closely resembles the heat release pattern of standard diesel, while other blends deviate more significantly. The concentration of eucalyptus oil in the blend correlates with an increased ignition delay and higher heat release, attributed to the lower cetane number of high eucalyptus oil blends. Notably, cylinder peak pressure shows a nuanced response to the proportion of eucalyptus oil at different loads, with a slight increase at medium and high loads and a slight decrease at low load. The deviation in heat release patterns and the observed trends in cylinder pressure underscore the intricate interplay of eucalyptus oil concentration, combustion characteristics, and load conditions.

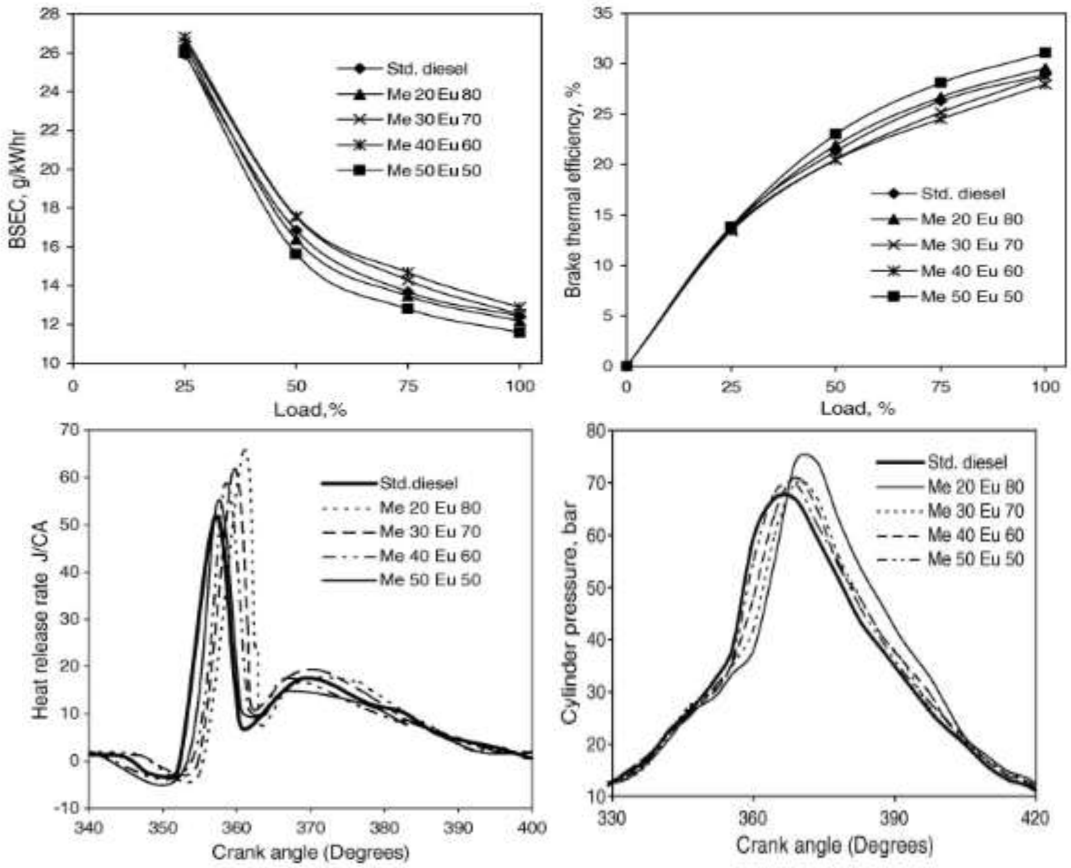

Figure 3 – Engine performance with fuel mixtures (Devan & Mahalakshmi, 2009a).

Senthur et al. (Senthur, Ravikumar, & John, 2014) conducted a rigorous investigation aimed at assessing the viability of eucalyptus biodiesel as a prospective alternative fuel in diesel engines. Employing the transesterification process, the researchers derived biodiesel from eucalyptus oil, subsequently subjecting the resultant blend, in conjunction with diesel, to empirical scrutiny utilizing a single-cylinder direct injection diesel engine. The empirical findings indicated that, across all load conditions, BSFC and BTE of the eucalyptus biodiesel blend surpassed those of conventional diesel. It is noteworthy, however, that despite the heightened BSFC and marginally reduced BTE, the physicochemical attributes of eucalyptus biodiesel closely paralleled those of diesel, affirming its amenability as a plausible alternative fuel. The discerned increase in BSFC with escalating biodiesel content within the fuel blend was attributed to a concomitant reduction in the heating value of the amalgamated fuel. Furthermore, the observed minor reduction in BTE for biodiesel blends compared to diesel was predominantly ascribed to the lower calorific value inherent in the composite mixture. This comprehensive evaluation underscores the utility of eucalyptus biodiesel as a viable alternative fuel, substantiated by its congruence with diesel in physicochemical properties, despite the nuanced variations in BSFC and BTE.

The essential oil from the orange peel was studied by M. A. Asokan et al (Asokan et al., 2021). They investigated BTE and BSFC of blends comprising Orange Peel Oil (OPO) and diesel across various brake power levels. The study reveals that, particularly at full load, the BTE of OPO/diesel blends aligns with that of diesel oil, a phenomenon attributed to enhanced atomization and mixing within the combustion chamber. The reported BTE values for B20 (20% OPO + 80% Diesel oil), B30 (30% OPO + 70% Diesel oil), B40 (40% OPO + 60% Diesel oil), B100 (100% OPO), and D100 (100% Diesel oil) are 34.77%, 34.98%, 32.48%, 28.63%, and 36.68%, respectively. Notably, BTE for B20 and B30 closely approximates that of diesel oil, exhibiting a marginal reduction of 5.2% and 4.6%, respectively, which may be ascribed to the improved combustion of OPO. Moreover, the presence of substantial oxygen content in OPO is posited as a contributing factor that enhances the combustion process. Conversely, B100 demonstrates a lower BTE compared to diesel, attributed to the lower heating value of OPO. The observed proximity of B20 and B30 to diesel, despite a slight reduction in BTE, underscores their promise as viable blends. The combustion efficiency gains attributed to the improved burning of OPO and the oxygen content in OPO are pivotal in mitigating the BTE reduction relative to diesel. The investigation extends to the BSFC, where it is discerned that, across all loads, BSFC for OPO blends exceeds that of diesel due to the lower calorific value and higher density of OPO. At full load, the reported BSFC values for B20, B30, B40, B100, and D100 are 0.25, 0.25, 0.27, 0.31, and 0.24 kg/kWh, respectively. Remarkably, B20 and B30 exhibit lower BSFC compared to other OPO blends, albeit slightly higher than diesel. However, B40 and B100 manifest higher BSFC values than diesel oil, primarily attributed to the elevated viscosity and density of biodiesel. Another research about OPO for diesel engine was made by A. M. Kumar et al (A. M. Kumar, Kannan, & Nataraj, 2020) scientific investigation depicted in the article delves into the alterations in BTE and BSFC concerning Brake Power (BP) for various fuels, including diesel, Orange Peel Oil Methyl Ester (OOME), and nanoemulsions of OOME with titanium dioxide at concentrations of 50% (OOME-T50) and 100% (OOME-T100). The comprehensive portrayal in Figure 4 elucidates a noteworthy augmentation in BTE with increasing BP across all tested fuels. Notably, the BTE for conventional diesel consistently surpasses that of all experimental fuels across different BP levels. The peak BTE values were observed at 31.5% for diesel, 26.5% for pure OOME, 28.1% for OOME-T50, and 29.5% for OOME-T100 at the maximum BP. Remarkably, both nanoemulsions, OOME-T50 and OOME-T100, exhibit higher BTE in comparison to pure OOME across all BP levels. The heightened BTE in nanoemulsion fuels is attributed to the occurrence of microdetonation because of oxygen in the fuel blends and the catalytic by-products of titanium dioxide, contributing to enhanced combustion. The presence of nanoparticles within the emulsion offers a large surface-to-volume ratio, facilitating rapid vaporization and improved atomization of the fuel. Additionally, oxygen molecules in the nanoemulsion of orange peel oil biodiesel promote swift evaporation and thorough mixing with air, enriching the combustion process and resulting in higher thermal efficiency. The BSFC results, as illustrated in Figure 4, reveal that at maximum BP, diesel exhibits the lowest BSFC at 0.237 kg/kWh, whereas pure OOME records a higher value at 0.256 kg/kWh. The rationale behind the increased BSFC for OOME is attributed to its lower calorific value compared to diesel. Notably, nanoemulsion fuels, particularly OOME-T50 and OOME-T100, demonstrate lower BSFC compared to pure OOME, suggesting an improvement in fuel efficiency. The presence of oxygen molecules in the nanoemulsion fuels is identified as a contributing factor, reducing droplet size during secondary atomization and increasing the rate of fuel evaporation. Citrus peel oil has been investigated as a fuel by other researchers.

V. Dhana Rajuet al (Dhana Raju et al., 2022b) used mixtures of essential oils from LPO (lemon peel oil) in different proportions to which he also added DEE (diethyl ether). They report that the variation of brake thermal efficiency (BTE) with engine load is presented, highlighting that BTE is improved by 3.7% for the LPO20 DEE10 blend (20% LPO, 70% diesel, and 10% diethyl ether) compared to LPO20 (20% LPO and 70% diesel oil) at full load. Although lemon peel oil has a slightly lower energy content than diesel oil, it exhibits superior BTE due to the enhanced combustion phenomenon, influenced by its reduced viscosity and lower boiling point.

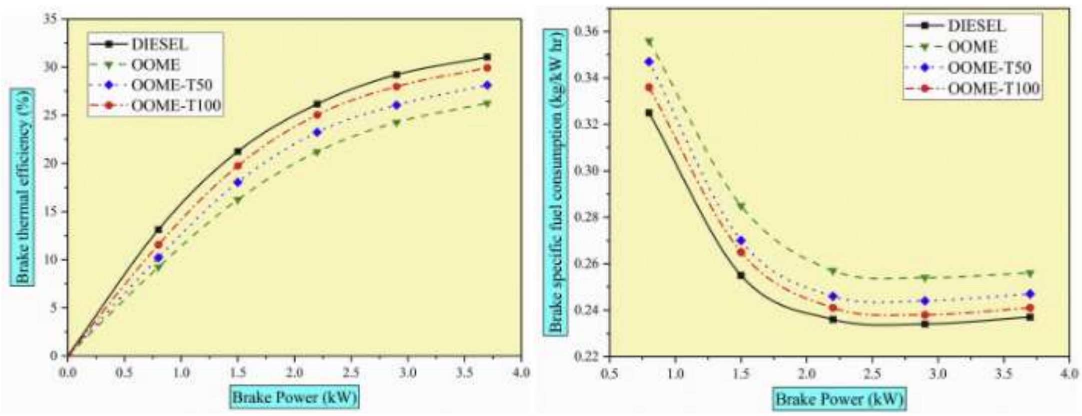

Figure 4 – Engine performance with nano-emulsion biodiesel(A. M. Kumar et al., 2020).

The BSFC values at maximum load for diesel, LPO10 (10% LPO and 90% diesel), LPO20 (20% LPO and 80% diesel), LPO30 (30% LPO oil and 70% diesel), LPO20 DEE5 (20% LPO, 75% diesel, and 5% diethyl ether), and LPO20 DEE10 are, respectively, 0.24 kg/kWh, 0.28 kg/kWh, 0.27 kg/kWh, 0.29 kg/kWh, 0.26 kg/kWh, and 0.25 kg/kWh. The addition of 10% DEE led to a reduction in BSFC at maximum load compared to the other blends. Additionally, the net energy of lemon peel oil is competitive with diesel, and its inherent

O_2 content supports the enhanced ignition process. BSEC, an effective parameter in the comparative assessment of fuel utilization, decreases with the increase in indicated mean effective pressure (IMEP). The BSEC values at maximum load for diesel, LPO10, LPO20, LPO30, LPO20 DEE5, and LPO20 DEE10 are, respectively, 10.2 MJ/kWh, 11.88 MJ/kWh, 11.44 MJ/kWh, 12.26 MJ/kWh, 10.88 MJ/kWh, and 10.49 MJ/kWh. Although the lower heating value of lemon peel oil indicates a slight increase in BSEC compared to diesel, the addition of 10% DEE resulted in a reduction in BSEC at maximum load. The cylinder pressure significantly increases for the investigated fuels, and the addition of LPO to diesel markedly raises the cylinder pressure and ignition delay period. This is due to the reduced viscosity of lemon peel oil, which supports fuel evaporation and atomization, leading to improved combustion. The cylinder pressure values for diesel, LPO10, LPO20, LPO30, LPO20 DEE5, and LPO20 DEE10 are, respectively, 68.5, 66.6, 66.8, 65, 67.4, and 67.9 bar at maximum load, with higher pressures observed for diesel and LPO20 DEE10. The total heat release rate (HRR) is significantly affected by the fuel's energy content and ignition nature. The authors reported a similar trend in HRR for all fuel blends, with LPO20 DEE10 highlighting a higher HRR at maximum load. The HRR values for diesel, LPO10, LPO20, LPO30, LPO20 DEE5, and LPO20 DEE10 are, respectively, 75.51 J/°CA, 71.31 J/°CA, 72.68 J/°CA, 70.84 J/°CA, 73.05 J/°CA, and 74.84 J/°CA. These findings underscore the positive contribution of adding citrus peel oil and DEE to the combustion dynamics and engine efficiency, opening significant prospects for the use of these blends in the context of alternative fuels.

The use of diesel in combination with alcohols, known as "diesel-alcohol," is a growing strategy to optimize engine performance and reduce environmental impact. This blend may include alcohols such as ethanol or methanol, adding a renewable and more environmentally friendly component to traditional diesel fuel. Diesel-alcohol has the potential to improve combustion characteristics, reducing particulate and greenhouse gas emissions. It can also contribute to diversifying energy sources and reducing dependence on fossil fuels in the transportation sector. However, ongoing research is needed to assess the efficiency, safety, and long-term impact of this technology in the context of evolving energy sustainability. W. Zhao et al (Zhao, Yan, Gao, Lee, & Li, 2022), investigated the in-cylinder pressure and HRR for various types of fuels tested at different engine loads, focusing on blends of diesel with higher percent of alcohols. They report that both peak in-cylinder pressure and HRR increase with higher engine loads, attributed to increased fuel injection for greater power output, leading to more heat released during the combustion process and resulting in higher peak in-cylinder pressure and HRR values. It is noteworthy that diesel/higher alcohol blends exhibit delayed combustion phases compared to diesel, as evidenced by the in-cylinder pressure and HRR curves shifting towards larger crank angles. The investigated alcohols have lower cetane numbers, higher self-ignition temperatures, and greater latent heat of vaporization compared to diesel. These properties contribute to a weaker ignition property and longer ignition delays, despite the higher oxygen content of the blends. These fuel characteristics result in delayed combustion phases for diesel/higher alcohol blends under the test conditions. Blends with different alcohols exhibit varied combustion phases due to differing ignition delays. All diesel/alcohol blends show longer ignition delays compared to diesel. At higher engine loads, the elevated in-cylinder temperatures lead to shorter ignition delays for all tested fuels, and the differences in ignition delays among the fuels decrease. Overall, the study highlights the specific contributions of alcohols and engine load to combustion dynamics, opening interesting perspectives for the use of these blends as alternative fuels.

The impact of mixtures on pollutant emissions

Investigating the pollutant emissions of fuels is crucial in the context of global concerns regarding the environment and air quality. Fuels used in internal combustion engines are a significant source of pollutant emissions, such as CO, NO_x, HC, and fine particles. These substances can have a substantial impact on air quality, negatively affecting human health and ecosystems. Greenhouse gas emissions from burning fossil fuels are a major factor in climate change. Investigating pollutant emissions helps deepen the understanding of the impact of different types of fuels on global warming and climate change. Research on pollutant emissions encourages the development of cleaner and more sustainable fuels. Identifying and promoting alternatives to fossil fuels, such as biofuels or renewable energy sources, is essential for reducing carbon footprint and minimizing the negative impact on the environment. The findings of research on pollutant emissions contribute to the development of regulations and emission standards for industry and transportation. These regulations promote innovation and encourage the adoption of cleaner technologies. Chemicals emitted into the atmosphere can have harmful effects on human health, causing respiratory, cardiovascular, and other health issues. Investigating pollutant emissions provides vital information for assessing risks and developing strategies to protect public health. In the context of increasing social awareness and a focus on corporate responsibility, companies are increasingly concerned about the ecological impact of their activities. Studies on pollutant emissions enable them to adjust their practices to minimize their environmental impact.

The HSU (Hartridge Smoke Unit) is a measurement unit used to quantify the density of smoke emitted from an engine. In the context mentioned, a lower value of HSU indicates that the smoke is cleaner or more transparent. The decrease in HSU values is attributed to the use of oxygenated blends in the fuel. Oxygenated blends refer to fuel mixtures that contain a certain percentage of oxygen-containing compounds, such as ethanol or other biofuels. These blends are known for their potential to improve combustion efficiency and reduce emissions. The reduction in smoke emission (R. Kumar et al., 2023b), as indicated by the decrease in HSU values, highlights the positive impact of oxygenated blends on the environmental performance of the engine. Specifically, the researchers report a significant reduction in smoke emission of about 66% and 64.4% for Eu10A and Eu10B blends, respectively, under higher load conditions. This substantial decrease in smoke emission underscores the effectiveness of incorporating oxygenated blends into the fuel composition.

PK Devan et al (Devan & Mahalakshmi, 2009a) present the experimental data clearly and provide relevant interpretations of the results. A notable aspect of the study is the investigation of NO_x emissions (Figure 5) in the case of Me–Eu (methyl ester-eucalyptus oil) blends. The authors report an increase in NO_x emissions, possibly due to the presence of oxygen in both components of the blends. This observation aligns with previous research indicating that oxygenated blends can lead to an increase in NO_x emissions. The authors explain this trend by complete combustion, resulting in higher combustion temperatures that favour NO_x formation. Additionally, the decrease in cetane number at higher proportions of eucalyptus contributes to increased NO_x emissions, as a lower cetane number leads to ignition delay and rapid heat release at the beginning of combustion. Interestingly, NO_x emissions for blends with higher eucalyptus percentages are higher than those for standard diesel, especially for the Me20–Eu80 blend, where emissions are 8% higher. However, it is observed that for the Me50–Eu50 blend, the increase is smaller, approximately 2.7%. Regarding HC emissions (Figure 5), an increase is highlighted at lower loads for blends with a higher eucalyptus content, but this level is lower than that of diesel. At higher loads, standard diesel exhibits the highest HC emissions, while Me–Eu blends, especially Me50–Eu50, show a significant reduction of 34%. CO emissions (Figure 5) show an interesting trend, with significant decreases at higher loads for Me–Eu blends compared to standard diesel. This reduction is explained by the oxygen enrichment resulting from the addition of eucalyptus oil and biodiesel, promoting further oxidation of CO during the engine exhaust process. There is a 37% reduction in CO emissions for the Me50–Eu50 blend. The significant reduction in smoke emissions is a positive outcome of the oxygenated blends. Smoke is primarily produced in the diffusive combustion phase, and the oxygenated fuel blends contribute to the improvement of diffusive combustion for the Me50–Eu50 blend, resulting in a reduction of approximately 49% in smoke emissions (Figure 5) at full load.

The study (Senthur et al., 2014) indicates a significant reduction in CO emissions for biodiesel blends compared to diesel fuel. This decrease is attributed to more efficient and complete combustion facilitated by the increased number of oxygen atoms in biodiesel. Researchers emphasize CO emissions in engines, attributing them to incomplete combustion caused by a lack of oxygen atoms or insufficient time for effective burning. The study reveals a significant decrease in HC emissions in eucalyptus oil blends with diesel compared to pure diesel fuel. Remarkably, the E30 blend (30% eucalyptus oil and 70% diesel) records the lowest HC emissions, showing a 32.5% reduction compared to the E20 blend (20% eucalyptus oil and 80% diesel). The efficient and complete combustion in biodiesel fuel blends is credited for the decrease in HC emissions. Variations in NO_x emissions for diesel and eucalyptus oil blends are explored, indicating an increase in NO_x emissions with higher engine loads. The higher combustion temperature and increased oxygen concentration in eucalyptus oil contribute to higher NO_x emissions compared to diesel at all engine loads. This observation aligns with the understanding that NO_x formation is influenced by the combustion temperature and oxygen availability.

This research (Asokan et al., 2021) investigates the emissions of CO in Orange Peel Oil (OPO) and its blends with diesel under different loads. At full load, it is evident that CO emissions for OPO and its blends are lower than those for pure diesel. This reduction is attributed to the effective combustion of OPO blends compared to diesel. Specifically, at full load, the CO percentages for B20 20% OPO + 80% Diesel, B30 30% OPO + 70% Diesel, B40 40% OPO + 60% Diesel, B100 100% OPO, and D100 100% Diesel are recorded as 0.085%, 0.131%, 0.118%, 0.12%, and 0.165%, respectively. Notably, there is a significant reduction in CO emissions for B20 compared to other fuel blends and diesel. Furthermore, HC emissions at full load are generally higher for all tested fuels, but B20 and B100 exhibit lower HC emissions than diesel. The study reveals a substantial 30.66% reduction in HC emissions for B20 compared to pure diesel (D100). This reduction is attributed to the higher percentage of oxygen content in biodiesel, which enhances combustion efficiency. The article also touches upon the impact of oxygen content and combustion temperature on NO_x

emissions, referencing previous studies. Orange peel oil, despite having a lower heating value and a cetane number similar to diesel, exhibits a higher ignition delay, leading to increased NO_x in the exhaust.

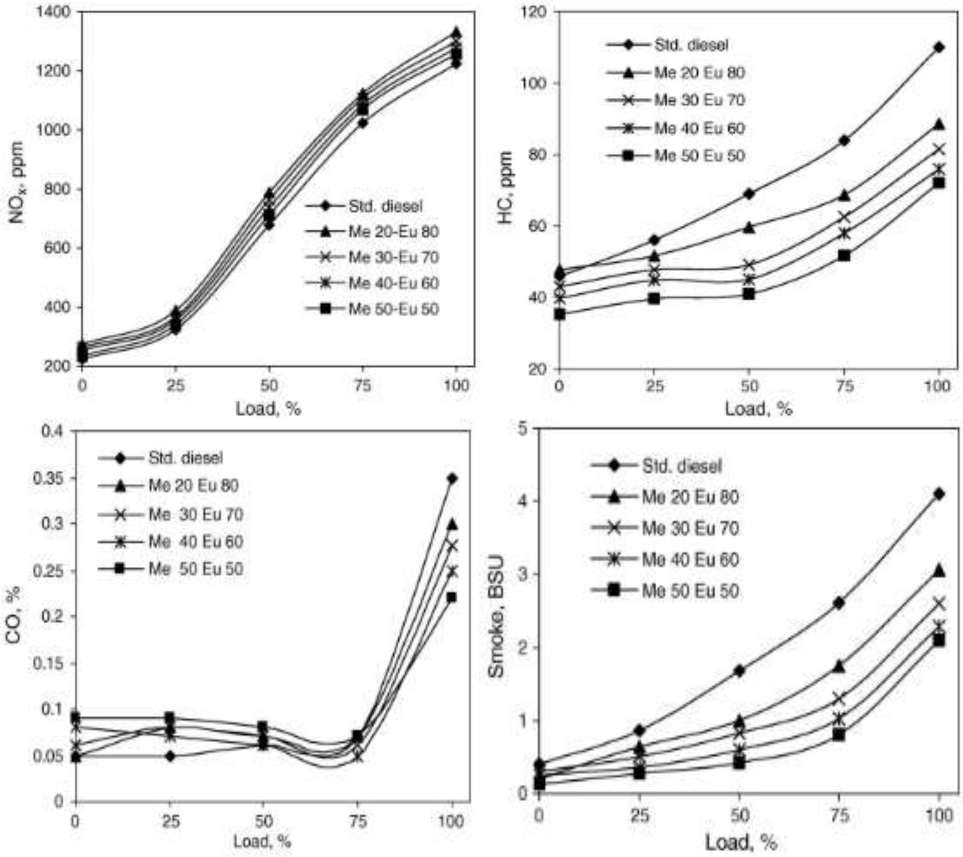

Figure 5 – Engine emissions for paradise oil methyl ester and eucalyptus oil blends (Devan & Mahalakshmi, 2009a).

The pollutant results of orange peel oil blends (A. M. Kumar et al., 2020) indicate a significant reduction in CO emissions (Figure 6) for OPO blends and nanoemulsions compared to diesel. This reduction is attributed to more efficient and complete combustion and richer oxygen conditions in the fuel blends, especially in the case of pure OPO. At maximum load, CO emissions for mineral diesel are higher than for all other tested fuels due to insufficient oxygen and the formation of a fuel-rich mixture inside the combustion chamber. Pure OPO blends show a notable reduction in CO emissions, and this reduction is further emphasized in the case of nanoemulsions, thanks to the presence of TiO_2 acting as an oxidation catalyst, providing more oxygen for combustion. HC emissions (Figure 6) generally increase with engine power, as more fuel is supplied to maintain a constant engine speed. However, OPO blends and nanoemulsions exhibit lower HC emissions compared to diesel, with an additional decrease in HC emissions observed for nanoemulsions. NO_x emissions (Figure 6) are influenced by the maximum cycle temperature and oxygen content. The study indicates an increase in NO_x emissions with increased engine power, with pure OPO blends showing higher NO_x emissions than other fuel types. Nevertheless, nanoemulsions with TiO_2 have a reduced effect on NO_x emissions, as the nanoparticles act as NO_x reducing agents, converting nitrogen oxides into nitrogen and oxygen. Smoke emissions Figure 6 are significantly reduced for OPO blends and nanoemulsions compared to diesel. This reduction is attributed to rapid evaporation and the formation of an improved air-fuel mixture, generated by microscopic explosions and secondary atomization of the fuel within the cylinder.

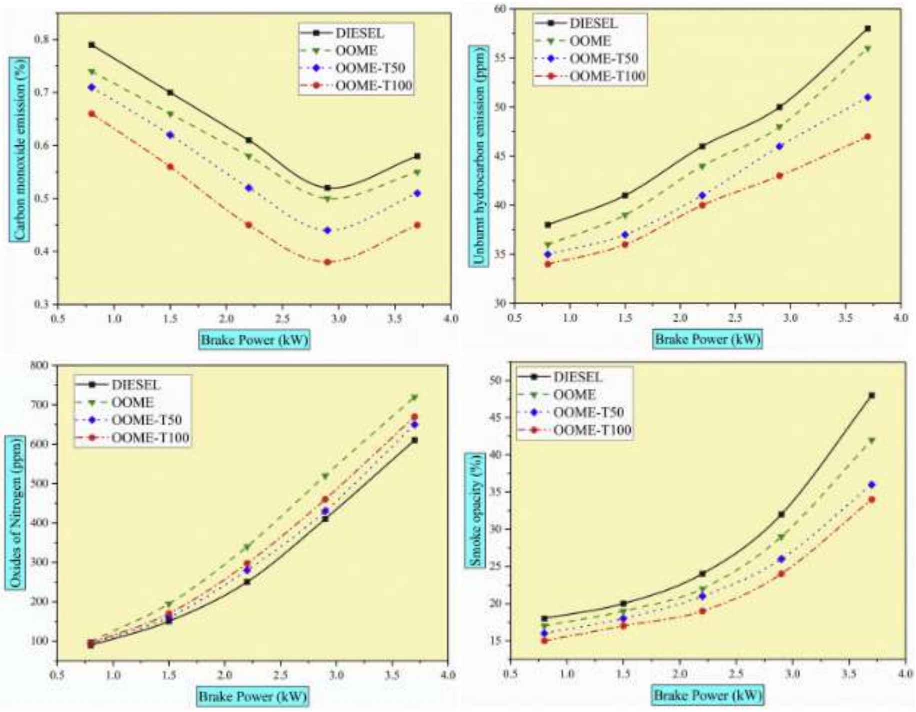

Figure 6 – Pollutant emissions of engine with nanoemulsion biodiesel (A. M. Kumar et al., 2020).

In another study (Dhana Raju et al., 2022b) LPO10, LPO20, LPO30, LPO20 DEE5, and LPO20 DEE10 biodiesel blends exhibit CO values of 0.048%, 0.058%, 0.059%, 0.062%, 0.053%, and 0.049%, respectively. Notably, LPO20 DEE10 demonstrates a 16.94% reduction in CO emissions compared to LPO20 at full load, attributed to its low viscosity and fine atomization promoting better ignition. HC emissions, indicative of partial or incomplete combustion, vary with engine load. LPO10, LPO20, LPO30, LPO20 DEE5, and LPO20 DEE10 biodiesel blends exhibit respective values of 30 ppm, 42 ppm, 41 ppm, 44 ppm, 36 ppm, and 31 ppm for carbon monoxide. LPO20 DEE10 consistently shows reduced hydrocarbon emissions at all load conditions, with a significant 24.4% reduction compared to LPO20 at peak load, attributed to the addition of oxygenated fuel. NO_x emissions, released due to increased oxygen availability and high cylinder temperature, are slightly lower for the LPO20 DEE10 blend compared to others. At peak load, LPO10, LPO20, LPO30, LPO20 DEE5, and LPO20 DEE10 biodiesel blends exhibit NOx values of 1618 ppm, 1930 ppm, 1967 ppm, 1878 ppm, 1812 ppm, and 1735 ppm. LPO20 DEE10 shows an 11.8% reduction in NO_x emissions compared to LPO20. Smoke opacity, representing the concentration of smoke and combustion efficiency, is influenced by the combustion process. LPO10, LPO20, LPO30, LPO20 DEE5, and LPO20 DEE10 biodiesel blends exhibit smoke values of 71%, 65%, 64%, 69%, 61%, and 56%, respectively, at maximum load. LPO20 DEE10 demonstrates a lower smoke opacity, with reductions of 21.1% and 12.5% compared to diesel and LPO20 at full load. The study suggests that higher oxygen availability in DEE contributes to improved ignition and reduced fuel-rich zones which lead to lower smoke opacity. Another study (Chen et al., 2022) shows that when alcohol fuel is added to diesel the results indicate an increase in CO emissions with the rise in engine load, attributed to a decrease in the air-fuel ratio at high loads, but also a significant reduction in these emissions through the addition of alcohols, especially methanol. The introduction of Al_2O_3 nanoparticles to diesel and ethanol blends demonstrates a substantial decrease in CO emissions, suggesting a catalytic effect of the nanoparticles. HC emissions increase with the engine load, and alcohol blends exhibit higher emissions, explained by the formation of a lean air-fuel mixture. The addition of Al_2O_3 nanoparticles reduces HC emissions, and this effect is more pronounced at higher nanoparticle concentrations, attributed to the catalytic effect and facilitation of complete combustion. NO_x emissions increase with the engine load, and alcohol blends show a slight reduction at low loads but an increase at high loads, suggesting a decrease in the cooling effect of alcohols in high-temperature environments. The addition of Al_2O_3 nanoparticles increases NO_x emissions, with a more significant increase at high nanoparticle concentrations, highlighting a combined effect of catalysis and oxygen absorption capacity.

According to other research (Datta & Mandal, 2016), NO_x emissions with higher engine loads for diesel, ethanol-blended diesel (DE), and methanol-blended diesel (DM) fuels. Interestingly, the addition of ethanol and methanol results in a reduction of NO_x emissions, with a more pronounced effect observed with ethanol blends. The lower air-fuel ratio and reduced combustion temperature with alcohol blending contribute to this decrease, emphasizing the potential of alcohol-diesel blends in mitigating NO_x emissions. Furthermore, the investigation examines specific CO_2 emissions, representing the amount of CO_2 formed during fuel combustion to produce unit power. It is noted that, despite the opposing influences of the low carbon-to-hydrogen ratio in alcohols and the oxygen content promoting better combustion, there is no significant variation in CO_2 emissions with alcohol blending. Smoke opacity, indicating dry soot emissions and a primary contributor to particulate matter formation, is studied. The results reveal that the use of pure diesel leads to the highest smoke and PM emissions, followed by lower emissions with DE5 and DM5 blends. Notably, the lowest emissions are observed with DE15 and DM15 blends. The reduction in smoke and PM emissions is attributed to improved combustion, decreased fuel-rich zones, and enhanced oxygen delivery in the alcohol-diesel blends.

LONG TERM USE OF BIOFUELS IN THE COMPRESSION IGNITION ENGINE

The long-term use of biofuels in diesel engines raises many questions and challenges, which require a detailed analysis and a deep understanding of the technical, economic and ecological implications. In this chapter, we propose to examine several aspects, exploring the advantages and limitations of the long-term use of biofuels in the diesel engine context, as well as their prospects for long-term sustainability and energy efficiency. The specialized literature illustrates a wide range of relevant research for the integration of biofuels in the context of compression ignition engines. These investigations raise crucial issues that must be considered when evaluating the long-term use of biofuels in these engines. Through the specialized literature, not only the potential advantages of biofuels are highlighted, but also the limits and challenges associated with their integration into diesel technology.

The oxygenated biofuels obtain in the experimental tests mentioned above better characteristics in terms of engine performance and pollutant emissions compared to classic fuel, but when it comes to their use in long term tests (Patil, Singh, & Kumar, 2024) show that they can cause certain problems in what concerns carbon deposits on the metal surfaces of the engine. The authors performed long tests on engines both from the small sector (small automobile engines) and tests with large engines from the field of agriculture in different regimes according to the Figure 6.

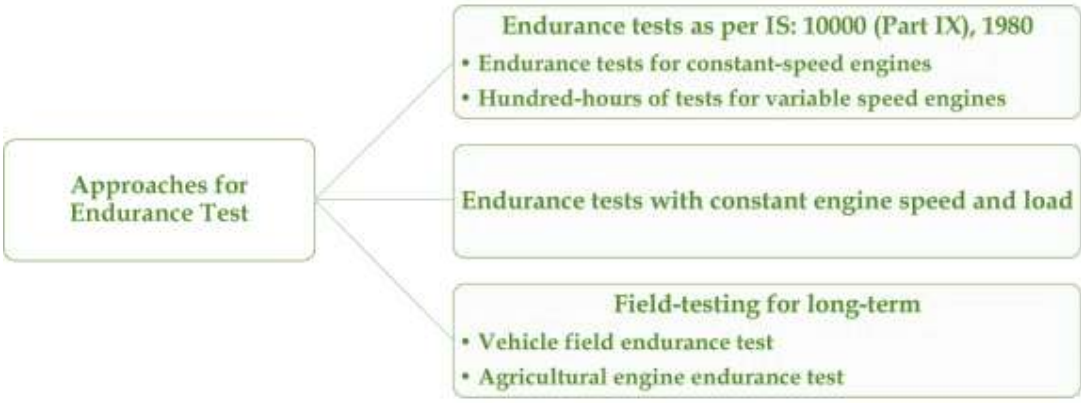

Figure 6 – Endurance test example, adapted from (Patil et al., 2024)

Engines operating long-term with vegetable oil register significant carbon deposits in the combustion chamber compared to conventional diesel as reported in (Bari, Yu, & Lim, 2002) In another study (Hoang & Pham, 2019), the authors tested another type of biofuel in the long term. They noticed significant carbon deposits after approximately 300 hours of operation. Carbon deposits are the result of a complex process that takes place at temperatures exceeding 350°C, based on two predominant mechanisms: the decomposition of hydrocarbons with the formation of solid carbon and the condensation of hydrocarbons into more complex aromatic molecules (Hoang & Pham, 2019).

Mixing biofuels with diesel fuel is also studied from the point of view of long-term deposits. In the studies (Agarwal & Agarwal, 2021b; Agarwal & Dhar, 2009, 2012; Reddy & Nanthagopal, 2021; Terry, McCormick, & Natarajan, 2006) the authors investigated this and concluded that carbon deposits are slightly increased in the combustion chamber when the engine is fuelled with a mixture of biofuel and diesel, in addition, when fuel mixtures are used, traces of erosion were also observed in the upper part of the piston. These deposits over time affect the performance of the engine leading to additional costs. Numerous studies reveal that carbon deposits in diesel engines on the injector nozzle significantly affect the engine's performance characteristics and polluting emissions (Birgel et al., 2012; Liaquat et al., 2013; Urzędowska & Stępień, 2016; Yüksek, Kaleli, Özener, & Özoğuz, n.d.). However, some tests have shown that certain combinations of biofuel and diesel lead to the formation of deposits in a smaller amount (Agarwal & Agarwal, 2021a; Kumar Patidar & Raheman, 2020; Suthisripok & Semsamran, 2018).

Certain advantages of the use of biofuels from the point of view of the lubrication of the high pressure pump components are also reported. In the studies (Agarwal & Agarwal, 2021a; Chourasia, Patel, Lakdawala, & Patel, 2018; Kumar Patidar & Raheman, 2020; Pehan, Jerman, Kegl, & Kegl, 2009) it was reported the lower wear of the pump and injectors when using biofuels.

DISCUSSIONS

The blending of diesel fuel with essential oils represents a burgeoning area of research aimed at enhancing the performance of internal combustion engines while mitigating their environmental footprint.

Implications for Engine Performance: One of the primary discussions centres around the impact of essential oil blends on engine performance metrics. Additionally, the combustion characteristics of diesel fuel may be altered by the inclusion of essential oils, potentially resulting in enhanced combustion efficiency and power output. However, variations in the chemical composition of different essential oils may yield divergent effects on engine performance, necessitating thorough investigation and optimization.

Effects on Emissions: Another key aspect of the discussion pertains to the influence of essential oil blends on pollutant emissions from diesel engines. While diesel combustion typically generates pollutants such as nitrogen oxides (NO_x) and particulate matter (PM), the introduction of essential oils may alter combustion kinetics and emissions profiles. Some studies suggest that certain essential oils possess antioxidant, which could potentially mitigate the formation of harmful pollutants. However, the complex interactions between essential oil components and combustion processes warrant comprehensive emissions testing to assess their net environmental impact. An important thing is the fact that the research results are influenced by many factors, from the region where the biofuel comes from to the type of engine in which it is introduced. A disadvantage of essential oil is its degradation over time, especially if it comes into contact with oxygen and ultraviolet light. The advantage of these biofuels lies in the fact that the plants from which they come absorb throughout their life a part of the carbon dioxide removed when the fuel is burned.

However, some studies show that the long-term use of certain biofuels can affect the operation of the engine due to the deposits inside the engine, leading to a decrease in performance and an increase in pollutant emissions, reaching the complete destruction of the engine.

CONCLUSION

This study endeavours to evaluate the use of essential oil and alcohol blends in diesel fuel, focusing on their combined effects on engine performance metrics and pollutant emission profiles. Through a synthesis of existing literature and empirical data, the study aims to elucidate key research inquiries and methodological approaches, thereby providing a foundation for further analysis and discourse. Furthermore, it underscores the broader significance of investigating alternative fuel sources within the context of environmental sustainability and engine optimization, aiming to offer insights into potential strategies for reducing environmental impact and enhancing engine efficiency without significant alterations. The following conclusions emerge from the analysis conducted in this present review:

- steam distillation is proving to be a promising next step for the extraction of biofuels, offering both favourable economic prospects and high yield. Detailed analysis of the literature and empirical data highlights the potential of these techniques to contribute to the sustainable development of biofuel industries. Efficiency and cost-effectiveness are supported by its advantages in the purification and concentration of biofuels from varied feedstock. However, to maximize the benefits, it is essential to continue research to create technological processes and reduce the impact on the environment. In light of these findings, steam distillation remains a promising solution for obtaining biofuels, with significant implications towards sustainability and energy efficiency.
- the transesterification of oils to obtain biofuels intended for diesel engines stands out as an efficient and promising method from a technical and economic point of view. Detailed analysis of the literature and empirical data reveals the potential of this technique to significantly contribute to the reduction of greenhouse gas emissions and other pollutants associated with the use of fossil fuels. In addition, transesterified biofuels have demonstrated the ability to improve engine performance and extend engine life. However, to fully exploit the benefits of this technology, continuous research is needed to optimize the processes and raw materials used.
- blending distillate alcohol with essential oil, transesterified vegetable oil and diesel fuel turns out to be a promising strategy for improving the combustion characteristics and performance of diesel engines. In addition, this mixture can be considered an economical solution, with significant impacts on the operating and maintenance costs of diesel vehicles.

- in some cases, a decrease in BSFC of up to 5% is observed, indicating a better use of the energy provided by the mixture. At the same time, engine power and torque can increase by up to 4%, reflecting improved mechanical performance. Also, the BTE and the amount of heat released in the cylinder can show an increase of about 6%, which suggests a greater efficiency in the conversion of chemical energy into mechanical energy. In-cylinder pressure may also increase for some fuel blends, indicating more complete combustion and more efficient use of the mixture by the engine.
- hydrocarbon (HC) emissions are reduced by up to 7%, reflecting more complete combustion and better utilization of the fuel mixture. Smoke emissions are also reduced by around 12%, indicating cleaner burning and lower particulate emissions. Although CO may decrease in some situations compared to the reference fuel, with values up to 4% lower, it is important to note that NO_x emissions may increase slightly, up to 6%. This increase can be attributed to the higher temperatures and oxygen content of certain biofuels, which can promote the formation of NO_x during the combustion process. Overall, the use of ternary fuel blends shows significant benefits in reducing pollutant emissions, with the exception of a slight increase in nitrogen oxide emissions, which underlines the importance of continuing research to optimize the blend and minimize environmental impact.
- from the research found in the literature, we conclude that performance parameters and pollutant emissions can be influenced by certain carbon deposits in the engine, this fact leads to additional research for the optimization of biofuel mixtures in compression ignition engines.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

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ENHANCING URBAN MOBILITY: THE ROLE OF IN MOTION CHARGING IN MODERN TROLLEYBUS SYSTEMS

In Motion Charging (IMC) is an innovative power system for trolleybuses that combines traditional overhead lines (OHL) with modern traction batteries. This system allows vehicles to charge while in motion, eliminating the need for stopping to recharge. As a result, trolleybuses can cover significant portions of their routes without relying on overhead lines, increasing the overall flexibility and functionality of the system. A key aspect of IMC is optimizing the length of overhead lines, which reduces the required battery capacity and lowers infrastructure costs. This article discusses the principles of the dynamic charging system, the benefits of its implementation, and practical examples of its application in European cities such as Solingen, Freiburg, and Gdynia.

Keywords: inm motion charging, trolleybus, electric buses, electromobility

INTRODUCTION

In the dynamic charging system (In Motion Charging - IMC), part of the route is covered with a trolleybus traction network (OHL - overhead line), which allows for the charging of traction batteries during movement (Fig. 1). The vehicles cover the rest of the route, i.e. the part in which there is no contact line, using traction battery power. This allows for the charging of the vehicle without stop-ping, increasing the flexibility and functionality of the system. In addition, covering a section of the route with a traction network reduces the length of the route to be travelled in battery mode, which in turn allows for a reduction in the capacity of the traction batteries.

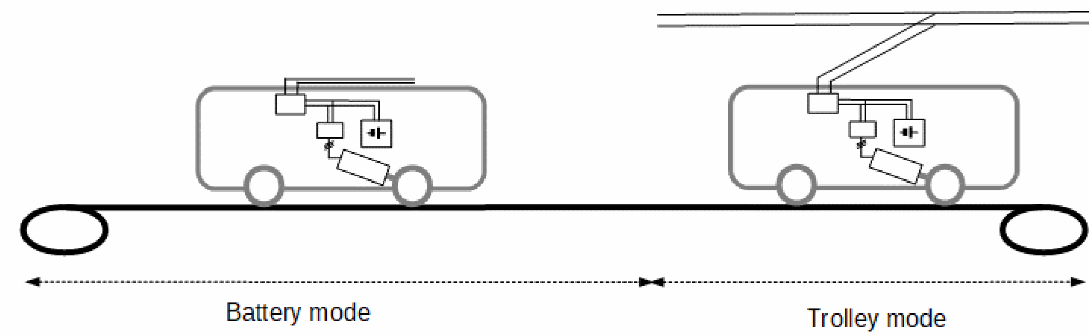

Fig. 1 − Idea of dynamic charging system (In motion charging)

The construction of a traction network is associated with significant financial outlays and is the most expensive element of dynamic charging system. For this reason, it is advisable to limit its length. The length of sections accompanied by contact line must be sufficient to charge the traction batteries with energy at least equal to the energy necessary to cover the catenary-free section. With currently used vehicles, the mini-mum degree of coverage with the traction network is at a level of 40% - 50% [3]. This value can be reduced by increasing charging power to 25%. In the case of a supply system of 750 V DC it is possible to decrease this rate to 20% [1-3]. In the case of a reduction in the heating power of the vehicle or use thermal pumps, it is possible to reduce the degree of coverage below 20%. Fig. 2 shows an estimation of the minimal coverage rate in function of charging power, based on, the energy consumption for a standard vehicle was assumed to be 3 kWh/km (winter) and, correspondingly, for an articulated vehicle 3,9 kWh/km [1, 7].

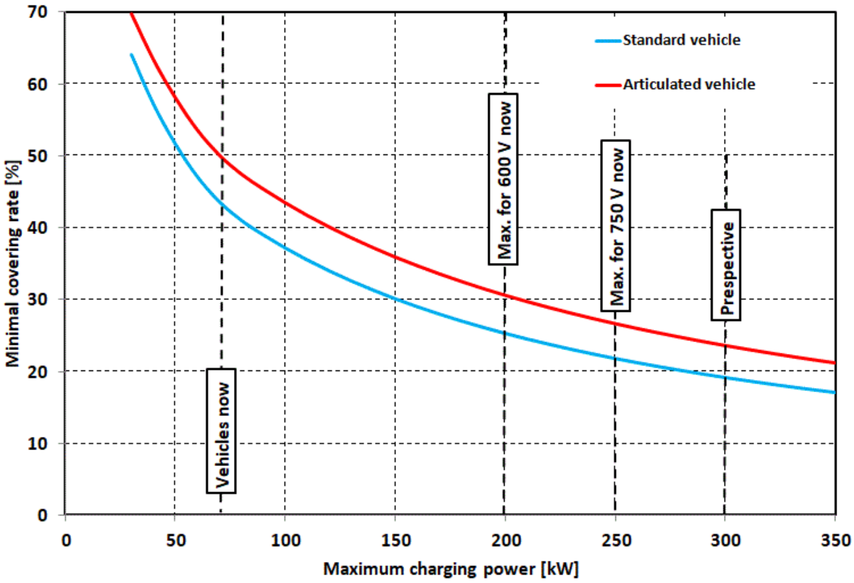

Fig. 2 − Minimum catenary coverage in function of maximal charging power [1, 7]

Modern technical solutions significantly increase the attractiveness of the trolleybus network for IMC charging. One of these is semi-automatic trolleybus pantographs, which enable the vehicle to be quickly connected to the trolleybus overhead line network (Fig. 3). Another solution is rapid charging stations for trolleybuses, which enable batteries to be charged via trolleybus pantographs with an output of 150 - 350 kW. Compared to classic electric buses, this solution has a significant advantage: Similar to the TOSA system, the charging process can begin immediately after connecting the pantograph (no charging station-vehicle synchronization is required) (Figures 4, 5, 6). The impact of the trolleybus overhead line on the appearance of public spaces can also be minimized. Thanks to the use of aesthetic masts and supporting elements, the trolleybus overhead line can be aesthetically integrated into the existing environment (Fig. 7). Importantly, the overhead power supply system for trolleybuses allows for easy integration with renewable energy sources.

Fig 3 − Automatic connection to trolleybus cathenary, fot. Mikołaj Bartłomiejczyk (Bern, Schweiz).

Fig 4 − Kummel+Matter Fast charging station for trolleybuses

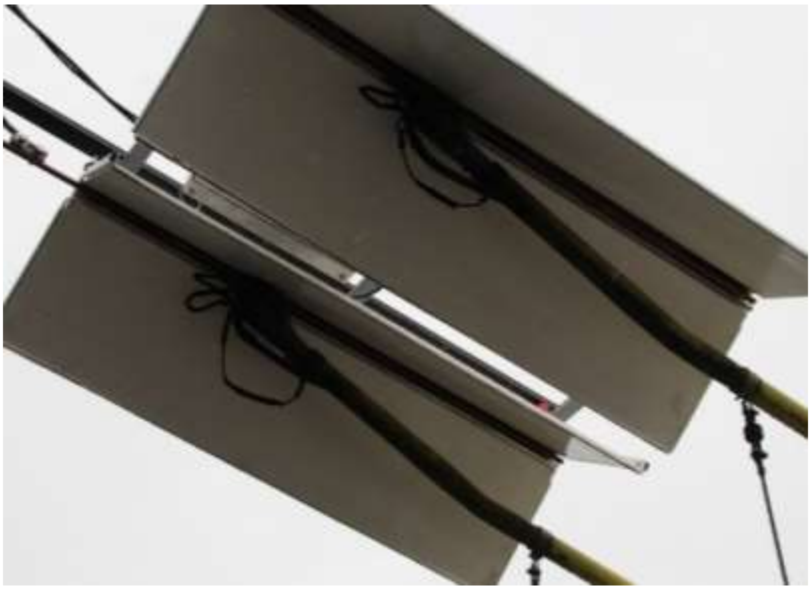

Fig. 5 − Fast charging connection point for trolleybuses, designed by the AREX company (Gdynia, Polen)

Fig. 6 − Stationary trolleybus charging station with energy storage (Firma AREX, Gdynia, Polen).

Fig. 7 − Trolleybus cathenary, fot. Mikołaj Bartłomiejczyk (Pescara, Italien).

PRACTICAL APPLICATION OF DYNAMIC CHARGING

Solingen

SWS, the public transport company in Solingen (Germany), implemented advanced dynamic charging system: They converted the diesel buses route 695 to IMC electric buses. The existing overhead cathenary wires (Solingen operates trolleybus system) will be used as a approximately 2 km long linear dynamic charging track, used as a charging infrastructure [6]. The new system, which is called BOB (Battery Overhead wire Buses) in Solingen, uses vehicles equipped with LTO traction batteries. Thanks to these batteries with the only 2 x 2.1 km long “IMC charging road” the BOBs can operate nonstop passenger service on the 18 km long (in both way) route (figure 9). Nearly 80 % of the route is operated in battery mode without overhead wires [6]. The vehicles were manufactured in cooperation of Solaris and Kiepe Electric (table 1, fig. 8).

Fig. 8 − The BOB Solaris Trollino Kiepe Electric in Solingen, photo Jürgen Lehmann

Table 1 – Technical data of BOB vehicles in Solingen [6]

Vehicle type	Articulated low-floor trolleybus of the type “Trollino 18.75” (Solaris / Kiepe Electric)
Vehicle size	18.75 length m x 2.55 m width x 3.5 m height
Electric motor	2 x 160 kW asynchronous motors on the 2nd and 3rd axles (4 powered wheels)

Energy of battery	Lithium-titanate-oxide (LTO); 48 kWh usable energy / 60 kWh installed energy; 200 kW continuous power / 300 kW peak power
Charging concept	IMC® (in motion charging) up to 240 kW and opportunity charging (standing)

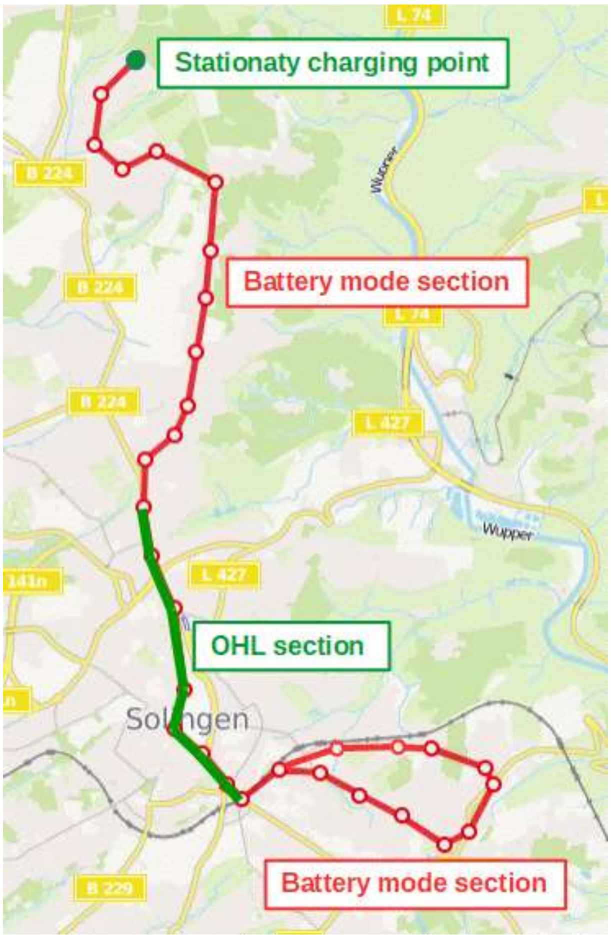

Fig. 9 − The scheme of BOB system (line 695) in Solingen, OHL - overhead trolleybus cathenary line, based on https://moovitapp.com/

Freiburg

An example of a modern IMC system is the city of Freiburg in Switzerland. The 10 km long line 1 is in the middle 3 km long section equipped with overhead lines. The operation is carried out by Hess battery trolleybuses with 66 kWh batteries 350 kW charging in motion (Fig. 10 and 11).

Fig. 10 − Line 1 in Freiburg, Switzerland, operated by IMC trolleybuses, only 30% covered by overhead cathenary, based on https://moovitapp.com/

Fig. 11 − Hess ligh Tram 19 DC trolleybus on line 1 in Freiburg (Switzerland) with the dynamic charging system IMC. The route is only 30% covered by the trolleybus network and a 66 kWh LTO traction battery can be seen on the roof of the first vehicle section. Foto Mikołaj Bartłomiejczyk

Gdynia

In Gdynia (Poland), as part of the Gepard program (supported by National Fund for Environmental Protection and Water Management) bus line 170 was electrified. This electrification was combined with the modification of the route (the route in the central part of the city was extended) and the change of its number to 32. Line 32 has a lengths of cca. 10 km one-way, of which 4 km is under the trolleybus OHL catenary and 6 km are driven in battery mode (Fig. 12).

Due to the specificity of line 32, it was decided to introduce dedicated vehicles with special electrical equipment to serve it – Trolleybus 2.0. In classic trolleybuses, due to the need to provide electric shock protection, all electrical equipment operating at 600 V (traction converter, traction motor, on-board converter, or traction batteries) must be equipped with two-stage insulation from the vehicle body. This requires the implementation of an electrical installation dedicated to trolleybus solutions. In the case of line 32, however, most of the route takes place in battery mode. For this reason, it was decided to use an unusual technical solution that would combine the features of a trolleybus and an electric bus under commercial name Trolleybus 2.0 (Fig. 11). It consisted in the maximum unification of the vehicle with a classic electric bus, i.e. the use of a standard electric bus installation with standard, single-stage insulation and a traction battery as the main power source. The battery is charged from the trolleybus catenary by means of an input DC-DC converter (charger) with a power of 150 kW (during standstill, the current received from the catenary is limited to 160A). So, from the point of view of the electrical installation, the vehicles purchased in the Gepard program are similar to standard battery electric buses, while from the point of view of the passenger or the driver, they are almost identical to the trolleybus. These buses also have double legal approval - as a trolleybus and an electric bus.

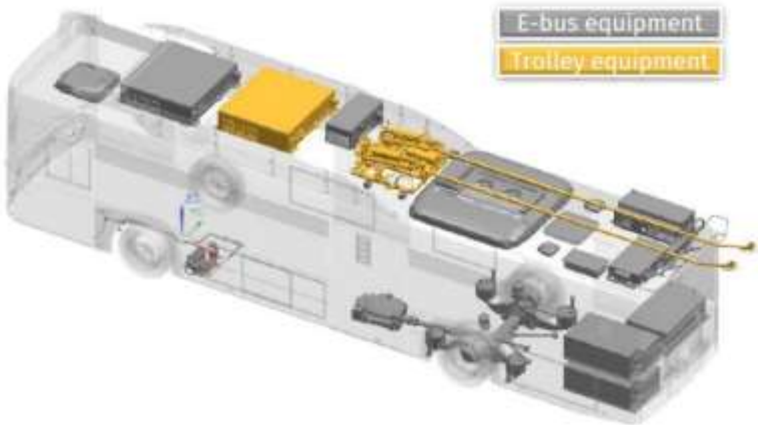

Fig. 12 − Trolleybus 2.0 vehicle © Solaris Bus & Coach

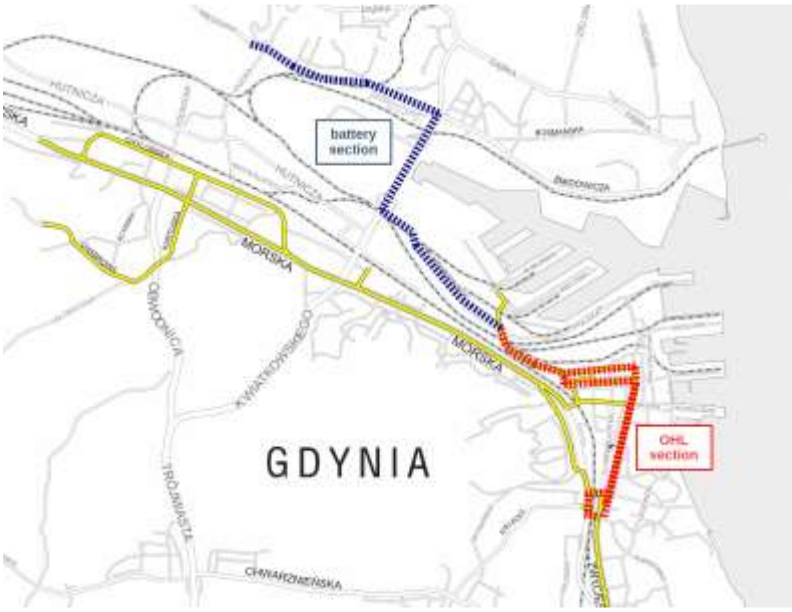

Fig. 13 − The scheme of 32 route, yellow lines: existing trolleybus OHL network

SUMMARY

The In Motion Charging (IMC) system represents a significant advancement in urban public transportation, offering a flexible and efficient solution for powering trolleybuses. By combining traditional overhead lines (OHL) with modern traction batteries, IMC allows vehicles to charge while in motion, reducing the need for extensive battery capacity and lowering infrastructure costs. This system enhances operational efficiency by enabling continuous travel without frequent stops for recharging.

Practical applications of IMC in cities like Solingen, Freiburg, and Gdynia demonstrate its effectiveness. In Solingen, the IMC system enables electric buses to operate on an 18 km route with only 20% of the distance covered by overhead lines. Freiburg's Line 1 shows that with 30% OHL coverage, trolleybuses can efficiently manage a 10 km route. In Gdynia, the integration of IMC with electric buses offers a hybrid solution, improving the flexibility and performance of public transport.

Overall, the IMC system provides a sustainable and aesthetically pleasing alternative to conventional electric buses, with the potential to integrate renewable energy sources. This innovative approach not only reduces emissions and energy consumption but also enhances the attractiveness and functionality of urban transport networks.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

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STUDY OF ENERGY CONSUMPTION BY TROLLEYBUSES MOVING UNDER REGULATED TRAFFIC CONDITIONS

At the current stage of development of electric transport, the task of studying the energy efficiency of such vehicles is still relevant. Various models of electricity consumption developed and proposed by scientists still do not reflect the actual energy consumption of vehicles. A particular problem in such studies is the need to take into account the amount of electricity recovered by the engine. The analysis of the literature shows a variety of approaches to modeling electricity consumption that take into account the actual operating conditions of vehicles. In this paper, we have studied the consumption of electric energy by trolleybuses moving along established routes in Vinnytsia. Based on the results of the studies, the total amount of energy consumed, the amount of energy consumed by the traction electric drive, the total amount of recovered energy, and the amount of recovered energy returned to the contact network were determined.

The data obtained were processed and it was determined that the difference between the amount of electric energy recovered by the vehicle traction motor and the total amount of recovered electric energy sent to the contact network is 6...14 %, while the amount of electric energy recovered by the vehicle traction motor ranges from 7 to 27 % of the electric energy consumed by the electric drive. The research results obtained indicate significant losses of part of the electrical energy recovered by the engine, as well as a significant variation in the amount of recovered energy, depending on the route. Further research should be aimed at improving mathematical models of electric energy consumption, taking into account the specific operating conditions of vehicles.

Keywords: consumption of electrical energy, trolleybus, energy recovery, specific energy consumption, traffic routes

INTRODUCTION

The recently adopted Law of Ukraine “On Certain Issues of the Use of Vehicles Equipped with Electric Engines and Amendments to Certain Laws of Ukraine on Overcoming Fuel Dependence and Development of Electric Charging and Electric Vehicle Infrastructure” [1] provides for the use of electric buses instead of buses with spark-ignition internal combustion engines for passenger transportation in Ukrainian cities.

The increase in the number of wheeled public transport vehicles on electric traction that carry out passenger transportation in Ukrainian cities will require an increase in the capacity of power supply systems of transport enterprises and cities in general.

Therefore, the task of studying the energy consumption of such vehicles that move in accordance with regulated traffic conditions becomes relevant.

Given the fact that a small number of electric buses are currently in operation in Ukraine, and their design is almost similar to that of trolleybuses, trolleybuses can be used as an object of study/

ANALYSIS OF LITERATURE DATA AND FORMULATION OF THE PROBLEM

In [2], a new model of MTECM energy consumption by an electric bus was developed using a multivariate linear regression method. Thus, based on the proposed model, it is possible to calculate the energy consumption for any route planned for the establishment of electric bus operation. Thus, in accordance with the obtained consumption, it is possible to make a correct determination and selection of parameters that significantly affect investment costs, such as route, vehicle length, engine power, and battery capacity.

In order to study the correlation between the type of route an electric bus travels and the amount of energy it consumes to run it, studies were conducted on three different routes [3].

Article [4] provides an overview of the Advanced Vehicle Simulator (ADVISOR), which provides a relatively easy-to-use analysis package for vehicle modeling. It is primarily used to quantify the fuel economy, performance, and emissions of vehicles that use alternative technologies, including fuel cells, batteries, electric motors, and internal combustion engines in hybrid (i.e., multiple power source) configurations.

The research, the results of which are presented in [5], is aimed at developing a model for estimating energy consumption on the road for planning, operating, and evaluating the life cycle of an electric bus fleet. The results show that: the average absolute percentage error of the proposed model is 12.108%; the accuracy of the model estimation with a probability of 99.7814% meets the requirements of EB fleet planning.

In [6], the authors present a two-stage electric vehicle routing problem (2sEVRP), which includes an improved assessment of energy consumption by considering detailed topography and speed profiles.

In [7], based on real data, the authors propose models that make it possible to predict the consumption of electric energy by vehicles on specific routes.

It is also worth noting [8], which proposes a new approach to forecasting changes in energy demand with a wide range of uncertain factors. The identification of factors was carried out to determine the range of changes in operating conditions. A computationally efficient surrogate model is generated on the basis of a previously developed numerical simulation model.

Based on the data of electric bus trips in China and Norway, the authors of [9] proposed a model of energy consumption taking into account the auxiliary systems of electric buses, such as heating, ventilation, air conditioning, and other vehicle systems.

The analysis of current areas of research on electricity consumption indicates the need to adapt mathematical models to specific operating conditions. Paper [10] demonstrates that operating conditions have a great impact on the consumption of electricity by vehicles, and this issue is especially acute for buses that transport passengers on established routes in cities.

In Ukraine, a number of studies have also been carried out, mainly related to the development of a mathematical model of the energy capacity of a traction battery [11] and the optimization of its parameters [12]. Studies have been carried out on the energy consumption of vehicles with an electric motor [13], as well as on the assessment of energy consumption by an electric bus and the parameters of the traction battery in operation. However, the issue of energy use by vehicles with an electric traction system has not been sufficiently studied, since this issue is not relevant for the subway, tram, and trolleybus, since they are powered by separate traction substations.

PURPOSE AND OBJECTIVES OF THE STUDY

The purpose of the research is to determine the consumption of electric energy by trolleybuses that move along established routes in Vinnytsia. The study was conducted on trolleybuses due to the fact that electric buses are currently not used in Ukrainian cities. On the other hand, the technical characteristics of electric buses and trolleybuses are almost identical, which makes it possible to extend the results to both types of transport (Table 1).

Table 1 - Comparison of technical characteristics of trolleybuses and electric buses

Name of the indicator	Vehicle model	
	Trolleybus T 70110	Electric bus Electron E191
Manufacturer	Subsidiary of Automobile Assembly Plant No. 1 of Public Joint Stock Company Automobile Company Bogdan Motors	Ukrainian-German joint venture Electrontrans
Overall length by body elements, mm	11960	12100
Overall width, mm	2550	2500
Overall height, mm	3800	3280
Wheelbase, mm	5860	5900
Front/rear axle track, mm	2160/1890	2160/1890
Passenger capacity, persons	105	100
Empty weight, kg	11800	12880
Technically permissible maximum weight, kg	18940	19000
Front axle	VOITH TURBO IFS 75-225	ZF, RL 82EC
Rear axle (drive)	ZF AV-132/80	ZF, AVE 130
Gear ratio of the final drive	9.82	22.63
Wheel tires	275/ 70R 22.5	275/ 70R 22.5
Tire pressure, kgf/cm^2	8.0	8.0
Traction motor	ЕД-139АУ2	AVE130-350VAC (2 шт)
IGBT	Cegelec CDC 050P	ENI-FT/ZF/AVE
Static converter 600/27 В, 3p 400 В	Cegelec SMTK 7.0Z	550/28 В ENI-BAT_24DC_6_U
Brake resistor block	R9PO4B125, 300 кВт	None

Name of the indicator	Vehicle model	
	Trolleybus T 70110	Electric bus Electron E191
Compressor drive motor	Siemens 1LA7113-4AA10-Z	S POL2-2 B3
Hydraulic pump drive motor	Siemens 1LA7106-4AA16	SLg100L-4B
Battery pack for powering low-voltage circuits	6CT-190, 12B, 190 Ah (2 pcs.)	6CT-190, 12B, 190 Ah (2 pcs.)
Traction battery pack	None	based on LiFeYPO4 cells Winston Battery WB-LYP 400AHA, (4 battery packs connected in series)
Front axle suspension	Independent, pneumatic with two-lever guide devices, two elastic elements, two telescopic hydraulic shock absorbers and a body position adjuster	
Rear axle suspension	Dependent, pneumatic with a rod guide, four elastic elements, four telescopic hydraulic shock absorbers and two body position adjusters	
Steering	Steering mechanism - integrated with hydraulic power steering. Steering column - adjustable in angle and height	
Service brake system	Pneumatic, dual-circuit with ABS system, brake mechanisms of all wheels - disc brakes, with automatic adjustment of the gap between the brake pads and the disc	
Parking brake system	One of the circuits of the working brake system	
Spare brake system	Mechanical drive brake mechanisms of the drive axle wheels from the spring energy accumulators of the rear axle with pneumatic control	
Auxiliary brake system	Electrodynamic braking as a function of the traction motor	

RESEARCH RESULT

The study of electricity consumption was conducted on trolleybuses T70110, which are operated on the routes of the Vinnytsia City Amalgamated Territorial Community. Figure 1 shows a diagram of the trolleybus routes of this community. The length of the routes of Vinnytsia city amalgamated territorial community is 165.44 km, the length of the contact network is 90.5 km.

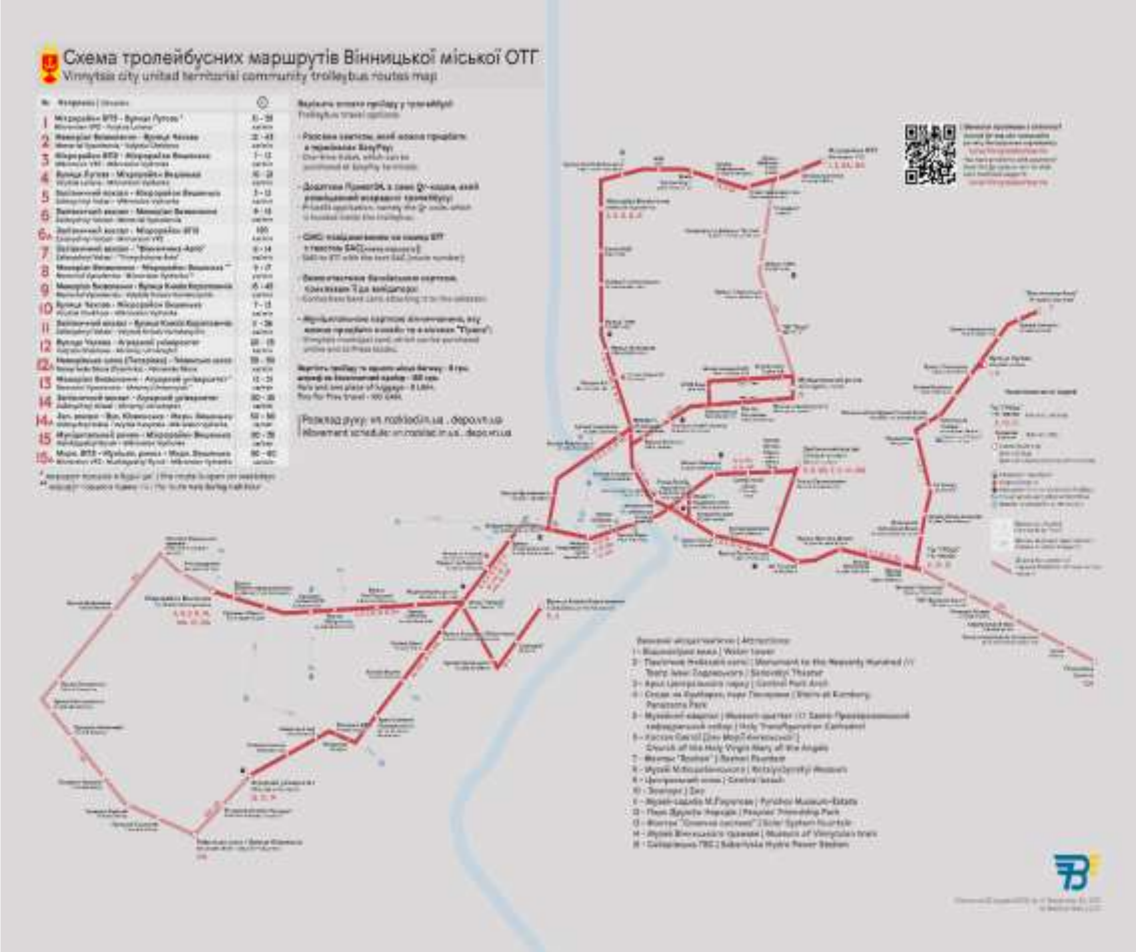

Figure 1 – Scheme of trolleybus routes of Vinnytsia city amalgamated territorial community [according to https://transphoto.org/articles/1236/]

During the research, we organized monitoring of electricity meters installed on T70110 trolleybuses. As a result, the following information was obtained

- the amount of energy consumed: total - since the beginning of the trolleybus operation and daily - for the last day of operation on the route;

- the amount of energy consumed by the traction drive is the amount of energy that was used to create the kinetic energy of the trolleybus (this energy does not include energy consumed for its own needs, namely: power supply of the compressor, hydraulic booster, air conditioner, external lighting, heating and interior lighting). The share of recovered energy generated during trolleybus braking is excluded from this energy;

- the amount of recovered energy is the amount of energy produced by the traction motor during regenerative braking of the trolleybus;

- the amount of energy consumed in total and for the last day is the amount of energy consumed from the contact network during passenger transportation, respectively, from the beginning of operation and for the last day;

- the total amount of recovered energy is the amount of energy that was returned to the overhead line during trolleybus braking;

- total trolleybus mileage and for the last day.

It is worth noting that not all of the recovered energy can be returned to the contact network, due to the characteristics of the contact network itself.

That is, if the voltage of the contact network reaches its maximum value, the recovered energy is sent to the braking resistors and converted into heat.

Tables 2 and 3 summarize the results of the observations.

Table 2 – Electricity consumption by Bogdan T70110 trolleybuses during their operation

Trolleybus number	Mileage. km	Energy consumed by the traction drive. kWh	Amount of recovered energy. kWh	Total amount of consumed energy. kWh	Total amount of recovered energy. kWh
3	375714.24	474516.73	93477.64	645007.34	78651.63
4	442414.51	531923.77	115543.43	727179.93	97528.24
4	441649.54	531078.59	115328.11	726135.93	97326.57
9	510751.44	586138.44	102710.64	781663.67	85266.44
11	441821.61	514884.80	104873.89	692838.83	91063.27
15	428055.09	514706.48	86763.95	707023.65	74410.58
16	483418.33	598761.80	138366.95	810720.29	116585.96
16	482475.34	597678.98	138150.28	809465.93	116377.09
17	407141.38	502849.98	82233.18	691844.40	68458.63
21	432074.01	501351.39	79974.12	362493.69	6134.39
22	481616.78	540970.90	122693.80	773530.56	105218.99
23	481769.18	543179.16	107896.20	753945.79	93115.87
27	416730.88	478682.90	96423.78	683102.97	85303.75
28	494240.03	594514.77	102236.44	766941.75	87245.98
28	493307.79	593492.11	102114.91	765801.53	87128.13
29	443339.96	518757.32	127492.33	739575.84	107923.46
30	423002.77	499332.62	102769.71	706851.97	88579.84
34	409786.89	500515.31	85895.20	672528.42	74259.16
34	408593.00	499201.18	85704.42	670979.15	74075.38
35	446936.53	495941.93	108044.46	741473.34	92191.76
39	411264.94	436537.88	72370.17	598042.38	60814.19
40	384886.99	431390.24	95124.43	626138.30	81288.25
40	384056.30	430529.67	94955.08	625097.34	81122.93
13	417591.61	472744.69	119989.36	680396.99	102017.29
37	450377.56	490666.14	117367.81	697848.85	100659.93
7	361802.16	403797.96	83555.11	573231.87	71289.81
5	404123.37	469742.28	83236.03	649735.13	69715.81
19	494793.48	555764.05	100050.91	747778.29	87860.41
25	408404.79	505372.47	104592.73	699849.11	85955.11
31	422818.97	514084.82	106560.90	727201.82	91158.88
38	464329.57	543190.44	88612.51	740536.90	76208.19
2	442814.51	533659.19	94014.52	999999.00	74339.09
32	425617.68	511023.90	107924.92	700794.87	90346.39
6	207811.60	310405.84	33869.42	425496.74	28369.28
26	474681.86	539671.07	105304.74	755980.09	91211.21
36	408973.78	479563.58	73737.62	698352.84	60519.09
14	460439.42	521290.10	115134.70	720887.14	98893.04

In order to estimate the amount of electricity consumed and recovered, the energy consumption figures are converted to specific kWh per 1 kilometer of travel. The results of the calculations are shown in Table 3.

Table 3 – Specific electricity consumption by Bogdan T70110 trolleybuses during their operation

Trolleybus number	Specific energy consumed by the traction drive. kWh/km	Specific amount of recovered energy. kWh/km	Total specific energy consumption. kWh/km	Total specific amount of recovered energy. kWh/km	% of recovered energy	% of the total amount of recovered energy	The difference
2	1.21	0.21	2.26	0.17	18	7	10
3	1.07	0.21	1.46	0.18	20	12	8
4	1.20	0.26	1.64	0.22	22	13	8
4	1.20	0.26	1.64	0.22	22	13	8
5	1.06	0.19	1.47	0.16	18	11	7
6	0.70	0.08	0.96	0.06	11	7	4
7	0.91	0.19	1.29	0.16	21	12	8
9	1.32	0.23	1.77	0.19	18	11	7
11	1.16	0.24	1.56	0.21	20	13	7
13	1.07	0.27	1.54	0.23	25	15	10
14	1.18	0.26	1.63	0.22	22	14	8
15	1.16	0.20	1.60	0.17	17	11	6
16	1.35	0.31	1.83	0.26	23	14	9
16	1.35	0.31	1.83	0.26	23	14	9
17	1.14	0.19	1.56	0.15	16	10	6
19	1.26	0.23	1.69	0.20	18	12	6
21	1.13	0.18	0.82	0.01	16	2	14
22	1.22	0.28	1.75	0.24	23	14	9
23	1.23	0.24	1.70	0.21	20	12	8
25	1.14	0.24	1.58	0.19	21	12	8
26	1.22	0.24	1.71	0.21	20	12	7
27	1.08	0.22	1.54	0.19	20	12	8
28	1.34	0.23	1.73	0.20	17	11	6
28	1.34	0.23	1.73	0.20	17	11	6
29	1.17	0.29	1.67	0.24	25	15	10
30	1.13	0.23	1.60	0.20	21	13	8
31	1.16	0.24	1.64	0.21	21	13	8
32	1.15	0.24	1.58	0.20	21	13	8
34	1.13	0.19	1.52	0.17	17	11	6
34	1.13	0.19	1.52	0.17	17	11	6
35	1.12	0.24	1.67	0.21	22	12	9
36	1.08	0.17	1.58	0.14	15	9	7
37	1.11	0.27	1.58	0.23	24	14	9
38	1.23	0.20	1.67	0.17	16	10	6
39	0.99	0.16	1.35	0.14	17	10	6
40	0.97	0.21	1.41	0.18	22	13	9

Based on the obtained data on specific electricity consumption, taking into account the amount of recovered energy, we have built graphs:

− the total amount of consumed and recovered electric energy (Fig. 2);

− the difference between the amount of electric energy recovered by the traction motor and the amount of electric energy consumed for further movement of the trolleybus (Fig. 3);

– the amount of electric energy recovered by the traction motor and the amount of electric energy consumed for further movement of the trolleybus (Fig. 4);

– Pareto diagram of the difference between the amount of electric energy recovered by the traction motor and the amount of electric energy consumed for further movement of the trolleybus (Fig. 5).

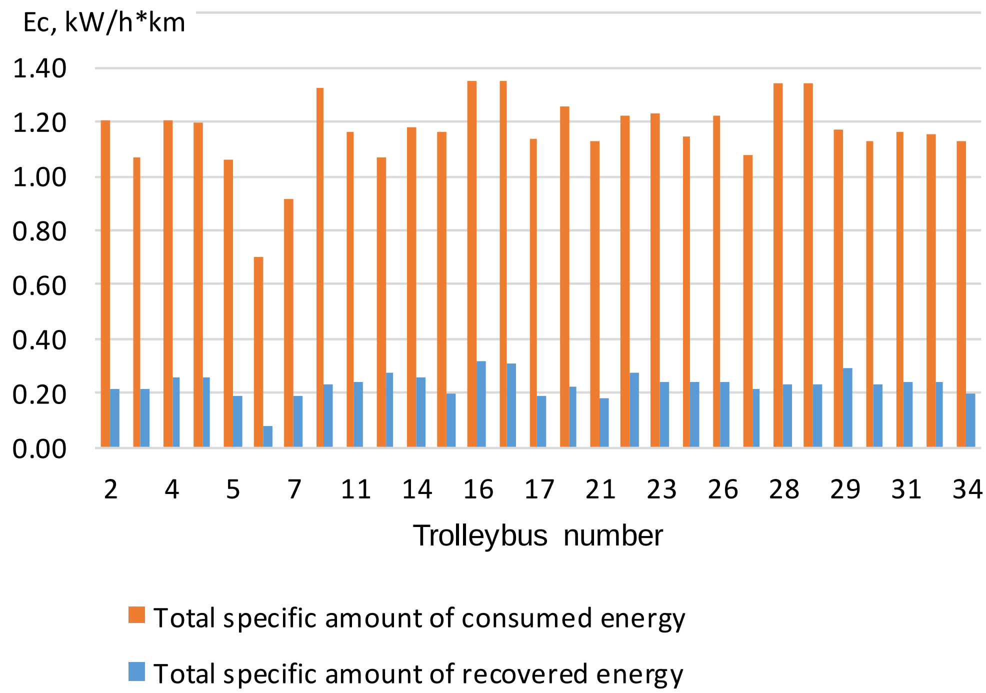

Figure 2 – The total amount of electricity consumed and recovered is reduced to specific indicators

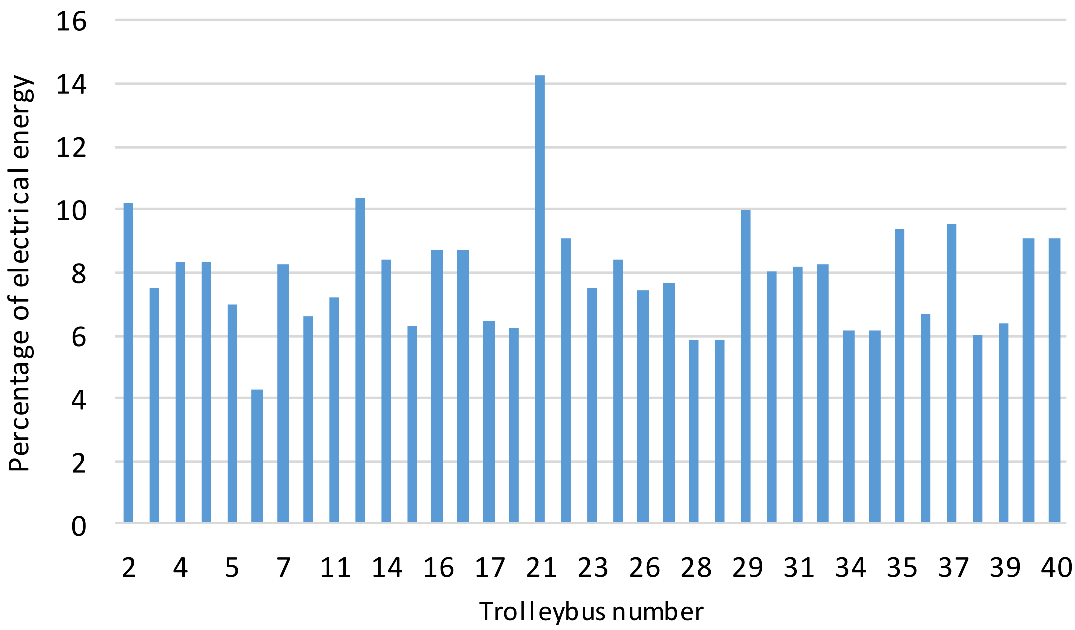

Figure 3 – The difference between the amount of electric energy recovered by the traction motor and the amount of electric energy consumed for further movement of the trolleybus

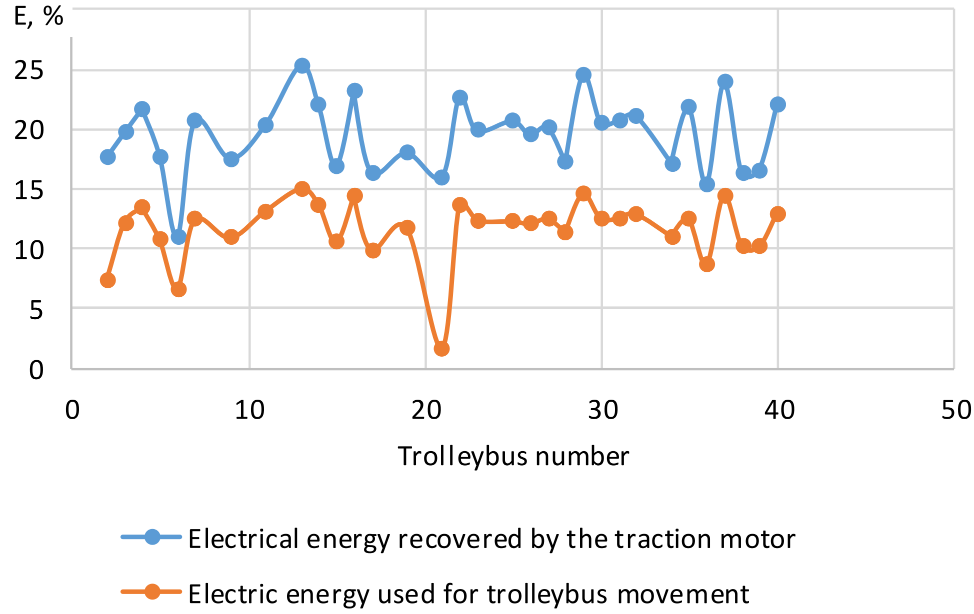

Figure 4 – Graphs of the amount of electric energy recovered by the traction motor and the amount of electric energy consumed for further movement of the trolleybus

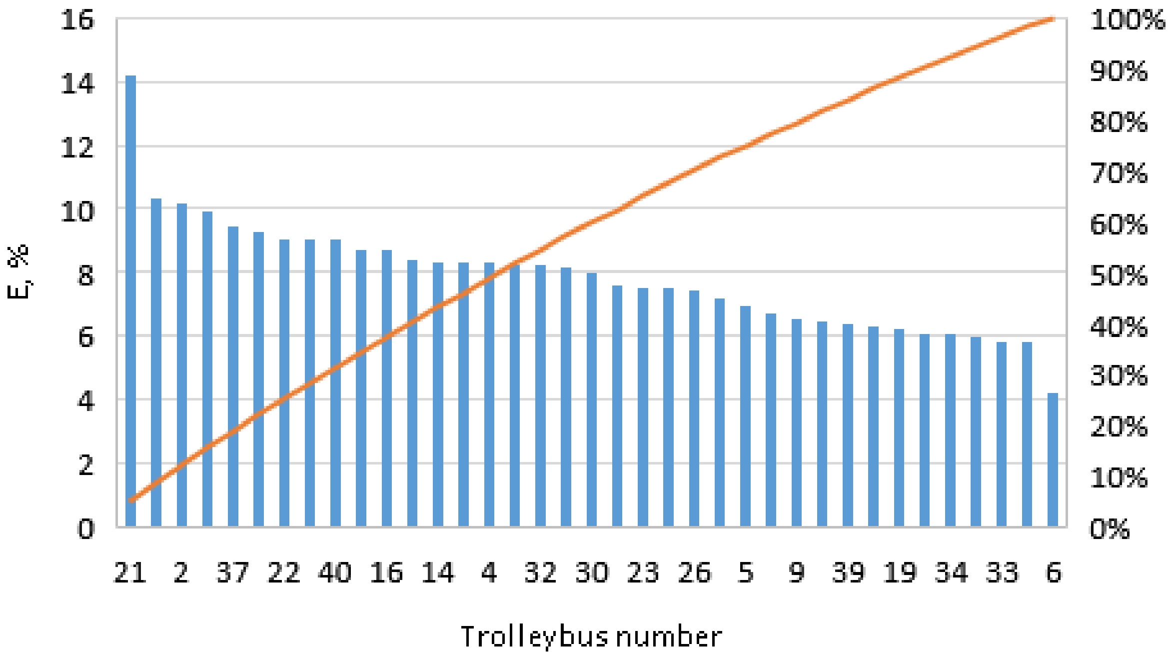

Figure 5 – Pareto diagram of the difference between the amount of electric energy recovered by the traction motor and the amount of electric energy consumed for further movement of the trolleybus

DISCUSSION OF THE RESULTS OF THE STUDY

As a result of the studies, it was found that when a trolleybus is moving along the established routes in Vinnytsia, the amount of electricity recovered by the traction motor of the vehicle ranges from 15 to 25 % of the electricity consumed by the electric drive.

The total amount of recovered electric energy that is sent to the contact network, i.e., actually spent on trolleybus movement, ranges from 2 to 15%.

Thus, the difference between the amount of electrical energy recovered by the traction motor of the vehicle and the total amount of recovered electrical energy sent to the contact network is 6...14 %.

The Pareto diagram shows that only 20 % of the rolling stock provides the maximum use of recovered energy, while the amount of electricity that is reused ranges from 9 to 14 %.

The study also obtained data on electricity consumption by trolleybuses during one day (Table 4).

Table 4 – Electricity consumption by Bogdan T70110 trolleybuses per day

Trolleybus number	Mileage. km	Energy consumed by the traction drive. kWh	Amount of recovered energy. kWh	Total amount of consumed energy. kWh	Total amount of recovered energy. kWh
3	132.95	131.89	20.84	149.73	19.41
4	88.33	97.54	21.59	121.02	20.73
11	58.83	67.45	13.74	80.34	12.94
15	61.92	55.25	8.29	65.38	8.04
16	59.08	71.98	14.21	82.37	13.56
16	58.74	74.34	16.22	85.60	15.45
21	103.35	115.73	9.61	69.90	1.24
22	63.36	51.07	6.88	69.15	7.17
27	95.25	106.78	22.90	129.95	22.34
28	83.52	80.29	10.10	90.99	9.78
29	61.74	63.79	12.52	76.42	11.86
30	103.59	114.21	20.48	139.02	20.26
34	61.84	56.68	5.26	66.39	5.19
34	62.02	57.55	4.97	67.29	5.04
35	59.51	60.67	11.74	199.66	5.32
39	125.06	152.73	15.02	171.86	14.04
40	124.70	131.08	26.22	156.62	25.73
40	47.48	49.56	10.31	63.31	10.21
13	49.67	59.12	16.04	71.09	15.08
37	63.39	62.70	11.41	74.83	11.23
5	62.73	67.39	7.73	76.13	7.44
19	108.69	116.96	17.11	136.05	17.55
25	135.78	138.56	9.19	161.56	8.86
2	65.76	81.06	13.02	92.68	11.55
32	61.66	66.24	10.87	75.93	10.24
6	67.15	84.88	10.42	96.53	9.75
26	109.94	107.42	16.24	133.21	16.46
36	100.15	130.97	21.07	149.03	19.96
14	125.15	127.97	24.03	145.14	23.42

Table 4 does not include trolleybuses that did not perform transportation work on the route.

According to the obtained daily electricity consumption, similar calculations of specific and percentage indicators were made. The results of the calculations are shown in Table 5 and Figures 6, 7, 8, 9.

Table 5 - Electricity consumption by Bogdan T70110 trolleybuses based on daily runs

Trolleybus number	Specific energy consumed by the traction drive. kWh/km	Specific amount of recovered energy. kWh/km	Total specific energy consumption. kWh/km	Total specific amount of recovered energy. kWh/km	% of recovered energy	% of the total amount of recovered energy	The difference
2	1.23	0.20	1.41	0.18	16	12	4
3	2.01	0.32	2.28	0.30	16	13	3
4	1.48	0.33	1.84	0.32	22	17	5
5	1.02	0.12	1.16	0.11	11	10	2
6	1.29	0.16	1.47	0.15	12	10	2
11	1.03	0.21	1.22	0.20	20	16	4
13	0.90	0.24	1.08	0.23	27	21	6
14	1.95	0.37	2.21	0.36	19	16	3
15	0.84	0.13	0.99	0.12	15	12	3
16	1.09	0.22	1.25	0.21	20	16	3
17	1.13	0.25	1.30	0.23	22	18	4
18	0.88	0.08	1.02	0.08	9	7	1
19	1.78	0.26	2.07	0.27	15	13	2
21	1.76	0.15	1.06	0.02	8	2	7
22	0.78	0.10	1.05	0.11	13	10	3
25	2.11	0.14	2.46	0.13	7	5	1
26	1.63	0.25	2.03	0.25	15	12	3
27	1.62	0.35	1.98	0.34	21	17	4
28	1.22	0.15	1.38	0.15	13	11	2
29	0.97	0.19	1.16	0.18	20	16	4
30	1.74	0.31	2.11	0.31	18	15	3
32	1.01	0.17	1.15	0.16	16	13	3
34	0.86	0.08	1.01	0.08	9	8	1
35	0.92	0.18	3.04	0.08	19	3	17
36	1.99	0.32	2.27	0.30	16	13	3
37	0.95	0.17	1.14	0.17	18	15	3
38	1.99	0.40	2.38	0.39	20	16	4
39	2.32	0.23	2.61	0.21	10	8	2
40	0.75	0.16	0.96	0.16	21	16	5

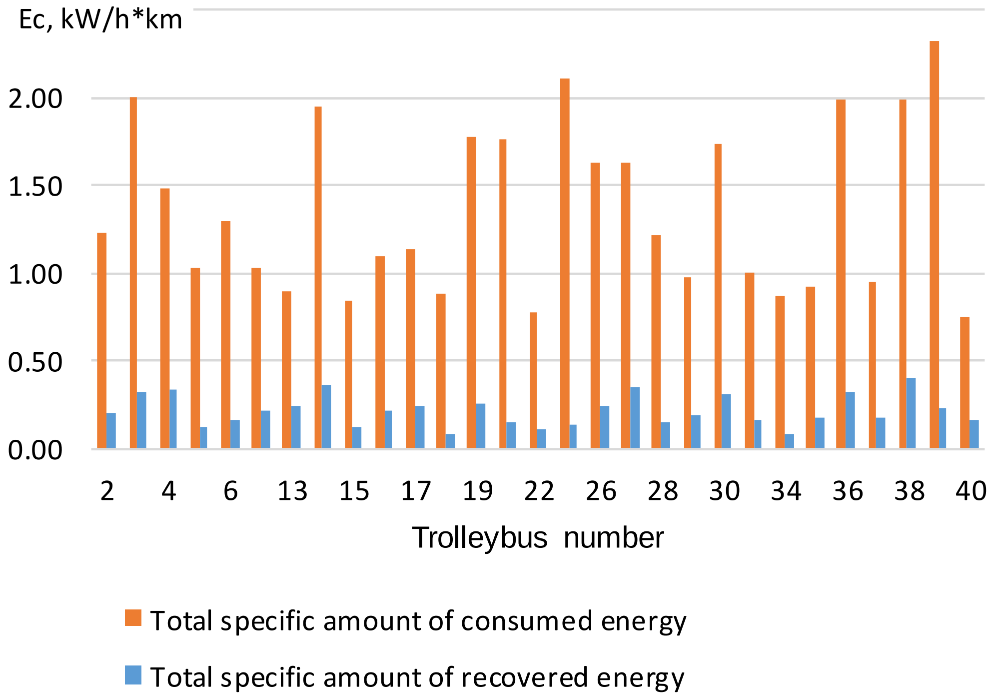

Figure 6 – The total amount of electricity consumed and recovered is reduced to specific indicators

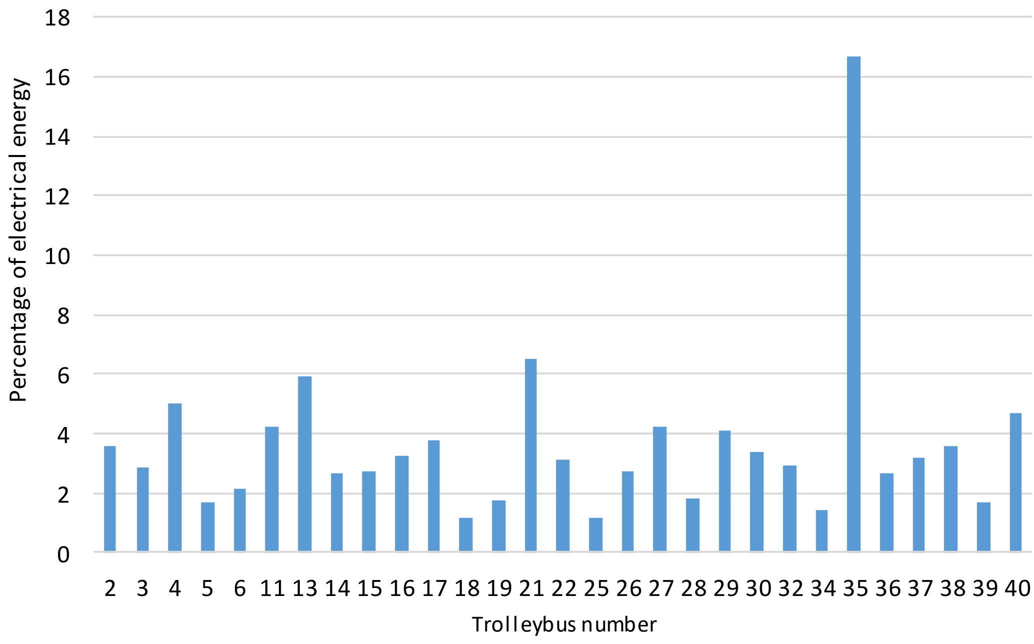

Figure 7 – The difference between the amount of electric energy recovered by the traction motor and the amount of electric energy consumed for further movement of the trolleybus

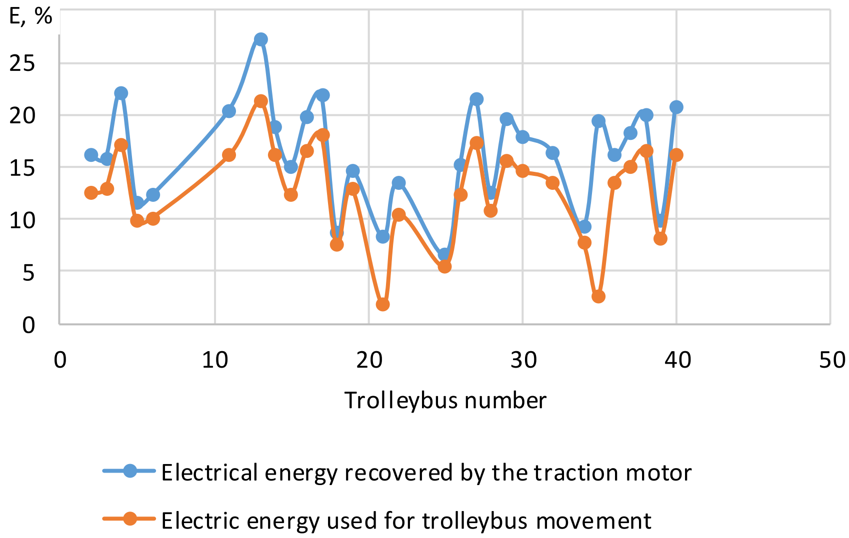

Figure 8 – Graphs of the amount of electric energy recovered by the traction motor and the amount of electric energy consumed for further movement of the trolleybus

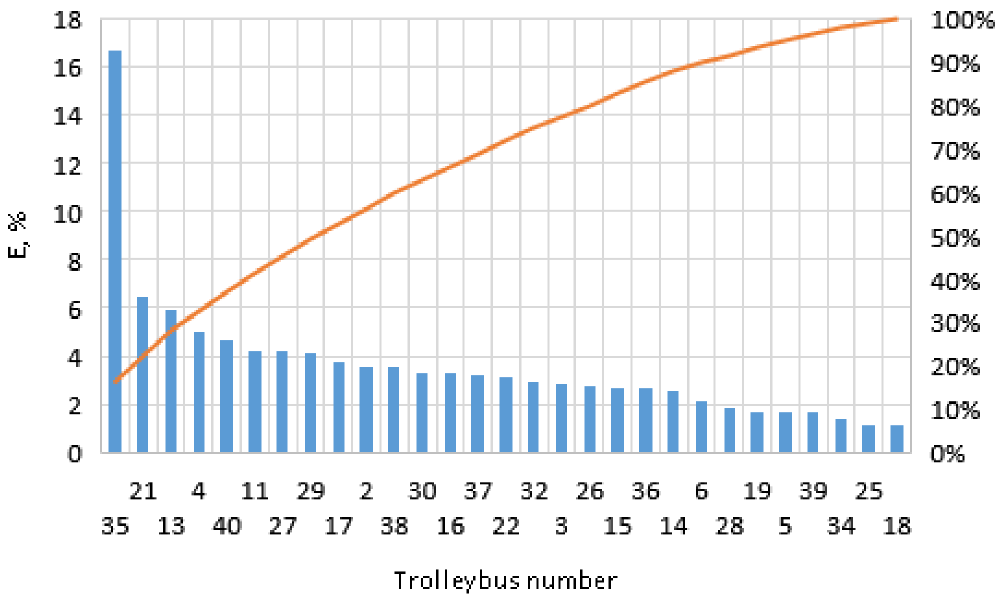

Figure 9 – Pareto diagram of the difference between the amount of electric energy recovered by the traction motor and the amount of electric energy consumed for further movement of the trolleybus

SUMMARY

As a result of the calculations on the daily values of electric energy consumption, it was found that during the movement of the trolleybus on the established routes in Vinnytsia

- the amount of electric energy recovered by the traction motor of the vehicle ranges from 7 to 27 % of the electric energy consumed by the electric drive;
- the total amount of recovered electric energy sent to the contact network, i.e. actually spent on trolleybus movement, ranges from 2 to 21 %;
- the difference between the amount of electric energy recovered by the traction motor of the vehicle and the total amount of recovered electric energy sent to the contact network is 1...16 %.

After comparing the data on electricity consumption collected from the beginning of trolleybus operation and during the day, it was found that the difference in electricity consumption is (see also Figure 10):

- specific energy consumed by the traction drive is up to 19 %;
- specific amount of recovered energy up to 5 %;
- total specific energy consumption of 3 %.

- total specific energy recovered up to 5 %.

Thus, the results of the studies indicate a discrepancy between the indicators obtained from the beginning of trolleybus operation and those obtained from the daily mileage data of up to 20 %. Such a deviation can be considered acceptable, given the stochastic nature of the processes caused by the influence of a significant number of external factors [15], such as the duration of heating systems in winter and air conditioning in summer.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

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