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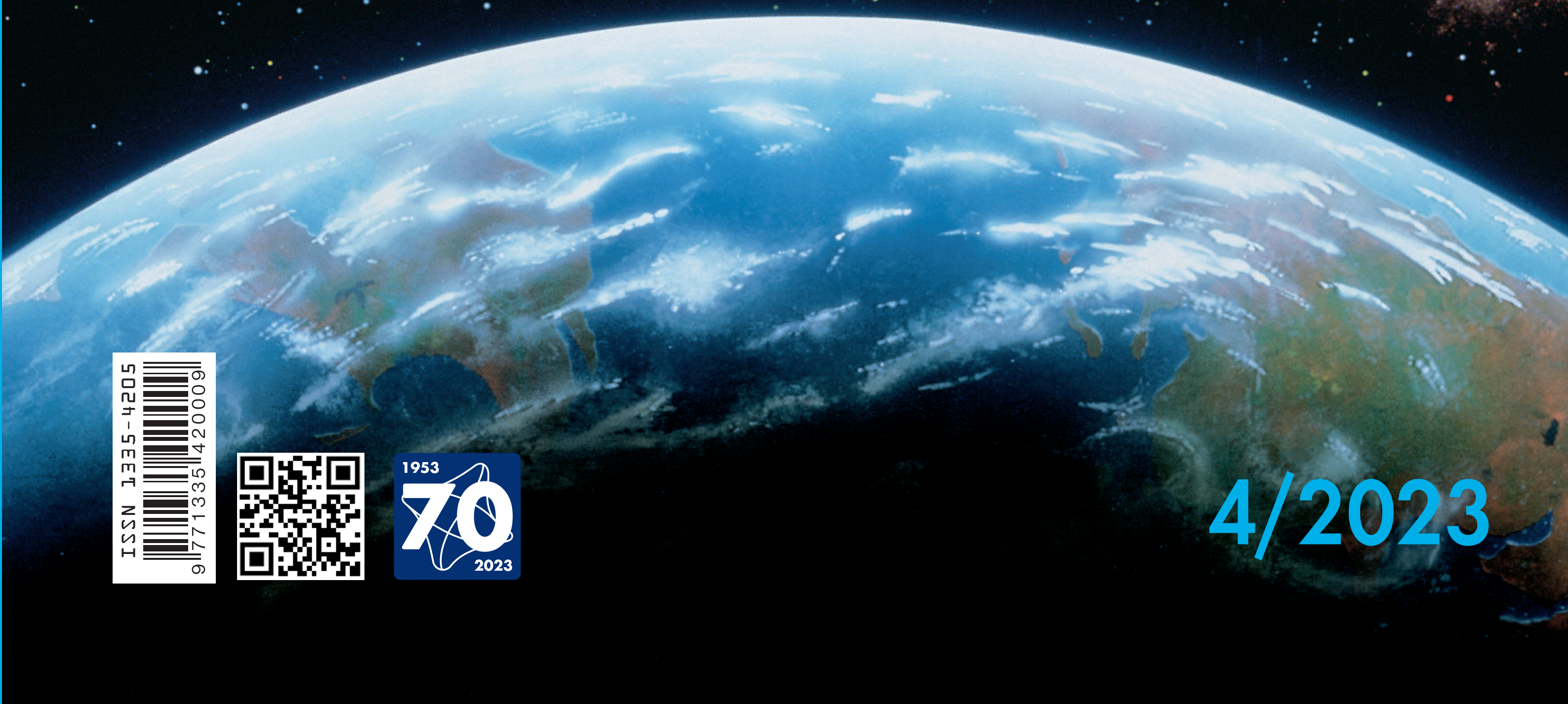

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SOLUTION TO THE CHICKEN-EGG DILEMMA OF ELECTRIC MOBILITY FOR INDIAN CITIES: A ROADMAP TO CLEAN ENERGY

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Resume

Since the electrical vehicles (EVs) are infrastructure-dependent technology, their penetration faces the problem of lacking recharging infrastructure. Thus, there is a dilemma of chicken-egg in the penetration of EVs and their charging infrastructure for the decision-makers. The article examines the e-mobility scenario of 3 Indian cities to understand issues and challenges in implementing EVs. The study suggests a co-diffusion strategy for the EVs and charging infrastructure. Firstly, the priority EV segment has been decided based on the transport mode preference. Then, suitability of charging facilities according to the segment of the EVs has been presented by analyzing the turnover rate and time spent at several places. The study recommends policies on the upfront cost of EVs, charging infrastructure, awareness generation and others, while leveraging the existing government schemes like Atmanirbhar Bharat and FAME-II.

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1 Introduction

Historically, efforts have been made to introduce electric mobility, which is successful only in some niche markets. However, over the last decade, a collection of circumstances like climate change, advances in renewable energy, rapid urbanization, the digital revolution, advances in battery technology and energy security have joined together to create an opening for electric mobility to enter into the mass market [1]. E-mobility is a cleaner mobility option to improve air quality by reducing carbon emissions and minimizing dependency on fossil fuels. In short, they are improving the quality of life locally. A comparison of life cycle greenhouse gas (GHG) emissions by internal combustion engine vehicles (ICEV) and electric vehicles (EV) shows that the EVs have a huge potential of reducing emissions [2]. The maximum air pollution takes place during the use phase of a vehicle. Though, in the case of EVs, the pollution is due to upstream emissions, which usually occur far from the place where vehicles are being used. Pollution caused due to manufacturing and recycling process is also away from the city. Since the tailpipe emission of an EV is zero [3], the impact of EVs in cities is zero. The pollutants released during the life cycle emission of vehicles can be trapped. Then, the carbon dioxide can be separated and transported for storage, which can be used for many purposes. This process of trapping the CO_2 is called carbon capture. In the case of fossil fuel vehicles, emissions occur in dispersed form and carbon capturing from vehicles is pretty impossible as even if the emissions are trapped, storing them in the vehicle and transporting them to the processing plant is way out of the league. In the EVs, these dispersed emissions are shifted to a concentrated emission source (electricity generation plants), from where the capturing can be done, thus increasing the efficiency of the process. Once captured, concentrated CO_2 can be transported to places where it can be used as an input-for example, cured in concrete or as a feedstock to make synthetic jet fuel-or simply stored underground [4]. During the "Janta Curfew" in India, amidst COVID-19, which was imposed on 22nd March 2020, leading to reduction in the number of on-road vehicles, resulting in a reduction of nitrogen oxide levels up to 51% and carbon dioxide levels up to 32%, as compared to 21st March [5]. However, experts say that these reduced emission levels are temporary due to lockdown. This saving in GHG emissions could be made permanent if vehicles on roads convert to EVs.

There is a need to increase the market share of EVs to decrease the emission of GHGs from the transportation segment. However, since EVs are infrastructure-dependent technology, their penetration faces a lack of recharging infrastructure [6]. There is a dilemma of whether to install charging infrastructure before deploying enough EVs or reverse. This dilemma is named the chicken-egg dilemma. In this paper, an attempt has been made to address this problem. The objectives of this study were (1) to determine obstacles to penetration of e-mobility from the literature review, (2) to identify the issues and challenges in e-mobility in Indian cities, (3) to plan a strategy for the diffusion of EVs and charging infrastructure in the Indian market, (4) to suggest policies that can address the barriers in the implementation of the e-mobility.

To solve this dilemma, a co-diffusion strategy has been suggested by this study for Indian cities, which suggests the deployment of EVs as per the preference of a mode of travel in a city. Meanwhile, the target for installing charging infrastructure is set as per the deployment strategy of EVs in a city. In addition, an approach has been made to understand the current e-mobility scenario of the Indian cities and identify issues and challenges. For this, three cities, viz Lucknow, Indore and Mumbai, that have got subsidies under the FAME-I scheme were visited and interviews of drivers of EVs and operators of charging infrastructure have been conducted.

The paper is structured as follows. Section 2 briefly describes the study methodology. In Section 3, a literature review of the obstacles to adopting electric vehicles worldwide is discussed. Section 4 describes the e-mobility scenario in India and reflects on the issues and challenges in the Indian cities. Section 5 gives a strategy for co-diffusion of EVs and charging infrastructure. Lastly, Section 6 concludes with policy recommendations for a way forward.

2 Study methodology

In the present study, at first, a detailed literature review has been conducted to understand the barriers to e-mobility adoption. According to which, major barriers to e-mobility include lack of charging infrastructure, interoperability issues, etc. In addition, existing scenario of e-mobility in India is studied, after which, 3 cities, i.e. Mumbai, Lucknow and Indore are finalised for case study. For all the three short listed cities e-mobility scenario in terms of infrastructure availability, fleet size, usage of infrastructure, vehicle category, etc. is studied in detail, after which strategies for co-diffusion of EVs and charging infrastructure is developed. At the end, the study is concluded with suggestions of policy measures, which can be integrated with existing schemes and initiative by government of India.

3 Literature review

Through an extensive literature review, several factors have been identified that act as barriers to e-mobility adoption worldwide. Among these, charging related issues and, in general, shortage of charging points appear to be the major barrier that need to be addressed to increase the adoption of EVs [7-11]. There is a limited availability of EV charging stations for journey within the city in some cities, but what if a trip was planned to a suburban area and then there would be lack of charging stations. Insufficient charging infrastructure creates charging point anxiety in the EV users, i.e., fear of not finding a charging point when needed. This anxiety is increased by lack of standardization of charging infrastructure, as there is fear of not finding the charger type compatible with the EV [12]. Apart from infrastructural barriers, the EVs have many downsides due to wide changes in their characteristics compared to conventional fossil fuel vehicles. The introduction of EVs in the transport fleet requires a wide change in the mindset of the consumers. There lies negative perception in the minds of consumers regarding EVs due to their high upfront cost, the shortrange of travel, long charging time, low top speed and uncertainty of new technology [13].

The major argument regarding e-mobility is spinning around the chicken-egg problem worldwide, that what should be deployed first? The charging infrastructure and eco-system for EVs or the EVs themselves [6]. Every alternate fuel vehicle (AFV) faces an obstacle of the lack of refuelling facility during an initial market diffusion. There is a vicious circle for EVs; if vehicles' sale is small, it leads to a disadvantage as saving in costs due to large production cannot be achieved. In addition, potential firms would not invest in recharging infrastructure. Therefore, due to the unclear growth scenario and small EV demand, economic risks lie in EV industry [14].

4 E-mobility scenario in India

In India, the real momentum in the sale of EVs came with phase-I of a scheme entitled ,"Faster Adoption and Manufacturing of (Hybrid and) Electric vehicles" or FAME-India scheme, which was sanctioned under the National Electric Mobility Mission Plan 2020 (NEMMP). According to the Annual Report, 2018-19 by the Ministry of Heavy Industries and Public Enterprises, about 0.278 million hybrid and EVs were supported by demand incentives amounting to US$ 41.7 million (approximately). This has resulted in a total fuel saving of 45.57 million litres and a CO_2 emission reduction of 0.1136 million tonnes. In addition, 465 buses were sanctioned to various cities/states under this scheme. Overall outcomes, in terms of fuel-saving and CO_2 emission reduction, are significantly below the target for FAME phase-I. According to Electric Vehicles Sales

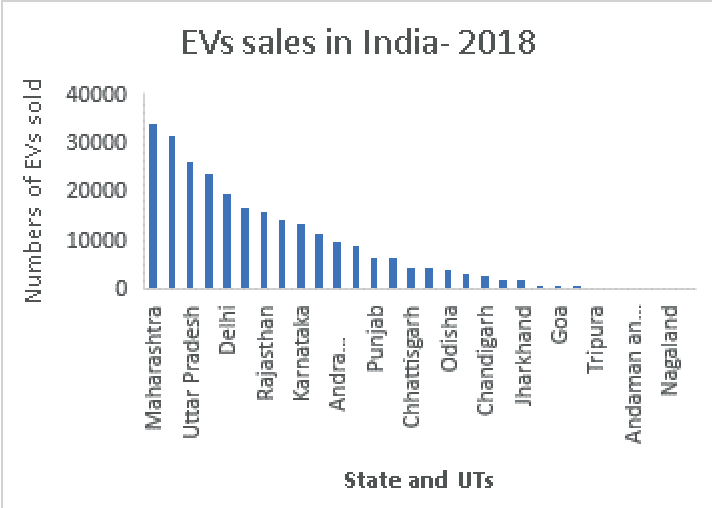

Figure 1 *State wise EVs sales in India 2018*

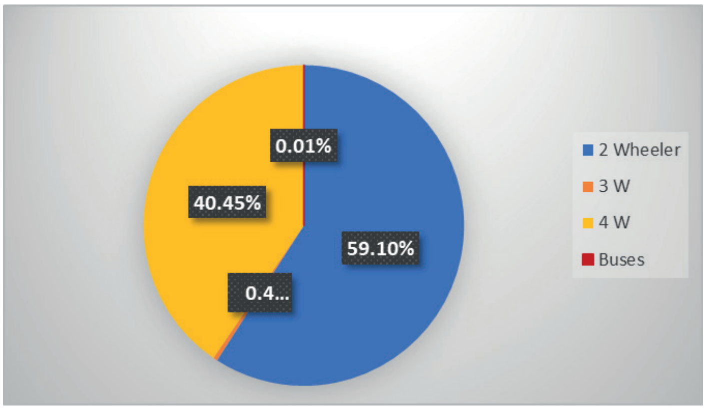

Figure 2 *Share of each type of vehicles in EV sale 2018*

Report in India 2018, Maharashtra and Gujarat stand top in the sale of EVs, whereas Meghalaya stands at the bottom, as shown in Figure 1. Further, as it can be seen from Figure 2 that the EV sales market is dominated by the two-wheelers having 59.10% of sales, followed by four-wheelers with 40.45% of sales and the least share of buses is observed. For FY2019, EV sales in India were 0.13 million which increased to 0.16 million for FY2020 [15].

In the second half of December 2017, the Central Government has provided Rs. 437 crore subsidies to 11 cities under the FAME-I scheme in India for launching 390 electric buses, 370 taxis and 720 three-wheelers. The cities include Delhi, Ahmedabad, Bangalore, Jaipur, Mumbai, Lucknow, Hyderabad, Indore and Kolkata, plus two cities - Jammu and Guwahati under a special category. The nine big cities on the list are given subsidies for 40 buses each, while Jammu and Guwahati for 15 buses each. Subsidy for taxis is given to Ahmedabad for 20 taxis, Bangalore for 100 taxis, Indore for 50 taxis and Kolkata for 200 taxis, based on their demand. Bangalore has been given subsidy for 500 three-wheelers, Indore for 200 and Ahmedabad for 20. Out of these eleven cities, three cities i.e. Lucknow, Indore and Mumbai have been visited as the case study to understand the practical setup of EVs in Indian cities. Lucknow, Indore and Mumbai were visited in November 2019, December 2019 and March 2020, respectively. The profile of these cities has been discussed in this section. As described in this section, EV drivers' and expert interview surveys have been conducted in these cities.

4.1 Profile of the cities visited

Lucknow is a city in northern India and is the capital of the state of Uttar Pradesh. The city covers an area of 349 sq. km. and has a population of 2.82 million, according to the census 2011. Since the population is greater than 1 million, the city belongs to the category of million-plus cities of **Class-I**. The city bus service in Lucknow is operated by "Lucknow City Transport Services Limited" (LCTSL). Currently, the fleet consists of 300 buses, out of which 40 are electric and the rest run on compressed natural gas (CNG). Apart from e-buses, e-rickshaws are also used in the city as a para-transit mode. The city had 17 thousand registered e-rickshaws till December 2018. The UP cabinet approved the

__Table 1__ Passenger modal share of road transport for Lucknow, Indore and Mumbai, Census 2011

Mode of travel	Modal Share (%)		
	Lucknow	Indore	Mumbai
On foot	22	26	45
Bicycle	26	26	2
2-W	34	32	8
4-W	6	5	9
Tempo/Autorickshaw/Taxi	8	3	6
Bus	4	8	30
Total	100	100	100

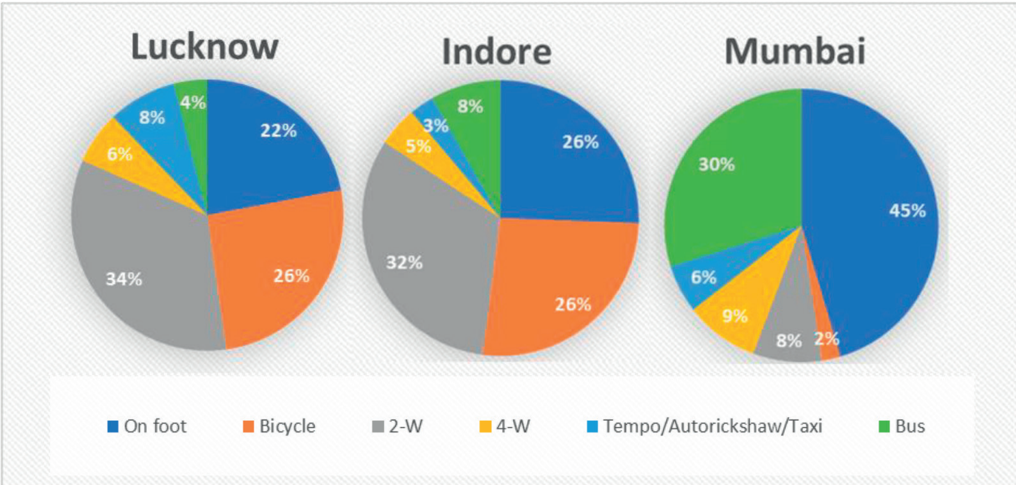

__Figure 3__ Passenger modal shares of road transport for Lucknow, Indore and Mumbai, Census 2011

scheme to distribute 27 thousand of e-rickshaws for free in Uttar Pradesh in 2015. The average trip length of the city is about 5 km.

Indore is a city in west-central India. It is a **Class-I** city in the Madhya Pradesh state of India, with a **million-plus** population. As of the census of 2011, the population of the city is 2.39 million and it covers an area of 530 sq. km. The city bus is run by "Atal Indore City Transport Services Limited" or AICTSL, which is currently operating 312 CNG buses and 40 e-buses. Along with e-buses, e-rickshaws have also been plying in the city. Under the E-Sawari project of the Madhya Pradesh government, 100 e-rickshaws driven by women were launched in Indore.

Mumbai is a densely populated city on India's west coast. The total area of Mumbai is 603.4 sq. km. As per the census of 2011, the city accommodates a population of 18.41 million. It is the biggest city in India in terms of population. Since the population is greater than 10 million, it comes under the **megacities** of **Class-I.** Most city buses in Mumbai are operated by the Brihanmumbai Electricity Supply and Transport Undertaking (BEST) and Navi Mumbai Municipal Transport (NMMT). Total number of buses under these operators are around 3,800. The fleet comprises of diesel, CNG, hybrid and electric buses.

The passenger modal share of road transport for these three cities has been shown in Table 1 and Figure 3.

In million-plus categories of Class-I cities, i.e., in Lucknow and Indore, the modal share by passengers is dominated by motorized 2-wheelers, including mopeds, scooters and motorcycles, followed by the non-motorized transport modes. In megacity Mumbai, the highest percentage is walking, followed by bus mode (30 %).

4.2 The E-bus scenario

The E-buses have been plying in all three cities. Essential parameters of e-buses have been summarized in Table 2, based on interaction with their drivers.

From Table 2 it can be observed that the range achieved on the road by e-buses is about half of the range claimed. In Lucknow, the Daily distance travelled by each driver is around 220-230 km, with one round trip length of about 70-80 km. After one round trip, the bus is kept for charging, which takes about 2-2.5 hours to get fully charged. While the first bus is charging, the driver takes another bus for the next trip and so on. Therefore,

***Table 2** E-bus parameters for Lucknow, Indore and Mumbai*

Parameter	Lucknow, LCTSL	Indore, AICTSL	Mumbai, BEST	Mumbai, NMMT
No. of buses	40	40	10	30
Model	Tata Ultra	Tata Ultra	Olectra-BYD eBuzz K7	JBM Solaris
Running from	February 2019	November 2019	September 2019	October 2019
Claimed range	150	150	200	225
Range achieved	80	80	110	120
Total daily distance (km)	150	135	80	90-100
Round trip length (km)	70-80	20-25	20-25	-
Charger type	DC fast charger	DC fast charger	AC slow charger	DC fast charger
Connector type	-	-	IEC 62196 Type 2	CCS 1.0
No. of chargers (Dual type)	12	6 (7 under construction)	10	2 (4 under construction)
Charging time (hrs)	2-2.5	2-2.5	3	1-1.5
Regenerative braking	No	No	Yes	Yes

***Figure 4** Informal charging of e- rickshaw*

each driver rides two buses in a day to complete 3 round trips. Thus, around 150 km distance is travelled by each bus daily.

In Indore, the round-trip length by e-bus is shorter compared to Lucknow. The AICTSL plans to increase the trip length after installing charging stations in the middle of the routes for opportunity charging.

In Mumbai, ten buses were procured by BEST and 30 by NMMT. The buses procured by both the state transport undertakings (STUs) have the feature of regenerative braking, i.e., in these buses, electrical energy is stored every time the brake is applied. Though regenerative breaking is there, the total daily distance covered by e-buses in Mumbai is less than in Lucknow and Indore.

For charging these buses, most of the STUs were using fast chargers, except for BEST in Mumbai, where both plugs of a charger were inserted at the same time in a bus for charging, reducing the total time taken by the slow charger and making it equivalent to the time taken by fast chargers. The adverse effects of fast charging on a battery can be avoided by using the slow chargers.

4.3 E-rickshaw scenario

E-rickshaws have been plying on Lucknow and Indore roads as para-transit mode. Lucknow city had 17 thousand registered e-rickshaws till December 2018. The UP cabinet approved the scheme to distribute 27 thousand of e-rickshaws for free in Uttar Pradesh in 2015. As per the guidelines, e-rickshaws are given the permit to operate only on feeder routes and within a colony. They are supposed to connect an arterial route with the main road and not ply on main roads as a measure to provide last-mile connectivity. Therefore, e-rickshaws were banned on many routes by the transport department and traffic police joint exercise. Some informal charging of rickshaws was observed during the survey, as shown in Figure 4.

Under the E-Sawari project of the Madhya Pradesh government, 100 e-rickshaws were launched in Indore by the CM on 7th December 2019, as shown in Figure 5. The Government gives a subsidy of 50 % of the initial cost of the rickshaw and the rest is to be paid in instalments by the drivers themselves. Females operated these

Figure 5 *E-rickshaws for women in Indore, source: AICTSL*

Figure 6 *Informal E-rickshaws stand near Rajwada, Indore*

Table 3 *E-rickshaw parameters for Lucknow and Indore*

Parameter	Lucknow	Indore
Running from	More than five years	Five years
Initial cost (in thousand US$)	1.4-2.1	1.4-2.7
Range achieved	60-80	70-90
Total daily distance (km)	70-100	70-100
Charging location	Home and depot	Home
Charging time (hrs)	2-12 (depending upon model)	2-6 (depending upon model)
No. of times charged	Half once a day and full at night	Half once a day and full at night
Driven by	Men	Both men and women
Average driving speed (km/h)	18-20	20-25
Top driving speed (km/h)	25-30	30-40

rickshaws. The rickshaws had a facility for digital payment, GPS tracking (by Chalo), radio-FM (sponsored by My FM) and free Wi-Fi sponsored by Jio.

There was no dedicated parking space for e-rickshaws in the city and the E-rickshaw sharing system was there, so vehicles had to wait on roads to collect passengers, as shown in Figure 6. Due to this, the roads were getting jammed and there was a restriction on many roads to park the rickshaws. Drivers sometimes face a shortage of charging in the middle of a trip. In this case, drivers had to drag the vehicle to the charging location.

Important parameters of e-rickshaws for Lucknow and Indore have been summarized in Table 3.

Not much difference is observed in the parameters of e-rickshaw between the two cities. The initial costs of an e-rickshaw were higher in Indore. In addition, e-rickshaws in Indore were better in terms of range achieved, charging time and top speed. This implies that the model of e-rickshaws was better in Indore than in Lucknow.

4.4 Charging points for personal vehicles

4.4.1 Workplace charging at Indore

The Government had also provided 16 electric cars to their employees at smart city cell until December 2019 and planned to provide 50 more cars. The model is Tata

Figure 7 *E-cars charging station at Smart City Cell, Indore*

Figure 8 *Different EV charging points at Vikhroli sub-station*

Tigor EV, claiming a range of 142 km per charge. Seven slow chargers and four fast chargers were installed within the Smart City Cell, Nehru Park, Indore. The employees had started using e-cars. The daily travel distance is about 40-60 km. They usually charge the cars at the office during day time, as shown in Figure 7 and at home during the night time if required. They get a travel range of about 100 km. It takes 4-6 hours for slow chargers and 2-3 hours for fast chargers to fully charge the car.

4.4.2 Tata Power Co. Ltd., car charging point, Mumbai

Tata Power established its first public EV charging station in Mumbai at Firoz shah nagar, Vikhroli having diverse charging standards and specifications. These chargers have been used free of cost for about two years. Its working has been kept on halt for a few weeks as the company was developing a payment method now for charging their EVs. The company has also developed a Tata Power EV Charging mobile app. It provides EV users with the facilities like locating charging stations on an aerial map, reserving a charging slot, getting updates on charging, recommendations on suitable time of day to use and paying charges online.

Since there were many types of chargers and connectors, as shown in Figures 8 and 9, it provides an opportunity for many EV owners to meet the standard for their vehicles. Still, there might be a situation where one type of charger is in very much demand and others might remain idle for a long time.

4.4.3 Magenta Power charging point, Mumbai

Magenta Power is in the business of providing green energy solutions. Its business unit, ChargeGrid, was setup to focus solely on providing the EV eco-system services based on the user's demand. The office was located near Alpha Garden, Sector-14, Kopar Khairane, Mumbai. Three slow charging points were installed outside the office. The chargers were mounted on the wall, as shown in Figure 10, having IEC (refer to Figure 11) and domestic connector types. About 5-6 EVs arrive in a day for charging, including cars and scooters. The vehicles were charged for about 4 hours. The payment was made via the app "ChargeGrid". The rate was Rs. 30 per unit. With the help of this app, the users can search the nearby charging stations and get the real-time availability of chargers before reaching the charging point.

Figure 9 *Different types of connectors at Vikhroli sub-station*

Figure 10 *Charging Station at Magenta Power office, Navi Mumbai*

Figure 11 *IEC 60309 connector*

Figure 12 *Personal charging point in a housing society*

A private charging point has been installed in a housing society in Vashi, Navi Mumbai, by Magenta Power, for a resident owning an EV, as shown in Figure 12. It has provided a charging point facility at Turbhe, Palava and other places in Mumbai on demand. Magenta Power has also setup fast chargers at Mumbai-Pune Expressway and is working on other such projects. The cost of a fast-charging point is very high compared to a slow charger. The huge difference is that the setup of a slow charger is small and can be mounted on a wall. In contrast, fast charger has a large setup, similar to or bigger than the size of a petrol pump setup and also because a proper foundation is required. In addition, the material, cables, connector, etc., in the case of fast charger, is expensive as it requires more power.

4.4.4. BEST car charging station, Mumbai

To support the Government's clean energy initiative, BEST has set up a fast charger for charging the car and other vehicles at Worli Shivaji Nagar bus depot, as shown in Figure 13. The connector has Bharat DC-001 standard (refer to Figure 14). The depot has a single charger with one charging plug; therefore, one vehicle can be charged at a time. It has been working for one year. The station receives hardly one or two vehicles for charging in four to five days. It takes 1.5 to 2 hours to charge a vehicle for up to 80%. The money charged is around US$ 0.10 (₹8.28 ~ US$ 0.10)per unit (refer to Figure 15). The payment was being accepted in cash only and there was no separate app for this. Since the

Figure 13 *Electric car charging point, Worli, Mumbai*

Figure 14 *Bharat DC-001 connector*

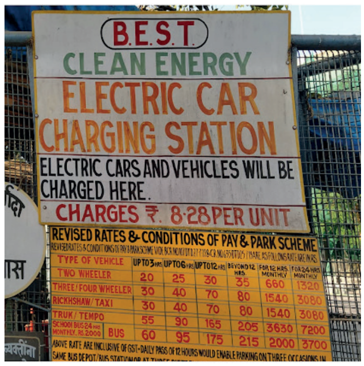

Figure 15 *EV charging fare*

frequency of vehicles coming for charging was very low, the charging station was left unattended.

4.5 Issues and challenges in the way of e-mobility in Indian cities

The Indian EV market requires a big change in its e-mobility eco-system, specifically in the case of manufacturing. Currently, most EV manufacturing companies rely on imports of major components like batteries and electric drivetrains from other countries (China, South Korea and Japan). In contradiction, if one looks at the ICE automobile industry, the major boost came through domestic manufacturing [16]. Even if the EV industry thinks about importing only raw materials from other resourceful countries and producing the components and battery packs in India, the shortage of talented workforce with experience in this field may be a roadblock [17].

From the e-mobility scenario of Indian cities it is observed that there is a wide gap between the claimed range by e-buses and the range accomplished. The assured range of buses was around 150-225 km, however, the range achieved was around 80-150 km only, equal to the range of e-rickshaws in the city. One of the reasons is heterogeneous traffic conditions in the city, which lead to congestion and the charge in the battery is exploited. Another reason could be the overloading of buses and frequent opening and closing of doors.

The EV owners sometimes come across a situation when there is a shortage of charge in the battery. Though charging points are installed at bus depots for e-buses and homes and workplaces for private vehicles, there is still a need for opportunity charging to use for a top-up charging. In Mumbai, there are some charging stations at a centralized location, however, the network is not dense enough to avoid the dead mileage. In addition, due to the very low frequency of consumers, the charging stations in Mumbai were often left unattended. Due to that, the EV users cannot get service even if a charging station is there.

Too many charging points were noticed, which might raise standardization issues for opportunity charging facilities in the future. In addition, the private charging points have developed their separate online platforms like a website and mobile navigation application, checking the availability of charging points, billing and payment. 80 % of the charging is done by fixed charging facilities at home and office. By using an opportunity charging facility once in a while, the EV users would not want to explore so many platforms, which might raise interoperability issues in the future.

5 Market diffusion strategy for electric vehicles and charging infrastructure

To tackle the chicken egg's dilemma in e-mobility, a co-diffusion strategy for EVs and charging infrastructure has been planned for Indian cities in this section. Firstly, the class-I cities have been classified based on the population into seven categories. Then, city-wise transport mode preference has been computed, which would help decide incentives for the type of vehicles in a city. The charging infrastructure

Table 4 City Categorisation [18]

City Category	Population
Category-1a	< 0.5 million with plain terrain
Category-1b	< 0.5 million with hilly terrain
Category-2	0.5-1 million
Category-3	1-2 million
Category-4	2-4 million
Category-5	4-8 million
Category-6	> 8 million

Table 5 Estimated mode share for selected cities for 2021

City Category	NMT	PT	2-W	Car	IPT	Avgerage trip length (km)
Category-1a	31	3	30	31	6	2.4
Category-1b	48	5	8	39	0	2.5
Category-2	43	6	31	16	4	3.5
Category-3	38	10	28	14	9	4.7
Category-4	41	8	31	13	7	5.7
Category-5	34	15	31	12	8	7.2
Category-6	29	31	14	15	11	10.4

NMT- Non-motorised transport,
PT- Public transport, buses
IPT- Intermediate public transport, auto-rickshaws

Table 6 Transport mode preference as per city size

City Category	Public transport (Buses, auto-rickshaws, cabs)		Personal transport (2-Ws, cars)	
	Share %	Preference	Share %	Preference
Category-1a	9	● (secondary)	60	● (primary)
Category-1b	5	● (secondary)	47	● (primary)
Category-2	10	● (secondary)	47	● (primary)
Category-3	19	● (primary)	43	● (secondary)
Category-4	15	● (primary)	44	● (secondary)
Category-5	23	● (primary)	43	● (secondary)
Category-6	42	● (primary)	29	● (secondary)

● Primary preference
● Secondary preference

requirement has been discussed, including the type of charging infrastructure and classification of the charging facility according to the land use. Then, the suitability of the charging facility according to different types of EVs and city categories has been presented by analyzing the turnover rate of different vehicles and time spent at several places.

5.1 City classification and their transport characteristics

The classification of cities with a population of 0.5 million to 8 million, as used in the "Final Report" by the Ministry of Urban Development, has been shown in Table 4.

Above is the classification of cities under the Class-I category, as per the Urban and Regional Development Plan Formulation and Implementation (URDPFI) Guidelines, 2015 [27]. The same classification has been used for the present study. Critical issues, like increasing GHG emission levels and deteriorating air quality, are associated with these cities only due to higher share of motorized transport. On the other hand, the smaller cities have higher share of non-motorized transport and, hence, have lesser issues of increasing emission levels and air pollution.

The passenger modal share data and average trip lengths for the above categories of cities for 2021 have also been retrieved from the report published by the Ministry of Urban Development. It is shown in Table 5.

By observing the share of motorized transport,

***Table 7** Time taken by different EVs to get charged, [20-23]*

Type of EV	Battery capacity (kWh) (approx.)	Time is taken by	
		Slow charger (in hrs)	Fast charger (in hrs)
2-W: Scooter	2.4	6-10	2.5-4
2-W: Motorcycle	3.24	4.5-6	0-80% in 36 mins. to 1.5 hrs.
3-W	4.5	6-7	1-2
4-W	12-40	6-10	0-80% in 1-2 hrs
Bus	320	7-8	2-3

***Table 8** Time spent at different locations*

Location	Less than 1 hr	1-2 hrs	2-5 hrs	5-10 hrs
Home	→	→	→	→
Workplace	→	→	→	→
Cafes	→	→		
Recreational Sports	→	→	→	
Restaurants	→	→		
Malls	→	→	→	
Theatre	→	→	→	
Visiting folks and acquaintances*				
Gym	→	→		

*uncertain

it can be seen that 2-wheelers and cars dominate the choice of mode for commuting by people in cities under Category-1a, while in Category-6 cities the leading choice of mode is public transport. As the trip length of the city increases, the choice of commuting by public transport and para-transit mode is also increasing.

The share for public and personal transport modes is computed by combining IPT and PT under 'Public transport' and 2-W and cars under 'Personal transport.' The transport mode for a city with a preference above or equal to 50 percentiles is marked as "●" and with below 50 percentiles is marked as "●" as presented in Table 6.

The primary preference for personal transport, i.e., electric 2-W and cars, has been set for 1a, 1b and 2 categories of cities, which lies in the top 50% category of cities with 2-W and cars as the mode share. Primary preference for public transport, i.e., electric buses and para-transit modes, has been set for category-3, 4, 5 and 6 cities which lie in the top 50% category with public transport as modal share. This analysis of mode preferences will guide policy-making for the penetration of EVs in different types of cities.

5.2 Requirements for the charging infrastructure

An EV charger, also called Electric Vehicle Supply Equipment (EVSE), is an element in EV infrastructure that supplies electric energy for recharging electric vehicles. The EV batteries require the DC power to get charged and the power flowing in an electric distribution grid is AC type. Therefore, it is always necessary to have an AC/DC converter (or charger). If the converter is placed in the vehicle, it is called an "on-board charger," and if it is placed in the charging point, it is called an "off-board charger" [19]. In the case of an on-board charger costs of the charging station would be lower and for an off-board charger cost of the vehicle would be reduced.

5.2.1 Classification of charging point facility according to location

Every mode of EV requires its place for charging. In most situations, an EV user can set their vehicle in charging while eating, playing, working, or sleeping at places like home, offices, restaurants, malls and gyms. While in some situations, the EV has to be charged in areas where there is no option of stalling time, like roadside charging at a highway or a petrol pump. To find the suitable charging locations for each transport mode, it was firstly identified how much time is taken to charge these vehicles and then it was determined how much time is spent at different places. Then, the classification of the charging facilities based on their locations and the charging facility's requirement for each vehicle category, have been recommended.

Time taken by different electric vehicles to get charged by slow and fast chargers is shown in Table 7.

It is observed that slow charging takes about 5-10 hours and fast charging takes around 1-4 hours. The time depends on the battery capacity and electric vehicle supply equipment (EVSE), which controls the flow of charge between the charging station and the electric vehicle.

In Table 8 is demonstrated how much time is usually spent at different locations by people.

From the above places, people generally spend their time at home daily, at workplace 5-7 days a week, at gym 3-6 days a week, at rest of the places once a week or twice a month, it can be more or less dependent on the person.

During the case study, charging points were found at various places. Based on location, the charging point facilities for EVs have been classified as follows. Seeing the time required by an EV to get charged (as per Table 7) and time spent at different places (refer to Table 8), the type of EV charger suitable for that place has been suggested.

I. Domestic charging facility

It includes a charging point at the residence, where the vehicle is parked. It is for personal use only unless an acquaintance who owns an EV wants to use it. Generally, the time spent at home is between 5-10 hours a day. Therefore, slow chargers would be suitable for domestic use.

II. Workplace charging facility

It means charging points installed at work, such as those installed at Smart City Cell, Indore (shown in Figure 7); considering the usual office hour from 9 am to 5 pm, i.e. 8 hours. This time is sufficient to charge a vehicle with a slow charger. However, it might not be possible to provide individual charging points for every employee owing EV at the office. Therefore, slow or fast charging points would be preferable at the workplace.

III. Common charging facility

It denotes the charging stations at the parking zone of recreational spots like malls, cafes and restaurants, theatres, gyms, sports clubs and resorts. These places will be more suitable for personal EVs than e-cabs or e-rickshaws. For example, an owner of the cafe would want only his customers to charge their vehicles and not a line of e-rickshaws outside his cafe. Generally, the time spent at these places lies between 1 and 5 hours. For places where the time spent is 1-2 hours, a fast charger is suitable and where time spent is around 2-5 hours, both a fast charger and slow chargers are preferable.

IV. Public charging facility

Charging stations at administration properties like railway stations, forts, zoos and public civic centres comes under this category. Time spent at these places is generally 1-5 hours. So, both slow and fast charging points would be suitable here.

V. Depot charging facility

Charging points at a place where vehicles are kept overnight come under this facility. It includes mainly bus depots and spaces where multiple e-rickshaws or e-cabs are left. The vehicles are generally stationed idle at depots for 5-8 hours at night. In addition, it is required to charge a vehicle during the daytime at these places. A charger, which will take minimum time is suitable during the daytime. Therefore, installing fast chargers at these places is suitable, considering the day charging, like in bus depots at Lucknow, Indore and Navi Mumbai, although the slow chargers can also be installed, as in the case of one of the BEST depots in Mumbai, where during the day time both the plugs of a charger are inserted in the same bus for fast charging and during the night time, both plugs of one charger are used individually, to charge two buses at a time by slow charging.

VI. Commercial charging facility

This facility includes charging stations on-road sides, along highways and expressways and at petrol pumps, for opportunity charging. Fast chargers and battery swapping stations are suitable for such facilities as the EV owners will have to wait for charging only.

5.2.2 Suitability of charging facility for different EVs

The type of charging facilities suitable for different electric vehicles and the type of chargers preferable for that charging facility have been summarised in Table 9.

Table 9 demonstrates that personal vehicles, including 2-wheelers and cars, can be charged at home, workplace, common, public and commercial. For routine charging, home and workplace charging facilities are sufficient. Rest facilities are utilized during unusual trips. The 3-wheelers and cabs can be charged daily at

Table 9 *Suitability of charging facility for different EVs*

Charging facility	2-W	Private car	3-W	Cab	Bus	Charger type
Home	🟢	🟢	🟢	🟢	🔴	Slow
Workplace	🟢	🟢	🔴	🔴	🔴	Slow, fast
Common	🟢	🟢	○	○	🔴	Fast
Public	🟢	🟢	🟢	🟢	🔴	Fast
Depot	🔴	🔴	🟢	🟢	🟢	Slow, fast
Commercial	🟢	🟢	🟢	🟢	🟢	Fast, battery swapping

🟢 Location is suitable ○ The location is partially suitable 🔴 Location not suitable home or at the depot where the vehicle is kept overnight. For these vehicles, common places, like malls and restaurants, are partially suitable in emergency because extra money would be required to park the vehicle in the mall. Depending on the route, public and commercial charging facilities can be used. For buses, the routes are fixed; therefore, the buses are charged mainly at the depot only and depending on the trip length, a dedicated opportunity charging point can be there.

5.2.3 Prioritizing charging facilities by the city category

The city-wise preference for mode of transport has been discussed in Section 5.1. As deliberated in Section 5.2.1, the charging facility should supplement the vehicle preference of the city. Therefore, with help of the transport mode preference (refer to Table 6) and suitability of charging facility for different types of EVs (refer to Table 9), priority for charging facility in a city is set, as described below and shown in Table.

- **Home charging facility:** compulsory installation of a charging point in a new or renovated building for domestic charging (already considered by the Ministry of Housing and Urban Affairs) and mandatory charging points at the place of residence of an EV owner in all the city categories.
- **Workplace charging facility:** this facility is suitable for private EVs; therefore, it should be installed in the "primary preference" cities for personal transport, according to Table 6.
- **The common charging facility is mainly suitable** for private EVs; therefore, it should be installed in cities with the "primary preference" for personal transport.
- **Public charging facility:** it is suitable for personal vehicles and para-transit modes; therefore, this facility should be provided in all city categories.
- **Depot charging facility** is suitable for buses and para-transit modes like e-rickshaws and cabs; therefore, this facility should be provided in cities with the "primary preference" for the public transport.
- **Commercial charging facility:** it is suitable for every transport mode, though this facility should be provided primarily in cities with an average trip length greater than 5 km.

As discussed before, there is a dilemma that if charging facility is installed first, whether enough vehicles would be there to use it or not. Table 10 helps in addressing the chicken-egg dilemma and in deciding where to provide charging facility according to the size of a city.

6 Conclusion and way forward

The present study aims to address major barriers in implementing e-mobility in India. To achieve this goal, several works of literature were studied to understand the global barriers to EV adoption. It was found that there is a dilemma of what should be deployed first, EVs or charging infrastructure. Globally, this dilemma is termed the chicken-egg dilemma. This study has also discussed the e-mobility scenario in India and issues and challenges for the e-mobility adoption in Indian cities have been identified.

As per the literature review, the major barriers to acceptance of the EVs are infrastructure barriers due to shortage of charging infrastructure and lack of standardization of charging infrastructure and negative perception towards EVs due to their high initial cost, the short range of travel, longer charging period, lower top speed and uncertainty for a new technology. By studying the e-mobility scenario in Indian cities, it was revealed that there is a huge gap between the range experienced by EVs and the range claimed. Drivers sometimes face a shortage of charging, in the middle of a trip. Due to the very low frequency of consumers, the charging stations were often left unattended. In addition, standardization and interoperability issues were seen. Some recommendations for a way forward have been discussed in the next section to address these barriers.

A co-diffusion strategy for the EVs and charging

Table 10 *Priority of charging facility as per city category*

Type of charging facility	City category						
	1a	1b	2	3	4	5	6
Home	● (primary)	● (primary)	● (primary)	● (primary)	● (primary)	● (primary)	● (primary)
Workplace	● (primary)	● (primary)	● (primary)	● (secondary)	● (secondary)	● (secondary)	●
Common	● (primary)	● (primary)	● (primary)	● (secondary)	● (secondary)	● (secondary)	● (secondary)
Public	● (primary)	● (primary)	● (primary)	● (primary)	● (primary)	● (primary)	● (primary)
Depot	● (secondary)	● (secondary)	● (secondary)	● (primary)	● (primary)	● (primary)	● (primary)
Commercial	● (secondary)	● (secondary)	● (secondary)	● (secondary)	● (primary)	● (primary)	● (primary)

● Primary target
● Secondary target

infrastructure as per the size of cities has been suggested in this study, which would resolve the dilemma for the decision-makers. The following section suggests some policies for the way forward that addresses the top barriers to the e-mobility adoption.

I. **City wise incentives on the upfront cost of vehicles:** Under the FAME-I scheme, from April 2015 to March 2019, a significant subsidy for private vehicles was provided and under the FAME-II scheme, which started in April 2019, the main focus is on the deployment of public vehicles. The study suggests providing incentives on the upfront cost of vehicles as per the city's primary preference of the transport mode. In cities with a higher preference for private vehicles (2-Ws, cars), subsidies should be given for private vehicles. In cities with higher share of public transport (buses, taxis, rickshaws, etc.), the incentives should be provided for public vehicles. For example, in Lucknow and Indore the modal share of private vehicles is higher than of the public vehicles. Therefore, incentives on upfront cost should be provided for 2-wheelers and cars in these cities. On the contrary, for Mumbai, subsidy for public vehicles should be provided.

II. **Manufacturing in India and developing expertise:** To bring down the upfront cost of vehicles, the primary step should be domestic manufacturing of batteries and EV components, which can get support under the "**Make in India**" initiative. By just importing the raw materials from mineral-rich regions for manufacturing batteries, India has an opportunity to save a significant amount [24]. Developing expertise in battery manufacturing and scaling domestic production capacity can build a strong economic advantage for the nation.

III. **Encouraging the battery swapping mechanism:** The battery is one of the most expensive components of EVs. It accounts for 30-40% of the cost of an EV. The battery swapping system allows users to buy/lease the vehicle without batteries from OEMs, thus reducing the upfront cost. It also facilitates the range anxiety issue and saves the time required to charge a battery. The MoP (Ministry of Power) has recognized battery swapping as another technology for charging batteries in an amendment notified on 8th June 2020 [25]. However, no subsidy is available under FAME-II for the battery swap technology. The Government should provide incentives for swap technology and reduce the Goods and Service Tax (GST) on swap services to 5%, which is currently 18%.

IV. **Expanding the scale of charging infrastructure:** It is strongly recommended by the MoP [26] to provide at least one charging station within a grid of 3km x 3km in a city. However, there is a dilemma regarding where to install charging points primarily. Therefore, the study defines criteria for providing a charging facility according to the mode of transportation for which the subsidy is recommended in I Point of this section.

V. **Giving advertisement rights at charging stations:** The charging rate for opportunity is as high as US$ 0.36 (Rs. 30) per unit. Putting a service kiosk for watching and warding chargers and bill payments can grab an opportunity to have the advertisement space. Providing the advertisement rights would help cater to the infrastructure and reduce the overhead expenses.

VI. **Promoting interoperable payment systems:** 80% of the time, charging is done at residences and offices. For occasional charging at centralized charging stations, interoperable payment systems should be encouraged, like automated payment on the spot and a single app for booking charging slots and payment. Synchronizing with already prevailing e-commerce payment systems like UPI and e-wallets can help to resolve interoperability issues.

VII. **Strict follow-up of standardization norms:** Technical standards for the EVs are issued by the Ministry of Road Transport and Highways and are governed by AIS (Automotive Industry Standards). Technical standards for charging stations and connectors exist under IEC (International Electrotechnical Commission) standards. These standards should be strictly followed.

VIII. **Reducing the dependency of charging stations on the grid:** The saving in emission levels by adopting e-mobility depends mainly on the source of power generation. Therefore, more and more renewable energy generation sources should be set up. The charging stations can be deployed at home, offices and parking, using the solar energy to reduce the dependency on the distribution grid. On 13th May 2020, Government of India started Aatmanirbhar Bharat Abhiyan (Self-reliant India Mission) towards making India Self-reliant. The concept of the net-zero energy building could be promoted considering the EV as an active component of the building's energy system which can get support under **"Atmanirbhar Bharat Abhiyan"** as infrastructure is one of the five pillars of this mission [28]. An EV owner with a green energy production system at their residence should be given a concession on electricity consumption tariff during the opportunity charging.

Vehicles with solar and/or wind energy systems could also reduce their reliance on the grid. Solar energy can be stored in a vehicle's battery while it is standing still and also when it is moving. The wind turbine system in vehicles allows for converting the kinetic energy from the wind into electric power, which can be used to charge a battery. Using the solar and wind energy can also improve the driving range of EVs.

IX. Taking India's "Swachh Bharat Abhiyan" (SBA) initiative to the next level [29]**:** There are visible benefits of using EVs regarding GHG emission level reduction compared to conventional ICE vehicles. However, a huge behavioural change is required by consumers to accept the EVs due to habits towards the conventional vehicles. Spreading awareness about environmental benefits could accelerate the penetration of EVs in India. It could be done in association with India's "Swachh Bharat Abhiyan" by taking the mission to the next level of cleanliness by including the 'air quality parameter'. **Government of India launched Swachh Bharat Abhiyan or Clean India Mission on 2nd October 2014. Under the mission a cleanliness survey is being conducted called as Swachh Survekshan. Based on the survey ranking of cities is done.** In Swachh Survekshan League-2020, a new category of cities with a 4 million-plus population has been added for the population-wise award [30]. In addition, in the Ministry of power's revised guidelines for the charging infrastructure, cities with a 4 million-plus population have been included in phase-I to provide charging infrastructure coverage. Therefore, primarily including a parameter for air quality improvement due to EVs in the SBA's focus area for these cities can inspire all the cities to adopt the EVs. Change in the air quality at most congested junctions can be monitored by identifying a drop in emission levels due to EV adoption. Since the SBA has successfully brought a behavioural change in every corner of the country and has a partnership with many famous influencers, celebrities and international agencies, thus this tie-up would be very beneficial for promoting the e-mobility.

X. Prohibiting ICE vehicles: Along with promoting the electric vehicles, some measures should be taken to slow down the ICE vehicles' penetration. Like, the Government should prohibit investment in the production plants of the new ICE vehicle and tighten the CO_2 emission regulations, which would force many automakers to produce the EVs. Excess tax on petrol and diesel can be imposed to develop charging infrastructure for EVs.

These ten policy measures have been proposed to address the top barriers in e-mobility implementation. Policy measures I, II and III focus mainly on reducing the high upfront cost of an EV. Policy measures II also encourages the training and preparation of human resources in India, increasing employment opportunities and improving the tech-savvy level of this emerging technology in India. Policy measure III for supporting battery swapping technology would also tackle the issues of shortage of charging infrastructure, range anxiety and long charging time for EV users. Policy measure IV concentrates on expanding the charging infrastructure for EVs in a city, reducing the range anxiety and charging point anxiety of EV owners. Policy measure V also diminishes the charging point anxiety by emphasizing the standardization of EVs and their chargers. Policy measure VI suggests providing advertisement rights at a charging point, catering to the infrastructure costs and reducing the bill for charging EVs, which was observed to be very high at private charging points during the site visits. The interoperable payment methods are recommended to be encouraged in policy measure VII to promote the use of centralized charging points. Policy measures VIII and IX focus on environmental concerns of e-mobility. Policy measure VIII is to promote the generation of electricity from renewable sources on-site, which would ultimately bring down the GHG emission level and reduce the dependency on the grid. Policy measure VII recommends spreading awareness among citizen about the environmental benefits of EVs to bring behavioural change in them to adopt EVs. The last policy measure, i.e., Policy measure X, asks to slow down the penetration of conventional ICE vehicles, without which the transition cannot take place. Thus, these ten policies complement each other so that the main obstacles can be removed and implementation of the e-mobility can be accelerated in developing countries like India.

To discuss the limitations of the present study, the strategies developed in the present study are specific to India, which are developed by studying issues and challenges in Indian cities. These strategies can be used for other developing countries with minor changes. If needed, similar strategies can be developed for other countries as well, using the methodology followed in the present study. In addition, the policy measures suggested are linked with schemes and initiatives in India, however, these can also be implemented in other parts of the world, especially developing countries.

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References

[1] JUYAL, S., SANJEEVI, H., SAXENA, A., SHARMA, S., SINGH, A., CHANDE, S., JHUNJHUNWALA, A. Zero emission vehicles (ZEVs): towards a policy framework. In: MOVE Global Mobility Summit: proceedings. 2018.

[2] Climate explained: the environmental footprint of electric versus fossil cars -The Conversation Media Group Ltd [online]. 2019. Available from: https://theconversation.com/climate-explained-the-environmental-footprint-of-electric-versus-fossil-cars-124762

[3] AMBROSE, H., KENDALL, A., LOZANO, M., WACHCHE, S. Trends in life cycle greenhouse gas emissions of future light duty electric vehicles. *Transportation Research Part D Transport and Environment*[online]. 2020, **81**(10), 102287. ISSN 1361-9209, eISSN1879-2340. Available from: https://doi.org/10.1016/j.trd.2020.102287

[4] BINIEK, K., HENDERSON, K., ROGERS, M., SANTONI, G. Driving CO2 emissions to zero (and beyond) with carbon capture, use and storage - McKinsey Quarterly[online]. 2020. Available from: https://www.mckinsey.com/capabilities/sustainability/our-insights/driving-co2-emissions-to-zero-and-beyond-with-carbon-capture-use-and-storage#/

[5] Blue skies, reduced emissions only temporary, won‘t benefit environment in long run: experts - The Economic Times [online]. 2020. Available from: https://economictimes.indiatimes.com/news/environment/pollution/blue-skies-reduced-emissions-only-temporary-wont-benefit-environment-in-long-run-experts/articleshow/75061943.cms

[6] GNANN, T., PLOTZ, P., WIETSCHEL, M. How to address the chicken-egg-problem of electric vehicles? Introducing an interaction market diffusion model for EVs and charging infrastructure. In: eceee Summer Study 2015: proceedings. 2015.

[7] BIRESSELIOGLU, M. E., KAPLAN, M. D., YILMAZ, B. K. Electric mobility in Europe: a comprehensive review of motivators and barriers in decision making processes. *Transportation Research Part A: Policy and Practice*[online]. 2018, **109**, p. 1-13. ISSN 0965-8564, eISSN1879-2375. Available from: https://doi.org/10.1016/j.tra.2018.01.017

[8] HARDMAN, S., JENN, A., TAL, G., AXSEN, J., BEARD, G., DAINA, N., FIGENBAUM, E., JAKOBSSON, N., JOCHEM, P., KINNEAR, N., PLOTZ, P., PONTES, J., REFA, N., SPREI, F., TURRENTINE, T., WITKAMP, B. A review of consumer preferences of and interactions with electric vehicle charging infrastructure. *Transportation Research Part D Transport and Environment*[online]. 2018, **62**, p. 508-523. ISSN 1361-9209, eISSN1879-2340. Available from: https://doi.org/10.1016/j.trd.2018.04.002

[9] FUNKE, S. A., SPREI, F., GNANN, T., PLOTZ, P. How much charging infrastructure do electric vehicles need? A review of the evidence and international comparison. *Transportation Research Part D Transport and Environment*[online]. 2019, **77**, p. 224-242. ISSN 1361-9209, eISSN1879-2340. Available from: https://doi.org/10.1016/j.trd.2019.10.024

[10] LEBEAU, K., MIERLO, J. V., LEBEAU, P., MAIRESSE, O., MACHARIS, C. Consumer attitudes towards battery electric vehicles: a large-scale survey. *International Journal of Electric and Hybrid Vehicles*[online]. 2013, **5**(1), p. 28-41. ISSN 1751-4088, eISSN1751-4096. Available from: https://doi.org/10.1504/IJEHV.2013.053466

[11] AZAROVA, V., COHEN, J. J., KOLLMANN, A., REICHL, J. The potential for community financed electric vehicle charging infrastructure. *Transportation Research Part D Transport and Environment*[online]. 2020, **88**,102541. ISSN 1361-9209, eISSN1879-2340. Available from: https://doi.org/10.1016/j.trd.2020.102541

[12] SACHAN, S., DEB, S., SINGH, S. N. Different charging infrastructures along with smart charging strategies for electric vehicles. *Sustainable Cities and Society*[online]. 2020, **60**,102238. ISSN 2210-6707, eISSN2210-6715. Available from: https://doi.org/10.1016/j.scs.2020.102238

[13] KESTER, J., DE RUBENS, G. Z., SOVACOOL, B. K. Public perceptions of electric vehicles and vehicle-to-grid (V2G): Insights from a Nordic focus group study. *Transportation Research Part D Transport and Environment* [online]. 2019, **74**, p. 277-293. ISSN 1361-9209, eISSN1879-2340. Available from: https://doi.org/10.1016/j.trd.2019.08.006

[14] JUNQUERA, B., MORENO, B., ALVAREZ, R. Analyzing consumer attitudes towards electric vehicle purchasing intentions in Spain: technological limitations and vehicle confidence. *Technological Forecasting and Social Change*[online]. 2016, **109**, p. 6-14. ISSN 0040-1625, eISSN1873-5509. Available from: https://doi.org/10.1016/j.techfore.2016.05.006

[15] Livemint [online]. 2020. Available from: https://www.livemint.com/companies/news/electric-vehicle-sales-in-india-up-20-in-2019-20-11587370389230.html

[16] NAIK, A. R. Inc42 [online]. 2020. Available from: https://inc42.com/features/will-covid-19-accelerate-growth-of-indias-electric-vehicle-ecosystem/

[17] VERMA, P. The economic times[online]. 2019. Available from: https://economictimes.indiatimes.com/jobs/modis-e-car-dream-has-a-problem-no-one-saw-coming/articleshow/70299606.cms

[18] Wilbur Smith Association. Study on traffic and transportation policies and strategies in urban areas in India. New Delhi: Ministry of Urban Development, 2008.[19] IRENA. Innovation outlook: smart charging for electric vehicles. Abu Dhabi: International Renewable Energy Agency, 2019.
[20] Best electric bike models - Greynium Information Technologies Pvt. Ltd. [online]. 2020. Available from: https://www.drivespark.com/best-electric-bikes/
[21] TVS king electric auto rickshaw specifications, review and price - Electricvehicles.in [online]. 2020. Available from: https://electricvehicles.in/tvs-king-electric-auto-rickshaw-specifications-review-and-price/
[22] Electric cars in India - carandbike[online]. 2020. Available from: https://www.carandbike.com/new-cars/electric-cars
[23] YADLAPALLI, B. Electric bus in India -goldstone ebus[online]. 2018. Available from: https://electricvehicles.in/electric-bus-in-india-goldstone-ebus/
[24] Enabling the transition to electric mobility in India. New Delhi: Rocky Mountain Institute, 2017.
[25] Amendment in the revised guidelines and standards for charging infrastructure for electric vehicles - reg. New Delhi: Ministry of Power, 2020.
[26] Charging infrastructure for electric vehicles (EV) - revised guidelines and standards reg. New Delhi: Ministry of Power, 2019.
[27] Urban and regional development plan formulation and implementation guidelines. Town and Country Planning Organisation, 2015.
[28] Innovative initiatives - G. o. I. Ministry Of Tribal Affairs [online]. Available from: https://tribal.nic.in/atmanirbhar-bharat.aspx
[29] Swachh Bharat mission - G. o. I. Ministry of Housing and Urban Affairs [online]. Available from : https://mohua.gov.in/cms/swachh-bharat-mission.php
[30] Swachh Survekshan. G. o. I. Ministry of Housing and Urban Affairs, 2020.

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IMPROVING THE MANAGEMENT OF OPERATIONS OF THE E-SCOOTER SERVICES IN SICILY: A FIRST STEP OF A DESCRIPTIVE STATISTICAL SURVEY

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Resume

The recent pandemic has changed the modal choices of users in the urban context, highlighting in the last two years an increase in the diffusion of electric scooters, which is not homogeneous in the Italian context. At the beginning of 2020, the first e-scooter services were launched in Sicily, with the city of Palermo leading the way. A survey was therefore conducted in Sicily involving approximately 550 regular users of e-scooter services. The descriptive statistical analysis undertaken compared three different periods pre, during and post pandemic, with particular attention to the gender and age gap and different trends in the diffusion of multimodality. The results provide not only some suggestions for the improvement of services by managers but some suggestions to local administrators for implementation of democratic and sustainable planning steps, as well.

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1 Introduction

The spread of electric micro-mobility is uneven in different European contexts and this is due to several economic, social, and even cultural factors [1]. In general, the use of electric scooters has several advantages. As they are not stuck in traffic, they are a relatively fast means of transport. They also take up little parking space. Unlike cars or motorbikes, they tend not to pollute the air, depending on how the electricity consumption is produced. All these characteristics make them an ideal means of transport. However, they do have some significant disadvantages, the main one being the danger of accidents [2].

The rapid spread of e-scooters in urban areas has emphasized the need to implement urban planning and transport strategies to improve safety when interacting with motorized vehicles and complement active transport modes. In addition, the spread of shared micro-mobility services has enabled different types of users to use electric scooters for single trips or integrated with other modes of transport. It is clear that the management of shared scooter services must strongly consider demand trends and characterization of the users who mainly use these means of transport. This can improve the service and thus increase demand for transport by reducing the use of private motorized vehicles.

While on the one hand, services are on the rise, on the other, there are still many gaps in regulation: in fact, the regulatory and normative aspect is not uniformly widespread and is changing from year to year.

As the use of e-scooters becomes more widespread, the rules throughout the EU are divergent. Conditions of use are regulated at the local and Member State level, and national regulations differ on many important points. The most important difference is whether the e-scooters are regarded as motor vehicles (e.g. in Ireland) [3], or whether the e-scooter users are regarded as pedestrians using sports or leisure equipment (as in Finland) [4].

In other European states, e.g. in Latvia or Luxembourg, e-scooter users are equated with cyclists [5]. This distinction gives rise to other differences between the national rules, such as in which areas e-scooters are allowed to circulate: on roads, cycle paths or pavements, or whether they are allowed in pedestrian areas, zebra crossings or public places. Other differences between the Member States include, for example, the possession of a driving licence, the registration of the vehicle, or the obligation to take out insurance. The use of protective equipment (e.g. bicycle helmets) also depends on the status of e-scooters, as does the minimum permitted age for drivers, which ranges from 8 years (in France) to 15 years (in Denmark). A study conducted in [5] defined a framework of criteria for the design of a network for scooter traffic, also shared with other modes of transport, and in particular investigated variables such as route continuity, the possibility of route change, appropriate operating speed, and others.

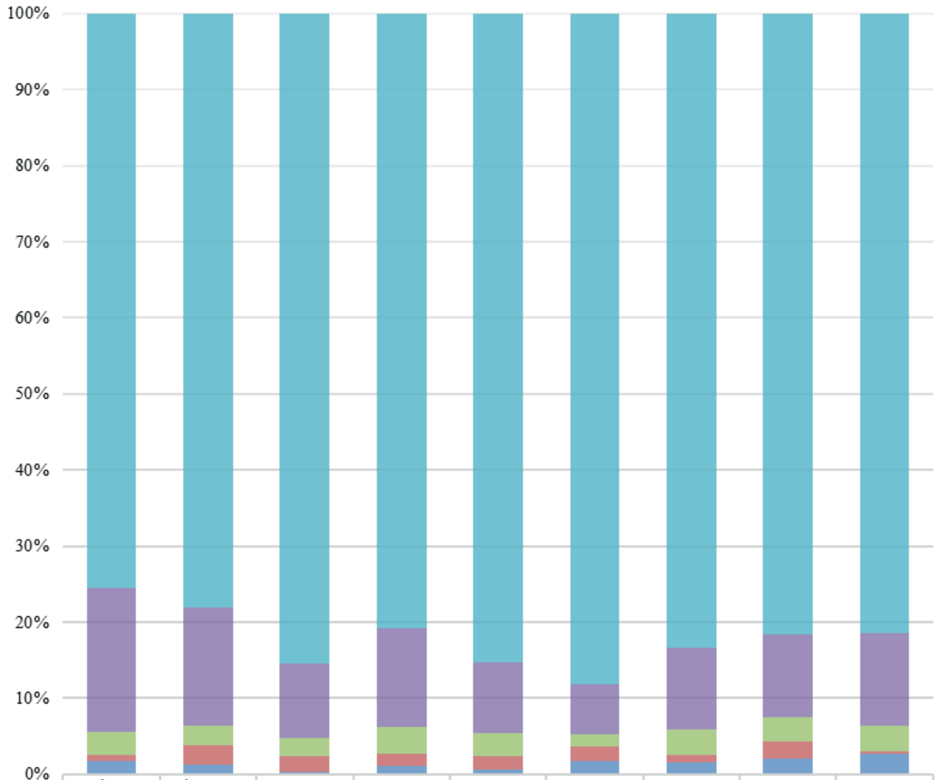
A study conducted in [6] defined a framework of criteria for the design of a network for scooter traffic, which is also shared with other modes of transport, and in particular investigated variables such as route continuity, the possibility of changing routes, appropriate operating speed, and others.

A research conducted in [7] found that drivers of e-scooters are three to five times more likely to be injured than cyclists or motorcyclists. Besides scooterists themselves, they can also injure pedestrians and drivers of other vehicles. Several studies have analysed injuries produced by scooter accidents resulting from the collision of scooters with vehicles and/or other pedestrians [8-9]. The inadequate parking of e-scooters is also an unresolved issue: as there are no specific parking spaces for e-scooters, they are often parked in spaces reserved for cars or bicycles or are abandoned in spaces needed for pedestrians to walk safely. For these reasons, they have already been banned from traffic in some city areas. In other cases, local authorities have reduced their number or periods of use. Several studies have analysed electric scooter (e-scooter) sharing services to investigate their strengths and weaknesses. In particular, the study conducted in [10] considered the situation in the city of Palermo where operators have witnessed a growth in demand in recent months, which has created several critical issues related to vehicle maintenance and vandalism, as well as defined the specific isochrones comparing walking to e-scooter use. The study through a SWOT analysis shows that although the e-scooters tend to be a transport solution with enormous potential, especially in overcrowded cities with increasing private car traffic, several legislative issues also need to be resolved before they can be a real success. Vehicle availability data from 30 European cities during the post-COVID-19 pandemic allowed for comparisons of temporal travel patterns, statistical characteristics (distance and travel time), utilisation efficiency and electricity wastage during the idle period [11]. The results showed that similarities and differences coexist in cities, and the efficiency of use is significantly correlated with the number of e-scooters per person and per unit area. The study conducted in [12] instead examined the different points of view of the operator, policy maker and user with particular reference to the city of Rome, highlighting a pre-competitive phase of the e-scooter sharing market in Italy compared to the United States and Europe, with various differences between cities. Few studies have analysed the integrated use of shared electric scooters and public transport systems, using panel data to measure spatial and temporal characteristics. A study conducted in Chicago by [13] examined the adoption and frequency of use of the shared e-scooters (using a probit model) to provide policy for implementation. The results showed a prevalence of male, low-income users belonging to the Millennials and Generation Z generation who do not own a vehicle.

A study conducted in Vienna analysed the socio-economic profiles and usage patterns of e-scooter users distinguishing between the two basic groups of e-scooter users (renters and owners) and showing that for both groups, e-scooter travel mostly replaces walking and public transport travel whereas the e-scooter owners also show a significant mode shift compared to private car travel [14]. The present work assessed the socio-demographic aspects and usage habits of e-scooters as follows.

2 Background

Modal choices in the post-pandemic phase have diversified with introduction of some services such as shared mobility in several Italian regions. Several studies have recorded almost 18 million rentals in Italy in the last two years. This phenomenon is growing while providing worrying dimensions for the all too often reckless and wild use of users, as well as for the number of accidents that have now surpassed those with scooters (2.07 accidents per 100 thousand kilometres, against 1.72 for mopeds) [15]. In November 2021, the Italian government intervened with a series of changes to the Highway Code precisely to bring order to an increasingly expanding sector: reduction of speed from 25 to 20 kilometres per hour (6 in pedestrian areas); ban on parking on pavements; parking areas to be identified by municipalities; ban on travelling on pavements or against the road and, after the sunset, the obligation to wear reflective vests; prohibition of carrying other passengers, animals and objects and compulsory helmets



	Bologna and Romagna	Florence and Tuscany	Genova and Savona	Milan and Lombardy	Naple and Campania	Palermo and Trapani	Rome and Lazio	Torino and Asti	Venice
Never / Do not exist in my town	75.60%	78.07%	85.48%	80.86%	85.31%	88.11%	83.39%	81.59%	81.42%
Rarely, a few times a year	18.80%	15.60%	9.70%	12.90%	9.30%	6.60%	10.70%	10.90%	12.20%
Occasionally, up to 5 times a month	3.03%	2.53%	2.42%	3.54%	3.09%	1.69%	3.31%	3.21%	3.38%
Frequently, up to 3 times a week	0.90%	2.50%	2.10%	1.60%	1.70%	1.90%	1.10%	2.30%	0.30%
Daily	1.70%	1.30%	0.30%	1.10%	0.60%	1.70%	1.50%	2.00%	2.70%

***Figure 1** Frequency of use of electric scooters in major Italian cities [20]*

for minors, for others only optional. Therefore, if in the past it was the rules that were lacking, today there is a lack of controls with negative consequences for urban road safety.

In 2021, the average rental of electric scooters in Italy was almost twelve minutes, for a distance of 2.3 kilometres. A good figure that testifies to their competitiveness in short distances for which, by now, taking the car is no longer convenient (at least in larger cities) [16].

The metropolitan city of Palermo was the first Sicilian city to have allowed several companies to include electric scooter-sharing services, introducing around 1600 vehicles by 2021 and reaching over 3600 after a few months [17]. The demand for regular users of electric scooters is constantly being analysed. Two studies conducted in [18-19] analysed the propensity to rent, share or buy, while another study analysed the perception of regular users of electric shared mobility services in the city, Figure 1.

Several studies have shown that there is no gender parity in the propensity to use scooters and therefore the demand for mobility can only be strongly characterised by a mostly male component. The study conducted in [21], in the metropolitan cities of Palermo and Catania, revealed the most influential factors on the gender parity variable by emphasising how age, employment and perceived safety level of micro-mobility modes play the most important role. From the point of view of distances that can be travelled, there is no doubt that electric scooters can be useful for short distances or as a complementary means of transport to public transport.

Unfortunately, the city is still far from the "City in 15 minutes" model and this is underlined by a study that compared some 110 European cities [22] and in which the city of Palermo ranks 94th among the cities that come closest to realising this model.

This means that there is still much to be done to reshape Palermo so that it is on a human scale. It is useful to analyse the data provided by platforms of companies that manage these services in the context examined: the platform data show that practically the entire city is not within walking distance in 15 minutes to fulfil all the primary needs of a citizen, apart from the North-South axis of the central area between Liberta and the Central Station. Particularly unserved is the parallel of the previous axis, from Giachery to

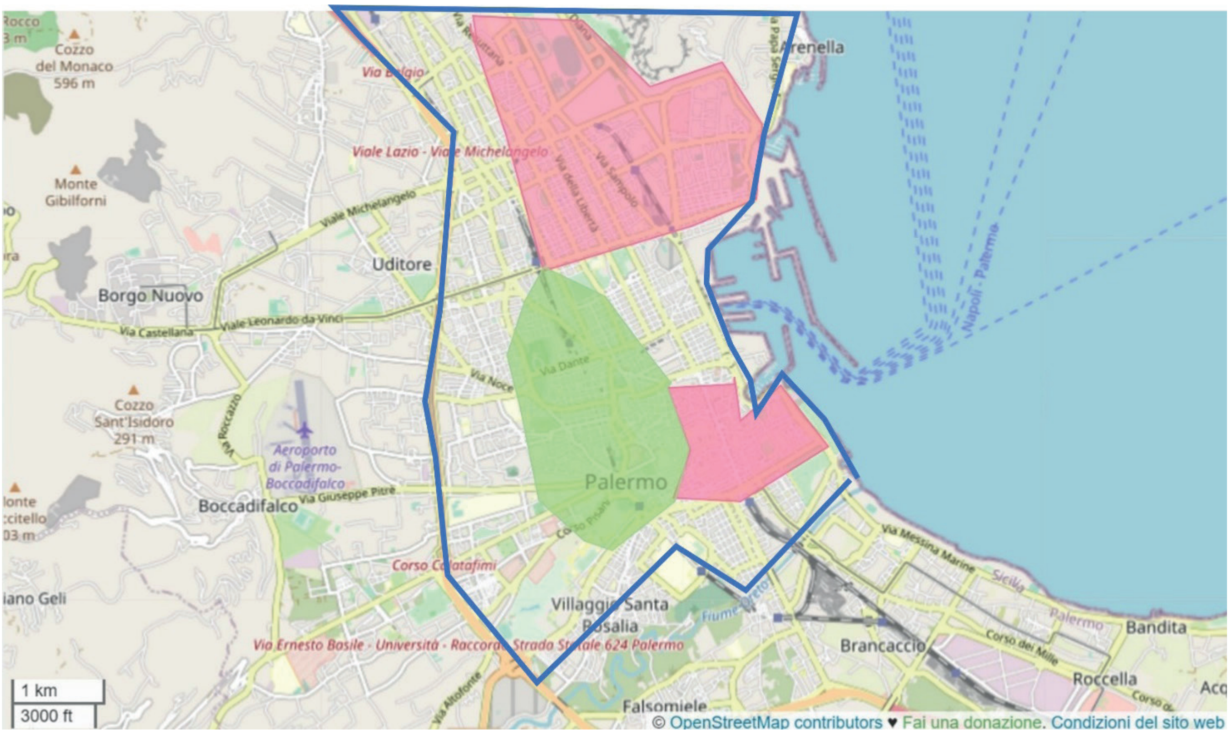


Figure 2 *Geolocation of areas most served by electric scooter services (in green) and least served (in pink) [23]*

the Orto Botanico, Pallavicino, Mondello, Sferracavallo, Zen, La Malfa, Resuttana, San Lorenzo, Borgo Nuovo, Settecannoli, Montegrappa, the Politeama area and Villagrazia, as shown in Figure 2.

Currently the e-scooter rental service is available either in "pay per use" mode, i.e. based on occasional use, paying a certain fee per minute for each rental, or with a subscription. The e-scooters are located in the areas where users leave them and mostly correspond to what is described in Figure 2.

For the electric micro mobility to play an essential role in integrating the city's public transport service and helping citizens to travel more efficiently, it is necessary to analyse the characteristics of demand, i.e. the socio-demographic aspects and the frequency and motivation of travel, also taking into account the trend variations experienced in the different pre- and post-pandemic periods. The following paragraphs describe the steps for implementing and disseminating a survey and analysing the data acquired and the interdependence between some of the variables.

3 Outline of the current operational management of electric micro-mobility services in Italy

The majority of the vehicles on the roads in Italy, however, are private, over 500,000. Approximately 230,000 of them are sold every year, and the trend is steadily increasing [24]. In 2020, despite the lockdowns due to the pandemic, the sector recorded more than 7 million rentals, testifying to the interest of citizens in this new type of mobility, used in urban areas mainly for short journeys instead of cars and as a first/last mile solution for trips interconnected with public transport. The operators for their part have always guaranteed both solid management reliability, with at least 90% of the authorised fleet available and therefore usable by the citizens, as well as constant investments for example, in upgrading the scooters to technology with interchangeable batteries, in the use of electric vehicles and cargo-bikes for logistics activities, or the experimenting with multi-modality systems, offering the pedal-assisted bicycles or other electric vehicles, as well. Finally, to raise user awareness of sustainable mobility and train them on correct traffic and parking regulations, it should be noted that the operators have organised a total of more than 100 driving courses and other training activities in various cities. Shared micro-mobility vehicles are vehicles that are constantly monitored by the operators.

They are equipped with advanced technology, which by way of example makes it possible to:

- Control speed, limiting it automatically in the selected zone,
- Control parking.

Finally, the number of shared micro-mobility vehicles in Italy is lower than in other European countries, a sign that the conversion to use of the soft mobility means should be further encouraged. Various aspects have been discussed between the operators of electric scooter-sharing services and the Italian Ministry of Infrastructure and Transport since 2021.

Table 1 Description of the main actions promoting the road safety and improving service

ROAD SAFETY	REF.	SERVICE IMPROVEMENT	REF.
Definition of complete, organic and permanent regulation to replace the current regime of „experimentation“.	[25]	Dissemination of information on local parking rules provided via app to the user.	[28, 35]
Definition of uniform regulations for e-scooter and bicycles.	[26]	Obligation for the user to take end-of-ride photos to verify proper parking.	[36]
Reduction of the maximum speed limit for scooters, lowering it from 25 km/h to 20 km/h, to reduce potential risks and improve control of the vehicle while driving.	[27]	Invest in more bicycle lanes, possibly in their own lanes, to ensure safe circulation for micro-mobility vehicles.	[37]
Inclusion of in-app information notes for the user for the correct use of the service.	[28]	Plan and design „30 zones“ to increase e-scooter users' safety, as welll as to reduce the speed difference between micro-mobility vehicles and cars when they travel side by side.	[38]
Confirmation of the helmet requirement for minors.	[29]	Activation of a 24-hour customer service by each operator to report badly parked scooters and a dedicated number for the emergency administration.	[39]
Inclusion of mandatory front and rear position lights constantly switched on during the ride.	[30]		
Insertion of the vehicle identification number for vehicles used in the sharing service.	[31]		
Reduction of the environmental impact of fleet renewal.	[32]		
Raising the maximum speed limit in pedestrian areas to 10 km/h (currently 6 km/h) as too low a speed does not allow a sufficiently stable balance to be in full control of a vehicle.	[33]		
Organising awareness campaigns and training activities.	[35]		

Underlying the numerous meetings were discussions on:

- Improving the regulation of scooter services in terms of safety standards and urban decorum in Italian cities,
- Investment in technology to improve services and also reduce operating costs,
- Entrusting the service to companies that can guarantee the highest standards of safety and urban decorum.

The non-standardisation of minimum requirements at the national level for participating in municipal public tenders, allows the service to be awarded without necessarily going through a qualitative examination of the offer of the same.

This lack is remedied, in some cases, through application of the formula “awarding the service in chronological order of dispatch of the application” and not on the qualitative evaluation of the offer.

Several proposals have been put forward by the scooter service operators, regarding the main issues dealt with in Table 1.

To be able to apply a series of actions to improve shared e-scooter services, it is necessary to know what trends users have changed in their travel frequencies and motivations during the last few years and the last pandemic phases. Furthermore, it is fundamental to understand whether certain socio-demographic variables influence these trends to be able to implement targeted policies aimed at developing the shared services analysed.

4 Methodology

The present study was conducted through the creation and administration of an online questionnaire consisting of two sections: the first relating to socio-demographic data and the second to use of electric scooters in different pre- and post-pandemic periods, in particular before 8 March 2020 (the day identified as the start of the pandemic in Italy), during the period May 2020-December 2021 (the period characterised by the post-lockdown period until the discovery of vaccines) and finally from January to May 2022. The questionnaire was circulated from June to September 2022.

The analysis was conducted using an inferential statistical approach and the interdependence of some variables in the first section with those in the second section of the questionnaire was implemented to identify a possible correlation useful for improving the management of shared transport services in the context examined.

All the variables predicted responses of a single type. Each user took on average less than 10 minutes to fill out the aforementioned questionnaire. After an analysis of the aforementioned data in statistical-descriptive terms, the primary and secondary variables were identified and the presence or absence of a form of interdependence between two sets of variables was analysed.

The probabilistic independence of variables was tested using the Pearson's chi-squared test. The starting formulation of the chi-squared test is defined by:

$$H_0 : P(AB) = P(A)P(B), \quad (1)$$

$$H_1 : P(AB) \neq P(A)P(B). \quad (2)$$

where: H_0 is the null hypothesis;
H_1 is the alternative hypothesis;

A and B are two variables whose independence must be tested.

The equation used to define the χ^2 is:

$$\chi^2 = \sum_{i=1}^{g} \sum_{j=1}^{k} \frac{(n_{ij} - E_{ij})^2}{E_{ij}}, \quad (3)$$

where: n_{ij} is the number of cases observed in sample j and which correspond to the i-th modality;
E_{ij} is the number of cases expected in sample j and for the i-th modality in the case the null hypothesis was true;
g is the number of ways in which the nominal variable is expressed;
k is the number of samples.

The number of expected cases, due to the hypothesis of independence of the samples, is determined as:

$$E_{ij} = \frac{n_{\cdot j} n_i}{n}, \quad (4)$$

where: $n_{\cdot j} = \sum_{i=1}^{g} n_{ij}$ is the numerosity of each of the k samples;
$n_{i.} = \sum_{i=1}^{k} n_{ij}$ is the number of each sample.

5 Results

The sample analysed consisted of 545 units randomly selected through dissemination of the questionnaire on the main social channels (i.e., Facebook).

Table 2 below reveals the statistical data acquired about section 1 .

Likewise for the variables analysed in the second section of the questionnaire as shown in Table 3.

It is therefore denoted that the sample is mostly male with an intermediate adult age between 31 and 50. The typical user is an office worker, however, similarly a freelancer as well, with an average salary of EUR 1001-1500.

As far as vehicle ownership is concerned, the vehicle fleet circulating in Palermo consists of 565,644 vehicles, an increase of 3,088 vehicles (+0.5%) as compared to 2020. Of these, 69.9% are passenger cars, and 22.4% motorbikes. [40].

The results obtained are in line with the characterisation of Italian and European e-scooter user. Concerning the possession of means of transport, almost the entire sample owns a car and about 70% of a bicycle, while a value below 30% identifies the possession of an electric scooter.

In the pre-pandemic period, the electric scooter was mostly used for work-related trips, while in the post-lockdown period, it was used for leisure, and later for both leisure and work purposes. As regards frequency of use, it was a couple of times a week in the first period, rarely in the second period, and once a week in the third period.

These values probably also reflect trends in travel governed by national restrictions and the frequency of use of other transport systems, such as local public transport. Concerning the main use in phases one and two, the predominance of renting is denoted by the predominance of sharing in the third period. This is due

***Table 2** Description of the main variables analysed in the survey (section 1)*

	1ST SECTION	
GENDER	AGE	JOB
F (74)(14%) M (455)(83%) n.d. (16)(3%)	18-30 (112) (20%) 31-50 (281) (52%) 51-65 (129) (24%) >66 (23) (4%)	Student (44) (8%) Employee (167) (31%) Freelancer (161) (29%) Retired (12) (2%) Other (161) (30%)
	OWNERSHIP	
E-scooter	Bike	Car
Yes (152) (28%)	Yes (382) (70%)	Yes (535) (98%)
No (393) (72%)	No (163) (30%)	No (10) (2%)
	*H-L=Home -Leisure; H-S=Home-School; H-W=Home-Work	

Table 3 Description of the main variables analysed in the survey (section 2)

VARIABLES	2ND SECTION		
	1ST PERIOD	2ND PERIOD	3RD PERIOD
Main purpose of e-scooter travel*	H-W (294) (54%) H-S (12) (2%) HL (239) (44%)	H-W (30) (5.5%) H-S (0) (0%) HL (515) (94.5%)	H-W (246) (45.2%) H-S (46) (8.4%) HL (253) (46.4%)
Frequency of travel by e-scooter	rarely (7) (1%) once a week (78) (14%) twice a week (197) (36%) once a day (180) (33%) two or more times a day (83) (16%)	rarely (489) (90%) once a week (36) (7%) twice a week (19) (3%) once a day (1) (0%) two or more times a day (0) (0%)	rarely (39) (7%) once a week (247) (45.5%) twice a week (226) (41.5%) once a day (33) (6%) two or more times a day (0) (0%)
Main use of e-scooter	Own (106) (20%) Rent (439) (80%) Shared (0) (0%)	Own (123) (22.5%) Rent (397) (73%) Shared (25) (4.5%)	Own (75) (14%) Rent (32) (6%) Shared (438) (80%)
Main multimodal use	single use (461) (85%) use integrated with other forms of soft mobility (43) (8%) use integrated with other forms of motorized mobility (41) (7%)	single use (463) (85%) use integrated with other forms of soft mobility (42) (8%) use integrated with other forms of motorized mobility (40) (7%)	single use (72) (13%) use integrated with other forms of soft mobility (418) (77%) use integrated with other forms of motorized mobility (55) (10%)

*H-L=Home -Leisure ; H-S=Home-School; H-W=Home-Work

Table 4 Interdependency between selected variables and relative results

	Chi-square value			
	Gender	Significant	Age	Significant
Before	33.8589		79.7715	
During	226.7399	Yes	116.6968	Yes
After	11.4086		99.0143	

to the absence in the first period of shared service and a slow spread from mid-2021 onwards in the examined context. Finally, multimodality was not considered in the first and second periods assuming a single service of scooters from one origin to one destination, instead in the last period the use of scooters was associated with other forms of soft mobility, such as walking for example.

To assess the interdependence of socio-demographic variables with the frequency of travel during the three examined periods, in particular, the age, gender and income variables, present in section 1, were correlated with the frequency present in section 2.

Results are shown in Table 4.

The chi-square calculation, therefore, shows that for the three pandemic periods analysed, there is an acceptance of the null hypothesis about both the correlation of displacement frequency with gender and age. Therefore, the dependence of the aforementioned variables must be considered to improve the micro-mobility services and implement urban planning actions by local administrations that take into account possible democratic participation in the choices to be made, emphasising measures dedicated to different population groups both by gender and age.

6 Discussion and conclusions

Development of sustainable mobility requires a careful analysis of the demand to be able to provide the best services to users. In recent years, various means of transport sharing services have spread and among these the one of electric scooters is depopulating. As of June 2021, some 42,000 electric scooters were active in Italy, managed by 10 operators in more than 40 cities, in cooperation with the respective municipalities. The sector, mostly formed by innovative start-ups, employs over 2000 people in Italy, mostly young people, and has so far generated local investments of around EUR 50 million, which are, however, at risk if the use of micro-mobility is discouraged.

On the whole, it is a sector that can boast not only results in terms of mobility, but in terms of sustainability as well: one thinks, for example, of the quantities of CO_2 saved during rides, compared to those emitted to cover the same kilometres with a medium-sized car. Finally, to raise user awareness of sustainable mobility and train them on correct traffic and parking regulations, it should be noted that operators have organised a total of over 100 driving courses and other training activities in Italy in various cities.

Shared micro-mobility vehicles are vehicles that are constantly monitored by the operators.

They are equipped with advanced technology, which by way of example makes it possible to:

- Control speed, limiting it automatically in selected zones and
- Control parking with virtual zones where parking is inhibited, forced or encouraged parking controlled through the GPS signal of the users' scooter and mobile phone.

Finally, the number of shared micro-mobility vehicles in Italy is lower than in other European countries, a sign that the conversion to use of the soft mobility means should be further encouraged. Italian regulations are absolutely in line with those of the main European countries, if not even more restrictive, even about the most controversial topics, such as the obligation of helmets, number plates or insurance. The micro-mobility sharing vehicles are constantly monitored by the operators and municipalities and equipped with advanced control systems, as well as by the administrations. All of them are equipped with a GPS and a data card that can constantly detect the position and speed of a vehicle through artificial intelligence systems. In addition, the management system regulates the speed by modulating it, as different zones vary, and parking is also inhibited where expressly prohibited by municipal regulations. All the data can be shared in real-time, anonymised in compliance with the GDPR regulations, to have a constant traceability of mobility flows in the city. In addition, for several months now, various operators have also been implementing various methodologies to monitor the passenger's driving style and to assess his or her psycho-physical state before the start of the ride. Finally, the companies offering sharing services constantly maintain their fleets of vehicles, much more frequently than all other types of private vehicles. All these details show how the evolution of the micro-mobility and improvement of the management of these services can represent an opportunity to test technologies and, at the same time, emphasise the need to know more and more data on users to make the tariffs and the dissemination of these services more efficient. In this way, a series of variables encourage the use of scooters in urban areas, especially for connecting the first and last mile: for example, think of the reduced rental costs, the growing availability of vehicles scattered throughout the different cities, the possibility of having discounts and incentives on purchases, possibility of access in limited traffic areas. While on the one hand the sharing service operators have to consider various strategies to make the use of scooters more appealing, on the other they find themselves having to put up with acts of vandalism and in various contexts even a reduced knowledge of the users' characteristics. Therefore, the present study shows the first step of investigation connected to the spread of scooter services in Sicily, in southern Italy, where dozens of e-scooters sharing service companies have been operating for only a few years. Through the drafting and administration of an online questionnaire it was possible to acquire both socio-demographic variables and variables connected to the frequency and motivation of the move. Particular attention was paid to variation of the usage trends during the various pre- and post-pandemic phases. The data were analysed statistically and particular attention was paid to evaluation of the interdependence of the gender and age variables with variation in the frequency of the scooters' use. The results showed a significance for which interdependence between the respective variables in the three periods was analysed.

The short- and medium-term actions that governments, local administrations and operators in the sector can take to improve these services can be divided into.

Actions to protect road safety, such as the revision of national regulations and municipal limits, or the inclusion of mandatory in-app information notes with a tutorial explaining to the user the most important rules on the correct use of the service. Awareness-raising campaigns and training activities are also hoped for through a dedicated fund for road education on electric scooters spread by collaboration between each municipality and micro-mobility service operators actions related to urban decorum and dedicated infrastructures by micro-mobility service operators, such as the inclusion of information on local parking rules provided via app to the user and/or the activation of a 24/24 customer service of each operator to report scooters, or even actions by public administrations to invest in the construction of more bicycle lanes, possibly in their own lanes, to ensure safe circulation for micro-mobility vehicles.

The spread of e-scooters, as well as the spread of electric bicycles, in the city of Palermo, and in Italy in general, has increased thanks to state incentives on the purchase and use of shared e-scooters is connected to a service that has been expanding in the city in recent years thanks to the increase in number of companies and therefore the number of e-scooters present in the area examined.

The City of Palermo's bike sharing system allows citizens to use a fleet of public bicycles in a simple and intuitive way. It is a public service and represents a serious alternative to use of private motorised transport, complementing the car sharing service with the advantage of being able to pick up cars and bicycles from the fleet managed by a single company with a single card, in a convenient, healthy and, above all, economical way. It is also useful to underline that while the shared mobility service (cars, bicycles) and public transport is managed by a single company, scooter sharing services are currently connected to different companies that only deal with these services.

It is also necessary to underline that in Italy the use of cars and bicycles is historically characterized by an increase over time throughout the peninsula for cars, and the use of bicycles especially in lowland areas as a means of transport to go to work and not just for leisure. However, the use of electric scooters is recent and the regulations for their use in Italy are not yet complete.

The results shown by this first step of investigation can therefore be implemented to encourage the use of scooters by specific categories of users.

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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.

References

[1] TZOURAS, P. G., MITROPOULOS, L., STAVROPOULOU, E., ANTONIOU, E., KOLIOU, K., KAROLEMEAS, C., KARALOULIS, A., MITROPOULOS, K., TAROUSI, M., VLAHOGIANNI, E. I., KEPAPTSOGLOU, K. Agent-based models for simulating e-scooter sharing services: a review and a qualitative assessment. *International Journal of Transportation Science and Technology* [online]. 2022, **12**(1), p. 71-85. ISSN 2046-0430, eISSN 2046-0449. Available from: https://doi.org/10.1016/J.IJTST.2022.02.001

[2] SEVERENGIZ, S., SCHELTE, N., BRACKE, S. Analysis of the environmental impact of e-scooter sharing services considering product reliability characteristics and durability. *Procedia CIRP* [online]. 2021, **96**, p. 181-188. eISSN 2212-8271. Available from: https://doi.org/10.1016/J.PROCIR.2021.01.072

[3] CARROLL, P. Perceptions of electric scooters prior to legalisation: a case study of Dublin, Ireland, the ´final frontier´ of adopted e-scooter use in Europe. *Sustainability* [online]. 2022, **14**(18), 11376. eISSN 2071-1050. Available from: https://doi.org/10.3390/SU141811376

[4] PAZZINI, M., CAMELI, L., LANTIERI, C., VIGNALI, V., DONDI, G., JONSSON, T. New micromobility means of transport: an analysis of e-scooter users´ behaviour in Trondheim. *International Journal of Environmental Research and Public Health* [online]. 2022, **19**(12), 7374. eISSN 1660-4601. Available from: https://doi.org/10.3390/IJERPH19127374

[5] SOKOLOWSKI, M. M. Laws and policies on electric scooters in the European Union: a ride to the micromobility directive? *European Energy and Environmental Law Review* [online]. 2020, **29**(4), p. 127-140. Available from: https://doi.org/10.54648/EELR2020036

[6] IGNACCOLO, M., INTURRI, G., COCUZZA, E., GIUFFRIDA, N., LE PIRA, M., TORRISI, V. Developing micromobility in urban areas: network planning criteria for e-scooters and electric micromobility devices. *Transportation Research Procedia* [online]. 2022, **60**, p. 448-455. ISSN 2352-1457, eISSN 2352-1465. Available from: https://doi.org/10.1016/J.TRPRO.2021.12.058

[7] MURROS, O., PUOLAKKAINEN, T., ABIO, A., THOREN, H., SNALL, J. Urban drinking and driving: comparison of electric scooter and bicycle related accidents in facial fracture patients. *Medicina Oral, Patologia*

Oral y Cirugia Bucal [online]. 2023, **28**(3), p. e238-e246. ISSN 1698-4447, eISSN 1698-6946. Available from: https://doi.org/10.4317/MEDORAL.25662

[8] DIAS, G., ARSENIO, E., RIBEIRO, P. The role of shared e-scooter systems in urban sustainability and resilience during the COVID-19 mobility restrictions. *Sustainability* [online]. 2021, **13**(13), 7084. eISSN 2071-1050. Available from: https://doi.org/10.3390/su13137084

[9] KLEINERTZ, H., VOLK, A., DALOS, D., RUTKOWSKI, R., FROSCH, K. H., THIESEN, D. M. Risk factors and injury patterns of e-scooter associated injuries in Germany. *Scientific Reports* [online]. 2023, **13**, 706. eISSN 2045-2322. Available from: https://doi.org/10.1038/s41598-022-25448-z

[10] WEI, W., PETIT, Y., ARNOUX, P. J., BAILLY, N. Head-ground impact conditions and helmet performance in e-scooter falls. *Accident Analysis and Prevention* [online]. 2023, **181**, 106935. ISSN 0001-4575, eISSN 1879-2057. Available from: https://doi.org/10.1016/J.AAP.2022.106935

[11] CAMPISI, T., NIKITAS, A., AL-RASHID, M. A., NIKIFORIADIS, A., TESORIERE, G., BASBAS, S. The rise of e-scooters in Palermo: a SWOT analysis and travel time study. In: *Computational Science and Its Applications - ICCSA 2022 Workshops. Lecture Notes in Computer Science* [online]. GERVASI, O., MURGANTE, B., MISRA, S., ROCHA, A. M. A. C., GARAU, C. (eds.). Vol 13380. Cham: Springer, 2022. ISBN 978-3-031-10541-8, eISBN 978-3-031-10542-5, p. 469-483. Available from: https://doi.org/10.1007/978-3-031-10542-5_32

[12] LI, A., ZHAO, P., LIU, X., MANSOURIAN, A., AXHAUSEN, K. W., QU, X. Comprehensive comparison of e-scooter sharing mobility: evidence from 30 European cities. *Transportation Research Part D: Transport and Environment* [online]. 2022, **105**, 103229. ISSN 1361-9209, eISSN 1879-2340. Available from: https://doi.org/10.1016/J.TRD.2022.103229

[13] CARRESE, S., GIACCHETTI, T., NIGRO, M., ALGERI, G., CECCARELLI, G. Analysis and management of e-scooter sharing service in Italy. In: 2021 7th International Conference on Models and Technologies for Intelligent Transportation Systems MT-ITS 2021: proceedings [online]. IEEE. 2021. ISBN 978-1-7281-8995-6. Available from: https://doi.org/10.1109/MT-ITS49943.2021.9529274

[14] MOHAMMADIAN, A., RAHIMI, E., JAVADINASR, M., SHAMSHIRIPOUR, A., DAVATGARI, A., ALLAHYARI, A., BROWN, T. *Analyzing the impacts of a successful diffusion of shared e-scooters and other micromobility devices and efficient management strategies for successful operations in Illinois* [online]. FHWA-ICT-22-006. Chicago: Illinois Center for Transportation, 2022. ISSN 0197-9191. Available from: https://doi.org/10.36501/0197-9191/22-006

[15] LAA, B., LETH, U. Survey of e-scooter users in Vienna: who they are and how they ride. *Journal of Transport Geography* [online]. 2020, **89**, 102874. ISSN 0966-6923, eISSN 1873-1236. Available from: https://doi.org/10.1016/J.JTRANGEO.2020.102874

[16] 6th national report on sharing mobility (in Italian) [online]. 2022. Available from: https://osservatoriosharingmobility.it/wp-content/uploads/2022/10/6-Rapporto-Nazionale-sharing-mobility.pdf

[17] CHICCO, A., DIANA, M. Understanding micro-mobility usage patterns: a preliminary comparison between dockless bike sharing and e-scooters in the city of Turin (Italy). *Transportation Research Procedia* [online]. 2022, **62**, p. 459-466. ISSN 2352-1457, eISSN 2352-1465. Available from: https://doi.org/10.1016/j.trpro.2022.02.057

[18] CAMPISI, T., AKGUN, N., TICALI, D., TESORIERE, G. Exploring public opinion on personal mobility vehicle use: a case study in Palermo, Italy. *Sustainability* [online]. 2020, **12**(13), 5460. eISSN 2071-1050. Available from: https://doi.org/10.3390/SU12135460

[19] CAMPISI, T., AKGUN, N., TESORIERE, G. An ordered logit model for predicting the willingness of renting micro mobility in urban shared streets: a case study in Palermo, Italy. In: *Computational Science and Its Applications - ICCSA 2020. Lecture Notes in Computer Science* [online]. GERVASI, O., MURGANTE, B., MISRA, S., GARAU, CH., BLECIC, I., TANIAR, D., APDUHAN, B. O., ROCHA, A. M. A. C., TARANTINO, E., TORRE, C. M., KARACA, Y. Vol 12250. Cham: Springer, 2020. ISBN 978-3-030-58801-4, eISBN 978-3-030-58802-1, p. 796-808. Available from: https://doi.org/10.1007/978-3-030-58802-1_57

[20] CAMPISI, T., AKGUN-TANBAY, N., MD NAHIDUZZAMAN, K., DISSANAYAKE, D. Uptake of e-scooters in Palermo, Italy: do the road users tend to rent, buy or share? In: *Lecture Notes in Computer Science* [online]. GERVASI, O., MURGANTE, B., MISRA, S., GARAU, CH., BLECIC, I., TANIAR, D., APDUHAN, B. O., ROCHA, A. M. A. C., TARANTINO, E., TORRE, C. M. (eds.).Vol. 12953. Cham: Springer, 2021. ISBN 978-3-030-86975-5, eISBN 978-3-030-86976-2, p. 669-682. Available from: https://doi.org/10.1007/978-3-030-86976-2_46

[21] Public transit statistics by country and city - moovit Insights [online]. Available from: https://moovitapp.com/insights/it/Analisi_Moovit_sull_indice_per_la_mobilit%C3%A0_pubblica-countries

[22] CAMPISI, T., SKOUFAS, A., KALTSIDIS, A., BASBAS, S. Gender equality and e-scooters: mind the gap! A statistical analysis of the Sicily Region, Italy. *Social Sciences* [online]. 2021, **10**(10), 403. eISSN 2076-0760. Available from: https://doi.org/10.3390/SOCSCI10100403

[23] Palermo - Open Street Map [online]. https://www.openstreetmap.org/search?query=palermo#map=11/38.1373/13.3472&layers=HN

[24] Wind mobility [online]. Available from: https://www.camera.it/application/xmanager/projects/leg18/attachments/upload_file_doc_acquisiti/pdfs/000/006/288/19._Memoria_Wind_Mobility.pdf

[25] DELLA MURA, M., FAILLA, S., GORI, N., MICUCCI, A., PAGANELLI, F. E-scooter presence in urban areas: are consistent rules, paying attention and smooth infrastructure enough for safety? *Sustainability* [online]. 2022, **14**(21), 14303. eISSN 2071-1050. Available from: https://doi.org/10.3390/su142114303

[26] D'APUZZO, M., EVANGELISTI, A., CAPPELLI, G., NICOLOSI, V. An introductory step to develop distance decay functions in the Italian context to assess the modal split to e-bike and e-scooter. In: 2022 Second International Conference on Sustainable Mobility Applications, Renewables and Technology SMART: proceedings [online]. IEEE. 2023. ISBN 978-3-031-37122-6, eISBN 978-3-031-37123-3, p. 194-208. Available from: https://doi.org/10.1007/978-3-031-37123-3_16

[27] Decree 18 August 2022 - Ministry of sustainable infrastructures and mobility [online]. Available from: https://www.gazzettaufficiale.it/eli/id/2022/08/30/22A04913/sg

[28] INGOGLIA, M. Mobility as a service: state of the art overview, criticalities, Italian proposals and analysis of people's opinions and behaviour [online]. Master's degree thesis. Turin: Politecnico di Torino, 2022. Available from: http://webthesis.biblio.polito.it/id/eprint/25518

[29] BIANCHI, A., GALLINA, S., CIANFLONE, F., TAFURI, A., CERRUTO, M. A., ANTONELLI, A. E-scooter accidents: a rising cause of kidney injury. *Urologia Journal* [online]. 2022, **89**(4), p. 506-510. ISSN 0391-5603, eISSN 1724-6075. Available from: https://doi.org/10.1177/0391560321103761

[30] DIANA, M., CHICCO, A. The spatial reconfiguration of parking demand due to car sharing diffusion: a simulated scenario for the cities of Milan and Turin (Italy). *Journal of Transport Geography* [online]. 2022, **98**, 103276. ISSN 0966-6923, eISSN 1873-1236. Available from: https://doi.org/10.1016/j.jtrangeo.2021.103276

[31] GRIFFEE, J., CURRANS, K. M., LYONS, T., FITZPATRICK, Q. Scooting into a new era: a review of agency regulations on shared e-scooter programs. 2021.

[32] NOCERINO, R., COLORNI, A., LIA, F., LUE, A. E-bikes and e-scooters for smart logistics: environmental and economic sustainability in pro-e-bike Italian pilots. *Transportation Research Procedia* [online]. 2016, **14**, p. 2362-2371. ISSN 2352-1457, eISSN 2352-1465. Available from: https://doi.org/10.1016/j.trpro.2016.05.267

[33] LIAZOS, A., ILIOPOULOU, C., KEPAPTSOGLOU, K., BAKOGIANNIS, E. Geofence planning for electric scooters. *Transportation Research Part D: Transport and Environment* [online]. 2022, **102**, 103149. ISSN 1361-9209, eISSN 1879-2340. Available from: https://doi.org/10.1016/j.trd.2021.103149

[34] DIOGO, V., SANNA, V. S., BERNAT, A., VAICIUKYNAITE, E. In the scenario of sustainable mobility and pandemic emergency: experiences of bike-and e-scooter-sharing schemes in Budapest, Lisbon, Rome and Vilnius. In: *Becoming a platform in europe - on the governance of the collaborative economy* [online]. TELI, M., BASSETTI, CH. (eds.). Boston - Delfit: now publishers, 2021. ISBN 978-1-68083-840-4, e-ISBN 978-1-68083-841-1, p. 59-89. Available from: https://doi.org/10.1561/9781680838411.ch4

[35] VINAGRE DIAZ, J. J., FERNANDEZ POZO, R., RODRIGUEZ GONZALEZ, A. B., WILBY, M. R., ANVARI, B. Blind classification of e-scooter trips according to their relationship with public transport. *Transportation* [online]. 2023, p. 1-22. ISSN 0049-4488, eISSN 1572-9435. Available from: https://doi.org/10.1007/s11116-023-10382-4

[36] Voi launches enhanced "Parking Photo" feature to promote safe parking habits [online]. Available from: https://www.voi.com/blog/voi-launches-enhanced-parking-photo-feature/

[37] CORTICELLI, R., PAZZINI, M., DRAGONETTI, L., MAZZOLI, C., LANTIERI, C., FERRANTE, A., SIMONE, A. Analysis and evaluation of mobility solutions and targeted interventions to support the urban regeneration of the canal port of Rimini. In: 6th Conference on Sustainable Urban Mobility CSUM 2022: proceedings [online]. 2022. ISBN 978-3-031-23720-1, eISBN 978-3-031-23721-8, p. 1663-1675. Available from: https://doi.org/10.1007/978-3-031-23721-8_129

[38] FAZIO, M., GIUFFRIDA, N., LE PIRA, M., INTURRI, G., IGNACCOLO, M. Planning suitable transport networks for e-scooters to foster micromobility spreading. *Sustainability* [online]. 2021, **13**(20), 11422. eISSN 2071-1050. Available from: https://doi.org/10.3390/su132011422

[39] CURRANS, K. M., IROZ-ELARDO, N., EWING, R., CHOI, D. A., SIRACUSE, B., LYONS, T., FITZPATRICK, Q., GRIFFEE, J. Scooting to a new era in active transportation: examining the use and safety of e-scooters [online]. Final report 1281. Portland: National Institute for Transportation and Communities, 2022. Available from: https://ppms.trec.pdx.edu/media/project_files/NITC-RR-1281_Scooting_to_a_New_Era_in_Active_Transportation.pdf

[40] Statistical repertoire - Municipality of Palermo [online]. Available from: https://www.comune.palermo.it/palermo-statistica.php?sez=187&sel=7&per=2021&cap=8

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SMART CITY AND URBAN LOGISTICS - RESEARCH TRENDS AND CHALLENGES: SYSTEMATIC LITERATURE REVIEW

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Resume

The paper presents a systematic quantitative and qualitative literature review and classification of the last decades resources for a comprehensive and coherent view of smart city and urban logistics research trends and challenges. The review fully respects a six-step systematic literature review guideline and covers ninety-nine peer-reviewed articles from Web of Science Core Collection database.

The review focuses on the following aspects: a perspective state-of-art journal, methods, content, keywords, references, and citations. The relevant articles for subsequent detailed analysis were identified between 2014 and 2020. The analysis has brought the following result: more than one third of the articles was published in 2020, the most articles were published in the Sustainability, and the modelling method was prevailed.

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1 Introduction

City logistics or in other words urban logistics is a problem that affects urban areas, provided that by this time the roads are generated by freight distribution and public service vehicles. A lot of cities around the world see an opportunity to address the challenges by adopting the concept of "Smart city" [1]. This statement is related connected with urban logistics too. However, the term Smart city is a vague concept (various definitions of the Smart city) and the absence of the commonly accepted definition of Smart city make it difficult to implement and manage Smart city programs [2-5]. Researchers and scholars thus contended that numerous challenges associated with the pursuit of urban intelligence and smart urbanization exceed the purview and capacities of extant municipal entities, institutional frameworks, and governance systems [5-7]. This emphasis can be regarded as an immediate outcome of "perceived failures or insufficient impact resulting from Smart City's investments to date" [8-9]. The rising urbanization within European urban centers, coupled with heightened consumption rates, has engendered sustainability concerns within the cores of cities and their logistical systems [10]. The majority of urban logistics initiatives encompass a diverse array of stakeholders, including governmental bodies, participants in the supply chain, and academic research institutions [11-12]. The sustainable advancement of the logistics sector holds practical significance for the evolution of smart cities [13]. The worldwide populace is progressively concentrating within urban areas [14]. A study by Desa [15] revealed that in 2016, 45% of cities had a population between 5 and 10 million inhabitants. Thus, by 2030, a projected population of 730 million will live in cities with at least 10 million inhabitants, representing 8.7% of people in the world [16]. Considering this panorama, some cities started to manage and design their urban centers with the perspective of the Smart city concept, due to the growth of urbanization, and some aspects that move, manage, and leverage the tangible and intangible smart resources of a city, such as mobility, governance, economy, people, quality of life and environment [17].

Smart city and last mile logistics are growing research areas with a growing interest of scientists and practitioners, especially over the last seven years [18]. The last mile is frequently characterized as one of the costliest, most time-sensitive, and most environmentally detrimental segments of the supply chain [19]. Numerous definitions exist for last-mile logistics; however, there is a shared consensus that it represents the final leg of the supply chain spanning from the last distribution center to the ultimate destination of the recipient [12, 20-21]. Last mile logistics and urban logistics focus on delivering packages to the preferred location of end customers instead of buying goods in various brick-and-mortar stores, which increases the number of freight shipments, which is exacerbated by the fact that each package is often small [22-23]. Urban logistics and last mile logistics cause various externalities, in particular greenhouse gas emissions [24-25], noise [26], traffic congestion [27] and air pollution [28]. Among the pivotal constituents contributing to the realization of an efficacious Smart city, transportation and goods delivery, public transit services, and traffic management hold a central position in shaping the urban layout, business applications, and infrastructure [29]. In the context of freight transportation, urban logistics, also referred to as urban freight transport logistics, encompasses the intricate process of delivering goods to their urban destinations. This undertaking is guided by a range of objectives, including the provision of efficient services, cost-effectiveness, and the promotion of sustainable development within urban areas [22]. Urban logistics is experiencing profound transformations in response to the burgeoning urban population and the explosive growth of e-commerce [30]. Academies and the logistic industry have recognized that one of the major challenges of Smart city logistics is integrated stakeholder involvement and the development of effective decision-making tools to improve its global performance [31]. One of the important works for Smart city logistics is the problem of integrated production and transport planning [32]. Within the framework of sustainability, the goal is to mitigate the adverse external impacts of logistical operations, while concurrently guaranteeing service accessibility and enhancing the overall quality of life for all urban residents [33]. Many authors have focused on new challenges related to sustainable city logistics (sustainable urban logistics); recently published works that provide in-depth analysis of the problem [22, 29, 34-36]. The shift toward intelligent and sustainable logistics in smart cities and port cities is directed at handling the constantly escalating volumes of imports and exports, along with the ensuing congestion, in a digitally resilient manner; this approach seeks to curtail vulnerability and alleviate anthropogenic pressures on urban environments [37-38]. The study by Hu et al. [39] states trends and gaps research to a contribution of city logistic problem to sustainable urban development based on statistical analysis more than 500 publications from relevant citation databases from 1993 to 2018.

City logistics encompasses the optimization of logistical and transportation operations, involving the active engagement of private enterprises supported by advanced information systems; this optimization focuses on the urban transport landscape, its effects on traffic congestion, security, and energy conservation [40-41]. Precise, punctual, and streamlined delivery operations are imperative for the resilience of supply chains and logistics providers within a digitally empowered business ecosystem; the objectives of smart city logistics, which encompass sustainability, mobility, and viability, are aimed at mitigating the presence of trucks, traffic congestion, and pollution [42]. The movement of goods into the Smart city is economically critical. Therefore, understanding the relationship between freight flow logistics and the operation of Smart cities is essential when implementing policy in future cities [43]. The challenges associated with the coordinated development of the metropolitan (city) economy and logistics have attracted a great deal of attention [44]. The contemporary logistics sector has evolved into an increasingly significant component of the modern economy, flourishing on a global scale thanks to the swift progress of the world economy and advancements in science and technology [45-46]. In recent decades, the idea has arisen that it is necessary to use decision support systems. Decision support systems for Smart cities have been proposed in the world literature because they can face various application problems such as electro mobility [47], convenience [48-49], logistics [50-52] or cyber security [53].

Seven review articles in the field of smart city and urban logistics were identified as part of the theoretical background of the issue [28, 54-59]. However, none of these review articles strictly focuses on the areas of smart city and urban logistics, including their interconnection. In conclusion, it can be clearly stated that a research gap has been identified, or that there is no research article in the field of smart city and urban logistics, even though these are nowadays very topical and emerging societal topics. The aim of this article is to provide a systematic literature review and classification of the literature to provide comprehensive and more coherent view of smart city and urban logistics research trends and challenges.

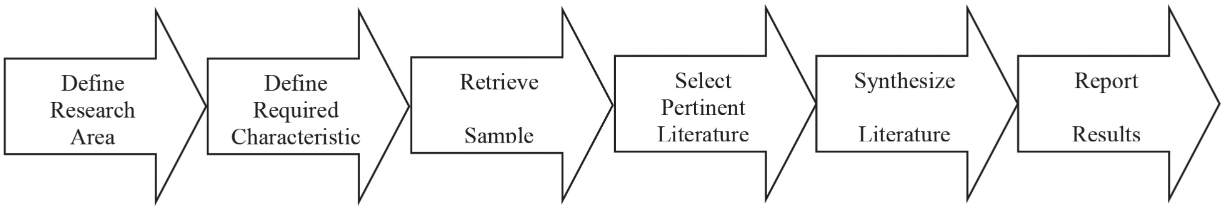

Figure 1 *Systematic literature review guideline used [60]*

2 Methodology

This systematic literature review of smart city and urban logistics fully respects a six-step guideline defined by Durach, Kembro and Wieland [60]. These steps have been proposed upon previous scientific work [61-62] and are increasingly used in supply chain management and logistics research to achieve transparent systematic literature reviews. This approach (Figure 1) was used, for example, by Olsson, Hellstrom and Palsson [18] in a systematic literature review of last mile logistics research.

The individual steps of the guideline are presented in the following subsections.

2.1 Define research and required characteristics

A state-of-the-art literature review was undertaken to identify gaps, establish the objective of the systematic literature review, and gain insight into pertinent terminology within the monitored thematic domains. A list of inclusion and exclusion criteria to select the included literature is based on the processed state of art study. Inclusion criteria include title, abstract, and keywords shall demonstrate smart city and urban logistics as the clear focus of the research; the articles must be included in the world scientific database Web of Science; articles must be classified by the scientific database as an article or review article; articles must be published in peer-reviewed journals; articles must be published between 2005 and 2020. The exclusion criterion is literature focusing on electrical engineering, electronic engineering, healthcare, social sciences is excluded from the systematic literature review performed.

2.2 Retrieve sample and select pertinent literature

Literature was analyzed exclusively in the world's largest and most widely used Web of Science database. As of 1 June 2022, the database indexed 23 218 literary outputs focused on the topic of smart city and its variations (after entering this input - topic: smart* cit*), and 443 150 literary outputs focused on the topic of logistics and its variations (after entering this input - topic: logistic*). The number of relevant literary outputs after merging with the logical conjunction "AND" was reduced to 421 outputs (after entering these inputs - topic: smart* cit* AND topic: logistic*). Only 242 of the 421 identified literary outputs were articles or reviews, and only 196 of the 242 literary outputs were published between 2005 and 2020. The next step was a three-round content analysis of all 196 identified articles by four independent researchers. The researchers evaluated each article according to inclusion and exclusion criteria and finally summarized their results to define the final basis for conducting a comprehensive qualitative and quantitative systematic literature review. Finally, researchers identified 99 scientific articles for the next steps.

2.3 Synthesize literature and report results

Firstly, we analyzed publication trends in the context of the number of publications in individual years and journals. Next, we analyzed article keywords, article references, article citations, using frequency analysis. Finally, a content analysis was carried out from the perspective of article themes, article methods, and article content. The systematic literature review clearly shows that the smart city and urban logistics issues are an emerging research area with growing interest of researchers, practitioners, and other stakeholders. On the other hand, this research area is very diversified and contains many research sub-areas that have been identified. Many scientific methods are also used, especially combinations of them.

3 Results

The results are presented in accordance with the quantitative and qualitative parts of the standardized systematic literature review. The results are divided into main article journals, article keywords, references, citations, themes, methods, and content.

3.1 Evolutionary timeline and main journals

Smart city and logistics issues are an emerging research area with growing interest of researchers,

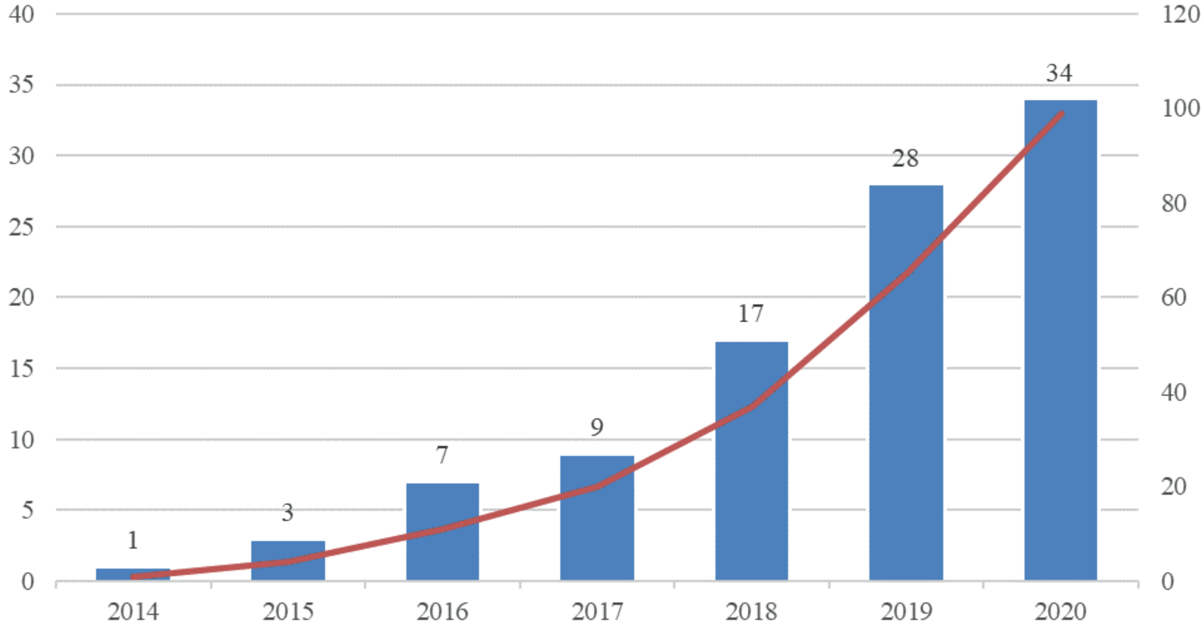

Figure 2 *Evolutionary timeline of the reviewed literature*

practitioners, and other stakeholders. The systematic literature review covers the period since 2005, but relevant articles for subsequent detailed analysis were identified only between 2014 and 2020. In total, 99 relevant articles were published in the following years: 1 article in 2014, 3 articles in 2015, 7 articles in 2016, 9 articles in 2017, 17 articles in 2018, 28 articles in 2019 and 34 articles in 2020 (Figure 2). It clearly shows the increasing trend and extreme growth of published articles in this research area. At the same time, this trend can be expected to continue in the coming years.

Most of the analyzed articles (96) are in English. Only 3 articles are in languages other than English, namely: 1 in Portuguese [63] and 2 in Russian [64-65]. Research on smart city and logistics has been published in many journals. In the period under review, there were 72 journals in total. Most articles (9) were published in the journal Sustainability, all of which were published in the last three analyzed years (2018-2020). Four articles were published in the journal Production Planning and Control and IEEE Access, three articles were published in the journal Sensors, Sustainable Cities and Society and IEEE Transactions on Intelligent Transportation Systems. Two articles were published in the other seven journals. One article was published in 59 other journals. A total of 92 out of 99 articles can be characterized as articles. The remaining 7 articles [28, 54-59] are review articles. Most of the review articles (5 out of 7) were published in 2020, which is not surprising since many articles had already been published by then and it was necessary to summarize the findings and aggregate the results. The remaining two review articles [28, 59] were published in 2017 and 2018.

3.2 Keywords

The keywords of the articles cover a wide range of areas. Most keywords (55) cover the phrase “smart” and its variations. The next most used keywords phrase (28) was “urban” and its variations. A total of 16 to 18 times the keywords phrase “transport” or “transportation”, “Internet of Things” or “IoT”, “logistic” or “logistics” and their equivalents were used. The keywords “city logistics” and “big data” and their variations were used more than ten times (twelve times in total). Other keywords and their semantic variations were used less than ten times in the analyzed articles.

3.3 References

All analyzed articles contain a total of 5 768 references. The median number of references is 48, while the average number of references corresponds to 58.26. The article by Oliveira et al. [66] contains the most references (196). The fewest references (10) include the article by Tsitsiashvili [65]. Most articles (39) contain 26-50 references. 21 articles are based on 51-75 references and 16 articles contain up to 25 references. Only 3 articles contain more than 150 references [55, 66-67] (Figure 3).

3.4 Citations

All analyzed articles have been cited 1 592 times so far. The median number of citations is 10, while the average number of references corresponds to 16.08. The

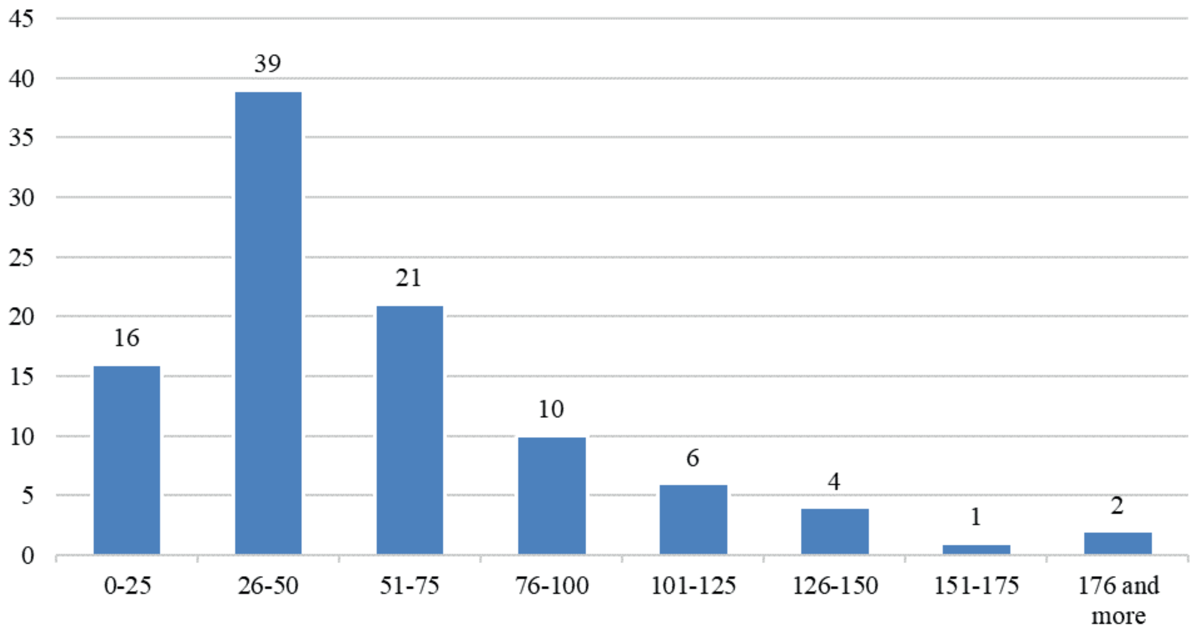

Figure 3 *Histogram of reference frequencies*

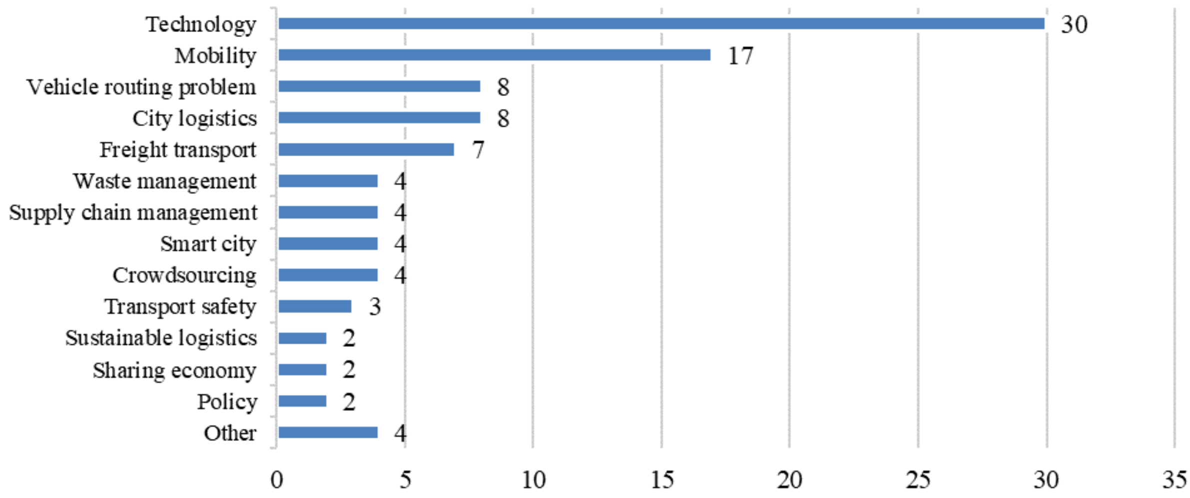

Figure 4 *Article themes*

article by Ranieri et al. [28] is the most cited analyzed article (90 citations as of 22 November 2022). This article is a research article, so it is quite understandable that it is heavily cited. Only 4 analyzed articles have no citations so far. Most articles (79) have up to 25 citations. 13 articles have 26-50 citations and 6 articles [68-73] have 51-75 citations. Only one article [28] has more than 76 citations, specifically 90 citations.

3.5 Themes

All relevant articles were thoroughly analyzed using content and semantic analysis by the author team and the main theme of each article was identified. The predominant theme of all analyzed articles is technology (30 articles in total) [54, 58, 66, 68, 70-71, 74-97]. Another important theme is mobility (17 articles) [56-57, 59, 63, 66, 98-109]. The research theme of vehicle routing problem includes a total of 8 articles [76, 110-116]. The same number of articles (8) covers the theme of city logistics [12, 28, 117-122]. The following 7 articles correspond to the freight transport theme [72, 123-128]. Other themes were always identified in fewer than five articles (Figure 4).

3.6 Methods

Most of the analyzed articles generally use multiple scientific methods. The analyzed articles mostly use the modelling method (29 articles) [65, 71, 77, 87, 90-93,

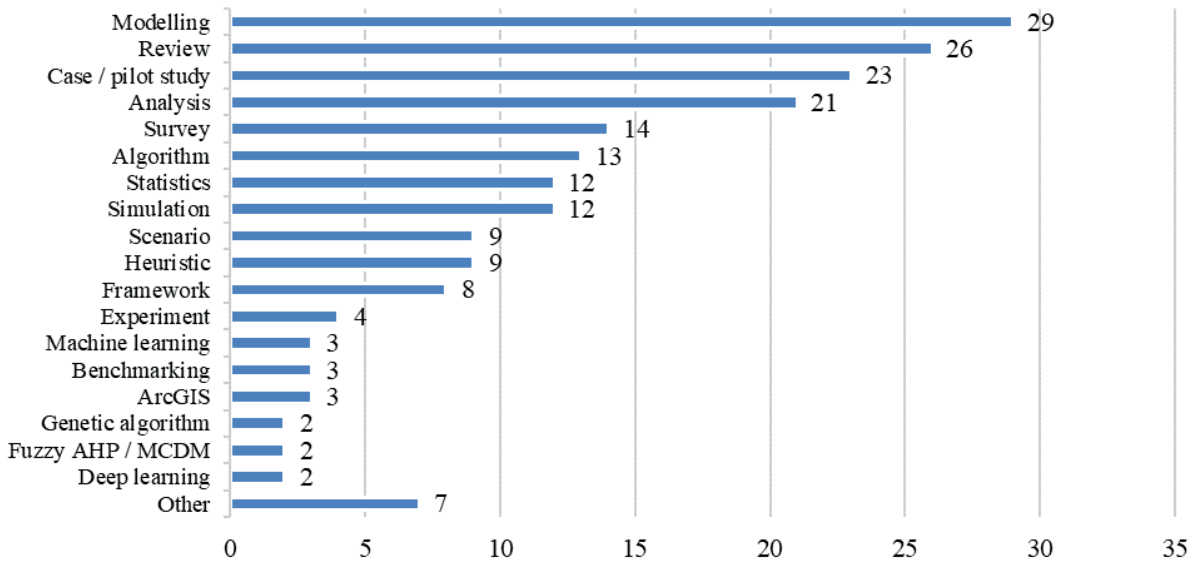

***Figure 5** Article methods*

96, 100, 105, 117, 120-122, 124-125, 127, 129-139]. The review method was used in 26 articles [28, 54-59, 63-64, 66, 68-69, 72-73, 79, 83, 89, 95, 99, 103, 119, 123, 126, 137, 140-141]. The case or pilot study method was used in 23 articles [12, 70, 77-78, 85, 87, 92, 94, 102, 106-108, 113, 115, 119, 126, 130, 136, 138, 142-144]. The analysis method and its variations was used in 21 articles [28, 64, 67, 69, 72, 73, 82, 91, 97, 104, 105, 113, 125-126, 131, 138, 141, 144-146]. The other scientific methods were used less than 14 times (Figure 5).

3.7 Content

The content of the articles is divided based on the processed content analysis and its results. The following subchapters provide the detailed content of the articles according to the identified thematic areas. Articles of two or less thematic areas are not considered.

3.7.1 Technology

Wong et al. [54] highlighted the lack of a comprehensive review on blockchain applications in smart sustainable cities. Wong, Tai and So [74] developed a container drayage optimization model for efficient container movements in Hong Kong. Ahad et al. [68] extensively reviewed enabling technologies in smart cities, addressing technical, socio-economic, and environmental challenges. Chauhan et al. [75] proposed a system that simplifies the process of finding available parking slots in real-time using IoT infrastructure. Chen et al. [142] developed a hierarchical service framework for transportation and traffic pattern analysis. Xia et al. [77] put forth a distributed model, employing weighted long short-term memory, to analyze time window-based data within the context of a parallel processing framework. Ryan et al. [78] explored the use of Smart Information Systems to address Sustainable Development Goals and discussed ethical considerations across various application areas. Yang et al. [79] summarized autonomous moving platforms, their taxonomy, technologies, applications, challenges, and open issues. Oliveira et al. [66] discussed transportation technologies and systems in the context of the IoT and value concepts. Guerra, Dardari and Djuric [80] proposed a dynamic radar network of unmanned aerial vehicles for real-time tracking of targets. Iranmanesh et al. [81] presented path optimization algorithms for drone multi-hop communications networks, optimizing both parcel deliveries and data transmission. Astarita et al. [58] reviewed the application of blockchain-based systems in transportation. Asthana and Dwivedi [82] analyzed the capabilities and requirements of 3PL service providers and users in the context of distributed manufacturing and smart city products. Chen [83] conducted a thorough examination of these issues and put forth relevant measures and suggestions concerning the development and practical innovation of smart cities amidst the integration of new technologies. Zhao et al. [84] used data-driven approaches to improve delivery fleet management, including destination prediction and real-time incident detection. Shao, Xu and Li [85] introduced a smart product-service system approach for the development of route optimization systems based on the IoT. Araujo et al. [86] evaluated the performance of the FIWARE cloud based IoT platform for large-scale deployments relevant to smart cities. Sicari, Rizzardi and Coen-Porisini [87] explored the use of Node-RED, a flow-based programming tool for IoT applications, in different contexts. Liu et al. [88] applied big data analytics to enhance smart manufacturing services in commercial laundry. Hussein [89] discussed the recent advancements in IoT technologies and explored future applications and research challenges in the field. Aqib et al. [90] devised a comprehensive methodology for real-time traffic prediction, harnessing the power of big data, deep learning, in-memory computing, and GPUs. Sarker et al. [91] conducted an exploration into the propensity to share travel-related information when using daily transit applications. Abbasi, Khan and Ul Haq [92] analyzed various conceptual modeling approaches for the IoT. Liao and Wang [93] scrutinized the design and utilization of blockchain technology in the context of Intercontinental Exchange logistics. Gohar, Muzammal and Rahman [94] put forth a conceptual architecture for big data analytics tailored to Intelligent Transportation Systems. Hopkins and Hawking [70] discussed the role of big data analytics and the IoT in improving driver safety and operational efficiency in logistics. Goudos et al. [95] introduced various IoT application domains, encompassing areas such as smart cities, transportation, logistics, and healthcare. Mehmood et al. [71] developed a model for load and capacity sharing in smart cities to improve operational efficiency. Erkollar and Oberer [96] investigated the integration and utilization of FLEXTRANS4.0 applications in logistics and smart city initiatives within the European Union. Li, Cao and Yao [97] examined the smart city concept, its development, motivations, and goals in China.

3.7.2 Mobility

Adamczak et al. [98] explored eco-driving incentives for drivers in short-term rentals. Ceder [56] analyzed future urban transportation, highlighting the inefficiency of private cars and advocating for autonomous and electric vehicles in urban transportation systems. Perkumiene et al. [57] conducted an integrative review on the right to a clean environment, emphasizing the importance of green logistics and sustainable tourism as solutions to climate change. Nagy and Csiszar [99] discussed the requirements and optimization needs for smart mobility. Del Vecchio et al. [100] demonstrated the utility of system dynamics in optimizing decision-making for people's mobility. Shi et al. [101] proposed ParkCrowd, a crowd-sensed parking system that provides reliable real-time parking information to drivers using logistic regression-based evaluation. De Oliveira et al. [145] presented a low-cost deployment proposal called URCa, which suggests sharing cars considering logistic aspects. Mazzarino and Rubini [102] evaluated the feasibility of a mixed passenger and freight transport system in the Venice Lagoon, addressing issues of accessibility and social cohesion. Pereira et al. [63] discussed the dimensions of logistics and urban mobility in smart city contexts, noting an increase in related publications. Peprah, Amponsah and Oduro [103] assessed the smart mobility of Ghanaian cities and proposed strategies to mitigate the adverse effects of urbanization. Mozos-Blanco et al. [104] analyzed sustainable mobility plans in Spain, emphasizing the reduction of congestion, pollution, and car dependency while promoting active transportation. Keimer et al. [105] analyzed the influence of emerging mobility services on traffic flow and transportation efficiency, offering a structured framework for modeling and understanding these evolving trends. Kresak et al. [106] explored the use of a high-speed suspended cableway for urban mobility in Slovakia. Melo, Macedo and Baptista [107] evaluated re-routing for vehicles in Lisbon, assessing the impact of guidance information on traffic performance, operational costs, and environmental conditions. Turon, Czech and Juzek [108] discussed walkability as a form of smart mobility in urban logistics, addressing sustainable development and transport. Mangiaracina et al. [59] conducted a comprehensive review of intelligent transportation systems supporting urban smart mobility, identifying research gaps and proposing future directions. Pronello, Veiga-Simao and Rappazzo [109] assessed the effects of Optimod'Lyon, a real-time information navigator, on travel behavior in Lyon, France.

3.7.3 Vehicle routing problem

Chen et al. [142] proposed a heuristic repair method for the dial-a-ride problem. Lu and Yang [110] introduced the Iterative Logistics Solution Planner, a hybrid approach for quickly finding and improving logistics solutions while considering real constraints. Reyes-Rubiano et al. [111] conducted an analysis of a practical vehicle routing problem that incorporates driving-range limitations and uncertain, stochastic travel times. Yu and Lam [112] proposed an optimal route determination method for an AV logistic system in smart cities. Alvarez et al. [113] underscored the significance of factoring in congestion expenses when optimizing delivery routes. Perboli, Gobbato and Maggioni [114] tackled the multi-path traveling salesman problem involving uncertain travel costs, specifically tailored for Smart Cities and City Logistics. Abbatecola et al. [115] introduced an urban decision support system geared towards the coordinated management of logistical services in smart cities, including tasks like postal delivery and waste collection, all within a unified framework. Muelas, LaTorre and Pena [116] introduced a distributed algorithm based on request partitioning and route combination.

3.7.4 City logistics

Kim, Moon and Jung [117] proposed a mixed integer programming model and a block stacking heuristic for drone operation planning. Iranmanesh and Raad [118] introduced a heuristic flight path planning method for drone networks that includes both parcel delivery and data delivery. Wang et al. [119] developed innovative solutions to enhance last mile parcel delivery using crowd intelligence. De Carvalho, Kalid and Rodriguez [120] proposed a model for evaluating city logistics performance. Ranieri et al. [28] conducted a literature review on recent contributions to innovative strategies for last mile logistics. Demirtas, Tuzkaya and Tanyas [121] investigated the layout design of an urban distribution center, specifically a fruits and vegetable hall. Harrington et al. [12] introduced an innovative approach to the development and assessment of last-mile solutions, taking into account the social and economic viewpoints of critical stakeholders. Ahmad and Mehmood [122] conducted a study on establishing a success predictive model for enterprise systems benefits.

3.7.5 Freight transport

He and Haasis [123] formulated a theoretical research framework for sustainable urban freight transport, encompassing considerations of future urban development, distribution innovations, and appropriate research methodologies. Comi, Schiraldi and Buttarazzi [124] introduced an architectural approach and methodology for the integration of delivery bay planning with transportation demand modeling through simulation. Cavone, Dotoli and Seatzu [125] conducted a comprehensive survey of Petri net models in the context of freight logistics and transportation systems. Heddebaut and Di Ciommo [126] focused their research on assessing the impact of intermodal transport infrastructures, such as city-hubs, on social organization and the urban environment. Gatta, Marcucci and Le Pira [127] proposed an innovative decision-making approach for urban freight planning. Rodrigue, Dablanc and Giuliano [128] introduced the concept of the freight landscape, which pertains to the spatial distribution and intensity of freight activity within metropolitan areas. Juan et al. [72] identified and reviewed research challenges associated with the adoption of electric vehicles in logistics and transportation operations.

3.7.6 Waste management

Laurieri et al. [143] found that door-to-door collection of glass waste is inefficient, with bins often remaining partially filled and less frequently emptied. Bulatov et al. [133] developed an efficient logistics system for handling solid municipal waste. Wu et al. [134] developed a mathematical model for addressing the low-carbon vehicle routing problem in the context of waste management systems, taking into account probabilistic constraints. Misra et al. [147] introduced a pioneering integrated sensing system designed to automate the solid waste management process.

3.7.7 Supply chain management

Jiang et al. [129] scrutinized the factors contributing to the effectiveness of supply chain management systems, underscoring the pivotal role of urban intelligent transportation systems in their success, encompassing aspects like safety, accessibility, information management, and flexibility. Ogbuke et al. [140] conducted an extensive review of big data supply chain analytics, investigating its applications and the advantages it offers to organizations and society. Guerlain et al. [146] proposed the implementation of decision support systems to enhance construction logistics and supply chain management, utilizing evidence-based mechanisms. Tachizawa, Alvarez-Gil and Montes-Sancho [73] examined the influence of smart city initiatives and big data on supply chain management, with a specific focus on elucidating the interconnections between smart cities, big data, and the characteristics of supply networks.

3.7.8 Smart city

Rana et al. [69] discerned the primary obstacles to smart city development by synthesizing findings from a literature review and expert opinions. Mora et al. [67] introduced a research methodology tailored for conducting multiple-case studies, offering guidance to cities on how to effectively approach smart city development. Buyukozkan and Mukul [137] tackled the evaluation of smart city logistics solutions as a multi-criteria decision-making problem, taking into account their diverse components. Paskannaya and Shaban [141] examined the characteristics of green logistics and the advantages of its implementation in urban development, drawing insights from successful Smart City projects in the USA and the EU.

3.7.9 Crowdsourcing

Feng et al. [30] investigated a novel problem involving crowdsource-enabled production and transportation scheduling. This problem was formulated as a mixed-integer linear program and was proven to exhibit strong nondeterministic polynomial time-hardness. Hoseinzadeh et al. [130] assessed the accuracy of Waze speed data specifically on surface streets, conducting a case study in Sevierville. Tu et al. [148] introduced an online crowdsourced delivery approach for on-demand food services, encompassing order collection, solution generation, and sequential delivery processes within a dynamic optimization framework. Huang et al. [132]

developed a research model grounded in the Push-Pull-Mooring theory to elucidate the factors that influence the participative behavior of crowd workers.

3.7.10 Transport safety

Dominguez et al. [149] suggested utilizing machine learning models to enhance vehicle detection in smart crosswalks. Vilaca et al. [135] conducted an analysis of spatial and temporal patterns within urban areas and formulated a predictive model to assess the probability of accidents involving vulnerable road users. Dhakal et al. [150] investigated the behavior of cyclists riding in the wrong direction on one-way segments.

4 Discussion

In this article is presented a comprehensive systematic literature review within the realm of emerging trends and challenges in smart city and urban logistics research. Smart cities represent an evolved stage of information city development, characterized by the extensive utilization of cutting-edge information technologies like the IoT, cloud computing, and mobile Internet access. Additionally, they incorporate tools and methodologies derived from social networks. The detailed content of the articles according to the identified thematic areas were technology, mobility, vehicle routing problem, city logistics, freight transport, waste management, supply chain management, smart city, crowdsourcing, and transport safety. These identified thematic areas also partially correspond to the smart city logistics framework developed by Pan et al. [29].

It should be noted that some limitations may appear in this article. Although every effort has been made to make the review comprehensive, some articles may not have been included in the review, not intentionally. Another limitation is that the authors used only articles from the internationally recognized Web of Science database. On the other hand, it can be noted that this approach is also standard for other authors, e.g. [151-152]. Another limitation may be the structure of the keywords and the composition of the search phrase. Keyword selection has been discussed among researchers, but it is possible that due to the structure of search phrases and the use of search operators, some relevant articles may have been omitted from the search. Finally, it should be noted that the basis of this article has lain in the review of available research articles from the period 2012-2022. The resulting findings and conclusions are relevant in December 2022. The authors of the article state that due to the rapid development in smart cities and urban logistics, it can be assumed that many new findings and technologies will emerge soon.

5 Conclusion

The aim of this article was to provide the systematic literature review and classification of the literature to provide comprehensive and more coherent view of smart city and urban logistics research trends and challenges. Numerous cities earn the “smart” designation when they possess key attributes such as widespread broadband access, a knowledgeable workforce, and a commitment to digital inclusion. One of the primary objectives of smart cities is to enhance the quality of services provided to their residents while concurrently reducing administrative expenditures through the application of technology. Because using the IoT, while very useful, leads to security issues in data management. Cities are the breeding ground for innovation and socio-economic progress, but their dynamic development is also changing continuity and sustainability. Sustainability of cities in terms of ecology, social dynamism and vulnerability of cities requires careful management and development of a strategy with a balanced future. There is a risk of population explosions, but also extensive industrialization and urbanization. This article discussed some important aspects related to smart city, urban logistics and related scientific terms from transport sector. During the development of this article, it was felt that several key elements needed to be mentioned. The diversified approach of researchers to the issue of smart city and urban logistics, in summary, makes it possible to distinguish the mainstream and directions of further development of the concept of intelligent logistics. Urban development has exacerbated the challenges of urban logistics, especially in megacities around the world. Urban development trends, such as exogenous urban freight transport trends, have motivated logistics providers to seek endogenous solutions to meet these challenges.

Based on approaches to smart cities, a search of world literature in the field of smart city and urban logistics was examined. The quality of smart mobility should be interpreted at a strategic level around the world. The smart city will have to use innovative approaches in all human areas in the future. The growth of e-commerce also caused by the growing sales of the online market, new information and communication technology and the paradigm of industry 4.0, which enable the acquisition of huge amounts of data generated from infrastructures, equipment, and vehicles, are factors that need to be managed in the city. One of the main goals of the smart city is to significantly reduce the externalities generated by shipment delivery activities. The commitment of all stakeholders and the application of the proposed solutions are essential to achieve sustainable logistics in urban areas. The future for smart city, urban logistics and transport sector is the benefits of logistics 4.0 in terms of digitization; in a very short time, the whole supply chain will be digitized and able to work intelligently on its own, and this will be possible further research in this sector in the future.

This article also provides a basis for follow-up research, which will yield new knowledge and skills that will contribute to the development of new technologies which will soon be implemented in everyday life. As the authors hope, they also contributing to making modern cities even more “smart”.

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Conflicts of 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.

References

[1] ALLWINKLE, S., CRUICKSHANK, P. Creating smarter cities: an overview. *Journal of Urban Technology* [online]. 2011, **18**(2), p. 1-16. ISSN 1063-0732, eISSN 1466-1853. Available from: https://doi.org/10.1080/10630732.2011.601103

[2] ALBINO, V., BERARDI, U., DANGEICO, R. M. Smart cities: definitions, dimensions, performance, and initiatives. *Journal of Urban Technology* [online]. 2015, **22**(1), p. 3-21. ISSN 1063-0732, eISSN 1466-1853. Available from: https://doi.org/10.1080/10630732.2014.942092

[3] ALKANDARI, A., ALNASHEET, M., ALSHEKHLY, I. F. T. Smart cities: Survey. *Journal of Advanced Computer Science and Technology Research* [online]. 2012, **2**(2), p. 79-90. ISSN 2231-8852. Available from: http://irep.iium.edu.my/24446/1/smart_cities-2012.pdf

[4] CHOURABI, H., NAM, T., WALKER, S., GIL-GARCIA, J.R., MELLOULI, S., NAHON, K., SCHOLL, H. J. Understanding smart cities: an integrative framework. In: Annual Hawaii International Conference on System Sciences: proceedings [online]. IEEE. 2012. ISBN 978-1-4577-1925-7, eISBN 978-0-7695-4525-7, p. 2289-2297. Available from: https://doi.org/10.1109/HICSS.2012.615

[5] GIL-GARCIA, J. R., PARDO, T. A., NAM, T. What makes a city smart? Identifying core components and proposing an integrative and comprehensive conceptualization. *Information Polity* [online]. 2015, **20**(1), p. 61-87. ISSN 1570-1255, eISSN 1875-8754. Available from: https://doi.org/10.3233/IP-150354

[6] BOLIVAR, M. P. R. Mapping dimensions of governance in smart cities. In: 17th International Digital Government Research Conference on Digital Government Research: proceedings [online]. 2016. ISBN 978-1-4503-4339-8, p. 312-324. Available from: https://doi.org/10.1145/2912160.2912176

[7] CARAGLIU, A., DEL BO, C. Smartness and European urban performance: assessing the local impacts of smart urban attributes. *Innovation: The European Journal of Social Science Research* [online]. 2012, **25**(2), p. 97-113. ISSN 1351-1610, eISSN 1469-8412. Available from: https://doi.org/10.1080/13511610.2012.660323

[8] BARNS, S. Smart cities and urban data platforms: designing interfaces for smart governance. *City, Culture and Society* [online]. 2018, **12**, p. 5-12. ISSN 1877-9166, eISSN 1877-9174. Available from: https://doi.org/10.1016/j.ccs.2017.09.006

[9] RUHLANDT, R. W. S. The governance of smart cities: a systematic literature review. *Cities* [online]. 2018, **81**, p. 1-23. ISSN 0264-2751, eISSN 1873-6084. Available from: https://doi.org/10.1016/j.cities.2018.02.014

[10] TOLENTINO-ZONDERVAN, F., BOGERS, E., VAN DE SANDE, L. A managerial and behavioral approach in aligning stakeholder goals in sustainable last mile logistics: a case study in the Netherlands. *Sustainability* [online]. 2021, **13**(8), 4434. eISSN 2071-1050. Available from: https://doi.org/10.3390/su13084434

[11] MACHARIS, C., TURCKSIN, L., LEBEAU, K. Multi actor multi criteria analysis (MAMCA) as a tool to support sustainable decisions: state of use. *Decision Support Systems* [online]. 2012, **54**(1), p. 610-620. ISSN 0167-9236, eISSN 1873-5797. Available from: https://doi.org/10.1016/j.dss.2012.08.008

[12] HARRINGTON, T. S., SINGH SRAI, J., KUMAR, M., WOHLRAB, J. Identifying design criteria for urban system ‘last-mile’ solutions - a multi-stakeholder perspective. *Production Planning and Control* [online]. 2016, **27**(6), p. 456-476. ISSN 0953-7287, eISSN 1366-5871. Available from: https://doi.org/10.1080/09537287.2016.1147099

[13] LAN, S., TSENG, M.L., YANG, C., HUISINGH, D. Trends in sustainable logistics in major cities in China. *Science of The Total Environment* [online]. 2020, **712**, 136381. ISSN 0048-9697, eISSN 1879-1026. Available from: https://doi.org/10.1016/j.scitotenv.2019.136381

[14] FOLTYNSKI, M. Sustainable urban logistics plan - current situation of the city of Poznan. *Transportation Research Procedia* [online]. 2019, **39**, p. 42-53. Available from: https://doi.org/10.1016/j.trpro.2019.06.006

[15] DESA, U. N. World urbanization prospects. The 2014 revision [online]. United Nations, Department of Economic and Social Affairs, Population Division, 2015. Available from: https://population.un.org/wup/publications/files/wup2014-report.pdf

[16] SEE, S. Artificial intelligence computing for a smart city. In: International Conference on Smart Cities, Infrastructure, Technologies and Applications: proceedings. Springer. 2017. ISBN 978-3-319-94179-0, eISBN 978-3-319-94180-6, p. 6-8. Available from: https://doi.org/10.1007/978-3-319-94180-6

[17] GIFFINGER, R. City-ranking of European medium-sized cities [online]. Vienna: Centre of Regional Science, Vienna University of Technology, 2007. Available from: https://ign.ku.dk/ansatte/landskabsarkitektur-planlaegning/?pure=files%2F37640170%2Fsmart_cities_final_report.pdf

[18] OLSSON, J., HELLSTROM, D., PALSSON, H. Framework of last mile logistics research: a systematic review of the literature. *Sustainability* [online]. 2019, **11**(24), 7131. eISSN 2071-1050. Available from: https://doi.org/10.3390/su11247131

[19] GEVAERS, R., VAN DE VOORDE, E., VANELSLANDER, T. Cost modelling and simulation of last-mile characteristics in an innovative B2C supply chain environment with implications on urban areas and cities. *Procedia - Social and Behavioral Sciences* [online]. 2014, **125**, p. 398-411. ISSN 1877-0428. Available from: https://doi.org/10.1016/j.sbspro.2014.01.1483

[20] LIM, S. F. W. T., JIN, X., SRAI, J. S. Consumer-driven e-commerce: a literature review, design framework, and research agenda on last-mile logistics models. *International Journal of Physical Distribution and Logistics Management* [online]. 2018, **48**(3), p. 308-332. ISSN 0960-0035. Available from: https://doi.org/10.1108/IJPDLM-02-2017-0081

[21] GEVAERS, R., VAN DE VOORDE, E., VANELSLANDER, T. Characteristics of innovations in last mile logistics-using best practices, case studies and making the link with green and sustainable logistics [online]. 2021. Available from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.676.5843andrep=rep1andtype=pdf

[22] SAVELSBERGH, M., VANWOENSEL, T. City logistics: challenges and opportunities. *Transportation Science* [online]. 2016, **50**(2), p. 579-590. ISSN 0041-1655, eISSN 1526-5447. Available from: https://doi.org/10.1287/trsc.2016.0675

[23] ROSENBERG, L. N., BALOUKA, N., HERER, Y. T., DANI, E., GASPARIN, P., DOBERS, K., RUEDIGER, D., PATTINIEMI, P., PORTHEINE, P., VAN UDEN S. Introducing the shared micro-depot network for last-mile logistics. *Sustainability* [online]. 2021, **13**(4), 2067. eISSN 2071-1050. Available from: https://doi.org/10.3390/su13042067

[24] EDWARDS, J. B., MCKINNON, A. C., CULLINANE, S. L. Comparative analysis of the carbon footprints of conventional and online retailing: a "last mile" perspective. *International Journal of Physical Distribution and Logistics Management* [online]. 2010, **40**, p. 103-123. ISSN 0960-0035. Available from: https://doi.org/10.1108/09600031011018055

[25] VAN LOON, P., DEKETELE, L., DEWAELE, J., MCKINNON, A., RUTHERFORD, C. A comparative analysis of carbon emissions from online retailing of fast moving consumer goods. *Journal of Cleaner Production* [online]. 2015, **106**, p. 478-486. ISSN 0959-6526, eISSN 1879-1786. Available from: https://doi.org/10.1016/j.jclepro.2014.06.060

[26] ALJOHANI, K., THOMPSON, R. G. A stakeholder - based evaluation of the most suitable and sustainable delivery fleet for freight consolidation policies in the inner - city area. *Sustainability* [online]. 2018, **11**(1), 124. eISSN 2071-1050. Available from: https://doi.org/10.3390/su11010124

[27] ALLEN, J., BEKTAS, T., CHERRETT, T., FRIDAY, A., MCLEOD, F., PIECYK, M., PIOTROWSKA, M., AUSTWICK, M. Z. Enabling a freight traffic controller for collaborative multidrop urban logistics: practical and theoretical challenges. *Transportation Research Record: Journal of the Transportation Research Board* [online]. 2017, **2609**, p. 77-84. ISSN 0361-1981, eISSN 2169-4052. Available from: https://doi.org/10.3141/2609-09

[28] RANIERI, L., DIGIESI, S., SILVESTRI, B., ROCCOTELLI, M. A review of last mile logistics innovations in an externalities cost reduction vision. *Sustainability* [online]. 2018, **10**(3), 782. eISSN 2071-1050. Available from: https://doi.org/10.3390/su10030782

[29] PAN, S., ZHOU, W., PIRAMUTHU, S., GIANNIKAS, V., CHEN, C. Smart city for sustainable urban freight logistics. *International Journal of Production Research* [online]. 2021, **59**, p. 2079-2089. Available from: https://doi.org/10.1080/00207543.2021.1893970

[30] FENG, X., CHU, F., CHU, C. B., HUANG, Y. Crowdsource-enabled integrated production and transportation scheduling for smart city logistics. *International Journal of Production Research* [online]. 2021, **59**(7), p. 2157-2176. ISSN 0020-7543, eISSN 1366-588X. Available from: https://doi.org/10.1080/00207543.2020.1808258

[31] WITKOWSKI, J., KIBA-JANIAK, M. The role of local governments in the development of city logistics. *Procedia - Social and Behavioral Sciences* [online]. 2014, **125**, p. 373-385. ISSN 1877-0428. Available from: https://doi.org/10.1016/j.sbspro.2014.01.1481

[32] HALL, N. G., POTTS, C. N. Supply chain scheduling: batching and delivery. *Operations Research* [online]. 2003, **51**(4), p. 566-584. ISSN 0030-364X, eISSN 1526-5463. Available from: https://doi.org/10.1287/opre.51.4.566.16106

[33] ANDERSON, S., ALLEN, J., BROWNE, M. Urban logistics-how can it meet policy makers' sustainability objectives? *Journal of Transport Geography* [online]. 2005, **13**(1), p. 71-81. ISSN 0966-6923, eISSN 1873-1236. Available from: https://doi.org/10.1016/j.jtrangeo.2004.11.002

[34] TANIGUCHI, E., THOMPSON, R. G., YAMADA, T. New opportunities and challenges for city logistics. *Transportation Research Procedia* [online]. 2016, **12**, p. 5-13. 2352-1457, eISSN 2352-1465. Available from: https://doi.org/10.1016/j.trpro.2016.02.004

[35] DABLANC, L., MORGANTI, E., ARVIDSSON, N., WOXENIUS, J., BROWNE, M., SAIDI, N. The rise of on-demand 'instant deliveries' in European cities. *Supply Chain Forum: An International Journal* [online]. 2017, **18**(4), p. 203-217. ISSN 1625-8312, eISSN 1624-6039. Available from: https://doi.org/10.1080/16258312.2017.1375375

[36] HOLGUIN-VERAS, J., AMAYA LEAL, J., SANCHEZ-DIAZ, I., BROWNE, M., WOJTOWICZ, J. State of the art and practice of urban freight management: Part I: Infrastructure, vehicle- related, and traffic operations. *Transportation Research Part A: Policy and Practice* [online]. 2020, **137**, p. 360-382. ISSN 0965-8564, eISSN 1879-2375. Available from: https://doi.org/10.1016/j.tra.2018.10.037

[37] ALZAHRANI, A., PETRI, I., REZGUI, Y. Analysis and simulation of smart energy clusters and energy value chain for fish processing industries. *Energy Reports* [online]. 2020, **6**(1), p. 534-540. eISSN 2352-4847. Available from: https://doi.org/10.1016/j.egyr.2019.09.022

[38] D'AMICO, G., SZOPIK-DEPCZYNSKA, K., DEMBINSKA, I., IOPPOLO, G. Smart and sustainable logistics of port cities: a framework for comprehending enabling factors, domains and goals. *Sustainable Cities and Society* [online]. 2021, **69**, 102801. ISSN 2210-6707, eISSN 2210-6715. Available from: https://doi.org/10.1016/j.scs.2021.102801

[39] HU, W., DONG, J., HWANG, B., REN, R., CHEN, Z. A scientometrics review on city logistics literature: research trends, advanced theory and practice. *Sustainability* [online]. 2019, **11**(10), 2724. eISSN 2071-1050. Available from: https://doi.org/10.3390/su11102724

[40] MAJERCAK, J., MAJERCAK, P. *Logistics / Logistika*. Bratislava: DOLIS, 2015. ISBN 978-80-8181-019-0.

[41] SKULTETY, F., BENOVA, D., GNAP, J. City Logistics as an imperative smart city mechanism: scrutiny of clustered EU27 capitals. *Sustainability* [online]. 2021, **13**(7), 3641. eISSN 2071-1050. Available from: https://doi.org/10.3390/su13073641

[42] BUYUKOZKAN, G., GOCER, F. Prioritizing the strategies to enhance smart city logistics by intuitionistic fuzzy CODAS. In: 11th Conference of the European Society for Fuzzy Logic and Technology EUSFLAT 2019: proceedings [online]. Vol. 1. 2019. ISBN 10.2991/eusflat-19.2019.110, p. 805-811. Available from: https://doi.org/10.2991/eusflat-19.2019.110

[43] SHEE, H., MIAH, S., TABOADA, I., DE VASS, T. Smart city - smart logistics amalgamation. In: 2020 IEEE European Technology and Engineering Management Summit E-TEMS: proceedings [online]. IEEE. 2020. eISBN 978-1-7281-0903-9, p. 1-4. Available from: https://doi.org/10.1109/E-TEMS46250.2020.9111852

[44] EKICI, S., KABAK, O., ULENGIN, F. Linking to compete: logistics and global competitiveness interaction. *Transport Policy* [online]. 2016, **48**, p. 117-128. ISSN 0967-070X, eISSN 1879-310X. Available from: https://doi.org/10.1016/j.tranpol.2016.01.015

[45] HIRSCHINGER, M. The Future of logistics in emerging markets - fuzzy clustering scenarios grounded in institutional and factor-market rivalry theory. In: *Essays on supply chain management in emerging markets. Essays on Supply Chain Management* [online]. Wiesbaden, Germany: Springer Fachmedien, 2016. ISBN 978-3-658-11945-4, eISBN 978-3-658-11946-1. Available from: https://doi.org/10.1111/jscm.12074

[46] JAISWAL, A., SAMUEL, C., GANESH, G. A. Pollution optimisation study of logistics in SMEs. *Management of Environmental Quality* [online]. 2019, **30**(4), p. 731-750. ISSN 1477-7835. Available from: https://doi.org/10.1108/MEQ-04-2018-0077

[47] CLEMENTE, M., FANTI, M. P, IACOBELLIS, G., NOLICH, M., UKOVICH, W. A decision support system for user-based vehicle relocation in car sharing systems. *IEEE Transactions on Systems, Man, and Cybernetics: Systems* [online]. 2018, **48**(8), p. 1283-1296. ISSN 2168-2216, eISSN 2168-2232. Available from: https://doi.org/10.1109/TSMC.2017.2665881

[48] NOLICH, M., SPOLADORE, D., CARCIOTTI, S. BUQI, R., SACCO, M. Cabin as a home: A novel comfort optimization framework for IoT equipped smart environments and applications on cruise ships. *Sensor* [online]. 2019, **19**(5), 1060. eISSN 1424-8220. Available from: https://doi.org/10.3390/s19051060

[49] SPOLADORE, D., ARLATI, S., CARCIOTTI, S., NOLICH, M., SACCO. M. Roomfort: an ontology-based comfort management application for hotels. *Electronics* [online]. 2018, **7**(12), 345. eISSN 2079-9292. Available from: https://doi.org/10.3390/electronics7120345

[50] CASCETTA, E., CARTENI, A., PAGLIARA, F., MONTANINO, M. A new look at planning and designing transportation systems: a decision-making model based on cognitive rationality, stakeholder engagement and quantitative methods. *Transport Policy* [online]. 2015, ***38***, p. 27-39. ISSN 1879-310X, eISSN 0967-070X. Available from: https://doi.org/10.1016/j.tranpol.2014.11.005

[51] FANTI, M. P., IACOBELLIS, G., NOLICH, M., RUSICH, A., UKOVICH, W. A decision support system for cooperative logistics. *IEEE Transactions on Automation Science and Engineering* [online]. 2017, ***14***(2), p. 732-744. ISSN 1545-5955, eISSN 1558-3783. Available from: https://doi.org/10.1109/TASE.2017.2649103

[52] CUZZOCREA, A., NOLICH, M., UKOVICH, W. A Big-data-analytics framework for supporting logistics problems in smart-city environments. *Procedia Computer Science* [online]. 2019, ***159***, p. 2589-2597. eISSN 1877-0509. Available from: https://doi.org/10.1016/j.procs.2019.09.257

[53] CUZZOCREA, A., NOLICH, M., UKOVICH, W. An innovative architecture for supporting cyber-physical security systems. In: Computational Science and Its Applications ICCSA 2018: proceedings [online]. 2018. ISBN 978-3-319-95173-7, eISBN 978-3-319-95174-4, p. 658-667. Available from: https://doi.org/10.1007/978-3-319-95174-4

[54] WONG, P. F., CHIA, F. C., KIU, M. S., LOU, E. C. W. Potential integration of blockchain technology into smart sustainable city (SSC) developments: a systematic review. *Smart and Sustainable Built Environment* [online]. 2020, ***11***(3), p. 559-574. ISSN 2046-6099. Available from: https://doi.org/10.1108/SASBE-09-2020-0140

[55] SZMELTER-JAROSZ, A., RZESNY-CIEPLINSKA, J., JEZIERSKI, A. Assessing resources management for sharing economy in urban logistics. *Resources* [online]. 2020, ***9***(9), 30. eISSN 2079-9276. Available from: https://doi.org/10.3390/resources9090113

[56] CEDER, A. Urban mobility and public transport: future perspectives and review. *International Journal of Urban Sciences* [online]. 2020, ***25***(4), p. 455-479. ISSN 1226-5934, eISSN 2161-6779. Available from: https://doi.org/10.1080/12265934.2020.1799846

[57] PERKUMIENE, D., PRANSKUNIENE, R., VIENAZINDIENE, M., GRIGIENE, J. The right to a clean environment: considering green logistics and sustainable tourism. *International Journal of Environmental Research and Public Health* [online]. 2020, ***17***(9), 23. eISSN 1660-4601. Available from: https://doi.org/10.3390/ijerph17093254

[58] ASTARITA, V., GIOFRE, V.P., MIRABELLI, G., SOLINA, V. A Review of Blockchain-based systems in transportation. *Information* [online]. 2020, ***11***(1), 24. eISSN 2078-2489. Available from: https://doi.org/10.3390/info11010021

[59] MANGIARACINA, R., PEREGO, A., SALVADORI, G., TUMINO, A. A comprehensive view of intelligent transport systems for urban smart mobility. *International Journal of Logistics Research and Applications* [online]. 2017, **20**(1), p. 39-52. ISSN 1367-5567, eISSN 1469-848X. Available from: https://doi.org/10.1080/13675567.2016.1241220

[60] DURACH, C. F., KEMBRO, J., WIELAND, A. A new paradigm for systematic literature reviews in supply chain management. *Journal of Supply Chain Management* [online]. 2017, **53**(4), p. 67-85. ISSN 2051-3771, eISSN 2050-7399. Available from: https://doi.org/10.1111/jscm.12145

[61] MULROW, C. D. The medical review article: state of the science. *Annals of Internal Medicine* [online]. 1987, **106**, p. 485-488. ISSN 0003-4819, eISSN 1539-3704. Available from: https://doi.org/10.7326/0003-4819-106-3-485

[62] TRANFIELD, D., DENYER, D., SMART, P. Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British Journal Management* [online]. 2003, **14**, p. 207-222. eISSN 1467-8551. Available from: https://doi.org/10.1111/1467-8551.00375

[63] PEREIRA, B. G. R., GUIMARAES, L. G., ANTONIO, L., NETO, A. R., MENDONCA, C. M. Bibliometric analysis in publications related to logistics and urban mobility in the smart city context. *Revista Tecnologia e Sociedade* [online]. 2019, **15**(36), p. 58-76. ISSN 1984-3526. Available from: https://doi.org/10.3895/rts.v15n36.8148

[64] GRISHAEVA, Y. M., MATANTSEVA, O. Y., SPIRIN, I. V., SAVOSINA, M. I., TKACHEVA, Z. N., VASIN, D. V. Sustainable development of transportation the cities of russia: experience and priorities. *South of Russia: Ecology, Development* [online]. 2018, **13**(4), p. 24-46. ISSN 1992-1098, eISSN 2413-0958. Available from: https://doi.org/10.18470/1992-1098-2018-4-24-46

[65] TSITSIASHVILI, G. S. Non stationary poisson model of continuously functioning queuing system. *Journal of Physics: Conference Series* [online]. 2020, **1680**, 012050. ISSN 1742-6596. Available from: https://doi.org/10.17223/19988605/52/12

[66] OLIVEIRA, T. A., GABRICH, Y. B., RAMALHINHO, H., OLIVER, M., COHEN, M. W., OCHI, L. S.,

GUEYE, S., PROTTI, F., PINTO, A. A., FERREIRA, D. V. M., COELHO, I. M., COELHO, V. N. Mobility, citizens, innovation and technology in digital and smart cities. *Future Internet* [online]. 2020, **12**(2), 27. eISSN 1999-5903. Available from: https://doi.org/10.3390/fi12020022

[67] MORA, L., DEAKIN, M., REID, A., ANGELIDOU, M. How to overcome the dichotomous nature of smart city research: proposed methodology and results of a pilot study. *Journal of Urban Technology* [online]. 2019, **26**(2), p. 89-128. ISSN 1063-0732, eISSN 1466-1853. Available from: https://doi.org/10.1080/10630732.2018.1525265

[68] AHAD, M. A., PAIVA, S., TRIPATHI, G., FEROZ, N. Enabling technologies and sustainable smart cities. *Sustainable Cities and Society* [online]. 2020, **61**, 12. ISSN 2210-6707, eISSN 2210-6715. Available from: https://doi.org/10.1016/j.scs.2020.102301

[69] RANA, N. P., LUTHRA, S., MANGLA, S. K., ISLAM, R., RODERICK, S., DWIVEDI, Y. K. Barriers to the development of smart cities in indian context. *Information Systems Frontiers* [online]. 2019, **21**, p. 503-525. ISSN 1387-3326, eISSN 1572-9419. Available from: https://doi.org/10.1007/s10796-018-9873-4

[70] HOPKINS, J., HAWKING, P. Big data analytics and IoT in logistics: a case study. *The International Journal of Logistics Management* [online]. 2018, **29**(2), p. 575-591. ISSN 0957-4093. Available from: https://doi.org/10.1108/IJLM-05-2017-0109

[71] MEHMOOD, R., MERITON, R., GRAHAM, G., HENNELLY, P., KUMAR, M. Exploring the influence of big data on city transport operations: a Markovian approach. *International Journal of Operations and Production Management* [online]. 2017, **37**(1), p. 75-104. ISSN 0144-3577. Available from: https://doi.org/10.1108/IJOPM-03-2015-0179

[72] JUAN, A., ALEJANDRO MENDEZ, C., FAULIN, J., DE ARMAS, J., GRASMAN, S. E. Electric vehicles in logistics and transportation: a survey on emerging environmental, strategic, and operational challenges. *Energies* [online]. 2016, **9**(2), 21. eISSN 1996-1073. Available from: https://doi.org/10.3390/en9020086

[73] TACHIZAWA, E. M., ALVAREZ-GIL, M. J., MONTES-SANCHO, M. J. How smart cities will change supply chain management. *Supply Chain Management* [online]. 2015, **20**(3), p. 237-248. ISSN 1359-8546. Available from: https://doi.org/10.1108/SCM-03-2014-0108

[74] WONG, E. Y. C., TAI, A. H., SO, S. Container drayage modelling with graph theory-based road connectivity assessment for sustainable freight transportation in new development area. *Computers and Industrial Engineering* [online]. 2020, **149**, 11. Available from: https://doi.org/10.1016/j.cie.2020.106810

[75] CHAUHAN, V., PATEL, M., TANWAR, S., TYAGI, S., KUMAR, N. IoT Enabled real-Time urban transport management system. *Computers and Industrial Engineering* [online]. 2020, **86**, 106810. ISSN 0360-8352, eISSN 1879-0550. Available from: https://doi.org/10.1016/j.compeleceng.2020.106746

[76] CHEN, M., CHEN, J., YANG, P., LIU, S., TANG, K. A heuristic repair method for dial-a-ride problem in intracity logistic based on neighborhood shrinking. *Multimedia Tools and Applications* [online]. 2020, **80**, p. 30775-30787. ISSN 1380-7501, eISSN 1573-7721. Available from: https://doi.org/10.1007/s11042-020-08894-7

[77] XIA, D., ZHANG, M., YAN, X., BAI, Y., ZHENG, Y., LI, Y., LI, H. A distributed WND-LSTM model on MapReduce for short-term traffic flow prediction. *Neural Computing and Applications* [online]. 2021, **33**, p. 2393-2410. ISSN 0941-0643, eISSN 1433-3058. Available from: https://doi.org/10.1007/s00521-020-05076-2

[78] RYAN, M., ANTONIOU, J., BROOKS, L., JIYA, T., MACNISH, K., STAHL, B. The ethical balance of using smart information systems for promoting the united nations' sustainable development goals. *Sustainability* [online]. 2020, **12**(12), 22. eISSN 2071-1050. Available from: https://doi.org/10.3390/su12124826

[79] YANG, J., GUIZANI, N., HU, L., GHONEIM, A., ALRASHOUD, M., HOSSAIN, M. S. Smart autonomous moving platforms. *IEEE Network* [online]. 2020, **34**(3), p. 116-123. ISSN 0890-8044, eISSN 1558-156X. Available from: https://doi.org/10.1109/MNET.011.1900263

[80] GUERRA, A., DARDARI, D., DJURIC, P. M. Dynamic radar network of UAVs: a joint navigation and tracking approach. *IEEE Access* [online]. 2020, **8**, p. 116454-116469. eISSN 2169-3536. Available from: https://doi.org/10.1109/ACCESS.2020.3001393

[81] IRANMANESH, S., RAAD, R., RAHEEL, M. S., TUBBAL, F., JAN, T. Novel DTN mobility-driven routing in autonomous drone logistics networks. *IEEE Access* [online]. 2020, **8**, p. 13661-13673. eISSN 2169-3536. Available from: https://doi.org/10.1109/ACCESS.2019.2959275

[82] ASTHANA, S., DWIVEDI, A. Performance measurement of India-based third party logistics sector: an empirical study of user versus provider perspectives. *Production Planning and Control* [online]. 2020, **31**(2-3), p. 259-272. ISSN 0953-7287, eISSN 1366-5871. Available from: https://doi.org/10.1080/09537287.2019.1631467

[83] CHEN, X. The development trend and practical innovation of smart cities under the integration of new technologies. *Frontiers of Engineering Management* [online]. 2019, **6**, p. 485-502. ISSN 2095-7513, eISSN 2096-0255. Available from: https://doi.org/10.1007/s42524-019-0057-9

[84] ZHAO, B., TEO, Y.S., NG, W.S., NG, H.H. Data-driven next destination prediction and ETA improvement for urban delivery fleets. *IET Intelligent Transport Systems* [online]. 2019, **13**, p. 1624-1635. eISSN 1751-9578. Available from: https://doi.org/10.1049/iet-its.2019.0148

[85] SHAO, S., XU, G., LI, M. The design of an IoT-based route optimization system: a smart product-service system (SPSS) approach. *Advanced Engineering Informatics* [online]. 2019, **42**, 9. ISSN 1474-0346, eISSN 1873-5320. Available from: https://doi.org/10.1016/j.aei.2019.101006

[86] ARAUJO, V., MITRA, K., SAGUNA, S., AHLUND, C. Performance evaluation of FIWARE: a cloud-based IoT platform for smart cities. *Journal of Parallel and Distributed Computing* [online]. 2019, **132**, p. 250-261. ISSN 0743-7315, eISSN 1096-0848. Available from: https://doi.org/10.1016/j.jpdc.2018.12.010

[87] SICARI, S., RIZZARDI, A., COEN-PORISINI, A. How to evaluate an internet of things system: models, case studies, and real developments. *Software: Practice and Experience* [online]. 2019, **49**(11), p. 1663-1685. eISSN 1097-024X. Available from: https://doi.org/10.1002/spe.2740

[88] LIU, C., LI, H.Y., TANG, Y.W., LIN, D.T., LIU, J.W. Next generation integrated smart manufacturing based on big data analytics, reinforced learning, and optimal routes planning methods. *International Journal of Computer Integrated Manufacturing* [online]. 2019, **32**(9), p. 820-831. ISSN 0951-192X, eISSN 1362-3052. Available from: https://doi.org/10.1080/0951192X.2019.1636412

[89] HUSSEIN, A. H. Internet of things (IOT): research challenges and future applications. *International Journal of Advanced Computer Science and Applications (IJACSA)* [online]. 2019, **10**(6), p. 77-82. ISSN 2156-5570, eISSN 2158-107X. Available from: https://doi.org/10.14569/IJACSA.2019.0100611

[90] AQIB, M., MEHMOOD, R., ALZAHRANI, A., KATIB, I., ALBESHRI, A., ALTOWAIJRI, S. M. Smarter traffic prediction using big data, in-memory computing, deep learning and GPUs. *Sensors* [online]. 2019, **19**(9), 34. eISSN 1424-8220. Available from: https://doi.org/10.3390/s19092206

[91] SARKER, R. I., KAPLAN, S., ANDERSON, M. K., HAUSTEIN, S., MAILER, M., TIMMERMANS, H. J. P. Obtaining transit information from users of a collaborative transit app: platform-based and individual-related motivators. *Transportation Research Part C: Emerging Technologies* [online]. 2019, **102**, p. 173-188. ISSN 0968-090X, eISSN 1879-2359. Available from: https://doi.org/10.1016/j.trc.2019.03.011

[92] ABBASI, K. M., KHAN, T. A., UL HAQ, I. Hierarchical modeling of complex internet of things systems using conceptual modeling approaches. *IEEE Access* [online]. 2019, **7**, p. 102772-102791. eISSN 2169-3536. Available from: https://doi.org/10.1109/ACCESS.2019.2930933

[93] LIAO, D. Y., WANG, X. Applications of Blockchain technology to logistics management in integrated casinos and entertainment. *Informatics* [online]. 2018, **5**(4), 21. eISSN 2227-9709. Available from: https://doi.org/10.3390/informatics5040044

[94] GOHAR, M., MUZAMMAL, M., RAHMAN, A. U. SMART TSS: Defining transportation system behavior using big data analytics in smart cities. *Sustainable Cities and Society* [online]. 2018, **41**, p. 114-119. ISSN 2210-6707, eISSN 2210-6715. Available from: https://doi.org/10.1016/j.scs.2018.05.008

[95] GOUDOS, S. K., DALLAS, P. I., CHATZIEFTHYMIOU, S., KYRIAZAKOS, S. A survey of IoT key enabling and future technologies: 5G, mobile IoT, sematic web and applications. *Wireless Personal Communications* [online]. 2017, **97**, p. 1645-1675. ISSN 0929-6212, eISSN 1572-834X. Available from: https://doi.org/10.1007/s11277-017-4647-8

[96] ERKOLLAR, A., OBERER, B. Flextrans 4.0 - smart logistics for smart cities. *Sigma Journal of Engineering and Natural Sciences* [online]. 2017, **8**(4), p. 269-277. ISSN 1304-7191, e-ISSN 1304-7205. Available from: https://sigma.yildiz.edu.tr/storage/upload/pdfs/1635949255-en.pdf

[97] LI, D. R., CAO, J. J., YAO, Y. Big data in smart cities. *Science China Information Sciences* [online]. 2015, **58**, 12. ISSN 1674-733X, eISSN 1869-1919. Available from: https://doi.org/10.1007/s11432-015-5396-5

[98] ADAMCZAK, M., TOBOLA, A., FIJALKOWSKA, J., CYPLIK, P., TORZ, M. Analysis of incentives to eco-driving for car rental companies' customers. *Sustainability* [online]. 2020, **12**(24), 20. eISSN 2071-1050. Available from: https://doi.org/10.3390/su122410579

[99] NAGY, S., CSISZAR, C. The quality of smart mobility: a systematic review. *Scientific Journal of Silesian University of Technology. Series Transport* [online]. 2020, **109**, p. 117-127. ISSN 0209-3324, eISSN 2450-1549. Available from: https://doi.org/10.20858/sjsutst.2020.109.11

[100] DEL VECCHIO, P., SECUNDO, G., MARUCCIA, Y., PASSIANTE, G. A system dynamic approach for the smart mobility of people: implications in the age of big data. *Technological Forecasting and Social Change* [online]. 2019, **149**, 15. ISSN 0040-1625, eISSN 1873-5509. Available from: https://doi.org/10.1016/j.techfore.2019.119771

[101] SHI, F., WU, D., ARKHIPOV, D.I., LIU, Q., REGAN, A.C., MCCANN, J. A. ParkCrowd: reliable crowdsensing for aggregation and dissemination of parking space information. *IEEE Transactions on Intelligent Transportation Systems* [online]. 2019, **20**(11), p. 4032-4044. ISSN 1524-9050, eISSN 1558-0016. Available from: https://doi.org/10.1109/TITS.2018.2879036

[102] MAZZARINO, M., RUBINI, L. Smart urban planning: evaluating urban logistics performance of innovative solutions and sustainable policies in the Venice lagoon - the results of a case study. *Sustainability* [online]. 2019, **11**(17), 27. eISSN 2071-1050. Available from: https://doi.org/10.3390/su11174580

[103] PEPRAH, C., AMPONSAH, O., ODURO, C. A system view of smart mobility and its implications for Ghanaian

cities. *Sustainable Cities and Society* [online]. 2019, **44**, p. 739-747. ISSN 2210-6707, eISSN 2210-6715. Available from: https://doi.org/10.1016/j.scs.2018.10.025

[104] MOZOS-BLANCO, A. M., POZO-MENENDEZ, E., ARCE-RUIZ, R., BAUCELLS-ALETA, N. The way to sustainable mobility. A comparative analysis of sustainable mobility plans in Spain. *Transport Policy* [online]. 2018, **72**, p. 45-54. ISSN 0967-070X, eISSN 1879-310X. Available from: https://doi.org/10.1016/j.tranpol.2018.07.001

[105] KEIMER, A., LAURENT-BROUTY, N., FAROKHI, F., SIGNARGOUT, H., CVETKOVIC, V., BAYEN, A. M., JOHANSSON, K. H. Information patterns in the modeling and design of mobility management services. *Proceedings of the IEEE* [online]. 2018, **106**(4), p. 554-576. ISSN 0018-9219, eISSN 1558-2256. Available from: https://doi.org/10.1109/JPROC.2018.2800001

[106] KRESAK, J., CAGANOVA, D., BINDZAR, P., BARTAKOVA, G. P. Use of mining FREIGHT cableway in urban mobility as a part of an integrated transport system. *Acta Montanistica Slovaca / Acta Montanistica Slovaca* [online]. 2018, **23**(2), p. 194-205. ISSN 1335-1788. Available from: https://actamont.tuke.sk/pdf/2018/n2/8kresak.pdf

[107] MELO, S., MACEDO, J., BAPTISTA, P. Guiding cities to pursue a smart mobility paradigm: an example from vehicle routing guidance and its traffic and operational effects. *Research in Transportation Economics* [online]. 2017, **65**, p. 24-33. ISSN 0739-8859, eISSN 1875-7979. Available from: https://doi.org/10.1016/j.retrec.2017.09.007

[108] TURON, K., CZECH, P., JUZEK, M. The concept of a walkable city as an alternative form of urban mobility. *Scientific Journal of Silesian University of Technology. Series Transport* [online]. 2017, **95**, p. 223-230. ISSN 0209-3324, eISSN 2450-1549. Available from: https://doi.org/10.20858/sjsutst.2017.95.20

[109] PRONELLO, C., VEIGA-SIMAO, J., RAPPAZZO, V. Can multimodal real-time information systems induce a more sustainable mobility? *Transportation Research Record: Journal of the Transportation Research Board* [online]. 2016, **2566**(1), p. 64-70. ISSN 0361-1981, eISSN 2169-4052. Available from: https://doi.org/10.3141/2566-07

[110] LU, E. H. C., YANG, Y. W. A hybrid route planning approach for logistics with pickup and delivery. *Expert Systems with Applications* [online]. 2019, **118**, p. 482-492. ISSN 0957-4174, eISSN 1873-6793. Available from: https://doi.org/10.1016/j.eswa.2018.10.031

[111] REYES-RUBIANO, L., FERONE, D., JUAN, A. A., FAULIN, J. A simheuristic for routing electric vehicles with limited driving ranges and stochastic travel times. *SORT-Statistics and Operations Research Transactions* [online]. 2019, **43**(1), p. 3-24. eISSN 2013-8830. Available from: https://doi.org/10.2436/20.8080.02.77

[112] YU, J. J. Q., LAM, A. Y. S. Autonomous vehicle logistic system: joint routing and charging strategy. *IEEE Transactions on Intelligent Transportation Systems* [online]. 2018, **19**(7), p. 2175-2187. ISSN 1524-9050, eISSN 1558-0016. Available from: https://doi.org/10.1109/TITS.2017.2766682

[113] ALVAREZ, P., LERGA, I., SERRANO-HERNANDEZ, A., FAULIN, J. The impact of traffic congestion when optimising delivery routes in real time. a case study in Spain. *International Journal of Logistics Research and Applications* [online]. 2018, **21**(5), p. 529-541. ISSN 1367-5567, eISSN 1469-848X. Available from: https://doi.org/10.1080/13675567.2018.1457634

[114] PERBOLI, G., GOBBATO, L., MAGGIONI, F. A progressive hedging method for the multi-path travelling salesman problem with stochastic travel times. *IMA Journal of Management Mathematics* [online]. 2017, **28**(1), p. 65-86. eISSN 1471-6798. Available from: https://doi.org/10.1093/imaman/dpv024

[115] ABBATECOLA, L., FANTI, M.P., MANGINI, A.M., UKOVICH, W. A decision support approach for postal delivery and waste collection services. *IEEE Transactions on Automation Science and Engineering* [online]. 2016, **13**(4), p. 1458-1470. ISSN 1545-5955, eISSN 1558-3783. Available from: https://doi.org/10.1109/TASE.2016.2570121

[116] MUELAS, S., LATORRE, A., PENA, J. M. A distributed VNS algorithm for optimizing dial-a-ride problems in large-scale scenarios. *Transportation Research Part C: Emerging Technologies* [online]. 2015, **54**, p. 110-130. ISSN 0968-090X, eISSN 1879-2359. Available from: https://doi.org/10.1016/j.trc.2015.02.024

[117] KIM, J., MOON, H., JUNG, H. Drone-based parcel delivery using the rooftops of city buildings: model and solution. *Applied Sciences* [online]. 2020, **10**(12), 20. eISSN 2076-3417. Available from: https://doi.org/10.3390/app10124362

[118] IRANMANESH, S., RAAD, R. A novel data forwarding strategy for a drone delay tolerant network with range extension. *Electronics* [online]. 2019, **8**(6), 14. eISSN 2079-9292. Available from: https://doi.org/10.3390/electronics8060659

[119] WANG, F. X., WANG, F., MA, X., LIU, J. Demystifying the crowd intelligence in last mile parcel delivery for smart cities. *IEEE Network* [online]. 2019, ***33***(2), p. 23-29. ISSN 0890-8044, eISSN 1558-156X. Available from: https://doi.org/10.1109/MNET.2019.1800228

[120] DE CARVALHO, S. P. P., KALID, R. A., RODRIGUEZ, M. J. L. Evaluation of the city logistics performance through structural equations model. *IEEE Access* [online]. 2019, **7**, p. 121081-121094. eISSN 2169-3536.

Available from: https://doi.org/10.1109/ACCESS.2019.2934647
[121] DEMIRTAS, N., TUZKAYA, U. R., TANYAS, M. Layout of urban distribution center using possibilistic programming. *International Journal of Computational Intelligence Systems* [online]. 2016, **9**(6), p. 1068-1081. ISSN 1875-6891, eISSN 1875-6883. Available from: https://doi.org/10.1080/18756891.2016.1256559
[122] AHMAD, N., MEHMOOD, R. Enterprise systems and performance of future city logistics. *Production Planning and Control* [online]. 2016, **27**(6), p. 500-513. ISSN 0953-7287, eISSN 1366-5871. Available from: https://doi.org/10.1080/09537287.2016.1147098
[123] HE, Z., HAASIS, H. D. A theoretical research framework of future sustainable urban freight transport for smart cities. *Sustainability* [online]. 2020, **12**(5), 28. eISSN 2071-1050. Available from: https://doi.org/10.3390/su12051975
[124] COMI, A., SCHIRALDI, M.M., BUTTARAZZI, B. Smart urban freight transport: tools for planning and optimising delivery operations. *Simulation Modelling Practice and Theory* [online]. 2018, **88**, p. 48-61. ISSN 1569-190X, eISSN 1878-1462. Available from: https://doi.org/10.1016/j.simpat.2018.08.006
[125] CAVONE, G., DOTOLI, M., SEATZU, C. A survey on petri net models for freight logistics and transportation systems. *IEEE Transactions on Intelligent Transportation Systems* [online]. 2018, **19**(6), p. 1795-1813. ISSN 1524-9050, eISSN 1558-0016. Available from: https://doi.org/10.1109/TITS.2017.2737788
[126] HEDDEBAUT, O., DI CIOMMO, F. City-hubs for smarter cities. The case of Lille EuraFlandres interchange. *European Transport Research Review* [online]. 2018, **10**, 10. ISSN 1866-8887, eISSN 1867-0717. Available from: https://doi.org/10.1007/s12544-017-0283-3
[127] GATTA, V., MARCUCCI, E., LE PIRA, M. Smart urban freight planning process: integrating desk, living lab and modelling approaches in decision-making. *European Transport Research Review* [online]. 2017, ***9***, 32. ISSN 1866-8887, eISSN 1867-0717. Available from: https://doi.org/10.1007/s12544-017-0245-9
[128] RODRIGUE, J. P., DABLANC, L., GIULIANO, G. The freight landscape: convergence and divergence in urban freight distribution. *Journal of Transport and Land Use* [online]. 2017, **10**(1), p. 557-572. ISSN 1938-7849. Available from: https://doi.org/10.5198/jtlu.2017.869
[129] JIANG, N., TIAN, E., DANESHMAND MALAYERI, F., BALALI, A. A new model for investigating the impact of urban knowledge, urban intelligent transportation systems and IT infrastructures on the success of SCM systems in the distributed organizations. *Kybernetes / Kybernetika* [online]. 2020, **49**(11), p. 2799-2818. ISSN 0368-492X. Available from: https://doi.org/10.1108/K-04-2019-0288
[130] HOSEINZADEH, N., LIU, Y.D., HAN, L.D., BRAKEWOOD, C., MOHAMMADNAZAR, A. Quality of location-based crowdsourced speed data on surface streets: a case study of Waze and Bluetooth speed data in Sevierville, TN. *Computers, Environment and Urban Systems* [online]. 2020, **83**, 14. ISSN 0198-9715, eISSN 1873-7587. Available from: https://doi.org/10.1016/j.compenvurbsys.2020.101518
[131] PAN, X., LI, M., WANG, M., ZONG, T., SONG, M. The effects of a smart logistics policy on carbon emissions in China: a difference-in-differences analysis *Transportation Research Part E: Logistics and Transportation Review* [online]. 2020, **137**, 101939. ISSN 1366-5545, eISSN 1878-5794. Available from: https://doi.org/10.1016/j.tre.2020.101939
[132] HUANG, L., XIE, G., BLENKINSOPP, J., HUANG, R., BIN, H. Crowdsourcing for sustainable urban logistics: exploring the factors influencing crowd workers' participative behavior. *Sustainability* [online]. 2020, **12**(8), 20. eISSN 2071-1050. Available from: https://doi.org/10.3390/su12083091
[133] BULATOV, N. K., TOILYBAYEV, A. E., SULEYEVA, N. Z., SARZHANOV, D. K. Development of the model (algorithm) of the efficient transportation logistics with the purpose of collection and transportation of the solid municipal waste to the places of their recycling. *Environment, Development and Sustainability* [online]. 2021, **23**, p. 2015-2037. ISSN 1387-585X, eISSN 1573-2975. Available from: https://doi.org/10.1007/s10668-020-00661-w
[134] WU, H., TAO, F., QIAO, Q., ZHANG, M. A Chance-constrained vehicle routing problem for wet waste collection and transportation considering carbon emissions. *International Journal of Environmental Research and Public Health* [online]. 2020, **17**(2), 21. eISSN 1660-4601. Available from: https://doi.org/10.3390/ijerph17020458
[135] VILACA, M., MACEDO, E., TAFIDIS, P., COELHO, M. C. Multinomial logistic regression for prediction of vulnerable road users risk injuries based on spatial and temporal assessment. *International Journal of Injury Control and Safety Promotion* [online]. 2019, **26**(4), p. 379-390. ISSN 1745-7300, eISSN 1745-7319. Available from: https://doi.org/10.1080/17457300.2019.1645185
[136] AQIB, M., MEHMOOD, R., ALZAHRANI, A., KATIB, I., ALBESHRI, A., ALTOWAIJRI, S. M. Rapid transit systems: smarter urban planning using big data, in-memory computing, deep learning, and GPUs. *Sustainability* [online]. 2019, **11**(10), 33. eISSN 2071-1050. Available from: https://doi.org/10.3390/su11102736
[137] BUYUKOZKAN, G., MUKUL, E. Evaluation of smart city logistics solutions with fuzzy MCDM methods. *Pamukkale University Journal of Engineering Sciences* [online]. 2019, **25**(9), p. 1033-1040. ISSN 1300-7009, eISSN 2147-5881. Available from: https://doi.org/10.5505/pajes.2019.32956

[138] RUSSO, F., RINDONE, C., PANUCCIO, P. European plans for the smart city: from theories and rules to logistics test case. *European Planning Studies* [online]. 2016, **24**(9), p. 1709-1726. ISSN 0965-4313, eISSN 1469-5944. Available from: https://doi.org/10.1080/09654313.2016.1182120
[139] BARRIOS, J. A., GODIER, J. D. Fleet sizing for flexible carsharing systems simulation-based approach. *Transportation Research Record: Journal of the Transportation Research Board* [online]. 2014, **2416**(1), p. 1-9. ISSN 0361-1981, eISSN 2169-4052. Available from: https://doi.org/10.3141/2416-01
[140] OGBUKE, N. J., YUSUF, Y. Y., DHARMA, K., MERCANGOZ, B. A. Big data supply chain analytics: ethical, privacy and security challenges posed to business, industries and society. *Production Planning and Control* [online]. 2020, ***15***(2-3), p. 123-137. ISSN 0953-7287, eISSN 1366-5871. Available from: https://doi.org/10.1080/09537287.2020.1810764
[141] PASKANNAYA, T., SHABAN, G. Innovations in green logistics in smart cities: USA and EU experience. *Marketing and Management of Innovations* [online]. 2019, **10**(1), p. 173-181. ISSN 2218-4511, eISSN 2227-6718. Available from: https://doi.org/10.21272/mmi.2019.1-14
[142] CHEN, X., ZHANG, S., DING, X., KADRY, S.N., HSU, C. IoTcloud platform for information processing in smart city. *Computational Intelligence* [online]. 2020, **37**(3), p. 1428-1444. eISSN 1467-8640. Available from: https://doi.org/10.1111/coin.12387
[143] LAURIERI, N., LUCCHESE, A., MARINO, A., DIGIESI, S. A door-to-door waste collection system case study: a survey on its sustainability and effectiveness. *Sustainability* [online]. 2020, **12**(14), 24. eISSN 2071-1050. Available from: https://doi.org/10.3390/su12145520
[144] RYBICKA, I., DROZDZIEL, P., STOPKA, O., LUPTAK, V. Methodology to propose a regional transport organization within specific integrated transport system: a case study. *Transport Problems* [online]. 2018, **13**(4), p. 115-125. ISSN 1896-0596, eISSN 2300-861X. Available from: https://doi.org/10.20858/tp.2018.13.4.11
[145] DE OLIVEIRA, R. C. H., FERREIRA COSTA, A. P., THOMAZ, V. F., SILVA, I. A. Low-cost deployment proposal to urban mobility in smart cities. *The Journal of Supercomputing* [online]. 2019, **75**, p. 7265-7289. ISSN 0920-8542, eISSN 1573-0484. Available from: https://doi.org/10.1007/s11227-019-02941-3
[146] GUERLAIN, C., RENAULT, S., FERRERO, F., FAYE, S. Decision support systems for smarter and sustainable logistics of construction sites. *Sustainability* [online]. 2019, **11**(10), 22. eISSN 2071-1050. Available from: https://doi.org/10.3390/su11102762
[147] MISRA, D., DAS, G., CHAKRABORTTY, T., DAS, D. An IoT-based waste management system monitored by cloud. *Journal of Material Cycles and Waste Management* [online]. 2018, **20**, p. 1574-1582. ISSN 1438-4957, eISSN 1611-8227. Available from: https://doi.org/10.1007/s10163-018-0720-y
[148] TU, W., ZHAO, T., ZHOU, B., JIANG, J., XIA, J., LI, Q. OCD: Online crowdsourced delivery for on-demand food. *IEEE Internet of Things Journal* [online]. 2020, **7**(8), p. 6842-6854. eISSN 2327-4662. Available from: https://doi.org/10.1109/JIOT.2019.2930984
[149] DOMINGUEZ, J. M. L., AL-TAM, F., DE J. MATEO SANGUINO, T., CORREIA, N. Analysis of machine learning techniques applied to sensory detection of vehicles in intelligent crosswalks. *Sensors* [online]. 2020, **20**(21), 17. eISSN 1424-8220. Available from: https://doi.org/10.3390/s20216019
[150] DHAKAL, N., CHERRY, C. R., LING, Z., AZAD, M. Using CyclePhilly data to assess wrong-way riding of cyclists in Philadelphia. *Journal of Safety Research* [online]. 2018, **67**, p. 145-153. ISSN 0022-4375, eISSN 1879-1247. Available from: https://doi.org/10.1016/j.jsr.2018.10.004
[151] RADOCAJ, D., PLASCAK, I., JURISIC, M. Global navigation satellite systems as state-of-the-art solutions in precision agriculture: a review of studies indexed in the Web of Science. *Agriculture* [online]. 2023, **13**(7), 1417. eISSN 2077-0472. Available from: https://10.3390/agriculture13071417
[152] MALANSKI, P. D., SCHIAVI, S. M. D., DEDIEU, B., DAMANSCENO, J. C. International research on labor in agri-food value chains: a bibliometric review from web of science. *Frontiers in Sustainable Food Systems* [online]. 2022, **6**, 852178. eISSN 2571-581X. Available from: https://10.3389/fsufs.2022.852178

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DEVELOPMENT AND PERFORMANCE INVESTIGATION OF THE DIRECT BRUSHLESS TORQUE MOTOR

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Resume

The paper deals with the brushless torque motor, that was designed for precise positioning device to substitute servo drive for high torque and low speed application. It describes the design, basic parameters as well as the analysis of torque characteristic. The paper also presents the results of realized measurements. Finally, the parameters of the brushless torque motor and servo drive applicated in precise positioning device are compared. A series of measurements like measurement of torque characteristics, loading characteristics and also measurements of drive performances are presented in this paper.

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1 Introduction

Brushless torque motors have gained immense popularity in recent years due to their high torque-to-weight ratio, high efficiency, and precise motion control capabilities. Difference from conventional motors that rely on brushes and commutators to transfer power, brushless torque motors use a system of magnets and windings to generate torque. This design eliminates the need for brushes and commutators, resulting in reduced maintenance requirements and improved reliability [1- 3].

The high torque density of brushless torque motors makes them ideal for a wide range of applications, including robotics, aerospace, and medical devices. They can provide precise control over rotational motion, making them suitable for tasks such as positioning, indexing, and driving linear motion [4-7]. Moreover, their ability to operate at high speeds and torques while maintaining high efficiency makes them an attractive option for power-hard applications.

Classical permanent magnet synchronous motors (PMSM), with a nominal mechanical torque ranging from 1 to 5Nm, are commonly used in servo drives. A linked gearbox is utilized with this one when a larger torque is required from the same PMSM motor [8-10]. These gears often have ratios between 70 and 150. As alternatives to the traditional PMSM with connected gearbox, Direct Drive motors and Slotless brushless ring motors with high torque output and low speed are possible. Industrial applications, such as high precision industrial servo drives, are increasingly using direct drives with brushless motors [11-13].

The EVPU Company designed a number of segments slotless PMSMs to replace PMSM with gearbox solutions. These designed PMSMs were submitted to a number of measurements [1-3]. Results from these measurements should validate the designed permanent magnet linear synchronous motor's electrical properties since it has an ironless moving part at rotation construction and is first referred to as a segment slotless PMSM. Results from these tests should also support the quality of the segment slotless PMSM drive that was designed (such as accuracy, repeatability, stabilization test, and operating instability - in this kind of measurement, the servo drive was in speed mode). Field-oriented control (cascade vector control with feed forward position loop) was put into place on this drive for these measurements (experimental verification). The next stage of development was the design of a DC brushless motor with high torque and low speed application. Target requirements for direct drive DC brushless torque motor for precise positioning device were: max. speed 5 to 40 rad/s, rated torque 150 Nm, supply voltage 300 V DC with alternative 24 V DC. Expected properties: very high accuracy, lower weight of the direct drive torque motor than servo drive, Brushless direct current (BLDC) motor provides the ability of movement without power, sustainability, soft start in freezing.

2 Design of direct brushless torque motor

Electromagnetic and thermal design of BLDC motor was based on volume of servo drive in the precise positioning device, characterized with the space for large

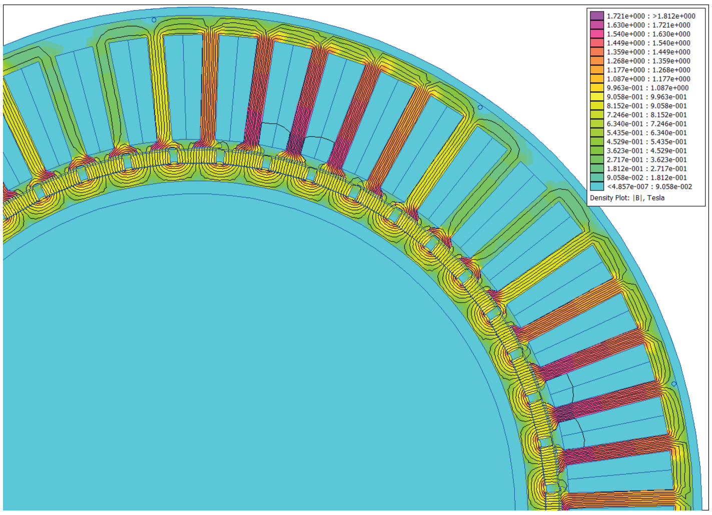

Figure 1 *2D magnetic flux distribution in cross section of BLDC motor at rated current*

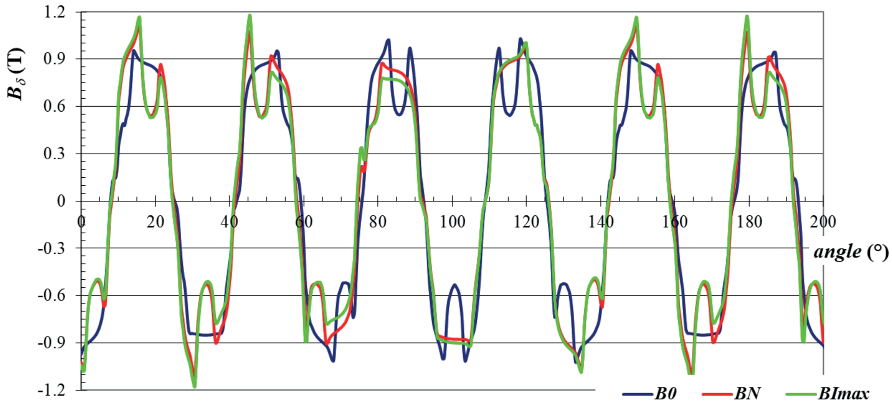

Figure 2 *Air gap magnetic flux density waveform*

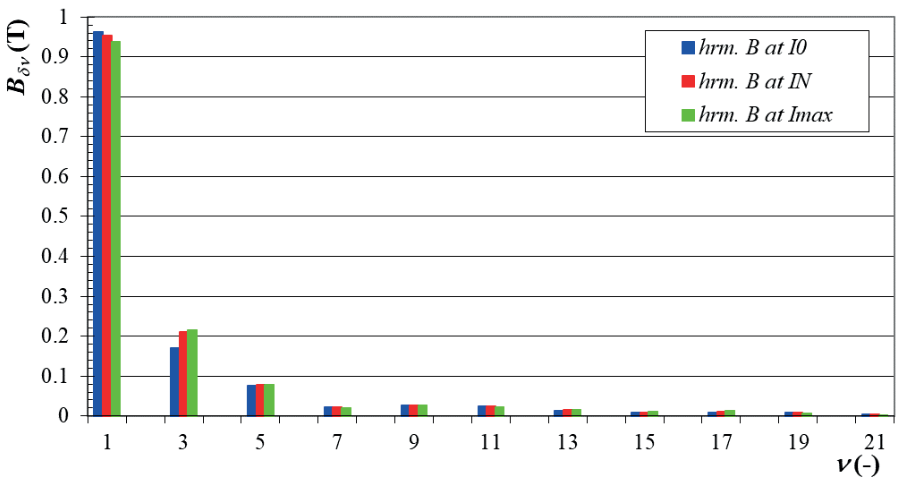

Figure 3 *Harmonic analysis of BLDC motor magnetic flux density at no-load state, at nominal and maximum current*

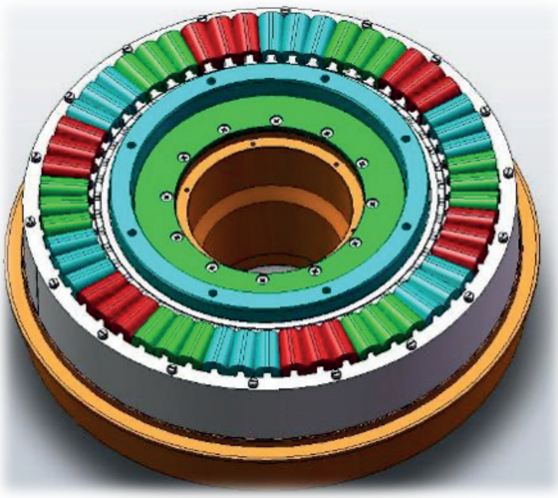

Figure 4 *3D model of designed 3phase BLDC motor with frame*

Q=54
m=3
$2p$=48
Q=0.375
Connection □
Winding diagram (repetition of the scheme from slots Q1÷Q9; 6x):

Slot:	1	2	3	4	5	6	7	8	9
Phase:	+A	-A	+A	+B	-B	+B	+C	-C	+C
Phase:	C-	A-	A+	A-	B-	B+	B-	C-	C+

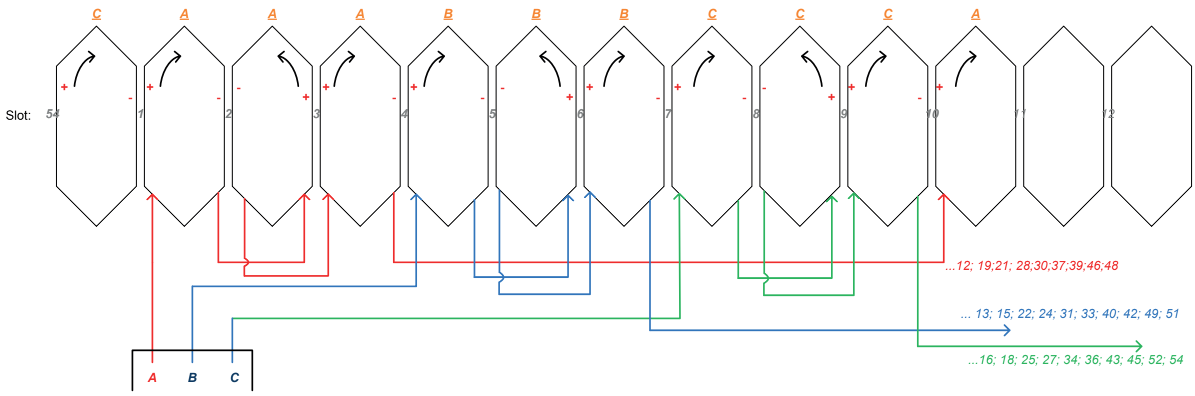

Figure 5 Winding diagram: connection: triangle, *2p=24, q=0.375, Q=27*

diameter and small length that is, a thin ring motor design. The content of the research and development work in design BLDC motor was:

- selection of the appropriate winding configuration and arrangement of the permanent magnets;
- calculation of the BLDC motor magnetic circuit; determining the volume of PM, the calculation of the magnetic field distribution in the air gap, the calculation of moments, torque ripple et al.

Figure 1 to Figure 3 shows the finite element analysis (FEA) result of the designed BLDC motor. It is well known that by using FEA is possible to optimize the electro-thermal and electro – magnetic properties of the electric machines and electric devices [14-16]. Considering proposed work, the same procedure was used as well.

Using the previously described design approach, then is possible to develop a 3D model of the proposed component. Figure 4 shows 3D interpretation of the construction of investigated BLDC motor, while Figure 5 represents the detailed winding diagram.

Both the dependency of motor torque on rotor position (Figure 6) and the dependence of torque on current (Figure 7) have been studied using FEM analysis. Because the predicted torque's magnitude depends on the mutual rotation of the stator and rotor, the torque ripple was also examined for each point of the vector magnetic field (Figure 8). The electromagnetic torque's dependency on the position of the magnetic field vector, as well as the rotation of the stator and rotor, was detected by combining the estimated changes.

Based on the compiled switching plan for the three-phase winding current vector, the dependence of the torque on the rotor angle for each switching state and position was also recalculated and thus the ripple torque

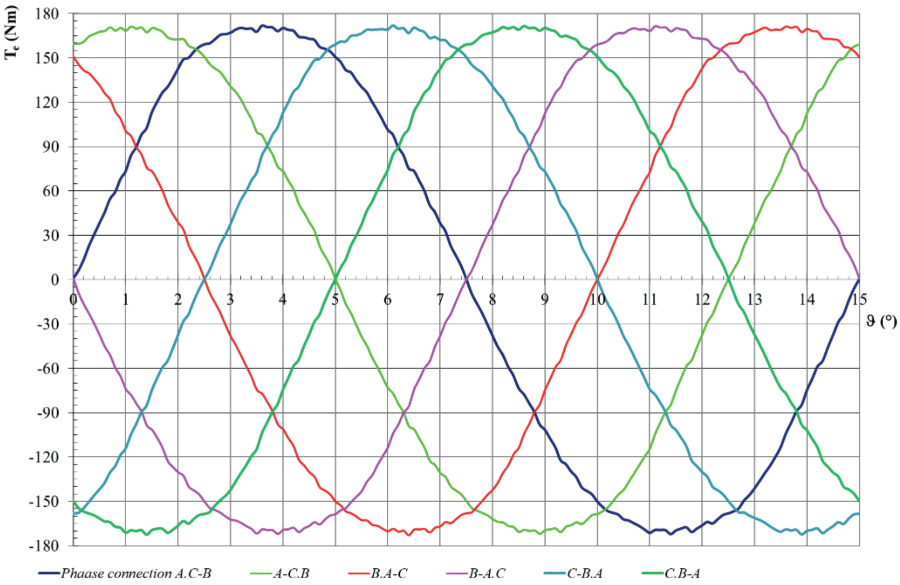

***Figure 6** Torque versus rotor angle*

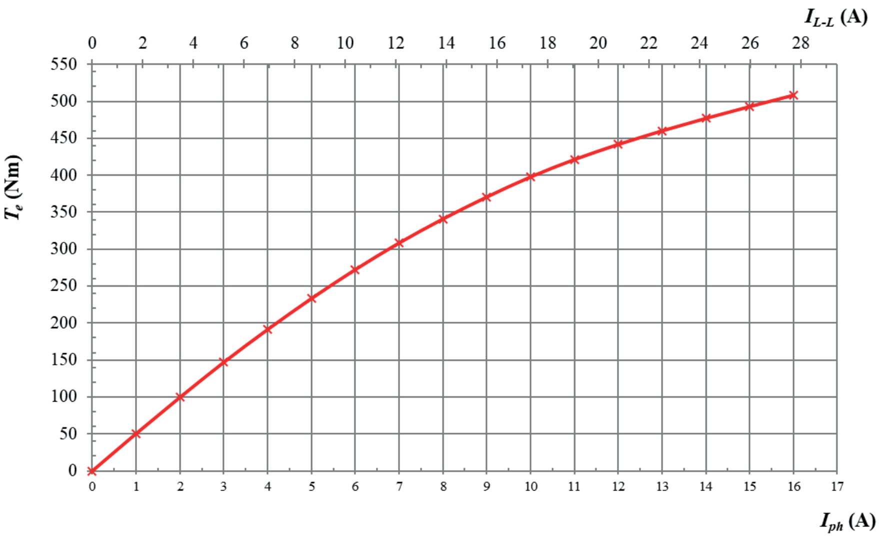

***Figure 7** Torque characteristics on the motor current calculated by FEM*

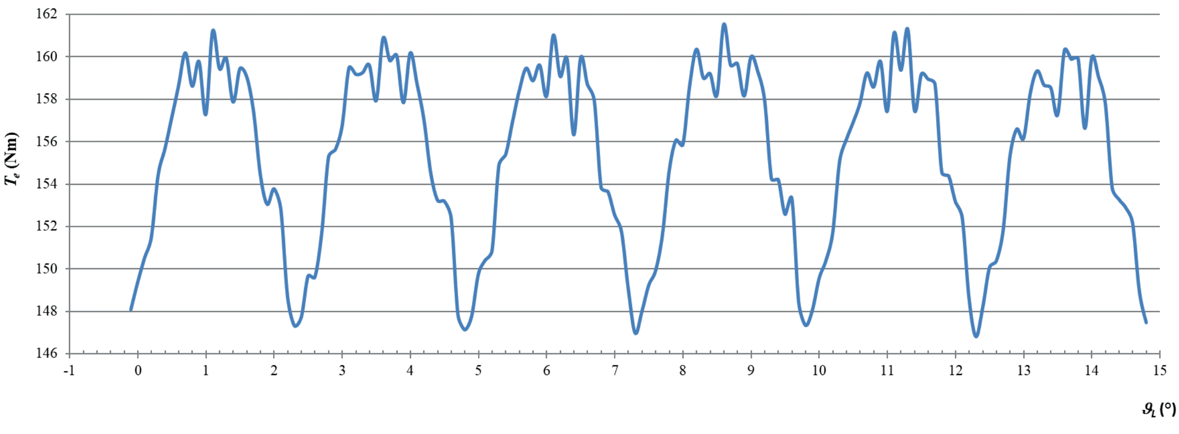

***Figure 8** Torque ripple characteristics calculated by FEM*

Table 1 *Results of the torque ripple determination*

Torques and values	
T_{avg}	155.3881 Nm
T_{max}	161.5306 Nm
T_{min}	146.8124 nm
ripple	0.094719

$$\text{ripple} = \frac{T_{max} - T_{minx}}{T_{avg}} \quad (-;\text{Nm},\text{Nm})$$

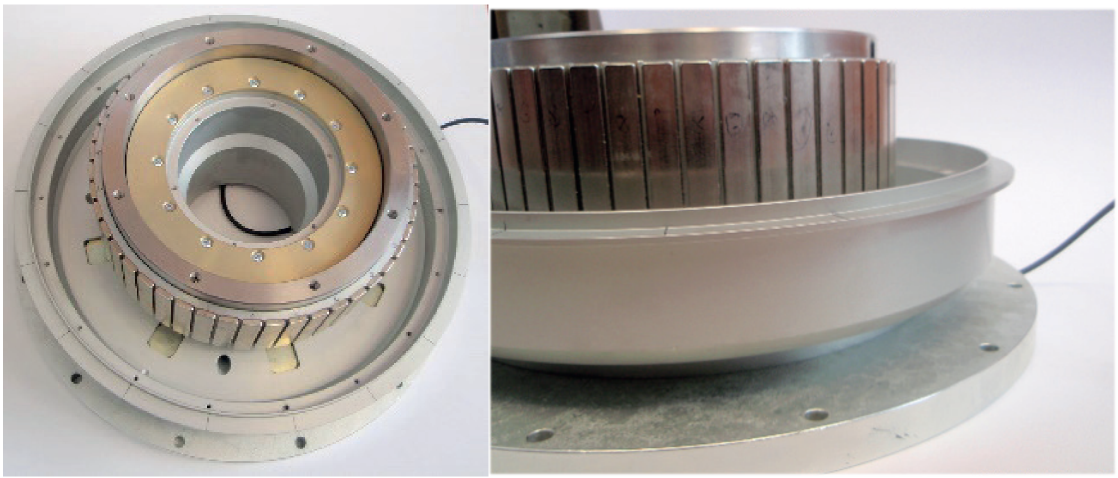

Figure 9 *Photography of the rotor of the BLDC motor with frame*

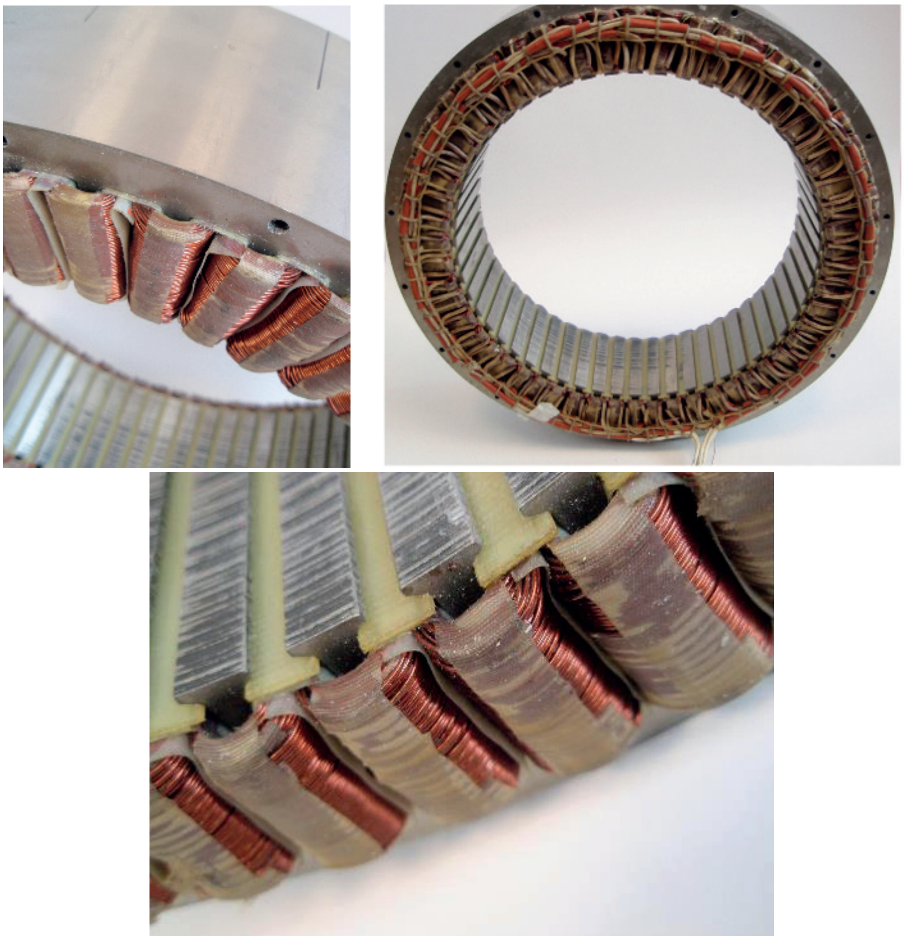

Figure 10 *Photography of the stator of the BLDC motor*

characteristic for the selected operating point was compiled. This calculated dependency is listed in Table 1. together with measured characteristics

3 The basic parameters and characteristics of the BLDC motor

In the Figure 9 and Figure 10 the construction details of the designed motor can be seen, while Table 2. is listing its basic parameters.

As was early mentioned, Figure 7 represents the dependency of the machine torque on the load angle calculated by using FEA. On the other side Figure 11 shows the same characteristic obtained by experimental measurement. For the comparison purposes, the characteristic achieved from the simulation result by using FEM (Figure 6) analysis is shown as well. The measurement was performed at a temperature below the operating temperature of 150°C, and the calculated dependence is for reference temperature.

Table 2 lists the electrical characteristics of the BLDC motor's equivalent circuit as well as other crucial drive characteristics for use with positioning systems. By using the measurement method of the self- and mutual-inductance curve, motor inductance was examined.

The proposed engine was measured on a test bench to investigate the basic parameters, verify the loading characteristics, measure torque ripples, the required starting torque at the lowest ambient temperature. The measurements were verified using a YOKOGAWA precision power analyzer type WT3000. The electrical torque was calculated from the difference between the motor input power and motor losses divided by the mechanical angular velocity. Mechanical losses have been evaluated as well during no-load test. Motor losses are caused only by armature winding copper losses, and are depended on winding temperature. Measured load characteristics of motor are shown in Figure 12 and Figure 13, torque characteristics are shown in Figure 14.

The measurements confirmed the suitability of the design methodology, its correctness and use in manipulators or wheel motor for electric vehicles. The investigated performances are in accordance with the analytical design.

4 Control structure

Field oriented control algorithm in cascade control structure was used. Field oriented structure allows an independent control of magnetic flux and torque of the stator current. In a cascade control arrangement, there are two (or more) controllers of which one controller's output drives the set point of another controller (Figure 15). Also, space vector modulation was used to supply motor phase voltages. Space vector modulation generates a minimum harmonic distortion of the currents in the winding of 3-phase AC motors. Space vector modulation also provides a more efficient use of the supply voltage in comparison with sinusoidal modulation methods.

Experimental verification was carried out with a drive using a 1.05 kVA inverter (type SN100 – 1.05) developed by EVPU with a TI TMS320F2818 digital

Table 2 *Basic parameters of the prototype of the designed motor*

Motor type: MPM BkDC-360-150		
Rated voltage U_{DC} (V)	300	24
Poles - 2p	48	
Stator teeth- N_{z1}	54	
Connection	3 phase, D	
	Serial connection of coils	Parallel connection of coils
Rated current I_s (A)	5.9	46
Overload current I_p (A)	27	156
Rated torque M_{mech} (Nm)	170	145
Frequency f_n (Hz)	0÷47	0÷9
RPM (min^{-1})	0÷166.7	0÷40
Isulation class	F	
Cooling	AN	
Efficiency η (%)	87.5 at 10 rad.s^{-1}	
Outer diameter of stator/iron lenght (mm)	Ø 360 / 75	
Winding resistance at terminals, 20°C (Ω)	4.33	0.119
Winding inductance $L_{\sigma 0}$ (mH)	76.7	1.1
L_d (mH)	110	1.7
L_q (mH)	64	0.75

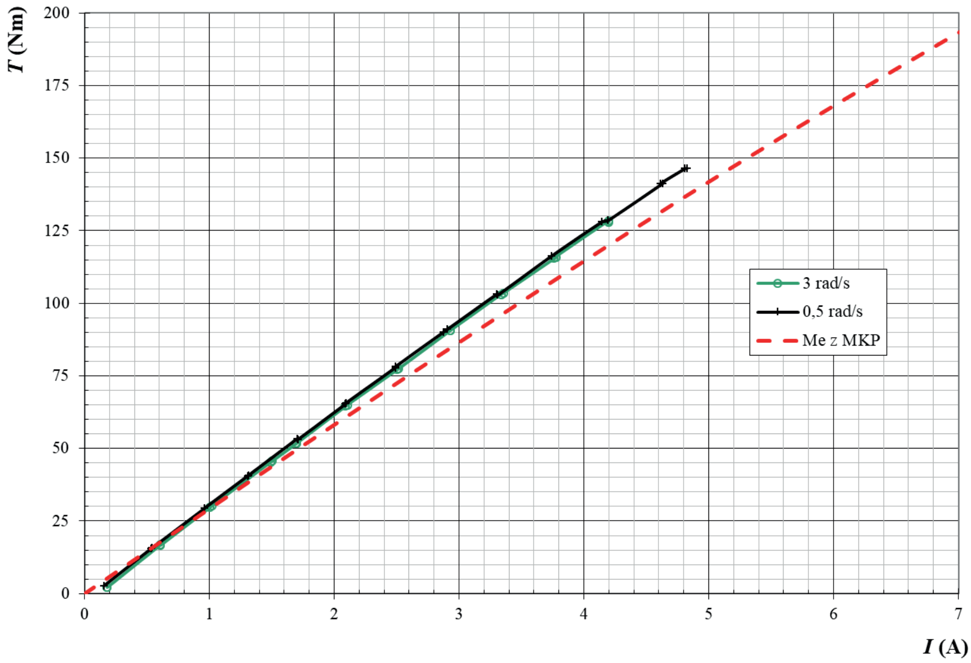

Figure 11 *Calculated and measured load characteristic of BLDC motor*

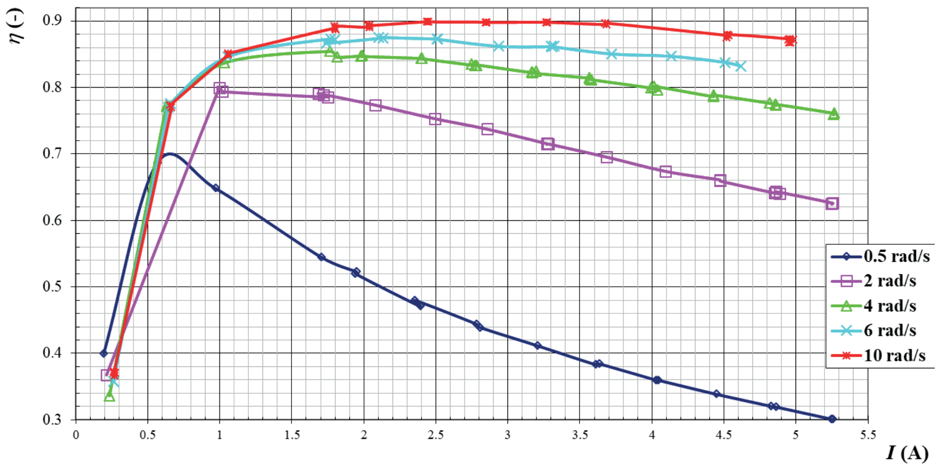

Figure 12 *Load characteristics: efficiency at different angular velocity*

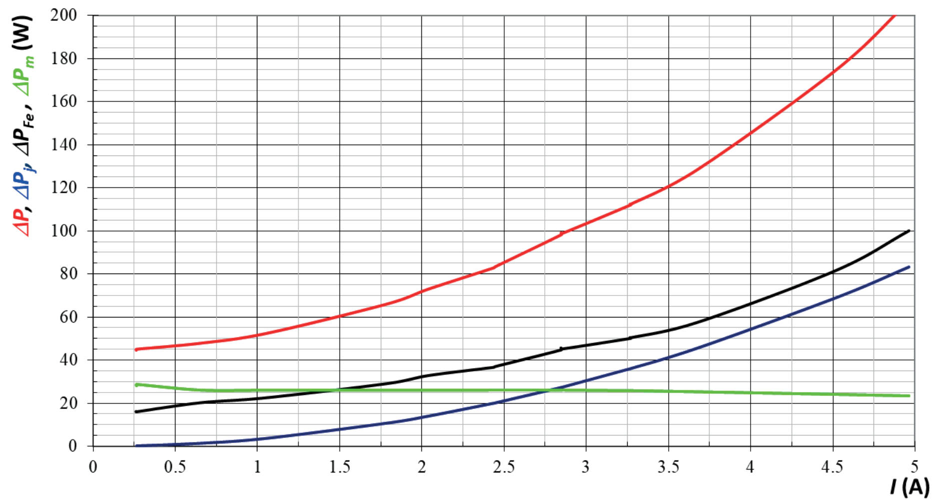

Figure 13 *Load characteristics: power and components of losses (winding, mechanical, iron) at angular velocity 10 rad.s*$^{-1}$

signal processor. An angular RESM sensor, an optical sensor of the SR read head and a SIGNUM system from RENISHAW with a resolution of 0.1 μm were used as a position sensor. The block diagram of position control loop is shown on Figure 16. The sampling frequency of the current loop was set to 15 kHz. The velocity measurement was performed in a 3 kHz loop to achieve suitable accuracy (pulse counting method was used).

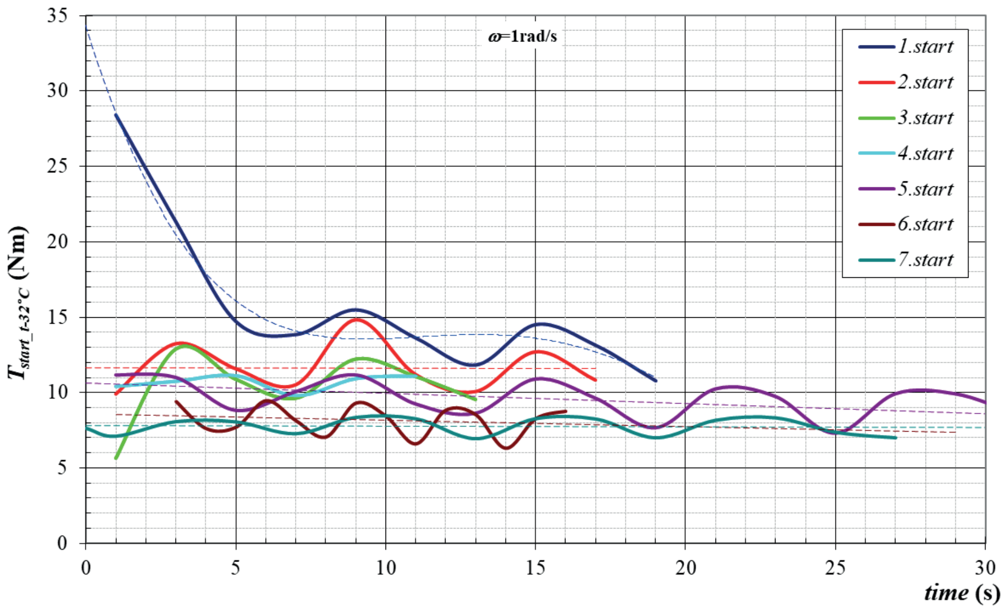

Figure 14 *Torque characteristic in dependency on time and nr. of motor starting (temperature of -32°C, influence of bearing lubricant)*

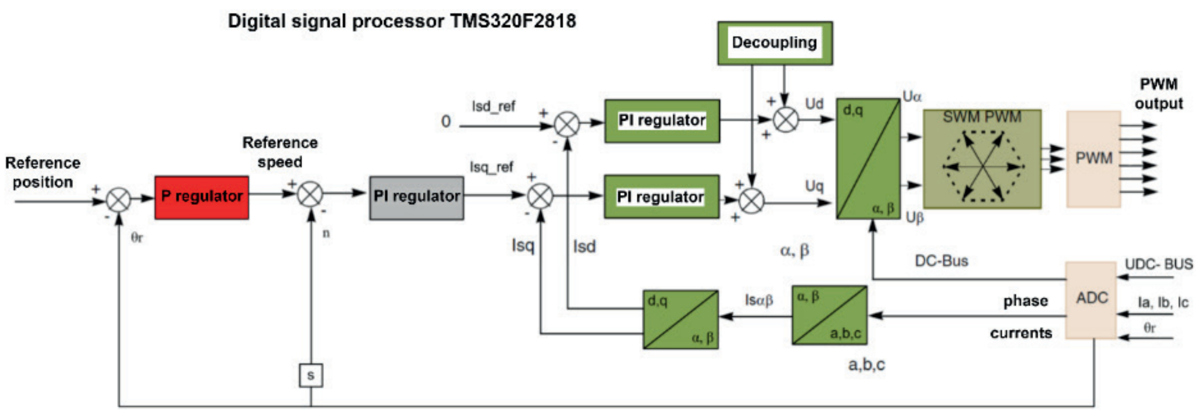

Figure 15 *Basic cascaded control structure was extended and modify with feedforward loops, for our reason, we use a speed feedforward to eliminate a speed latency*

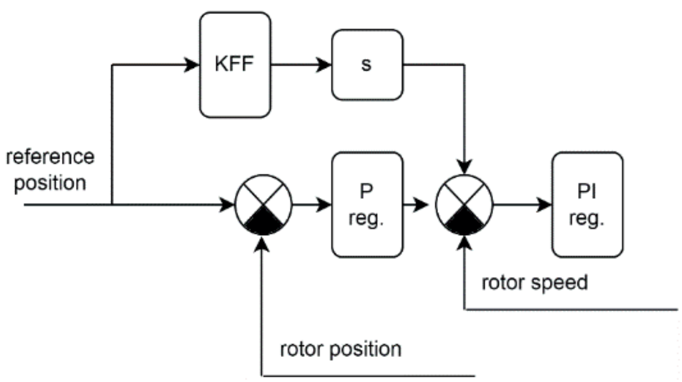

Figure 16 *Block scheme of the position control with feedforward loop of speed*

5 Conclusion

Direct drive with brushless DC motors have their advantages and disadvantages depending on the specific application in they are being used for. Direct drive motors offer high efficiency, high torque, and low noise levels due to the absence of gears and the direct coupling of the motor to the load. However, they are limited in their speed range and can be more expensive and complex to design and manufacture.

On the other hand, brushless DC motors offer a wider range of speeds, are generally more compact and affordable, and require less maintenance due to the absence of brushes, lubricants. They are also capable of high-power density and offer good control and efficiency. However, they can produce more electromagnetic interference (EMI) and have a limited torque density compared to direct drive motors.

Ultimately, the choice between direct drive and brushless DC motors will depend on the specific requirements of the application, including factors such as speed range, torque, efficiency, cost, and size constraints. Understanding the advantages and disadvantages of each type of motor can help designers to make decisions when selecting the best motor for their application.

The proposed motor has been compared with a conventional drive, as servomotor with gearbox, in a particular application such as a precision positioning manipulator. The disadvantages of this comparison were: slightly higher cost of a direct torque motor, 10% higher weight, and due to the larger current draw in sensitive applications, the requirements for a very low level of radiated electromagnetic field need to be addressed. The advantage is better configurability, positioning accuracy and maintenance-free operation.

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Conflicts of 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.

References

[1] KUCHTA, J., FRANKO, M., HRASKO, M., FULIER, M. Design of ironless synchronous linear motor with permanent magnet and experimental verification of field distribution for drive with high resolution of position. In: LDIA 2007 Symposium: proceedings. 2007. ISBN 978-2-915913-21-7, p.195-196.

[2] FERKOVA, Z., FRANKO, M., KUCHTA, J., RAFAJDUS, P. Electromagnetic design of ironless permanent magnet synchronous linear motor. In: International Symposium on Power Electronics, Electrical Drives, Automation and Motion: proceedings [online]. IEEE. 2008. ISBN 978-1-4244-1663-9, p. 721-726. Available from: https://doi.org/10.1109/SPEEDHAM.2008.4581085

[3] FRANKO, M., GRMAN, L., HRASKO, M., KUCHTA, J., BUDAY, J. Experimental verification of drive with segment slotless synchronous motor with permanent magnet. In: 2009 35th Annual Conference of IEEE Industrial Electronics IECON 2009: proceedings [online]. IEEE. 2009. ISBN 978-1-4244-4648-3, eISBN 978-1-4244-4650-6. Available from: https://doi.org/10.1109/IECON.2009.5414653

[4] GIERAS, J. F., PIECH, Z. J. *Linear synchronous motors*. Cleveland OH: CRC Press, 2000. ISBN 978-0849318597.

[5] KOLMAN, Z. *The control drive of machine tools* (in Czech). Prague: Research Institute of Machine Tools, 1989.

[6] CERMAK, R., KINDL, V., LAKSAR, J., FRANK, Z., KOMRSKA, T. Nine-phase induction motor with harmonic injection and different winding topology. In: 2020 International Conference on Electrical Machines ICEM: proceedings [online]. IEEE. 2020. eISBN 978-1-7281-9945-0, p. 2125-2131. Available from: https://doi.org/10.1109/ICEM49940.2020.9270999

[7] CACCIATO, M., CONSOLI, A., SCARCELLA, G., SCELBA, G., TESTA, A. A novel space-vector modulation technique for common node emissions reduction. In: 2007 International Aegean Conference on Electrical Machines and Power Electronics: proceedings [online]. IEEE. 2007. ISBN 978-1-4244-0890-0, p. 199-204. Available from: https://doi.org/10.1109/ACEMP.2007.4510501

[8] PALACKY, P., BARESOVA, K., SOBEK M., HAVEL, A. The control system of electrical energy accumulation. In: 2016 ELEKTRO: proceedings [online]. IEEE. 2016. eISSN 978-1-4673-8698-2, p. 346-349. Available from: https://doi.org/10.1109/ELEKTRO.2016.7512094

[9] TRAN, C. D., PALACKY, P., KUCHAR, M., BRANDSTETTER, P., DINH, B. H. Current and speed sensor fault diagnosis method applied to induction motor drive. *IEEE Access* [online]. 2021, **9**, p. 38660-38672. eISSN 2169-3536. Available from: https://doi.org/10.1109/ACCESS.2021.3064016

[10] EN 61800-1:2001 Adjustable speed electrical power drive systems. Part 1: General requirements rating specifications for low voltage adjustable speed D.C. power drive systems.
[11] HRASKO, M., MAKYS, P., FRANKO, M., KUCHTA, J. A Comparison of position control structures for ironless linear synchronous motor. In: Power Electronics and Motion Control Conference EPE-PEMC 2008: proceedings. 2008. ISBN: 978-1-4244-1741-4, p. 2538-2542.
[12] KUCHTA, J., FRANKO, M. Advantages and limitations of using a permanent magnet synchronous motor in the traction drive (in Slovak). In: 20. International Conference Current Problems in Rolling Stock - Prorail 2011: proceedings. 2011. Vol. II. ISBN 978-80-89276-31-8, p.183-191.
[13] FRANKO, M., ONDREJICKA, J., KUCHTA, J., Development and examination of interior permanent magnet synchronous traction motor. In: ELEKTRO 2012: proceedings [online]. IEEE. 2012. ISBN 978-1-4673-1178-6, p. 179-184. Available from: https://doi.org/10.1109/ELEKTRO.2012.6225634
[14] FRANKO, M., KUCHTA, J., BUDAY, J., Development and performance investigation of permanent magnet synchronous traction motor. In: International Symposium on Power Electronics Power Electronics, Electrical Drives, Automation and Motion SPEEDAM 2012: proceedings [online]. IEEE 2012. ISBN 978-1-4673-1300-1, p. 70-74. Available from: https://doi.org/10.1109/SPEEDAM.2012.6264450
[15] NIPP, E. Permanent magnet motor drives with switched stator windings. Stockholm: Royal Institute of Technology, 1999. ISSN 1102-0172.
[16] MUSZNICKI, P., TURZYNSKI, M., CHRZAN, P. J. Accurate modeling of quasi-resonant inverter fed IM drive. In: 39th Annual Conference of the IEEE Industrial Electronics Society IECON 2013: proceedings [online]. IEEE. 2013. eISBN 978-1-4799-0224-8, ISSN 1553-572X, p. 376-381. Available from: https://doi.org/10.1109/IECON.2013.6699165

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IMPROVEMENT OF THE SOFT CONTAINERS USE IN TRANSPORTATION OF THE BULK CARGO

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Resume

The advantages and disadvantages of using the soft containers for cargo transportation are analyzed. The issues of the use of soft containers in transport and technological schemes for the supply of bulk goods are considered. Approaches to the rational selection of parameters of soft containers, during the transportation of bulk cargoes, taking into account the characteristics of the transported cargoes, are defined.

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1 Introduction

Modern container technologies appeared in the middle of the 20th century and significantly influenced development of international trade. Their appearance changed the nature of cargo transportation [1-3]. The use of modern transport technologies and promising technical solutions lead to the faster and more efficient transportation of goods from the consignor to the consignee, including from the point of view of the transport process safety, [4-7].

The purpose of this article is to consider the advantages and disadvantages of using the soft containers in the transportation of bulk cargoes and to determine approaches to the rational selection of these containers parameters in transportation of the bulk cargoes, taking into account the characteristics of the transported cargoes.

2 Object of the research

When developing the transport and logistics systems for the delivery of goods, special attention should be paid to the rational choice of transport tare, which is considered as one of the types of transport equipment. It is an independent transport unit that ensures the effectiveness of transportation and performance of loading and unloading and warehouse work. This choice is related to solution of the tasks of optimizing the loading of rolling stock and the placement of goods in the warehouse, automation and mechanization of loading and unloading and transport and storage operations [8].

Currently, the cargo containers are widely used for transportation of various cargoes [9-13]. They are a type of transport equipment, used for transportation and temporary storage of goods and have constant technical characteristics and devices for mechanization of transshipment operations.

In the global practice, the volumes of transportation of bulk and bulk cargoes are growing increasingly. At the same time, the requirements for technical and environmental safety of transportation, technical condition of the rolling stock, preservation of cargo, convenience of the accepted transportation scheme for the consumer are also increasing [14-16]. In addition, from time to time there is a problem of lack of specialized railway rolling stock and transport equipment used for these transports. All this stimulates the introduction of new, effective technologies for loading, transportation and transshipment of bulk cargoes, which can more fully satisfy the needs of all the participants in the transport process [17].

One of the progressive directions of improvement of transport and logistics systems for the delivery of goods (primarily bulk goods) is the use of soft specialized containers (SC, Big-Bag or FIBC - Flexible Intermediate Bulk Conteiner) for their transportation and temporary storage, which have recently become increasingly popular application. According to the specific costs (that is, according to the costs of transport equipment per unit mass of transported products), soft containers are the most economical, especially when transporting and temporarily storing large batches of goods [18].

A soft container (hereafter SC) is actually a large bag with slings or loops and hooks for lifting and a bag-like body for filling, storing and transporting cargo. The carrying capacity of the SC usually varies from 500 to 2000 kg. Most often, the SC is made of polypropylene and has a cylindrical or parallelepiped shape. The length of one side of the container is usually in the range from 500 mm to 1200 mm and the volume is possible up to 3 m^3. The height of the SC can reach 2500 mm, with a minimum height of 800 mm. However, there are exceptions, for example, large-tonnage soft containers MK-14-10 with a capacity of up to 14 tons, which are allowed even for international transportation of dangerous goods [10].

The soft polymer containers, according to the parameters that determine their useful life, have the following components: disposable containers - are used exclusively in circulation once, then they go to disposal and, accordingly, to recycling, SC of cyclic using - which have the ability to be used in several cycles of their loading/unloading and multi-turn SC - containers that are used in chains of loading/unloading during the long time specified in the characteristics of this container. The frequency of the SC use in the cyclic transport process depends on the parameters responsible for its safety margin. Disposable SCs have a safety margin of 5:1, cyclic SCs have a safety margin of 6:1 (can be used several times) and reusable containers have a safety margin of 8:1. The order of the safety factor allows to use the SC for storing products in them with the construction of a stack with the levels of their arrangement on top of each other up to 7 tiers.

The SCs are reliable and durable, convenient for transportation and storage of various bulk goods, easy to manufacture. Depending on the specifics of the cargo, some SCs are additionally provided with protection elements against ultraviolet radiation, temperature changes, atmospheric moisture and static electricity.

Undoubtedly, the soft containers cannot be as widely used in modern transport and logistics systems of cargo delivery as the traditional metal cargo containers. However, for transporting a number of loads, they are almost an ideal solution. Such cargoes include, first of all, bulk cargoes, for example, powdery materials (flour, cement), granular (salt, sugar, grain, mineral fertilizers, various chemical products), as well as small-, medium- and large lumpy cargoes (construction materials, ferroalloys, concentrates). In addition to bulk products, the SC can also be used for transportation and storage of bulk and bulk cargoes, agricultural and forest products [14].

In recent decades, the soft containers have proven themselves as a universal type of transport equipment, as they can be structurally adapted to any loading and unloading mechanisms and various loading and unloading stations [19]. Their use in developed countries today has practically supplanted traditional means of transporting the bulk cargo, such as circulating metal containers, dumpcars truck and completely replaced plywood drums and barrels [20-21].

With the advent of SC, it became possible to solve many technological problems quite simply and effectively. So, for example, can store products in open areas for a long time. Costs for loading and unloading operations and cargo losses at various stages of their circulation also decreased. The analysis of the available information regarding the technologies of using the soft containers in the transportation of bulk cargo allows to note the following advantages of these technologies over traditional ones [14]:

- lack of need for scarce specialized rolling stock;
- absence of physical losses of transported goods;
- maintaining the quality and cleanliness of transported goods;
- protection of rolling stock and the surrounding environment from the negative impact of transported goods;
- no need to clean the body of the rolling stock after transporting the bulk cargo;
- simple mechanisms for introduction into the technological process during the SC loading/unloading;
- the possibility of temporary storage of cargo during transshipment at open port sites, which allows saving working capital for the construction of warehouses;
- improvement of the quality of working conditions of workers, including from the point of view of sanitary and hygienic conditions.

Taking into account these significant advantages, the rail transportation of bulk cargo using SC has recently become widespread.

In the technical conditions (TU) for loading and fastening cargo in an open rolling stock [22] there are recommended schemes for loading the soft containers in semi-wagons only for several of their standard sizes, which have a cross section of the bag in the form of a circle. However, the analysis of scientific and technical information and Internet data shows that several dozens of SC standard sizes are actually used for the bulk cargo transportation.

When planning transportation and choosing the necessary SC parameters, the transport characteristics of the bulk cargo should be taken into account. For example, the full use of the cargo capacity and capacity of the wagons with certain parameters of the soft containers depends significantly on the bulk weight of the cargo. At present, this issue receives relatively little attention. For example, work [23] analyzed options for transporting bulk goods in bags and in soft containers. Options for calculating the placement of cargo in the wagon were considered and a technical and economic calculation of the efficiency of transportation was carried out. Further, the other factors, which appear during transportation, such as movement of transport means (wagons, containers, cargo etc.), have to be considered, as well, [24-25]. That influences the running properties of a train-set, safety of transportation, dynamics of individual vehicles in a train-set, braking distances and other factors, which relate with the investigated issue [26-29].

Taking into account the modern capabilities and existing technologies for production of the SCs, it is possible to manufacture them in almost any shape with a fairly wide range of basic parameters (width, height, load capacity). At the same time, use of the SCs, which have a square cross section, is promising, as they allow the most complete use of the useful floor area of the cargo room of the rolling stock. Therefore, the purpose of the this work is to determine approaches to the rational selection of parameters of such soft containers during the transportation of a bulk cargo, taking into account the characteristics of the transported cargo.

3 Research methodology

Next is considered the issue of choosing the rational parameters of SCs that have a square cross-section, in accordance with the bulk mass of the transported cargo. At the same time, several conditions must be met:

- loading the wagon G_L with cargo should be as complete as possible (of course, not exceeding its stenciled carrying capacity $G_L^{\max}$,
- the number of used soft containers K should be minimal: $K \to K_{\min}$,
- the strength of SC at the required load capacity is provided technologically.

The combination of the two main parameters will be considered - width b_i and height h_j - as the ij - standard size of a soft container, which has a square cross-section.

The number of containers K_{ij} of the ij - standard size that can be placed in a gondola car can be calculated as follows

$$K_{ij} = N_{ij} \cdot M_{ij} \cdot Z_{ij}\,, \tag{1}$$

where:
N_{ij} - the number of containers of the ij-th standard size that can be loaded across the width of a gondola car;
M_{ij} - the number of containers of the ij-th standard size that can be loaded along the length of a gondola car;
Z_{ij} - the number of loading tiers of containers of the ij-th standard size in a gondola car.

The working volume of one such container will be $V_{ij} = b_i^2 \cdot h_j$ and its mass is $G_{ijk}^{*} = V_{ij}^{*} \cdot \gamma_k$, where γ_k is the bulk mass of bulk cargo.

If the internal dimensions of the gondola car body are known (B - width, L - length, H - height), it can be recorded:

$$\begin{aligned} N_{ij} &= \langle (B-x)/b_i \rangle \\ M_{ij} &= \langle (L-x)/b_i \rangle \\ Z_{ij} &= \langle (H-\Delta)/h_{ij} \rangle \end{aligned}\,, \tag{2}$$

where:
x - allowance for gaps when installing the SC in the body,
Δ - the height to which regulatory documents allow containers of the upper tier to protrude above the side of an open rolling stock in height.

The sign $\langle \dots \rangle$ here indicates the whole part of the result of division of the corresponding expression with rounding down.

The total loading of the wagon with loose cargo of a bulk mass γ_k using K_{ij} soft containers will add up to:

$$G_{ijk}^{W} = K_{ij} \cdot G_{ijk}^{*} = N_{ij} \cdot M_{ij} \cdot Z_{ij} \cdot b_i^2 \cdot h_j \cdot \gamma_k\,. \tag{3}$$

A rational choice of the soft containers parameters (b_i and h_j), in accordance with the transport characteristics of the cargo being transported (first of all, in accordance with the given value of the bulk mass γ_k) and the available means of transport, will allow to reduce the costs of containerization of railway transportation of a bulk cargo while obtaining all the known advantages of container transportation. At the same time, it is necessary to solve an optimization problem, which can be formulated as an integer optimization problem. One of the variants of the objective function for solving such a problem can be written in the form

$$K_{ij} = f(N_{ij}, M_{ij}, Z_{ij}, \gamma_k) \to \min\,, \tag{4}$$

where:
$N_{ij} = f(b_i, x),\ M_{ij} = f(b_i, x),\ Z_{ij} = f(h_j, \Delta)$.

When formulating the system of limitations of the problem, one should take into account the internal geometric dimensions of the body of a gondola car, the technological possibilities of the SC production and the requirements of the Technical conditions of loading [22], which forbid that the containers of the upper tier, when loaded into a semi-car, protrude above its side by more than 1/3 of their height (and generally no more than 400 mm).

In addition, several safety conditions of the transport process must be met, namely: the mass G^{*}_{ijk} of the loaded container with the bulk cargo must not exceed its maximum carrying capacity $G^{*}_{\max}$; loading G^{W}_{ijk} of the wagon with K_{ij} bulk cargo containers should be as complete as possible (of course, not exceeding its stenciled carrying capacity $G^{W}_{\max}$).

Taking this into account, the system of constraints of a problem is formulated as follows:

$$b_i^{\min} \le b_i \le b_i^{\max}; h_j^{\min} \le h_j \le h_j^{\max}; \quad G^{W}_{ijk} \to G^{W}_{\max}; G^{*}_{ijk} \le G^{*}_{\max}. \tag{5}$$

4 Results and discussion

For example, Figures 1 and 2 show some results of optimization of the dependency $K_{ij} = f(N_{ij}, M_{ij}, Z_{ij}, \gamma_k) \to \min$ with variable SC parameters. Solving the problem of discrete optimization was carried out using the optimization block of the MS Excel package.

In the calculations, the following is accepted: the vehicle is an all-metal gondola car model 12-295 with a carrying capacity of 71 tons with internal dimensions of the body $V = 2.89$ m, $L = 12.69$ m, $H = 2.05$ m; bulk mass of cargo $\gamma_k = 0.7$ to 1.8 t/m^3; $G^{W}_{\max} = 70$ t; $G^{*}_{\max} = 1.5$ t.

After analyzing the graphs of the indicated dependencies, it is possible to choose a rational ratio of the soft containers' parameters with a square cross-section (namely, their width b_i and height h_j), which achieves the maximum use of the wagon's carrying capacity for a set value of the bulk mass of the transported bulk cargo.

At the same time, the minimum number of such soft containers is used for transportation. Thus, for example, for the selected type of rolling stock and the bulk mass of the cargo $\gamma_k = 1.5$ t/m^3 according to Figures 1 and 2, the optimum, from the point of view of the efficiency of loading the car body with bulk cargo in SC with the minimum number of containers, will be the soft containers with the parameters $b_i^{opt} \approx 1$ m and $h_i^{opt} \approx 1$ m.

The authors believe that the method proposed in the paper for determining the rational parameters of flexible containers, which considers the characteristics of the

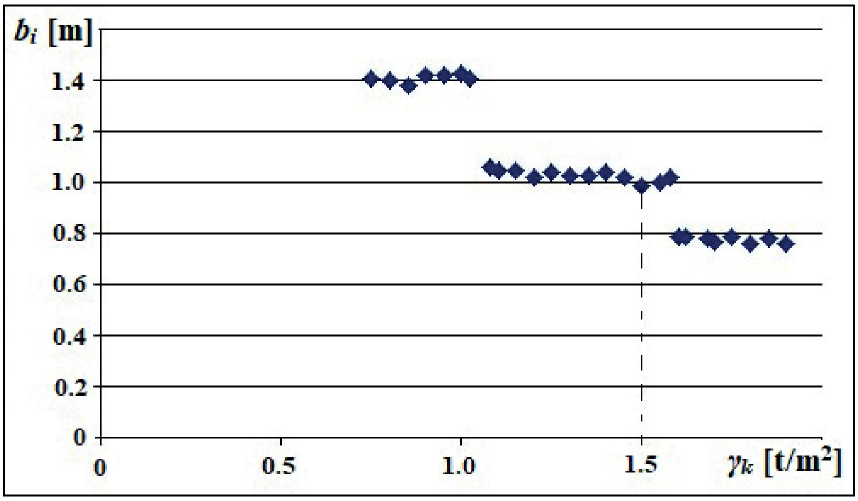

***Figure 1** Graph of dependence* $b_i^{opt} = f(\gamma_k)$

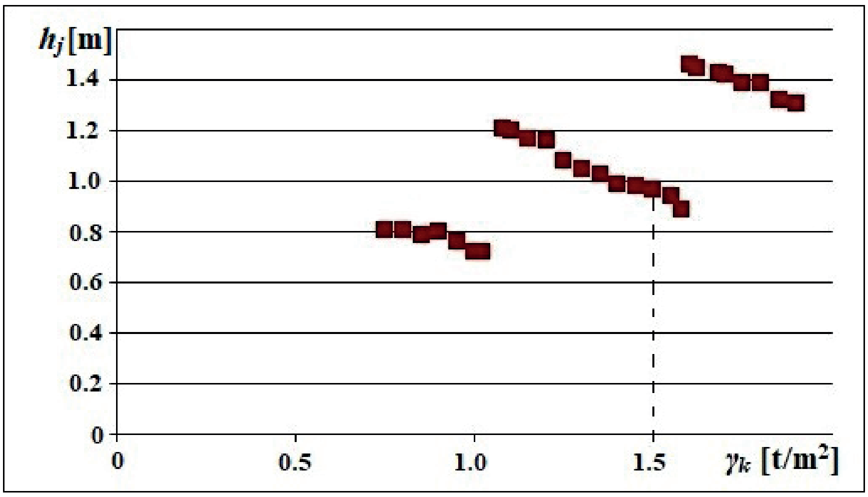

***Figure 2** Graph of dependence* $h_i^{opt} = f(\gamma_k)$

transported cargo and the geometric parameters of the cargo space of a vehicle, is quite simple and boils down to formulating and solving a discrete optimization problem. The objective function and the system of constraints of the problem in the reviewed work, in authors' opinion, are presented in full details. The graphs given in the work are presented only to illustrate how the proposed method can be used in practice. Those graphs are constructed based on solving the integer optimization problem for a specific bulk density of a bulk cargo and given geometric parameters of the vehicle cargo space. The solution of the discrete optimization problem, for the case under consideration, was carried out using the optimization block of the MS Excel package. Other mathematical programs can also be used to solve similar problems.

5 Conclusions

1. When developing the transport and logistics systems for delivery of goods, special attention should be paid to the rational choice of the transport equipment used. One of the progressive directions for improving the bulk cargo delivery systems is the use of soft specialized containers (SC) for the transportation and temporary storage of such a cargo.
2. Modern technological capabilities for production of the SC allow their production of almost any shape with a fairly wide range of basic parameters (width, height, load capacity).
3. It seems promising to use the SCs, which have the shape of a square in their cross section. With a rational selection of their parameters, such containers would allow the most complete use of the usable area of the cargo space of vehicles.
4. The paper proposes a method for selecting the rational parameters of soft containers having the shape of a square in their cross section in accordance with the characteristics of the cargo being transported and the dimensions of the cargo space of the vehicle. The method is based on optimizing the values of the geometric parameters of a flexible container (its width and height), taking into account the bulk density of the transported bulk cargo and the geometric parameters of the cargo space. The choice of rational geometric parameters of the soft container is carried out when solving the integer optimization problem according to the criterion of the most complete vehicle loading with the minimum number of used SCs.
5. A rational choice of the soft containers' parameters in accordance with the transport characteristics of the transported bulk cargo and parameters of the cargo space of the vehicle, would reduce the cost of containerization of the transportation of bulk cargo while obtaining all the known advantages of container transportation.

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Conflicts of 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.

References

[1] GRAWE, S. J., DAUGHERTY, P. J., ROATH, A. S. Knowledge synthesis and innovative logistics processes: enhancing operational flexibility and performance. *Journal of Business Logistics* [online]. 2011, **32**(1), p. 69-80. eISSN 2158-1592. Available from: https://doi.org/10.1111/j.2158-1592.2011.01006.x

[2] MAJERCAK, J., MAJERCAKOVA, E., NEDELIAKOVA, E. Management of optimization in logistics leads to savings in transport costs. In: 18th International Conference on Transport Means Transport Means 2014: proceedings. 2014.

[3] KOSTRZEWSKI, M. Implementation of distribution model of an international company with use of simulation method. *Procedia Engineering* [online]. 2017, **192**, p. 445-450. ISSN 1877-7058. Available from: https://doi.org/10.1016/j.proeng.2017.06.077

[4] Transport Logistics. Shared solutions to common challenges - OECD [online]. 2002. Available from: https://www.itf-oecd.org/sites/default/files/ docs/02logisticse.pdf

[5] MIKHAILOV, E., DIZO, J., KLIUIEV, S., SEMENOV, S., LACK, T., KRAVCHENKO K. Mechatronic system of control position of wheel pairs by railway vehicles in the rail track. *AIP Conference Proceedings* [online]. 2019, **2198**, 020009. Available from: https://doi.org/10.1063/1.5140870

[6] MIKHAILOV, E., SEMENOV, S., KLIUIEV, S., DIZO, J., BLATNICKY, M., GERLICI, J., HARUSINEC J., KOVTANETS, M. Clarification of features of the wheel movement with a perspective constructive scheme on a rail. *Applied Sciences* [online]. 2020, **10**, 6758. eISSN 2076-3417. Available from: https://doi.org/10.3390/app10196758

[7] KOSTRZEWSKI, M., KOSACKA-OLEJNIK, M., WERNER-LEWANDOWSKA, K. Assessment of innovativeness level for chosen solutions related to Logistics 4.0. *Procedia Manufacturing* [online]. 2019, **38**, p. 621-628. ISSN 2351-9789. Available from: https://doi.org/10.1016/j.promfg.2020.01.080

[8] NEDELIAKOVA, E., PANAK, M., SIPUS, D. Innovative trends in process-oriented quality management within railway transport. *Periodica Polytechnica Transportation Engineering* [online]. 2017, **45**(2), p. 84-89. ISSN 0303-7800, eISSN 1587-3811. Available from: https://doi.org/10.3311/PPtr.9582

[9] FOMIN, O., GERLICI, J., LOVSKA, A., KRAVCHENKO, K., FOMINA, Y., LACK, T. Determination of the strength of the containers fittings of a flat wagon loaded with containers during shunting. *IOP Conference Series: Materials Science and Engineering* [online]. 2019, **659**, 012056. ISSN 1757-8981, eISSN 1757-899X. Available from: https://doi.org/10.1088/1757-899X/659/1/012056

[10] AKHUNDOV, E. A., BATISHEV, I. A., SHISHENIN, E. A., VAGENGEIM, S. G. Flexible bulk container BK3: a new page in international rules on the transport of dangerous goods. *Transactions of the Krylov State Research Centre* [online]. 2018, **2**, p. 151-159. ISSN 2542-2324, eISSN 2618-8244. Available from: https://doi.org/10.24937/2542-2324-2018-2-S-I-151-159

[11] FOMIN, O., GORBUNOV, M., GERLICI, J., VATULIA, G., LOVSKA, A., KRAVCHENKO, K. Research into the strength of an open wagon with double sidewalls filled with aluminium foam. *Materials* [online] 2021, **14**(12), 3420. eISSN 1996-1944. Available from: https://doi.org/10.3390/ma14123420

[12] MIKHAILOV, E., SEMENOV, S., SHVORNIKOVA, H., GERLICI, J., KOVTANETS, M., DIZO, J., BLATNICKY, M., HARUSINEC, J. A study of improving running safety of a railway wagon with an independently rotating wheel's flange. *Symmetry* [online]. 2021, **13**(10), 1955. eISSN 2073-8994. Available from: https://doi.org/10.3390/sym13101955

[13] BUKOWSKI, T., RICHMOND, M. A Holistic view of the role of flexible packaging in a sustainable world. the flexible packaging association [online] 2018. Available from: https://perfectpackaging.org/wp-content/uploads/2018/09/FPA- Holistic-View-of-Sustainable-Packaging.pdf

[14] MIHAJLOV, E. V. *Technologies of cargo transportation in soft containers / Tehnologii perevezennja vantazhiv u m'jakih kontejnerah* (in Ukrainian). Beu Bassin: Lap Lambert Academic Publishing, 2018. ISBN 978-613-9-57815-3.

[15] STOMA, M., CABAN, J., DUDZIAK, A., KURANC, A. Selected aspects of the road traffic safety management system. *Communications - Scientific Letters of the University of Zilina* [online]. 2021, **23**(2), p. F33-F42. ISSN 1335-4205, eISSN 2585-7878. Available from: https://doi.org/10.26552/COM.C.2021.2.F33-F42

[16] CABAN, J., DROZDZIEL, P., STOMA, M., DUDZIAK, A., VRABEL, J., STOPKA, O. Road traffic safety in Poland, Slovakia and Czech Republic - statistic analysis. In: 12th International Science-Technical Conference Automotive Safety, Automotive Safety 2020: proceedings [online]. IEEE. 2020. eISBN 978-1-7281-5812-9. Available from: https://doi.org/10.1109/AUTOMOTIVESAFETY47494.2020.9293507

[17] PAVLIC SKENDER, H., ZANINOVIC, P. A., SRICA, E. Review of modern transportation technologies with focus on containerization. *Pomorski Zbornik / Journal of Maritime and Transportation Science* [online]. 2019, **57**(1), p. 111-121. ISSN 0554-6397, e ISSN 1848-9052. Available from: https://doi.org/10.18048/2019.57.08

[18] SOLOVIOVA, L., STRELKO, O., ISAIENKO, S., SOLOVIOVA, O., BERDNYCHENKO, Y. Container transport system as a means of saving resources. *IOP Conference Series: Earth and Environmental Science* [online]. 2020, **459**, 052070. ISSN 1755-1307, eISSN 1755-1315. Available from: https://doi.org/10.1088/1755-1315/459/5/052070

[19] SINGH, P., SINGH, J., ANTLE, J., TOPPER, E., GREWAL, G. Load securement and packaging methods to reduce risk of damage and personal injury for cargo freight in truck, container and intermodal shipments. *Journal of Applied Packaging Research* [online]. 2014, **1**(6), p. 47-61. ISSN 1557-7224. Available from: https://doi.org/10.14448/japr.01.0005

[20] FOMIN, O., GORBUNOV, M., LOVSKA, A., GERLICI, J., KRAVCHENKO, K. Dynamics and strength of circular tube open wagons with aluminum foam filled center sills. *Materials* [online]. 2021, **14**(8), 1915. eISSN 1996-1944. Available from: https://doi.org/10.3390/ma14081915

[21] FOMIN, O., GERLICI, J., VATULIA, G., LOVSKA, A., KRAVCHENKO, K. Determination of the loading of a flat rack container during operating modes. *Applied Sciences* [online]. 2021, **11**(16), 7623. eISSN 2076-3417. Available from: https://doi.org/10.3390/app11167623

[22] Technical conditions for loading and securing cargo on open rail vehicles/Tehnicheskie uslovija pogruzki i kreplenija gruzov na otkrytom podvizhnom sostave (in Russian). Moscow: Transport, 1990.

[23] SCHERBAKOV, A., LUNYAKOV, M., SMIRNOV, V., KAIGORODOVA, V., VERBOVA, N. Options for placement and transport of bulk goods by rail. *Transportation Research Procedia* [online]. 2022, **63**, p. 1498-1504. ISSN 2352-1457, eISSN 2352-1465. Available from: https://doi.org/10.1016/j.trpro.2022.06.161

[24] GORBUNOV, M., GERLICI, J., KARA, S., NOZHENKO, O., CHERNYAK, G., KRAVCHENKO, K., LACK, T. New principles schemes of freight cars bogies. *Manufacturing Technology* [online]. 2018, **18**(2), p. 233-238. ISSN 1213-2489, eISSN 2787-9402. Available from: https://doi.org/10.21062/ujep/83.2018/a/1213-2489/MT/18/2/233

[25] PIEKARSKI, W., STOMA, M., DUDZIAK, A., ANDREJKO, D., SLASKA-GRZYWN, B. How location shapes environmental awareness among inhabitants of Eastern Poland - an empirical study. *Polish Journal of Environmental Studies* [online]. 2016, **25**(2), p. 733-740. ISSN 1230-1485, eISSN 2083-5906. Available from: https://doi.org/10.15244/pjoes/60722

[26] CHUDZIKIEWICZ, A., MELNIK, R. Statistical analysis of vibration for the rail vehicle suspension monitoring system. In: 13th Mini Conference on Vehicle System Dynamics, Identification and Anomalies VSDIA 2012: proceedings. 2012.

[27] MELNIK, R., SOWINSKI, B. Application of the rail vehicle‘s monitoring system in the process of suspension condition assessment. *Communications - Scientific Letters of the University of Zilina* [online]. 2013, **15**(4), p. 3-8. ISSN 1335-4205, eISSN 2585-7878. Available from: https://doi.org/10.26552/com.C.2013.4.3-8

[28] YEVTUSHENKO, A., KUCIEJ, M., TOPCZEWSKA, K. Effect of the temporal profile of the friction power on temperature of a pad-disc brake system. *Journal of Theoretical and Applied Mechanics* [online]. 2019, **57**(2), p. 461-473. ISSN 1429-2955, eISSN 2543-6309. Available from: https://doi.org/10.15632/jtam-pl/105465

[29] YEVTUSHENKO, A., TOPCZEWSKA, K., KUCIEJ, M. Analytical determination of the brake temperature mode during repetitive short-term braking. *Materials* [online]. 2021, **14**(8), 1912. eISSN 1996-1944. Available from: https://doi.org/10.3390/ma14081912

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THERMOGRAPHIC MAPPING OF THE MELT POOL OF THE LASER POWDER BED FUSION PROCESS

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Resume

The article describes an advanced test stand for measuring temperatures during the 3D printing for additive manufacturing. Based on mathematical procedures, it analyzes the impact energy of the laser beam used in metal 3D printing.

The procedure is based on monitoring the flow of energy falling on the defined measuring object. Due to the design of this functional sample, it is also possible to analyze the incident and reflected energy to analyze and understand the physical properties, the precise quantitative distribution of temperatures, gradients, as well as the heating and cooling rates of the melt bath in laser bed fusion (L-PBF)

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1 Introduction

It appears from globally available sources and a current trend, that additive manufacturing (AM) is gradually being used in mass production in the aerospace, automotive, health and jewelry industries. From such extensive use of AM, it might seem that it is already a standard and mastered production technology. However, production is primarily focused only on components that do not depend on the safety or operational reliability of assemblies [1].

Unfortunately, however, it is increasingly apparent that many basic questions are still unanswered. Additive technologies, thanks to their short history (30 years), are very little mapped in terms of the final characteristics of products and do not have uniform standards, procedures and safety risks developed for them, as is the case with conventional production methods. The need for improved quantitative understanding of the temperatures, gradients, as well as heating and cooling rates within the melt pool in laser bed fusion (L-PBF), is widely known and studied. To address this need many studies has been initiated. A comprehensive summary of the available research in the field of additive technologies is collected in a paper initiated by the National Institute of Standards and Technology (NIST). Namely, the Measurement Science (MSAM) deals with measurement challenges concerning L-PBF and other metal Additive Manufacturing AM processes [2]. The principle of the Direct Metal Laser Sintering technology known in literature as DMLS is shown in the Figure 1.

Unlike the conventional materials, which are characterized by a polycrystalline microstructure formed by grains of different sizes and shapes, the microstructure of metallic AM products is typically cellular or dendritic and it is difficult to compare it to the structure of conventional materials. For AM products, the texture [3] produced by classical casting or forming of metals is not observed. The macrostructure of AM products differs significantly in the direction of printing

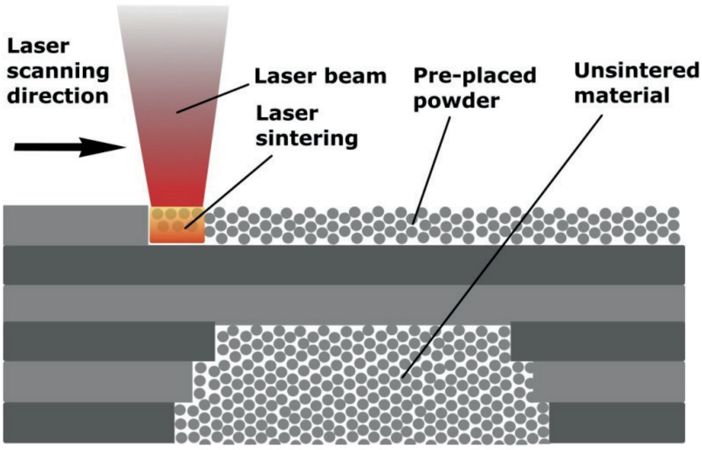

***Figure 1** Principle of Direct Metal Laser Sintering (DMLS) technology*

and in directions perpendicular to it. As a result, parts or test samples exhibit anisotropic mechanical properties when printed in the direction X, Y or Z, or at different angles of orientation and at different cross-sections of material thickness [4].

The strategy of the actual printing process includes the basic laser beam movements: contour movement and hatching. Hatching means that a metallic powder is sintered inside the part contour with a preset overlap between the partial movements of the laser, i.e. in its volume. In each layer, the angle of movement of the laser is subsequently changed. In addition, an overlap between the tracks is defined to ensure complete sintering in the entire volume of the component. This sintered material receives the final treatment by scanning the laser along the contour, which defines the respective cross-section. The final result also depends on whether the powder in one layer is sintered in only one direction or in perpendicular directions or alternating layers, etc. and on their combination, leading to the desired precision and surface roughness.

Based on this technology, defects are typically identified that affect repeatability, reliability, safety and, of course, mechanical properties, e.g. dynamic load, creep etc. Based on the new research, international standardization conditions that are focused on AM are constantly created and updated. However, this is very difficult because the AM process is affected by up to 50 parameters and inputs that are controlled by default, but some of them are difficult or almost impossible to control (e.g. powder size distribution, internal defects). Complex phenomena that occur during the melting, hardening and cooling of metallic powder (e.g. the direction and volume of the inert gas), impair the control of the sintering process. Current research is thus focused on optimizing or searching for the new methods, procedures, principles of solving inhomogeneity identified during the process and its elimination or minimization. Therefore, it is very important to have the input materials described in detail from the point of view of their structure and mechanical load, which the project aims to achieve with the 316L material.

There are several types of defects in metallic 3D printing [5], such as pores, cracks, residual stress and surface quality, which affect accuracy and stability. The tension in the material occurs during the melting process due to the rapid heating and cooling of the part. Significant manifestations of this phenomenon occur after the printing process. Therefore, it is important to be able to predict these states using numerical simulation. However, today's quality of calculations critically depends on the exact temperature field, which affects both residual stress and deformation. In work [6], the authors summarized the principles of voltage generation. As they state, it is still a combination of a high temperature gradient and fast cooling, which could be influenced by a special process or a different approach in the solution. They state that high residual tensile stress is very typical in the surface zone, while the presence of tension in the substrate is influenced by the total volume and construction of the part. Based on several experiments, they recommended several principles for stress minimization. Residual stress in metallic AM could be mitigated by in-process methods (e.g. preheating, process planning, feedback control, laser blasting) and post-process methods (e.g. machining and heat treatment, which is the most effective method for removing the residual stress). Another study was aimed at evaluating and predicting residual stress when changing heat (energy density) and layer thickness. Based on this, the layer thickness was optimized to improve the stress distribution. The main goal of the work [7] was to find the critical area and to eliminate stress-affected defects. The results were supported by a comparison between the FEM and practical results. An important conclusion that confirms the practical results is the possibility of reducing stress by more than 25 % when optimum layer thickness is used in the critical area and doubling the thermal input can reduce residual stresses by about 20 %.

***Table 1** Thermocouples*

Type	Material		Measurement range	Accuracy	
	+	-		Standard	Special
B	Pt 30%-Rh	Pt 6%-Rh	870 - 1700 °C	± 0.5%	± 0.25%
E	Ni-Cr	Cu-Ni	-270 - 0 °C	± 1.7% or ± 1.0%	-
			0 °C - 870 °C	± 1.7% or ± 0.5%	± 1.0% or ± 0.4%
J	Fe	Cu-Ni	0 - 760 °C	± 2.2% or ± 0.75%	
K	Ni-Cr	Ni-Al	-200 - 0 °C	± 2.2% or ± 2.0%	-
			0 °C - 1200 °C	± 2.2% or ± 0.75%	± 1.1% or ± 0.4%
N	Ni-Cr-Si	Ni-Si-Mg	0 °C - 1260 °C	± 2.2% or ± 0.75%	± 1.1% or ± 0.4%
R	Pt 13%-Rh	Pt	0 °C - 1480 °C	± 1.5% or ± 0.25%	± 0.6% or ± 0.1%
S	Pt 10%-Rh	Pt	0 °C - 1480 °C	± 1.5% or ± 0.25%	± 0.6% or ± 0.1%
T	Cu	Cu-Ni	-200 - 0 °C	± 1.0% or ± 1.5%	-
			0 °C - 370 °C	± 1.0% or ± 0.75%	± 0.5% or ± 0.4%

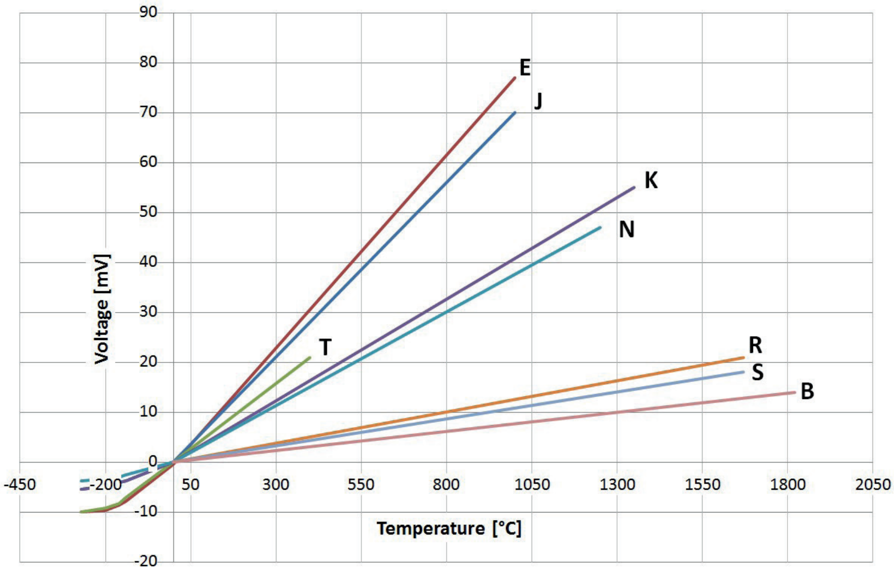

***Figure 2** Thermocouple sensitivity as thermocouple voltage vs temperature for common thermocouple types, using a cold junction at 0 °C*

Among the more recent works related to the topic, it is worth mentioning the article [8] presents a method of measuring the thickness of powder layers during laser bed melting using in-situ infrared thermographic control. This technique provides a local and non-destructive approach to quality control in additive manufacturing processes. And the work [9-11] that maps melt pool dynamics within L-PBF technology.

2 Description of the job solution

The issue of using a thermal camera to monitor high temperatures, concerning the use of a fast thermal imager (photon principle) to measure the power and emissivity of the surface in additive 3D printing, by means of laser sintering, has been studied [12].

A stand for thermal imager measurement consisting of the thermocamera FLIR SC-7500 equipped with f = 100 lens and a holder fixing the camera above a chamber view port has been compiled. The camera performs measurements simultaneously with the thermocouple, which measures the temperature directly on the measuring sample.

2.1 Direct thermocouple measurement

Direct Thermocouple Measurement - a survey of suitable thermocouples and their properties has been carried out (in terms of the maximum temperature range of measurement dynamics, etc.)

Non-insulated thermocouples have been selected and used and are ideal for applications where a quick response is required or where there is not enough space to store a standard thermocouple. The advantage is that

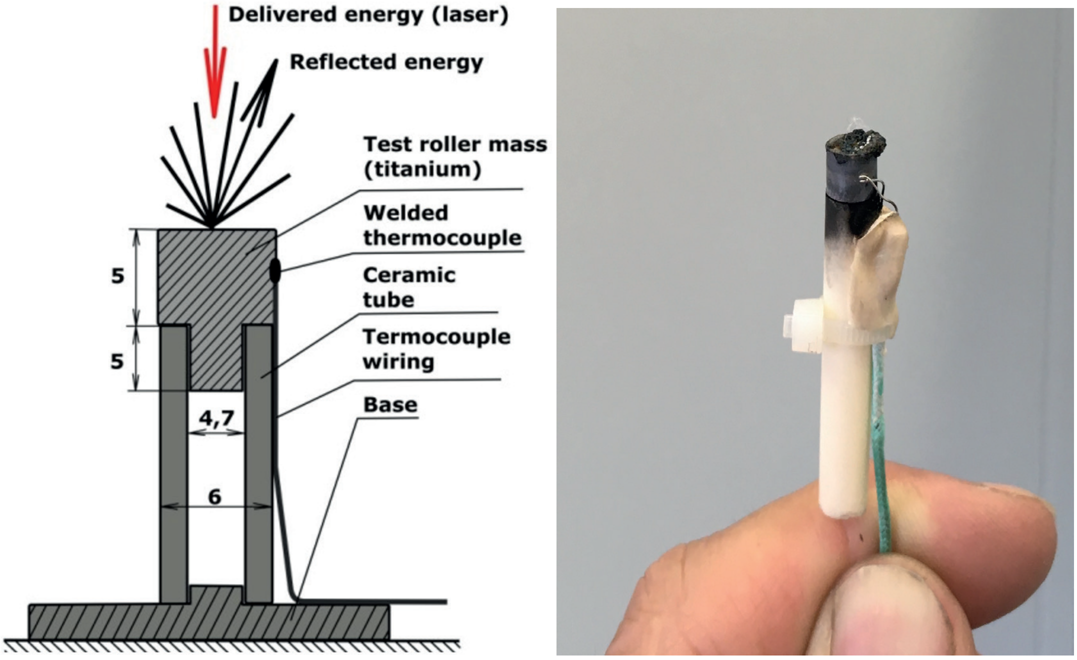

Figure 3 *Setting of measuring titanium roller and prepared surface*

the wire insulation materials cannot contaminate the process and have a quick response. They are available in thermocouples type K, T, J and E. Platinum/rhodium alloys are also available in thermocouples type R, S and B, Table 1.

The Figure 2 shows the relationship between temperature and voltage for various types of thermocouples.

To apply the new heat treatment processes with defined material structure and mechanical properties to 3D printing products, it was important to map the temperature field in the surface layer of the material in detail during the manufacturing process. The first experiments for detecting the thermal phenomena in the surface layer were based on the findings and default conditions from the device operator. First, the available measuring technology was specified.

Tests of direct temperature measurement on the surface of a defined titanium cylinder shape were performed (very small dimensions for good dynamic response and uniform heating of the entire volume in a short time with the help of laser supplied energy) and at the same time non-contact measurement was performed using a high-speed thermal imaging IR camera.

At the beginning, a thorough research was carried out in the field of the high-temperature contact measurements using thermocouples and a relatively less available thermocouple type B was chosen for measuring temperatures up to a range of around 1800 C°. Its advantage, in addition to the high limiting temperature, is also good linearity in the considered range, which is also related to the measurement accuracy. The disadvantage is the low thermoelectric voltage, especially in the lower thermal range, when this thermocouple is intended for measuring the lower limit of temperatures up to approx. 200-300 C°. The conversion characteristics of the most commonly used thermocouples is shown in Figure 2. From the point of view of the material composition of the measuring roller, a titanium alloy with a melting point of up to around 1800 C° was chosen, which guarantees that it is possible to subsequently perform melting with the help of laser doping for common materials used in the field of additive manufacturing and to monitor their phase transformations during simultaneous measurement current temperature. The roller has a diameter of 6 mm and its design, together with a high-temperature ceramic support to minimize heat dissipation through the line, can be seen in Figure 3. The parameters of the test roller were: volume 228.2 mm^3, weight: 0.001 [kg] and specific capacity of the material: 523 [J/kg/K].

2.2 Thermal imager

As mentioned above, during the contact measurements with the help of high-temperature thermocouples type B, a high-speed IR camera SC-7500 was used to display the temperature field. This measurement was chosen due to possible future calibration and the possibility of sensing and analyzing the temperature field only non-contact with the help of an IR camera. Since the thermocouple itself has order of magnitude higher measurement accuracy, it can then be used as a reference. The problem is the limited field of view through the small viewport in the hermetically sealed chamber of the additive printer (Figure 4) and the necessity to use the spectral filters (silicon glass) with additional attenuation, which, even after accounting for this attenuation, reduces the sensitivity of the system

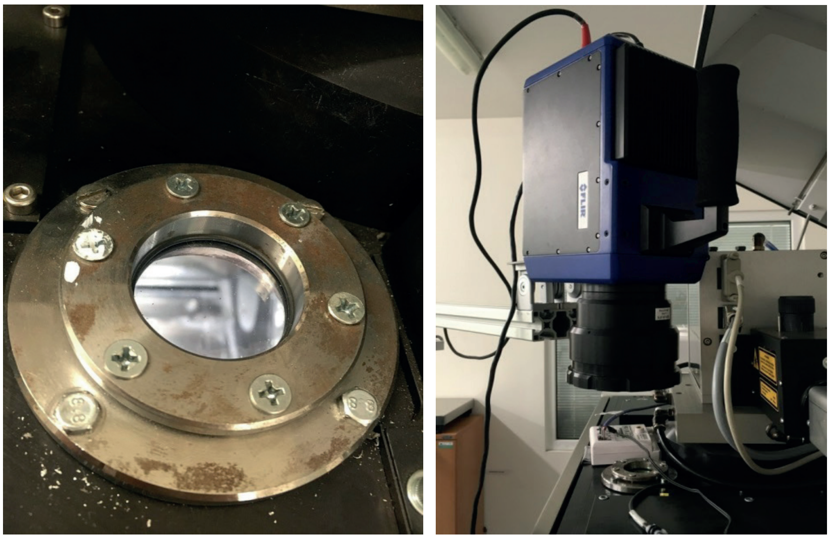

Figure 4 *The viewport with internal diameter 30 mm and the thermal camera attached above the viewport of the 3D printer*

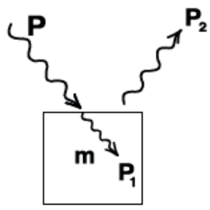

Figure 5 *Power transfer for a body of mass m*

and its overall accuracy. Some other features include the secondary viewport situated at the top of the printer that can include throughputs for thermocouple cabling. In Figure 4 is shown the location of the measuring high-speed camera above the window of the 3D printer itself.

3 Theoretical analysis of the thermal model

As a part of the experiment for indirect temperature measurement, tests of heating the test roller were carried out. The beam "hatched" the surface of the test roller for optimal and even energy transfer to the roller. Figure 5 shows the flow of heat energy relative to mass.

Subsequently, a theoretical analysis of the measured data was carried out in terms of temperature and power.

$$P = P_1 + P_2 \,. \tag{1}$$

Energy change P where P_1 is the energy absorbed in the roller and P_2 is the energy radiated

$$dw = m \cdot c \cdot dT \,. \tag{2}$$

dW represents the differential change in energy or work, measured in joules (J). It refers to the amount of energy transferred or work done. *dT* is a function of temperature and *c* represents the specific heat capacity of the material, measured in joules per kilogram per Kelvin (J/kgK).

Then the energy change P is:

$$P = dW/dt \,,\ P = m \cdot c \cdot dT/dt \,, \tag{3}$$

the power received by the body to increase the temperature is then:

$$P_1 = m \cdot c \cdot dT_1/dt \ , \tag{4}$$

while the time derivative of temperature is $\frac{dT}{dt}$.

The energy loss during the roller cooling is:

$$P_2 = m \cdot c \cdot dT_2/dt \,, \tag{5}$$

for T near the intersection of T_1 and T_2, the losses P_2 [W] and the power received by the body during the heating P_1 without losses are determined, Figures 6 and 7.

4 Experimental measurement

The aim was to set the measurement methodology to be suitable to the EOS M290 commercial L-PBF system. The same measurement methodology has always been followed, where the laser power on the machine was gradually adjusted to levels from 50 W to 350 W. The beam "hatched" the surface of the test roller for optimal and even transfer of energy to the roller. Subsequently, the power-to-temperature ratio was evaluated as the main output.

4.1 Emissivity

To convert a measured camera signal into a true temperature, the surface emissivity must be known. There are multiple methods for measuring emissivity. [13] notes several methods for calculating emissivity measurement uncertainty. The emissivity of titanium roller depends on various factors such as surface finish, temperature, and wavelength of radiation. Titanium has a relatively low emissivity. Polished or oxidized titanium surfaces typically have emissivity values ranging from 0.1 to 0.7. However in some cases, if the surface is rough or coated, the emissivity can be higher. The test titanium roller has its surface very rough, therefore the emissivity value on the camera was set to 1, the influence of the attenuation of the spectral filter has not yet been considered.

4.2 Measurement results and calculation

All the thermocouple measurements of temperature and data from IR camera are shown in Figures 8 to 11 depending on laser power. The maximum value represents the highest temperature recorded within the measured area and indicates the hottest point or object in the field of view. The mean value represents the average temperature calculated by summing up all the temperature values within the measured area.

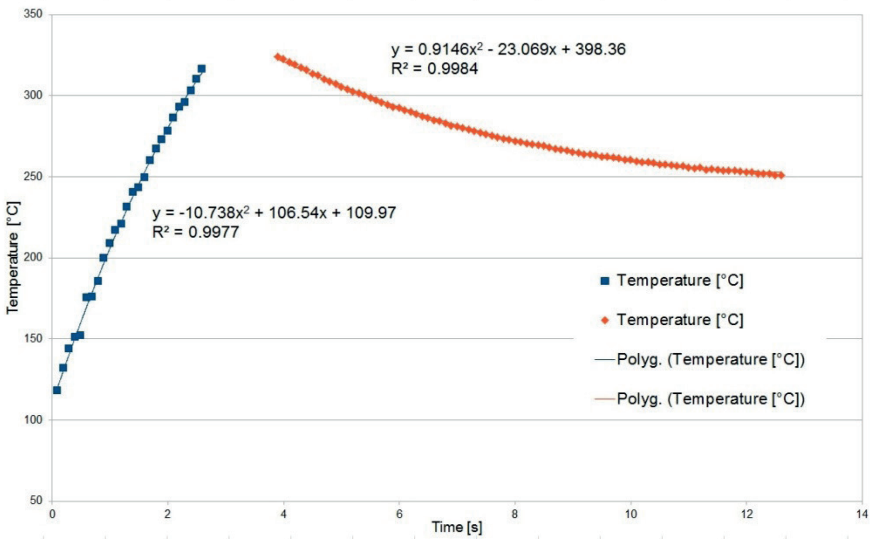

Figure 6 *Heating and cooling temperature measured data at a laser beam power level of 50W*

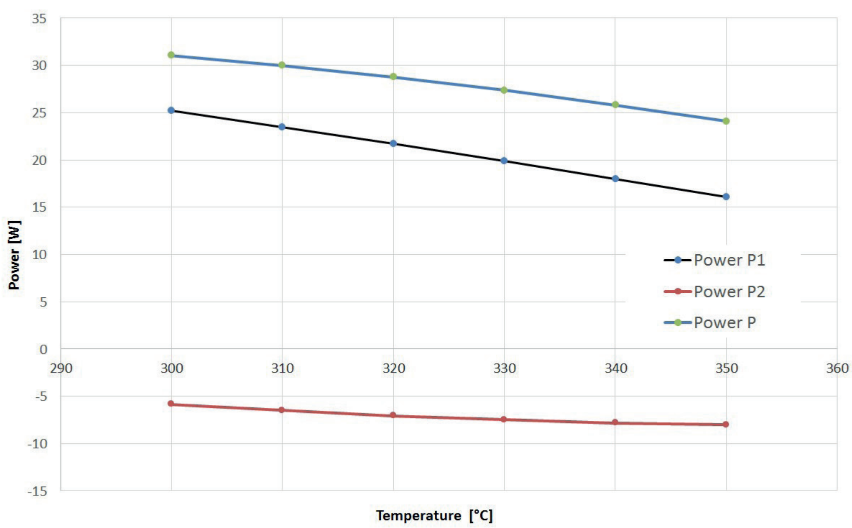

Figure 7 *Calculated power at a laser beam power level of 50W*

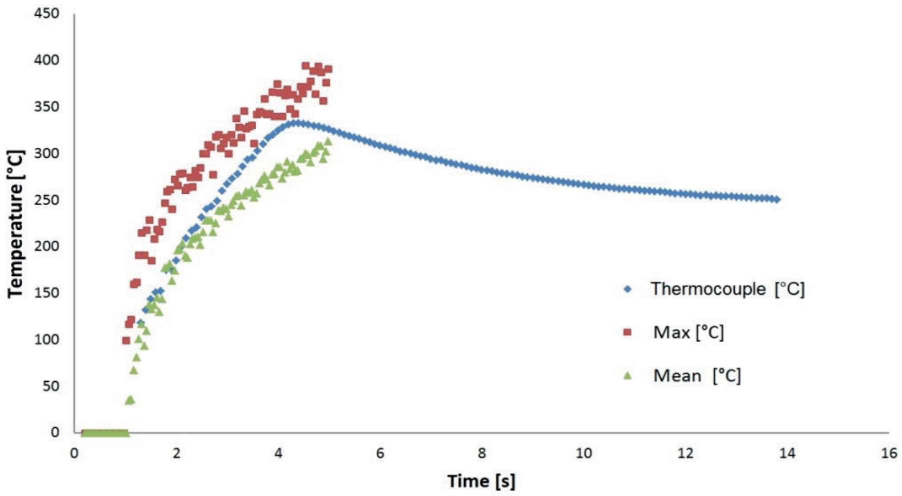

Figure 8 *Relationship between the thermocouple and IR camera for 50 W of laser power*

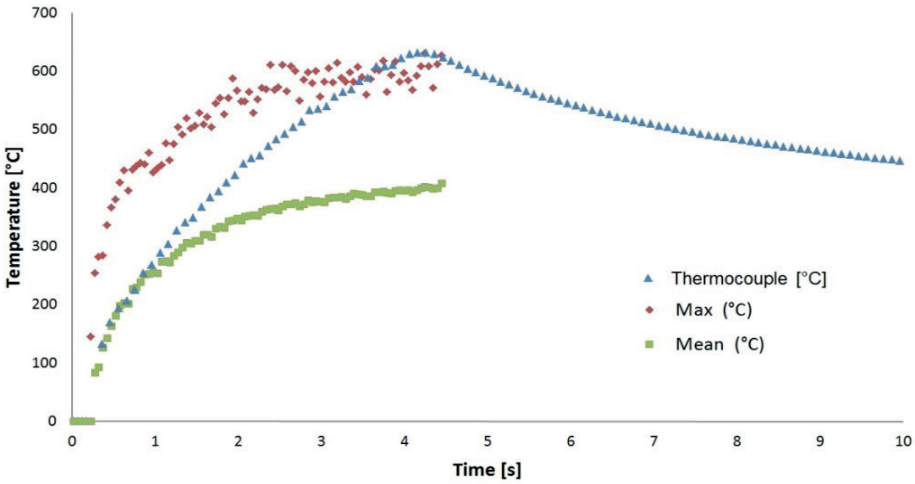

Figure 9 *Relationship between the thermocouple and IR camera for 100 W of laser power*

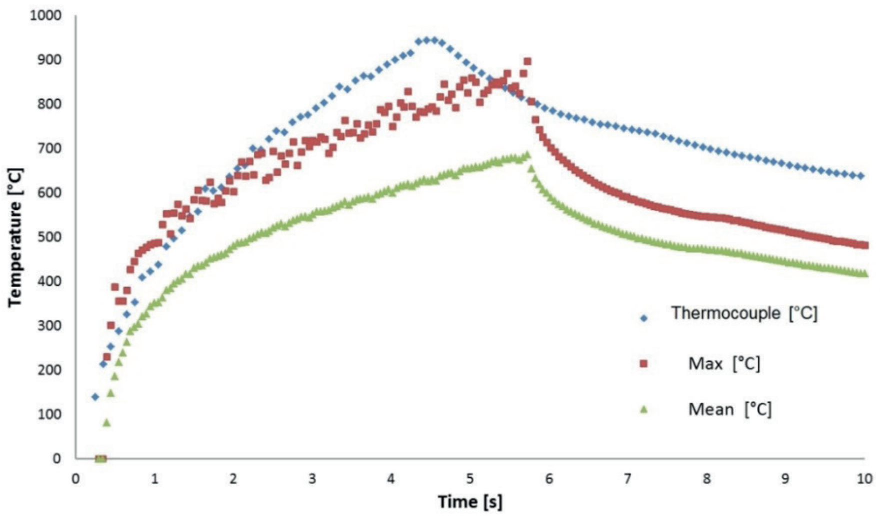

Figure 10 *Relationship between the thermocouple and IR camera for 150 W of laser power*

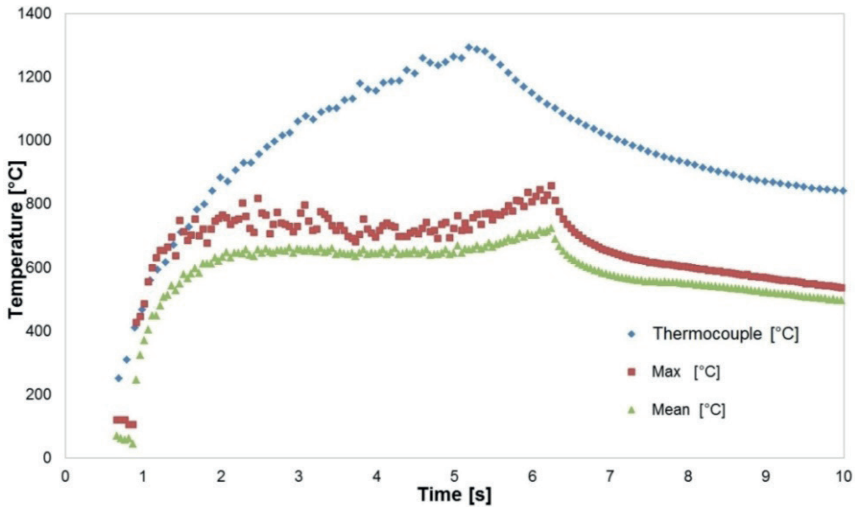

***Figure 11** Relationship between the thermocouple and IR camera for 300 W of laser power*

5 Discussion

The thermal imaging experiments of the heat process were performed while maintaining the same rendering time and path, at seven power levels (50, 100, 150, 200, 250, 300, and 350 W) of the commercial EOS 270M L-PBF machine.

A special B-type (Pt-Rh) thermocouple enabling the high measurement dynamics and measuring temperatures in the range of 870 to 1700 °C, placed (spot-welded on the surface) on a titanium roller, was used to measure the increase in temperature, which was in time correlation with the supplied energy.

At the same time, a FLIR SC-7500 high-speed thermal camera, with an external filter and calibration in the thermal range of 300 to 1500 degrees, was used. With the help of this camera, the irradiated surface of the measuring roller was scanned and its temperature was evaluated from the resulting video sequence.

There was a noticeable agreement between the measurement recorded by the IR camera and the real measurement using the thermocouple, i.e. the temperature increase depending on the supplied energy by the laser beam was determined by calculation and this was compared to the real measurement.

The measurement agreement between the thermocouple and the thermocamera was for values of 50, 100, 150 W of laser power. For higher values, the measurement values from the high-speed thermocamera were significantly lower than those of the reference thermocouple. The use of IR thermal vision at higher incident energies (LASER power higher than approx. 250 W) is problematic due to the divergence between the contact measurement using a thermocouple and non-contact measurement using an IR high-speed thermal camera. It is seen on the graph in Figure 8. This was probably caused by formation of a plasma cloud, which is caused by the too high impact energy of the laser beam. The mentioned plasma cloud then probably behaves as a spectral filter in the IR region.

6 Conclusion

In this research, the objective was to investigate the power delivered by a laser beam during metal 3D printing using the laser bed fusion method. The study focused on a specific mass in the form of a titanium roller, with the laser power on the machine gradually adjusted from 50 W to 350 W. By the end of the research, the measured data obtained through the calculation procedure confirmed the declared power supplied by the device to the titanium cylinder. This finding signifies the accuracy and reliability of the laser power settings on the machine, ensuring that the intended power levels were effectively delivered during the 3D printing process. The successful confirmation of the power supplied to the titanium roller enhances the understanding and control of the metal 3D printing process, providing valuable insights for optimizing parameters and achieving desired outcomes in similar applications.

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Conflicts of 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.

References

[1] MANI, M., LANE, B., DONMEY, M. A., FENG, S., MOZLAN, S., FESPERMEN, R. Measurement science needs for real-time control of additive manufacturing powder bed fusion process [online]. NIST Internal Report (NISTIR) 8036. Gaithersburg, MD, USA: National Institute of Standards and Technology, 2015. Available from: https://doi.org/10.6028/NIST.IR.8036

[2] LANE, B. M., MOLYAN, S. P., WHITEON, E. P., MA, L. Thermographic measurements of the commercial laser powder bed fusion process at NIST. *Rapid Prototyping Journal* [online]. 2016, **22**(5), p. 778-787. ISSN 1355-2546. Available from: https://doi.org/10.1108/RPJ-11-2015-0161

[3] SURYAWANSHI, J., PRASHANTH, K. G., RAMAMURTY, U. Tensile, fracture and fatigue crack growth properties of a 3D printed maraging steel through selective laser melting. *Journal of Alloys and Compounds* [online]. 2017, **725**, p. 355-364. ISSN 0925-8388, eISSN 1873-4669. Available from: https://doi.org/10.1016/j.jallcom.2017.07.177

[4] MONKOVA, K., ZETKOVA, I., KUCEROVA, L., ZETEK, M., MONKA, P., DANA, M. Study of 3D printing direction and effects of heat treatment on mechanical properties of MS1 maraging steel. *Archive of Applied Mechanics* [online]. 2019, **89**, p. 791-804. ISSN 0939-1533, eISSN 1432-0681. Available from: https://doi.org/10.1007/s00419-018-1389-3

[5] TAMMAS-WILLIAMS, S., ZHAO, H., LEONARD, F., DERGUTI, F., TODD, I., PRANGNELL, P. B. XCT analysis of the influence of melt strategies on defect population in Ti-6Al-4V components manufactured by selective electron beam melting. *Material Characterization* [online]. 2015, **102**, p. 47-61. ISSN 1044-5803, eISSN 1873-4189. Available from: https://doi.org/10.1016/j.matchar.2015.02.008

[6] LI, C., LIU, Z. Y., FANG X. Y., GUO, Y. B. Residual stress in metal additive manufacturing. *Procedia CIRP* [online]. 2018, **71**, p. 348-353. eISSN 2212-8271. Available from: https://doi.org/10.1016/j.procir.2018.05.039

[7] MUKHERJEE, T. ZHANG, W, DEBROY, T. An improved prediction of residual stresses and distortion in additive manufacturing. *Computational Materials Science* [online]. 2017, **126**, p. 360-372. ISSN 0927-0256, eISSN 1879-0801. Available from: https://doi.org/10.1016/j.commatsci.2016.10.003

[8] LIU, T., LOUGH, C. S., SEHHAT, H., REN, Y. M., CHRISTOFIDES P. D., KINZEL, E.C., LEU, M. C. In-situ infrared thermographic inspection for local powder layer thickness measurement in laser powder bed fusion. *Additive Manufacturing* [online]. 2022, **55**, 102873. ISSN 2214-8604, eISSN 2214-7810. Available from: https://doi.org/10.1016/j.addma.2022.102873

[9] REHMAN, A. U. PITIR, F., SALAMCI, M. U. Full-field mapping and flow quantification of melt pool dynamics in laser powder bed fusion of SS316L. *Materials* [online]. 2021, **14**(21), 6264. eISSN 1996-1944. Available from: https://doi.org/10.3390/ma14216264

[10] ZHENG, L., ZHANG, Q., CAO, H., WU, W., MA, H., DING, X., YANG, J., DUAN, X., FAN, S. Melt pool boundary extraction and its width prediction from infrared images in selective laser melting. *Materials and Design* [online]. 2019, **183**, 108110. ISSN 0264-1275, eISSN 1873-4197. Available from: https://doi.org/10.1016/j.matdes.2019.108110

[11] OBEIDI, M. A., AHAD I. A., BRABAZON, D. Investigating the melt-pool temperature evolution in laser-powder bed fusion by means of infra-red light: a review. *Key Engineering Materials* [online]. 2022, **926**, p. 235-241. ISSN 1662-9795. Available from: https://doi.org/10.4028/p-6fn67z

[12] BAYLE, F., DOUBENSKAIA, M. Selective laser melting process monitoring with high speed infra-red camera and pyrometer. In: Fundamentals of Laser Assisted Micro- and Nanotechnologies, 2007: proceedings [online]. SPIE. Vol. 6985. 2008. Available from: https://doi.org/10.1117/12.786940

[13] MADDING, R. P. Emissivity measurement and temperature correction accuracy considerations. In: AeroSense ‘99: proceedings [online]. SPIE. Vol. 3700 Thermosense XXI. 1999. Available from: https://doi.org/10.1117/12.342307

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INCREASING THE EFFICIENCY OF TRANSPORTATION OF CARGOES WITH A CYLINDRICAL SHAPE

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Resume

One of the most important directions of intensification and increasing the efficiency of the transportation process is to improve the use of the carrying capacity and capacity of vehicles. For this, it is necessary to the choose rational schemes for loading the cargo into cargo places of the rolling stock. The possible options for loading the vehicle body with cylindrical loads, which are transported when they are installed on the end, are considered. The conducted analysis showed that there are several typical schemes for loading such cargoes. Analytical dependencies have been obtained that allow choosing a rational loading scheme when transporting such cylindrical loads, considering their parameters and the characteristics of cargo places of vehicles. Based on the performed research, the best variant is proposed, i.e. the option with the clearance of 0.2 m, allowing transportation of 125 cylindrical cargo units in the space of a vehicle.

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1 Introduction

The situation on the logistics markets is becoming more complicated today due to the increase in transport costs due to the increase in fuel prices, transport tariffs, etc. The carrier cannot influence the monopolies' tariffs, while by increasing the percentage of his profit in the price of transportation, he risks losing customers. There is only one way left - to improve transportation planning and increase the work efficiency. Improving the use of the carrying capacity and capacity of vehicles is one of the most important areas of intensification and increasing the efficiency of the transportation process [1-4].

Faster and more efficient transportation of goods from the consignor to the consignee can be facilitated by use of the modern transport technologies and promising energy-efficient technical solutions [5-8]. Ensuring the safety of the transport process is no less important [9-12].

A common type of cargo transported by any mode of transport is cargo that has the shape of a cylinder (hereinafter - CCS). Such loads can be divided into several groups based on their weight and overall characteristics. The first group includes various pipes and containers. The ratio of the height of the cylinder to its diameter is high enough for such cargoes. Those cargoes are placed in the vehicle body in such a way that the generatrixes of cylinders are parallel to the longitudinal axis of the vehicle body. Schemes of loading such cargoes into vehicle bodies depend on the weight and overall characteristics of these cargoes and are usually developed by manufacturers. The other group includes loads in which the ratio of the height of the cylinder to its diameter is no more than 2 m to 3 m. These are both packaged and unpackaged goods: wooden and metal barrels, tanks, drums, rolls, coils, bays, and so on. Most often, such cargoes are transported by installing them on the base of the cylinder.

To increase the efficiency of transportation of such cargoes, it is necessary to rationally use the carrying capacity and capacity of vehicle bodies due to the optimization of cargo loading schemes. This can sometimes be quite a difficult task due to the specifics of the mass-dimensional characteristics of individual cargo packages.

When planning the loading of such cargoes into the body of vehicles, it is necessary to ensure the maximum use of their carrying capacity and floor area of the body. At the same time, it is necessary to take into account the basic conditions and requirements for their placement and fastening, which are defined in [13-15] and the corresponding rules of cargo transportation.

In our opinion, insufficient attention is paid to this topic. Those studies are quite few. For example, work [16] is devoted to the problem of improving the use of heavy-duty road trains by increasing their actual load. The task of optimization of loading schemes was solved in three stages. An example of solving the optimization problem of the cargo units placement in a five-axle road train is formulated and shown. In article [17], based on dynamic programming, recommendations were developed for selecting the optimal vehicle loading plan.

The use of information technologies in development of the load placement and fastening schemes significantly reduces development time, increases the productivity of scheme developers, who have the opportunity to concentrate their attention on more complex stages of calculation that are not amenable to automation. It is inefficient to determine the loading scheme experimentally. So, for example, in work [18] it is proposed to use a genetic algorithm for this - a search heuristic algorithm used to solve optimization tasks in the field of computer science and artificial intelligence.

However, in some cases, it is advisable to use the simpler means to choose a rational scheme for loading cargo into the body of optimize the scheme of loading cargo into the body, taking into account their mass and dimensions parameters and the characteristics of cargo places of rolling stock [19-20].

The purpose of this article was to determine analytical dependencies that allow choosing a rational loading scheme for the transportation of cylindrical loads, taking into account their parameters and the characteristics of cargo places of vehicles [21-25].

2 Research methodology

Analysis of possible options for loading vehicle bodies with cylindrical loads, when installing them on the end, shows that there are several typical loading schemes (Figure 1). These schemes are also depicted in 3D views (Figure 2).

For the most effective use of the vehicle's capabilities, when solving the problem of determining the maximum number of cylindrical cargo that can be placed in the body, depending on its characteristics and overall dimensions of one CCS cargo package, the following calculation dependencies were obtained for the considered loading schemes:

- for the loading scheme (Figure 1, *a*):

$$G_a = N_a \cdot M_a = \left[\frac{H}{h}\right] \cdot \left[\frac{B}{2R}\right] \cdot \left[\frac{L}{2R}\right], \tag{1}$$

- for the loading scheme (Figure 2, *b*):

$$G_b = N_b \cdot M_b = \left[\frac{H}{h}\right] \times \\ \times \left[\frac{B}{2 \cdot R + Z \cdot \left[\left(\frac{B}{2 \cdot R} - 1\right)\right]}\right] \cdot \left[\frac{L}{2 \cdot R - S}\right], \tag{2}$$

- for scheme (Figure 1, *c*) with an even total number of rows of cargo in the longitudinal direction:

$$G_{c1} = N_{c1}^{p} \cdot M_{c1}^{p} + N_{c1}^{np} \cdot M_{c1}^{np} = \left[\frac{H}{h}\right] \times \\ \times \left\{\left(\frac{B}{2 \cdot R + Z \cdot \left(\frac{B}{2 \cdot R}\right) - 1}\right) \cdot \frac{\left(\frac{L}{2 \cdot R - S}\right)}{2} + \right. \\ \left. + \left[\left(\frac{B}{2 \cdot R + Z \cdot \left(\frac{B}{2 \cdot R}\right) - 1}\right) - 1\right] \cdot \frac{\left(\frac{L}{2 \cdot R - S}\right)}{2}\right\}, \tag{3}$$

- for scheme (Figure 1, *c*) with an odd total number of cargo rows in the longitudinal direction:

$$G_{c2} = N_{c2}^{p} \cdot M_{c2}^{p} + N_{c2}^{np} \cdot M_{c2}^{np} = \left[\frac{H}{h}\right] \times \\ \times \left\{\left(\frac{B}{2 \cdot R + Z \cdot \left(\frac{B}{2 \cdot R}\right) - 1}\right) \cdot \left(\frac{\left(\frac{L}{2 \cdot R - S}\right)}{2} + 1\right) + \right. \\ \left. + \left[\left(\frac{B}{2 \cdot R + Z \cdot \left(\frac{B}{2 \cdot R}\right) - 1}\right) - 1\right] \cdot \frac{\left(\frac{L}{2 \cdot R - S}\right)}{2}\right\}, \tag{4}$$

where N_i is the number of cargo units placed in one row along the width of the body with the selected loading scheme,
M_i - the number of transverse rows of cargo stacking in the body with the selected loading scheme;
H, B, L - height, width and length of the vehicle body, respectively;
$2R$ - diameter of one cargo place;
h - height of one cargo place;
S - the depth of the "saddle", which is formed by two adjacent CCS cargo places when installing the second and subsequent rows of cargo in the body (Figure 2 for loading schemes (*b*) and (*c*)).

Rounded down values of the corresponding expressions are indicated by square brackets, [...].

The value of S, in the general case, depends on the diameter $D = 2 \cdot R$ of one cargo place of a cylindrical cargo and the size of the existing places Z between the cargo places in a row (Figure 3).

The analysis of geometric ratios, according to Figure 2, allows us to determine [25] that

$$S = 2R - \sqrt{4R^2 - (R + Z/2)^2}\,. \tag{5}$$

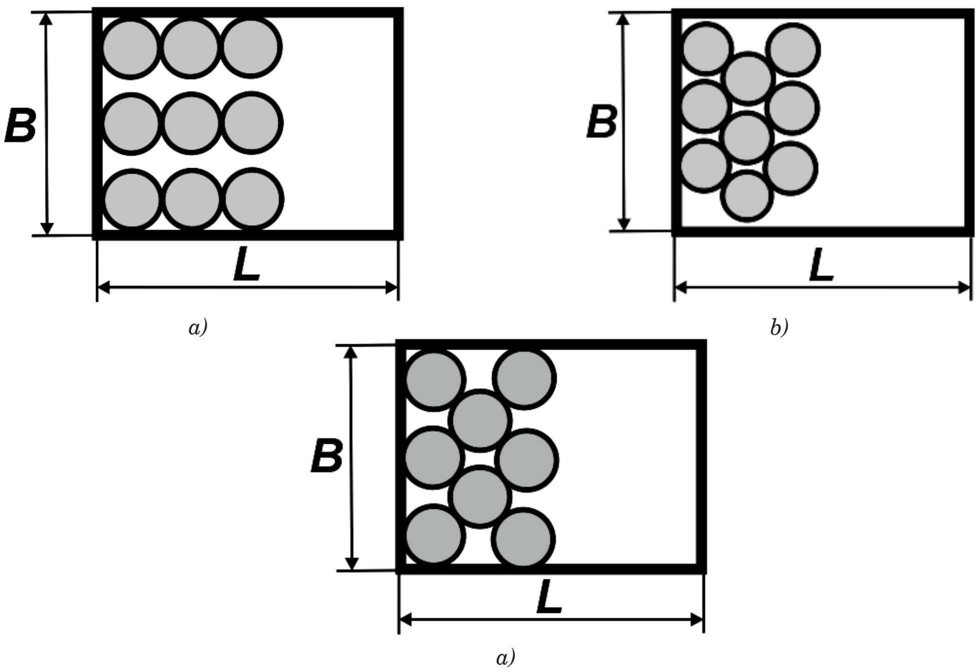

Figure 1 *Variants of CCS loading schemes in the body – 2D views*

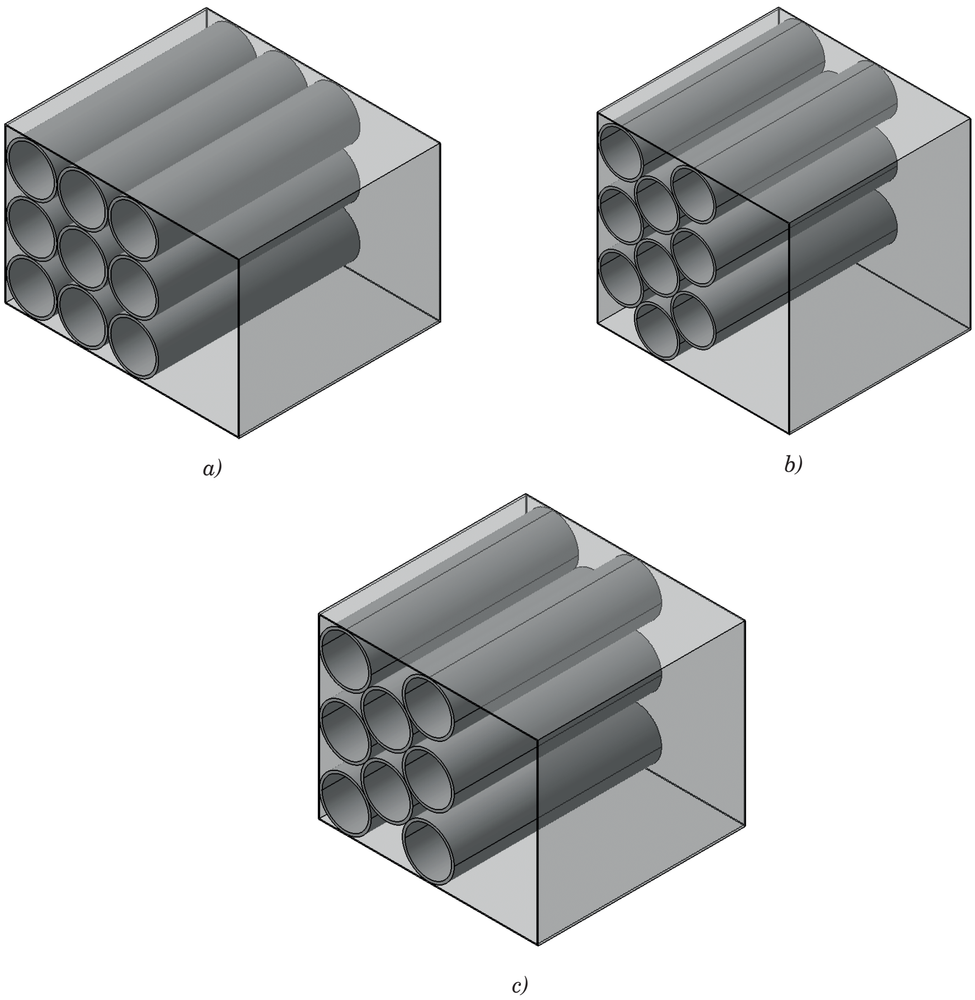

Figure 2 *Variants of CCS loading schemes in the body – 3D views*

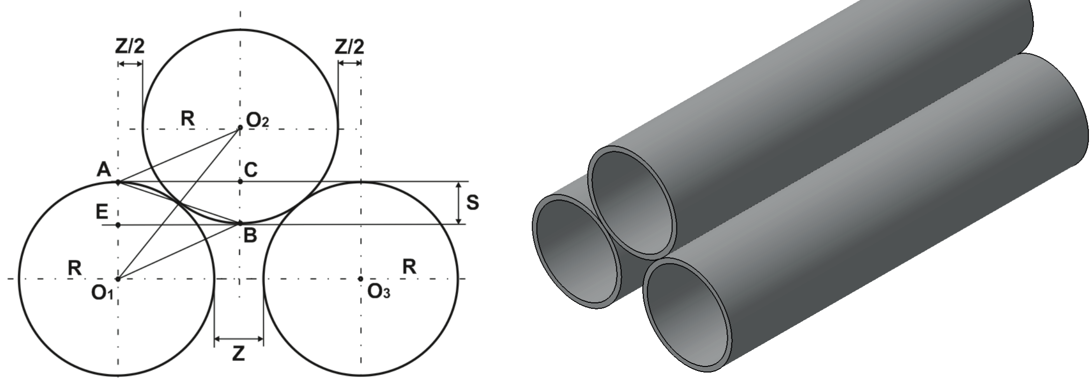

Figure 3 A calculation scheme

It should also be remembered that the scheme of placement and fastening of cargo, in different cargo transport units, depends on the type of cargo and the design of the body. For example, the strength of the side walls and the front and rear of the body is important for cars [13].

3 Results and discussion

A large number of different modifications of semi-trailers are used for cargo transportation by vans, among which one can distinguish both small semi-trailers with a volume of 75 to 80 m³ (with a body length of 12 to 13 m), and standard semi-trailers with a body volume of 82 to 96 m³. They have a body length of 13.6 to 15 m, a width of 2.4 to 2.5 m and a height of 2.5 to 2.7 m.

Some calculation results are given in Figures 4 and 5, as examples illustrating the dependencies $G_i = f(R, Z)$ for loading schemes *a* and *b* (Figure 1) and for loading scheme *a* and *c*2, respectively, when loading a cargo space, which has the geometric parameters of the cargo space of a semi-trailer with a width of 2.4 m and a length of 13.6 m. The quantity G_i is the total number of cylindrical cargoes that fit in the cargo space of the vehicle and it is unitless quantity. The scale 0 to 400 of the G_i is a scale for determining the total number of cylindrical cargoes, which are placed in the cargo space of a vehicle when using various loading schemes for the initial data adopted in the considered calculation example.

The height of one CCS cargo place is assumed equal to $h = 1$ m, loading is carried out in one tier.

The proposed analytical dependencies make it

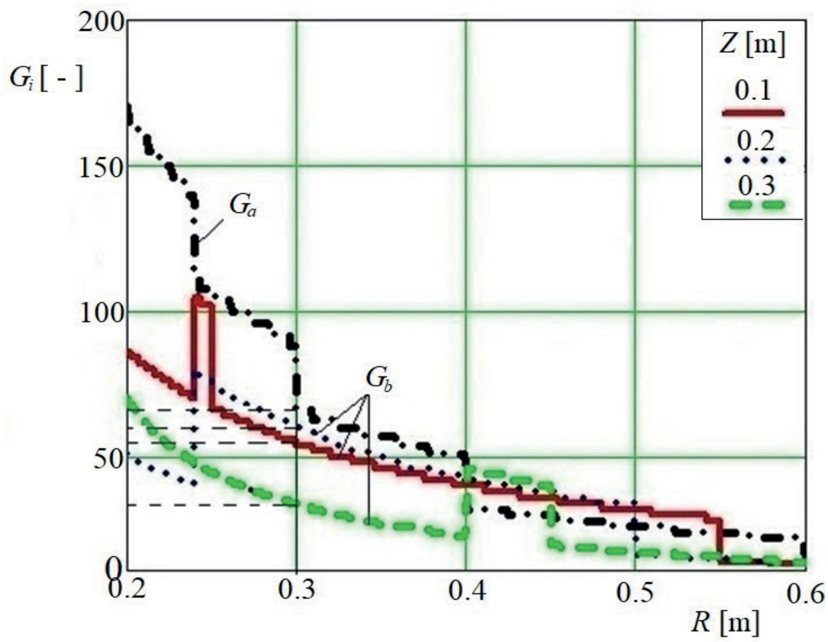

Figure 4 An example of dependence $G_i = f(R, Z)$ for the loading schemes (a) and (b)

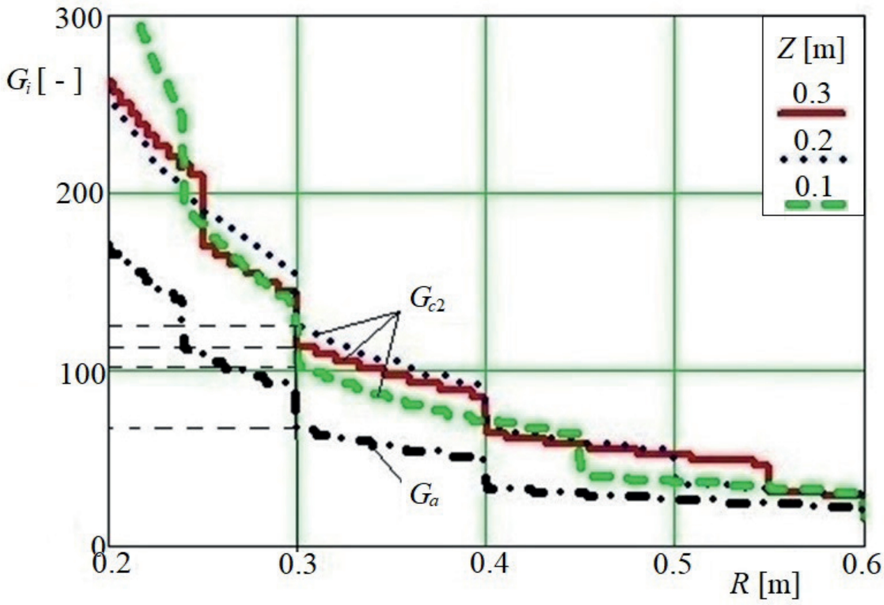

Figure 5 *An example of dependence $G_i = f(R, Z)$ for the loading schemes (a) and (c2)*

possible to substantiate the choice of the optimal loading scheme given the known parameters of the vehicle body and the given mass-dimensional indicators of cylindrical cargoes.

At the same time, it should be considered that the ratio must be fulfilled:

$$G_i \cdot q \leq Q_{\max}, \quad (6)$$

where q is the mass of one cargo place,
Q_{max} - carrying capacity of the vehicle.

Determining the most efficient schemes for loading the cylindrical cargo based on the proposed analytical design dependencies makes it possible to more rationally use the cargo capacity of the cargo space of a vehicle. The use of the carrying capacity of the vehicle in this case will depend on the weight q of one unit of cylindrical cargo, considering the maximum carrying capacity of the euro truck (in our case, up to 24 tons). This mass depends on properties of the cylindrical cargo itself and can vary widely.

4 Conclusions

Improving the use of the carrying capacity and capacity of vehicles is one of the most important directions of intensification and increasing the efficiency of the transportation process.

A common type of cargo transported by any mode of transport is cargo that has the shape of a cylinder. Those are both packaged and unpackaged goods: wooden and metal barrels, tanks, drums, rolls, coils, bays, and so on. Most often, such cargoes are transported by installing them on the end.

The analysis of possible options for loading the vehicle body with cylindrical cargoes when they are installed on the end showed that there are several typical schemes for loading such cargoes. Analytical dependencies have been obtained that allow choosing a rational loading scheme when transporting such cylindrical cargoes, taking into account their parameters and the characteristics of cargo spaces of vehicles.

For the initial data adopted in the calculation example, it was obtained that when loading cylindrical goods with a radius of 0.3 m into the cargo space of an automobile semi-trailer with a width of 2.4 m and a length of 13.6 m. when using the loading scheme (*a*), can be placed approximately 70 cargo units, while the use of the best variant of the loading scheme (*b*) with a clearance of Z = 0.2 m allows only 62 cargo units to be placed in the same space. For the initial data taken in the calculation, the best option would be to use the C_2 loading scheme (Figure 4), which, with a value of transverse clearances Z = 0.2 m between the packages, allows 125 cylindrical cargo units to be placed in the cargo space of vehicle.

Thus, determination of the most efficient schemes for loading the cylindrical cargo based on the proposed analytical design dependencies makes it possible to use the cargo capacity of the cargo space of a vehicle more rationally. The completeness of the use of the carrying capacity of the vehicle, in this case, depends on the mass of one unit of cylindrical cargo, considering the maximum carrying capacity of a vehicle.

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Conflicts of 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.

References

[1] Transport logistics. shared solutions to common challenges [online]. OECD 2002. Available from: https://www.itf-oecd.org/sites/default/files/ docs/02logisticse.pdf

[2] FILINA-DAWIDOWICZ, L., KOSTRZEWSKI, M. The complexity of logistics services at transshipment terminals. *Energies* [online]. 2022, **15**(4), 1435. eISSN 1996-107. Available from: https://doi.org/10.3390/en15041435

[3] NADER, M., KOSTRZEWSKI, A., KOSTRZEWSKI, M. Technological conditions of intermodal transshipment terminals in Poland. *Archives of Transport* [online]. 2017, **41**(1), p. 73-88. ISSN 0866-9546, eISSN 2300-8830. Available from: https://doi.org/10.5604/01.3001.0009.7388

[4] IMIDE, I. O., UNIVERSITY, E. O., OSADUME, R. C., FIDELIA, I. Globalization, transportation and marketing of goods made in Africa: the new paradigm. *LOGI - Scientific Journal on Transport and Logistics* [online]. 2022, **13**(1), p. 152-162. eISSN 2336-3037. Available from: https://doi.org/10.2478/logi-2022-0014

[5] MIKHAILOV, E., DIZO, J., KLIUIEV, S., SEMENOV, S., LACK, T., KRAVCHENKO. K. Mechatronic system of control position of wheel pairs by railway vehicles in the rail track. *AIP Conference Proceedings* [online] 2019, **2198**, 020009. ISSN 0094-243X, eISSN 1551-7616. Available from: https://doi.org/10.1063/1.5140870

[6] MIKHAILOV, E., SEMENOV, S., KLIUIEV, S., DIZO, J., BLATNICKY, M., GERLICI, J., HARUSINEC, J., KOVTANETS, M. Clarification of features of the wheel movement with a perspective constructive scheme on a rail. *Applied Sciences* [online]. 2020, **10**, 6758. eISSN 2076-3417. Available from: https://doi.org/10.3390/app10196758

[7] OPALA, M., KORZEB, J., KOZIAK, S., MELNIK, R. Evaluation of stress and fatigue of a rail vehicle suspension component. *Energies* [online]. 2021, **14**(12), 34.10. eISSN 1996-1073. Available from: https://doi.org/10.3390/en14123410

[8] KRAVCHENKO, A., KRAVCHENKO, K. Monitoring of the technical condition of semi-trailer trucks. *The Archives of Automotive Engineering* [online]. 2017, **81**(3), p. 17-28. eISSN 2084-476X. Available from: https://doi.org/10.14669/AM.VOL81.ART2

[9] MIKHAILOV, E., SEMENOV, S., SHVORNIKOVA, H., GERLICI, J., KOVTANETS, M., DIZO, J., BLATNICKY M., HARUSINEC, J. A study of improving running safety of a railway wagon with an independently rotating wheel's flange. *Symmetry* [online]. 2021, **13**(10), 1955. eISSN 2073-899. Available from: https://doi.org/10.3390/sym13101955

[10] SINGH, P., SINGH, J., ANTLE, J., TOPPER, E., GREWAL, G. Load securement and packaging methods to reduce risk of damage and personal injury for cargo freight in truck, container and intermodal shipments. *Journal of Applied Packaging Research* [online]. 2014, **1**(6) p. 47-61. ISSN 1557-7224. Available from: https://doi.org/10.14448/japr.01.0005

[11] STOPKA, O., LUPTAK, V., DROZDZIEL, P., RYBICKA, I. Modeling transportation routes of the pick-up system using location problem: a case study. *Open Engineering* [online]. 2020, **10**(1), p. 784-792. ISSN 2391-5439. Available from: https://doi.org/10.1515/eng-2020-0089

[12] BRUMERCIKOVA, E., BUKOVA, B., RYBICKA, I., DROZDZIEL, P. Measures for increasing performance of the rail freight transport in the north-south direction. *Communications - Scientific Letters of the University of Zilina* [online]. 2019, **21**(3), p. 13-20. ISSN 1335-4205, eISSN 2585-7878. Available from: https://doi.org/10.26552/com.C.2019.3.13-20

[13] International guidelines on safe load securing for road transport. IRU_CIT-2014. Geneva, Switzerland: IRU General Secretariat, 2014.

[14] Specifications for loading and securing cargo on open rolling stock / Tehnicheskie uslovija pogruzki i kreplenija gruzov na otkrytom podvizhnom sostav (in Russian). Moscow: Transport, 1990.

[15] JAGELCAK, J., VRABEL, J., NIEUWESTEEG, M. Draft of revision of the standard EN 12640 and EN 12641 regarding the securing of cargo on road means of transport. *LOGI - Scientific Journal on Transport and Logistics* [online]. 2017, **8**(2), p. 41-46. eISSN 2336-3037. Available from: https://doi.org/10.1515/logi-2017-0015

[16] OLISKEVYCH, M. Optimization of the load scheme of heavy vehicle for a given flow of goods. *Econtechmod: An International Quarterly Journal on Economics of Technology and Modelling Processes*. 2017, 6(1), p. 55-62. ISSN 2084-5715.

[17] LIANG, Q., ZHICHENG, W., LEI, M., DERU, D., ZHIYUN, Z., XIJIE, G., YUQING, G., WENQIANG, F. Study on optimization of loading plan in car carrier of vehicle logistics transportation. *Journal of System Simulation* [online]. 2015, **27**(8), p. 1868-1874. ISSN 004-731X. Available from: https://www.china-simulation.com/EN/Y2015/V27/I8/1868

[18] DU, Y., CHEN, F., FAN, X., ZHANG, L., LIANG, H. Research on cargo-loading optimization based on genetic and fuzzy integration. *Journal of Intelligent and Fuzzy Systems* [online]. 2021, **40**(4), p. 8493-8500. ISSN 1064-1246, eISSN 1875-8967. Available from: https://doi.org/10.3233/JIFS-189669

[19] GALLIKOVA, J., BARTA, D., CABAN, J. Maintenance system of semi-trailer and risk priority number. *Archives of Automotive Engineering* [online]. 2019, **86**(4), p. 101-109. eISSN 2084-476X. Available from: https://doi.org/10.14669/AM.VOL86.ART7

[20] VRABEL, J., JAGELCAK, J., STOPKA, O., KITKOVA, M., CABAN, J. Determination of the maximum permissible cargo length exceeding the articulated vehicle length in order to detect its critical rotation radius. In: 11th International Science and Technical Conference Automotive Safety, Automotive Safety 2018: proceedings [online]. IEEE. 2018. eISBN 978-1-5386-4578-9. Available from: https://doi.org/10.1109/AUTOSAFE.2018.8373347

[21] LACK T., GERLICI J., MANUROVA M. Freight car bogie properties analysis by means of simulation computations. *Manufacturing Technology* [online]. 2016, **16**(4), p. 733-739. ISSN 1213-2489, eISSN 2787-9402. Available from: https://doi.org/10.21062/ujep/x.2016/a/1213-2489/MT/16/4/733

[22] FABIAN, P., GERLICI, J., MASEK, J., MARTON, P. Versatile, efficient and long wagon for intermodal transport in Europe. *Communications - Scientific Letters of the University of Zilina* [online]. 2013, **15**(2), p. 118-123. ISSN 1335-4205, eISSN 2585-7878.Available from: https://doi.org/10.26552/com.C.2013.2.118-123

[23] PANCHENKO, S., GERLICI, J., VATULIA, G., LOVSKA, A., PAVLIUCHENKOV, M., KRAVCHENKO, K. The analysis of the loading and the strength of the flat rack removable module with viscoelastic bonds in the fittings. *Applied Sciences* [online]. 2023, **13**(1), 79. eISSN 2076-3417. Available from: https://doi.org/10.3390/app13010079

[24] LOVSKA, A., FOMIN, O., KUCERA, P., PISTEK, V. Calculation of loads on carrying structures of articulated circular-tube wagons equipped with new draft gear concepts. *Applied Sciences* [online]. 2020, **10**(21), 7441. eISSN 2076-3417. Available from: https://doi.org/10.3390/app10217441

[25] POLYANIN A., MANZHIROV A. *Handbook of mathematics for engineers and scientists.* New York, USA: CRC Press, 2006. ISBN 978-0429-1433-11.

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INFLUENCE OF THE DESIGN PARAMETERS OF A SCREW FEEDER LOADING MECHANISM ON THE TORQUE VALUE OF THE DRIVE SHAFT

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Resume

The processes of material capture and movement in a screw feeder are characterized by significant loads due to the pressure of a vertical load column, which creates additional resistance to the movement of the material, overcoming which leads to unproductive energy consumption. The paper aims to study the influence of the design parameters of the loading mechanism on the torque on the drive shaft of a screw feeder. The results of experimental studies and computer simulation of the design parameters of the loading mechanism relation (the length of the loading zone, the inclination angle of the rotating wall of the loading nozzle, its displacement value relative to the vertical axis of the auger operating part, and the height of the material in the loading nozzle), to the torque value on the drive shaft of the screw feeder for transportation of bulk cargo, are presented in this paper.

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1 Introduction

Screw transport and technological mechanisms are widely used in various industrial sectors. This is evidenced by a noticeable upward trend in their use in the construction, food, processing, metallurgy, and agricultural industries. The specific weight of such screw mechanisms in loading and unloading operations and transportation of bulk cargo reaches 40-45 %. Screw feeders are the most commonly used units for transport and technological operations and uniform feeding of various receiving devices. They provide efficient loading, unloading, transportation and technological processing (dosing, cleaning and pressing) of fine-dispersed building materials, chemicals, grain and other bulk materials that are required for the further extension of the technological cycle.

It is known that the screw feeders differ from conveyors of the same type by shorter transportation length, as a result, the hanger bearings are not available, which improves their design and improves transportation conditions, as well as increases the filling factor of the feeder. They are characterized by relatively increased productivity, engine power, and structural strength, since they are subjected to significant overloads that occur due to the action of the cargo pressure under the hopper opening or the loading nozzle on the auger operating parts. They are also able to overcome the higher resistance of material movement in the operating mode, which is caused by the weight of the material in the hopper above the outlet. Screw feeders are more energy-intensive since they change the direction of the cargo flow movement, coming from the hopper into the longitudinal movement of transportation. In this way, there is a change and transformation of the energy of the material coming in a continuous flow from the hopper, and the material captured by the flights of the auger operating part in the process of longitudinal transportation. At the same time, the screw feeders can perform the function of conveyors of the same type, moving the cargo to a short distance from the hopper opening.

Most types of screw feeders do not require separate hopper shutters, since when the feeder is stopped, it keeps the cargo from spontaneously spilling out. At the same time, the bulk cargo unloading from the hopper using feeders is characterized by the main function of their operating device on the cargo, which is especially important in the case of poorly flowing cargo, the flow of which through the hopper opening, only due to the action of its weight, is insufficient. In this regard, there are three types of such feeders: open, semi-open and closed.

The object of the presented research is a screw feeder, containing a semi-open loading hopper with free movement of the bulk cargo, and equipped with a single-threaded horizontal screw with a constant pitch of turns. The operating part can be partially displaced in the horizontal direction, relative to the outlet opening and the vertical axis of the hopper, and the material in the capture zone is fed tangentially to the rotation surface of the operating part. The movement of the bulk cargo flow is carried out under the action of the cargo gravity forces.

2 Analysis of the past research and publications

Many analytical, research and experimental studies, along with various patented studies, have been conducted to analyze the characteristics of screw feeders. The works [1-3] analyzed the mechanics of the screw feeder in connection with the characteristics of the bulk material in the feeder hopper, behavior of the material and flow control during its loading and transportation. The papers [4-5] propose a methodology for calculating the structural and power parameters and consider factors affecting the performance of the screw feeders and their optimization based on the results of experimental studies. Formalized descriptions and synthesis of schemes for shaping auger spirals of screw feeders were presented by the authors in [6-7].

Important, from the point of view of further improvement of the screw feeder designs, are the issues of predicting the torque and loading characteristics of bulk cargo transportation processes presented in [8-9], as well as the study of the conditions for formation of a “dead zone” during the loading of a screw feeder, considered by the authors in [10-11].

A significant number of publications are devoted to the study of the design principles of screw feeders: a non-proper design and selection of this device, which is present in large part of industrial processes, could mean poor performances, excessive power, severe wear of plant and degradation of the feeding material [12-13]. The design of a screw feeder is a highly complex procedure: for a correct and successful installation, it is essential to have a proper understanding of influences of all the parameters of the transport process [14-15].

The construction and exploitation parameters of screw feeders must meet the defined requirements concerning their efficiency, the filling rate of the trough, or providing the necessary power to the drive [16-17]. The behavior of bulk materials during transportation by a screw conveyor is very complicated. It depends on many factors, such as the type and shape of the screw flights, the rotational speed of the shaft, the way of proportioning the material, or the physical properties of the material. The study of these factors in the processes of loading and transportation of bulk cargo, their mutual influence and modeling were presented by the authors in [18-19]. The use of the Discrete Element Method (DEM) for simulation and validation of the screw feeders allows for optimizing their design, taking into account the conditions of use [20-23].

Theoretical methods for designing the screw conveyors do not consider all the factors mentioned above, or oversimplify them. In the case of typical bulk materials of uniform granulation and standard constructions of the screws (constant pitch, constant internal and external diameters) and fed by one source, e.g., a hopper, theoretical methods allow reasonable estimation of the exploitation parameters of the screw feeders [24-25].

In the case of materials of specific properties (cohesive or strongly aerated materials) or for unusual shapes of screws or multiple feeding points, these methods do not provide reliable results of efficiency and power [26-27]. For this reason, the external diameters of the screws and power demands are very often chosen to be safely larger. Such an approach is unfavorable because of the excessive use of materials, ineffective use of the drive unit, and high exploitation costs. On the other hand, the difficulties in making decisions on the design of screw feeders are often caused by insufficient exploitation data on the peculiarities of the process of transporting the bulk materials.

In the conditions of energy resource shortage in the world, the important directions of creation and design of the screw feeders are implementation of technical solutions characterized by the low energy consumption and high productivity. This is achieved by improving their layout schemes, auger operating parts and cargo-loading devices based on experimental studies and computer simulation [25, 28]. It is known that the geometric parameters of the loading mechanism and the features of its location relative to the vertical plane passing through the longitudinal axis of the operating part have an impact on the energy consumption of the bulk cargo transportation process [27].

That is why the issue of developing and researching the semi-open screw feeders with shifted loading nozzle, relative to its vertical axis 6, i.e., from the vertical plane passing through the longitudinal axis of the auger (Figure 1), is of scientific and practical interest. The main advantage of such a feeder design is that the material is fed into the capture zone not vertically, but along the inclined wall, the plane of which is tangential to the surface of rotation of the auger operating part.

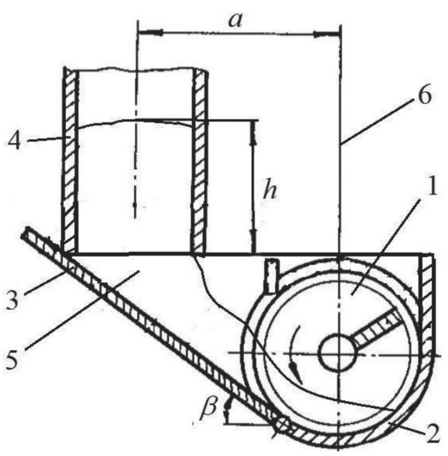

Figure 1 *Cross-sectional diagram of the screw feeder in the loading mechanism location area: 1 - auger operating part; 2 - housing casing; 3 - a rotating wall of the loading nozzle; 4 - loading nozzle; 5 - bulk cargo; 6 - the vertical axis of the auger operating part*

In this design, the torque value on the drive shaft, and therefore energy consumption, is affected by the inclination angle of the rotary wall of the loading nozzle β, the length of the loading zone L, the displacement value of the loading nozzle relative to the vertical plane a, passing through the longitudinal axis of the transporting auger, and the height of bulk cargo in the loading nozzle h.

Despite the considerable number of papers devoted to improving the designs of screw feeders, the problem of the above-mentioned design parameters of the screw feeder loading mechanism influence on the energy consumption of the bulk cargo transportation process has not been sufficiently investigated.

As it is known, the drive power of the screw feeders is consumed to overcome the following resistance forces: frictional forces of the load against the bunker walls; force along the screw, equivalent to the frictional torque of the screw against the cargo; force equivalent to the frictional torque in the bearing unit; the force equivalent to the internal friction in the material caused by the movement and grinding of the bulk cargo in the feeder bunker, which can only be determined by experimental means and by computer simulation.

3 Methods of mechanical and physical research

To carry out experimental investigations, a screw feeder is designed and manufactured to investigate the process of transporting bulk cargo and the influence of the design parameters of the loading mechanism on the torque value on its drive shaft.

Its creation is based on the design and principle of operation of the screw feeder with shifted loading nozzle, relative to the vertical axis of the auger, from the vertical plane passing through the longitudinal axis of the auger operating part (Figure 1).

The scheme of the screw feeder is shown in Figure 2. It consists of a frame 1, on which the drive (asynchronous three-phase electric motor), transporting and loading mechanisms are mounted.

The torque from the engine to the drive shaft 2 of the screw feeder is transmitted using the V-belt transmission to replaceable pulley 3.

The drive shaft is mounted in bearing supports 4, consisting of two angular-contract bearings and housings, which are fixed immovably to the frame using holders 5. At one end of the drive shaft 2, replaceable pulleys are installed, and at the other end, replaceable auger operating parts of the transportation mechanism are attached. This mechanism contains housing 6, made in the form of a pipe (casing) with the notch, which is used to feed the bulk cargo into the capture zone. The replaceable auger in the form of the hollow shaft 7 and the helical spiral 8 are placed in the housing. The housing is rigidly mounted on frame 1 by means of legs 9. The replaceable screw feeder auger is a cantilever fixed to the drive shaft 2. The hollow shaft 7 is installed by its inner diameter with the sliding fit on the free end of the drive shaft and is fixed by pin 10.

The loading mechanism is located above the loading opening of the transportation mechanism, which is mounted with the possibility of cross-movement relative to the vertical axis 11 of the auger. The loading mechanism consists of loading nozzle 12, unloading hopper 13 located above the nozzle, rotary wall 14, and mechanical measuring device 15 for measuring the inclination angle of the rotary wall β and the height of the bulk cargo h in the loading nozzle. The loading nozzle contains the horizontal slide valve 16 and insertable vertical plate 17, made along the width of the loading nozzle. They are installed with the possibility of changing their position relative to the vertical side wall of the nozzle. This makes it possible to adjust the length of loading zone L.

In the loading mechanism, longitudinal wall 18 and one of the cross walls 19 are made of transparent

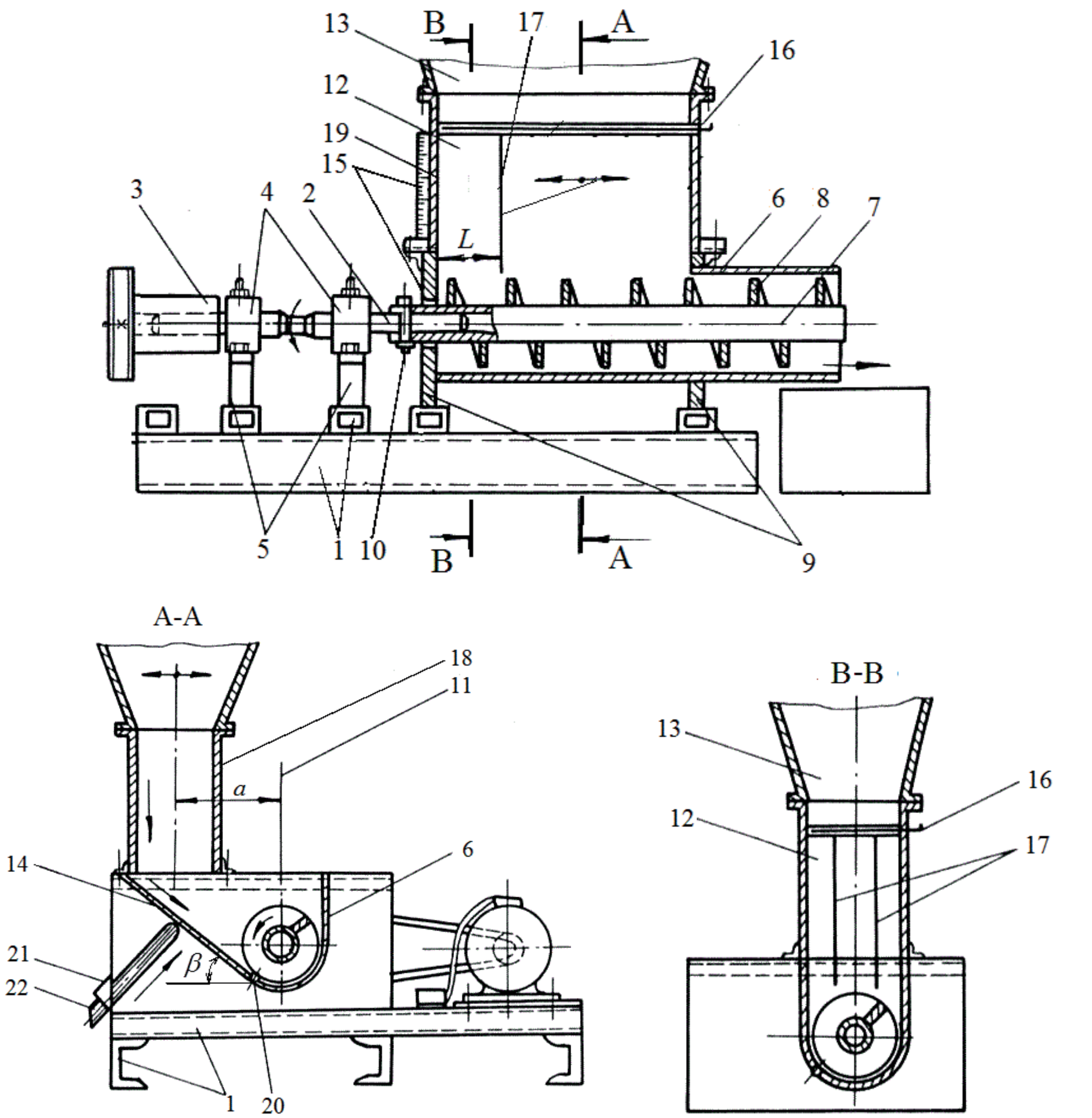

Figure 2 *Scheme of the screw feeder for conducting experimental investigations*

material to control the bulk cargo height in the loading nozzle.

The screw feeder is equipped with elements of movement with a certain step along the guides, which are installed on the legs 9 to fix the loading mechanism.

The rotary wall 14 is used to feed the bulk cargo coming from the loading nozzle 12 when it is displaced relative to axis 11 into the capture zone. The rotary wall is attached to the housing 6 by means of axis 20. The inclination angle of the wall is set using the mechanism that provides step-less control. It consists of a nut 21, which is firmly attached to legs 9, and screw 22, which is kinematically connected to the nut at one end, and is in contact with the rotary wall at the other end, and the axis of screw 22 is placed at an angle approximately 45° to the horizontal plane.

The screw feeder operates in the following way. The bulk cargo flows from the unloading hopper 13, through loading nozzle 12, enters rotary wall 14, sliding along which it is captured by the flights of helical spiral 8, and transported in housing casing 6 to the unloading area. The auger operating part is set in motion by the drive-through shaft 2. To adjust the displacement value a of the loading nozzle relative to vertical axis 11 of the transporting auger, loading nozzle 12 and unloading hopper 13 are moved along special guides to the predetermined value. The inclination angle β of the rotary wall 14 is adjusted using the screw 22.

The length of loading zone L is adjusted by moving the horizontal slide valve 16 and inserting vertical plate 17 relative to the vertical side wall of the nozzle. The torque value on shaft 2 varies depending on the displacement value a of the loading nozzle 12, the length of the loading zone L, and the inclination angle of the rotary wall 14.

The experimental screw feeder is designed with the

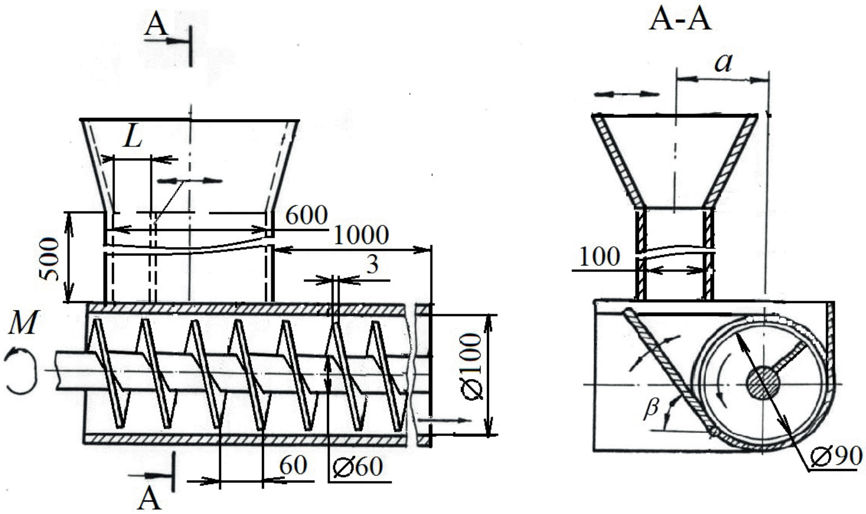

Figure 3 *Scheme of the screw feeder with dimensions of its structural elements*

following geometric parameters: height of the loading nozzle - 500 mm, length - 600 mm, width - 100 mm; helical spiral pitch T = 60 mm, the external diameter of the spiral D = 90 mm, the internal diameter of the spiral d = 60 mm, the thickness of the flights - 3 mm, the internal diameter of the housing - 100 mm. The electric drive ensured the rotation frequency of the auger operating part n = 380 rpm.

To establish the influence of the design parameters of the screw feeder's loading elements on energy consumption during the transportation of the bulk cargo, the dependence of torque value on its drive shaft on the geometric parameters of the loading mechanism and its displacement value a, relative to the vertical axis of auger operating part, is investigated.

The transportation process and torque on the drive shaft are investigated for three different materials: sand (bulk weight γ = 1400 kg/m^3, external friction ratio on steel f_1 = 0.32, internal friction ratio f_2 = 0.57, angle of natural slope φ = 30°, minimum angle of wall inclination β_g = 35°), wheat grains (γ = 650 kg/m^3, f_1 = 0.41, f_2 = 0.46, φ = 23°, β_g = 26°), and corn grains (γ = 750 kg/m^3, f_1 = 0.37, f_2 = 0.52, φ = 27°, β_g = 24°).

In investigation of the torque dependence on the displacement value of the loading nozzle a, relative to the auger operating part of the screw feeder, the inclination angle of the rotary wall is constant and equal β = 45° at the bulk cargo height in the loading nozzle h = 500 mm and the loading zone length L = 300 mm. The range of variation of displacement value is chosen in the range from 0 to 120 mm, which is approximately a = (0 - 1.3) D with the interval of 20 mm.

The torque dependence on the inclination angle of the rotary wall β is investigated within the range of values from 0° to 90° at h = 500 mm, L = 600 mm, a = 1.1 D = 100 mm. This displacement value, is chosen in such a way as the entire bulk cargo column, entering from the loading nozzle, would act on the inclined wall. The movement of cargo along the inclined wall depends on many factors. The main condition for this movement occurrence is that the inclination angle of the wall is greater than the friction angle of the bulk cargo to the wall surface (Figure 1), taking into account its granulometric composition and rheological properties.

To establish the geometric parameter of the screw feeder, which characterizes the height of the loading nozzle, the dependence of the torque value on the height of the bulk cargo in the loading nozzle is investigated. Therefore, the influence of the height h of such cargo in the loading nozzle on the torque value is determined within the range of h = 150-600 mm for L = 600 mm, in the absence of the displacement value of the loading nozzle relative to the auger operating part of the screw feeder. The inclination angle of the rotary wall equals β = 90°, that is, the wall occupies a vertical position and the loading nozzle is placed directly above the auger operating part. In this case, parameter β does not affect the parameters of the cargo transportation process.

The influence of the loading zone length L on the drive shaft torque is carried out under the conditions h = 500 mm, β = 90°, a = 0 mm, with the change in the loading zone length within 100-600 mm, using the vertical plate inserted into the loading pipe. By changing the location of this plate, relative to the front wall of the nozzle, the required size of the loading zone is set.

The scheme of the investigated screw feeder, with the marked main dimensions of its structural elements, is shown in Figure 3.

The Altivar 71 multisystem drive and the standard PowerSuite V.2.5.0 software from Schneider Electric were used to measure the torque and speed control of the screw feeder drive shaft (Figure 4).

This drive is a frequency converter and was designed for the control of the three-phase asynchronous and synchronous motors in constant-torque applications.

The Power Suite V2.5.0 software is designed to control the Altivar 71 drive and coordinate its multisystem multichannel frequency converters,

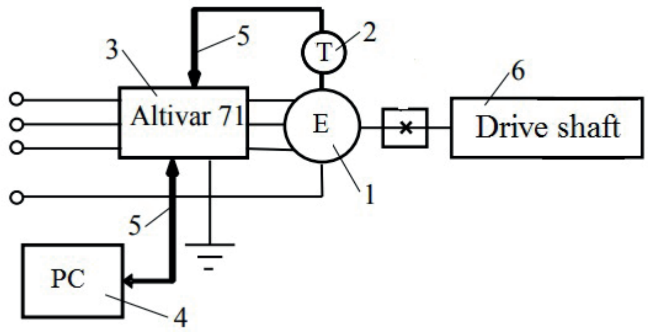

Figure 4 *Electrical circuit for the torque measurement and speed control of the screw feeder drive shaft: 1 - asynchronous electric motor, 2 - frequency transmitter E40S6-10Z4- 6L-5 for motor shaft rotation, 3 - multisystem control drive (frequency converter) Altivar 71, 4 - personal computer, 5 - communication cables*

a) *b)*

Figure 5 *Computer simulation of the grain material transportation process by the discrete elements method and elementary particles in the form of a polyhedron*

Altistart 48 soft starters, Lexium 05 servo drives and TeSysU intelligent starters, as well as to read data from the multisystem drive and display them on a computer monitor in the form of numerical values or their graphical representation.

The Altivar 71 drive is tethered to the computer using cable 5 VW3-A8106, which connects the plug on the front panel of the Altivar 71 to the computer's COM port.

Thus, the torque on the drive shaft of the screw feeder is measured using a frequency converter ALTIVAR 71, and its data are sent to the PC. The resulting changes in torque and engine power over time are obtained in the form of graphical and tabular dependencies in the display window of the computer. Experimental research is carried out to define the dependence of the torque on the magnitude of displacement of the loading pipe relative to the operating part of the screw feeder, the angle of the rotary wall, the material height in the loading pipe and the length of the loading zone.

To identify the peculiarities of the bulk cargo stagnation zone location, a computer simulation of the grain material transportation process is carried out (Figure 5, *a*).

The discrete element method is used to model the bulk cargo, a numerical method is designed to calculate the motion of a large number of particles, such as molecules, grains of sand, gravel, and other granular media. The grain of wheat is modeled as the elementary particle in the shape of a polyhedron (Figure 5, *b*) with 25 faces. The dimensions of the polyhedron are as follows: height 7.2 mm, width 3.8 mm, thickness 2.6 mm (volume 71.2 mm^3). The following physical and mechanical parameters of the material are set for the grain model: density 650 kg/m^3, modulus of elasticity 108 MPa, Poisson's ratio 0.3.

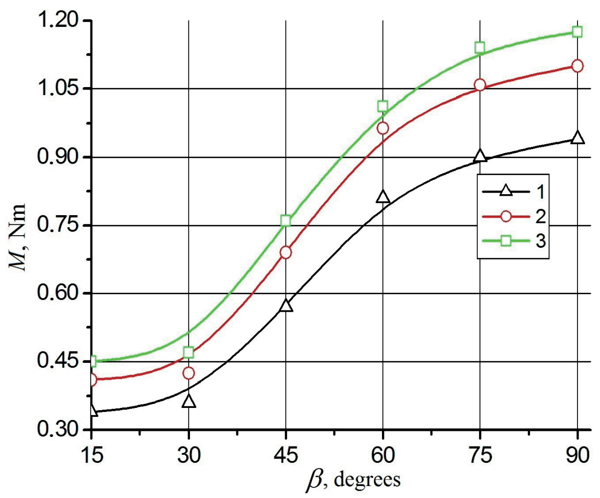

***Figure 6** Graph of the torque dependence on the inclination angle of rotating wall* β

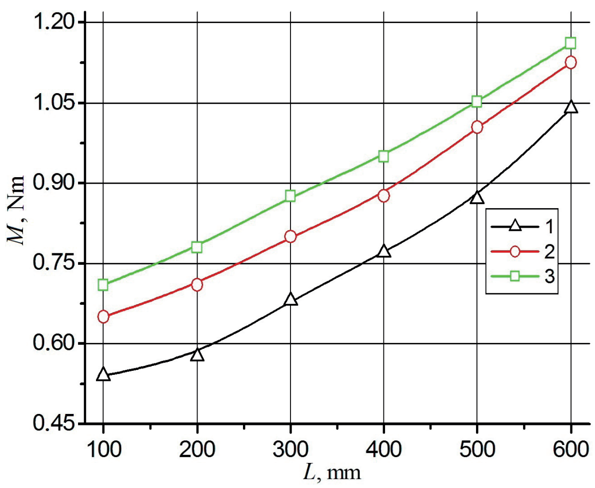

***Figure 7** Graph of the torque dependence on the length of loading zone L*

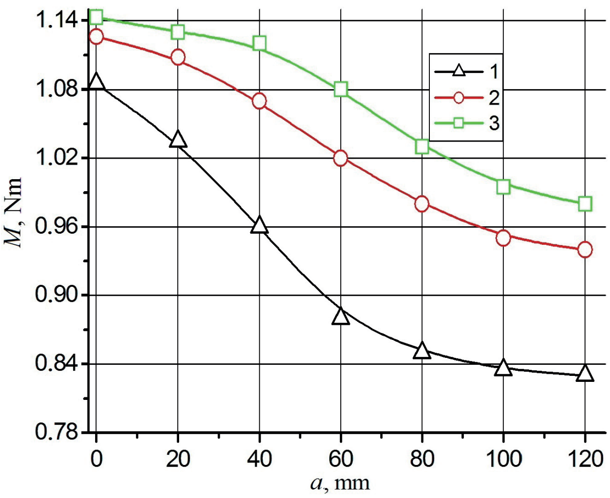

***Figure 8** Graph of the torque dependence on the displacement value of the loading nozzle a relative to the auger operating part of the screw feeder*

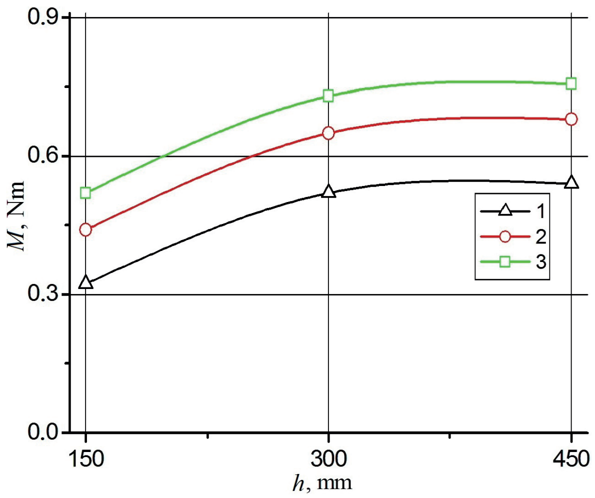

***Figure 9** Graph of the torque dependence on the bulk cargo height h in the loading nozzle*

The model of Hysteretic Linear Spring is used to simulate the normal interaction forces of bulk cargo particles. Linear Spring Coulomb Limit model is used to simulate the tangential forces. Linear Spring Rolling Limit model is used to simulate the sliding friction. The Numerical softening factor is 0.1. Thermal modeling and coarse-grained modeling are not used. During the computer simulation, the auger rotation frequency was 380 rpm, and the grain feed is 2000 kg/h. The type of bulk cargo feeding is continuous.

4 Results and discussion of experimental findings

The results of experimental research of the torque dependence on the inclination angle of a rotary wall β, loading zone length L, displacement of the loading nozzle relative to the operating part of screw feeder a, and the bulk cargo height h in the loading nozzle, for such materials as sand (1), wheat grain (2), and corn grain (3), are shown in Figures 6 to 9.

The graphs show that the inclination angle of the rotary wall of the loading nozzle significantly affects the energy consumption during the cargo transportation (Figure 6). At small inclination angle values (up to 20°-30°), the torque does not change intensively. Only when the wall inclination reaches the natural slope angle value of the transported bulk cargo, the torque starts to increase sharply. This is explained by the fact that with the increase in the angle, the normal component of the bulk cargo weight, acting on the wall, decreases, and the normal force, acting on the auger operating part, increases, resulting in an increased torque.

Thus, the experimental method has confirmed the statement that the inclined wall takes a significant part of the cargo weight and thereby reduces the load on the auger operating part of the screw feeder, which significantly reduces the torque value.

Computer simulation of this process (Figure 5) has confirmed the tendency to increase the torque and the duration of the stabilizing process of its value with

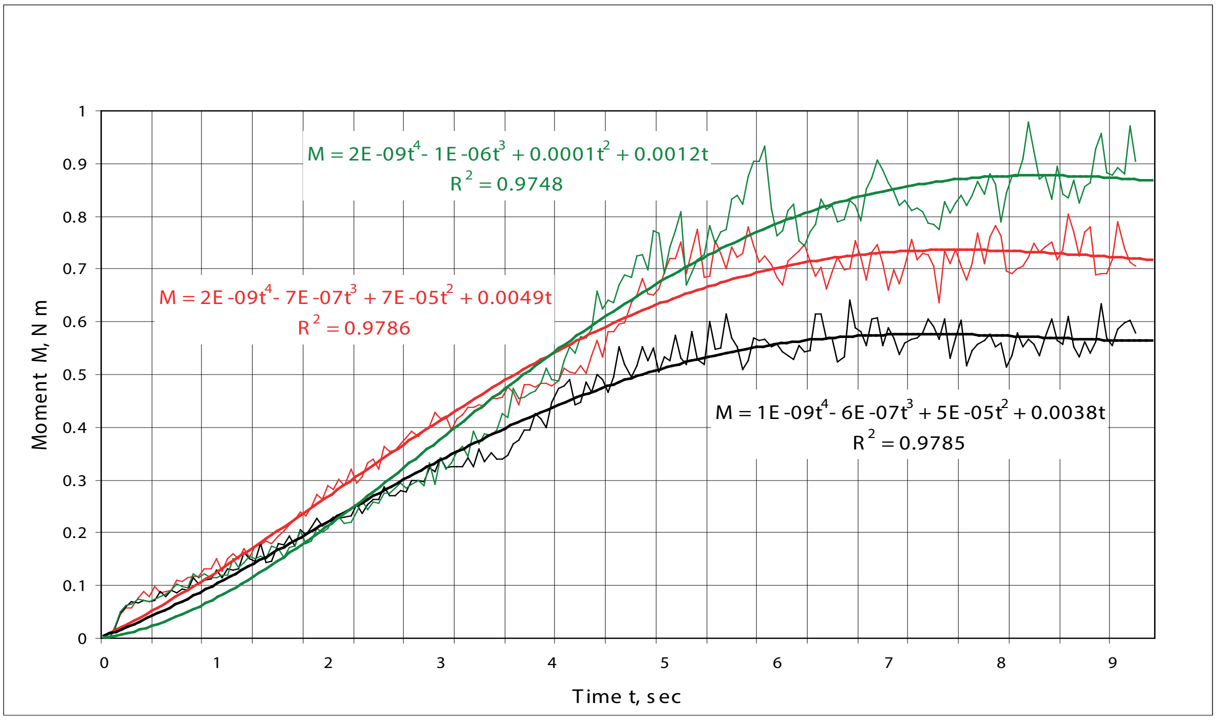

Figure 10 *Graphs of the torque dependence on time at loading zone length L = 100 mm for different inclination angles of the rotary wall based on the results of computer simulation of the bulk cargo transportation process*
- β = 45°, - β = 67.5°; - β = 90°

the increase in the inclination angle of rotary wall β. In the graph (Figure 10), the simulation results are approximated by the fourth-degree polynomials.

The equations shown in Figure 10 mathematically describe the general upward trend, i.e., the trend of changes in the torque on the drive of the screw feeder operating part. These equations are obtained by approximating the results of a virtual experiment with the standard deviation R^2, i.e., the scattering of the values of a random variable relative to its mathematical expectation.

In Figure 10, as well as in Figures 11, 13, and 16 below, the zero second is taken as the starting point. The "Zero second" is the moment when the screw drive of the operating part is switched on. In the time period, from 0 to 0.5 seconds, the rotary wall takes up the working position (the required angle β is set). The bulk material starts to flow into the loading nozzle 0.5 seconds after the auger drive has been started.

The torque values for different inclination angles of the rotary wall β, obtained by the computer simulation are, 25% lower than the values obtained experimentally. This is explained by the fact that computer simulation does not take into account the power losses due to the rotation of the screw feeder drive elements.

An important factor, affecting the energy consumption value when transporting the cargo in the screw feeder, is the length of the loading zone *L* (the open part of the auger operating part under the loading nozzle in the direction of transportation) (Figure 7). The graph shows that the increase in the loading zone length results in a significant increase in torque. This is explained by the fact that an increase in the loading zone length contributes to the formation of a larger, so-called "dead zone", which, due to its weight and the friction force, creates resistance to the movement of bulk cargo in the loading zone of the screw feeder.

This also confirms that the dimensions of the loading nozzle should be minimal and determined on the condition that it provides the required throughput, taking into account the rheological properties of the transported cargo and, especially, dome formation.

Computer simulation of this process (Figure 10, 11) has confirmed the tendency to increase torque with the increasing length of the loading zone.

Analysis of the results of computer simulation shows that in the process of transporting the bulk cargo in the loading zone, due to the point contact of elementary particles in the form of a polyhedron, the change in the direction of their movement is observed, that is, the change in the cargo kinetic energy, which also requires additional energy consumption. In addition, such cargo accumulated in the hopper opening above the transporting operating part (Figure 5, a) not in the loading zone, thereby creating additional resistance to the movement of bulk cargo in the operating mode due to the additional pressure of the vertical cargo column. As a result, the so-called "dead zone" is formed (Figure 12). Overcoming these resistance forces causes unproductive energy consumption during the technological operations.

The results of the transportation process simulation prove that the increase in the loading zone length,

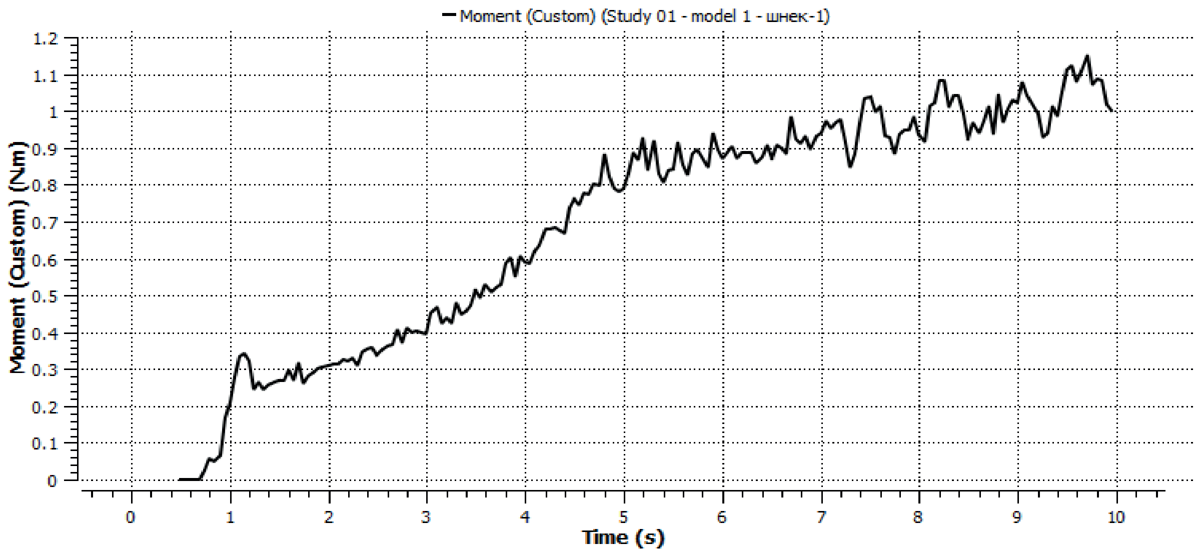

Figure 11 *Graph of the torque dependence on time for L = 300 mm and β = 90° based on the results of computer simulation of the bulk cargo transportation process*

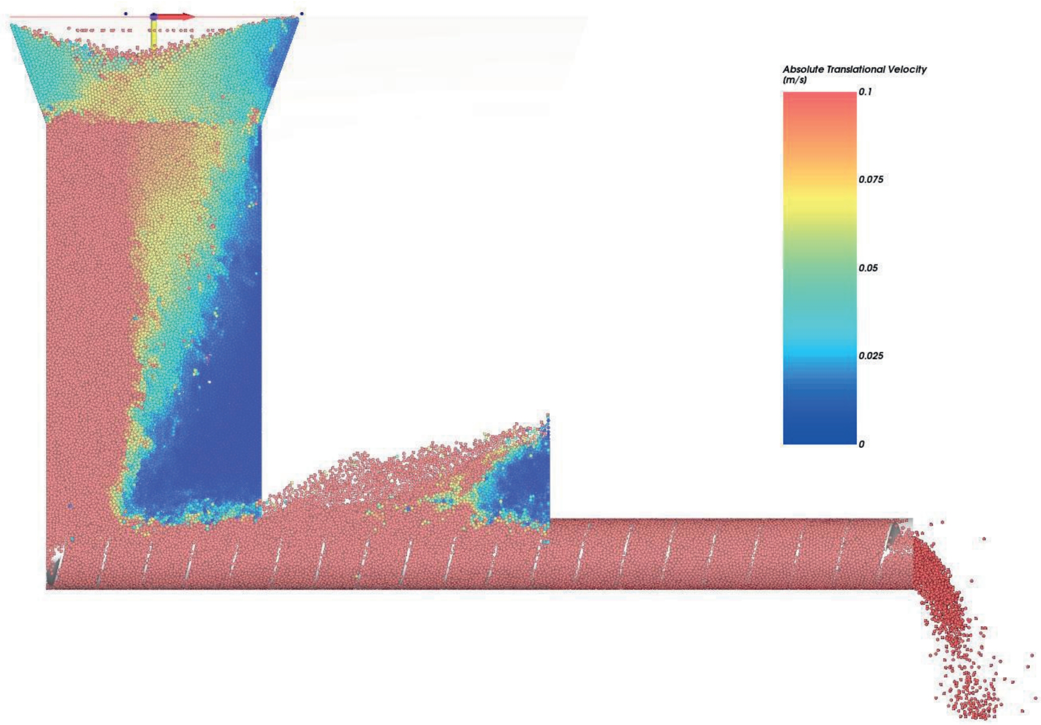

Figure 12 *Location of the stagnation zone ("dead" zone) of the bulk cargo (blue) according to the results of computer simulation of its transportation process at L = 300 mm, β =90°*

without shifting the loading nozzle relative to the auger operating part of the screw feeder, results in formation of a significant bulk cargo stagnation zone (blue color in Figure 12). Figure 8 shows the torque dependence on the drive shaft *M* of the experimental screw feeder on the displacement value of the loading nozzle relative to the auger operating part. The graphs show that the increase in the displacement value causes the decrease in torque, and, consequently, in energy consumption for the process of capturing and transporting the bulk cargo.

The analysis of the results of experimental investigations of torque dependence on the displacement of the loading nozzle, relative to the operating part of the screw feeder shows that within the range of displacement values a = (0 - 0.2) D there is a slight change in the torque value. Then, there is a sharp decrease in torque values with increasing displacement until its value reaches a = 0.9D. Subsequently, the change in torque becomes slower again and at values of a > 1.2 D practically does not change. In the future, the moment change becomes slower again and practically does not change at values of a > 1.2 D. The relative

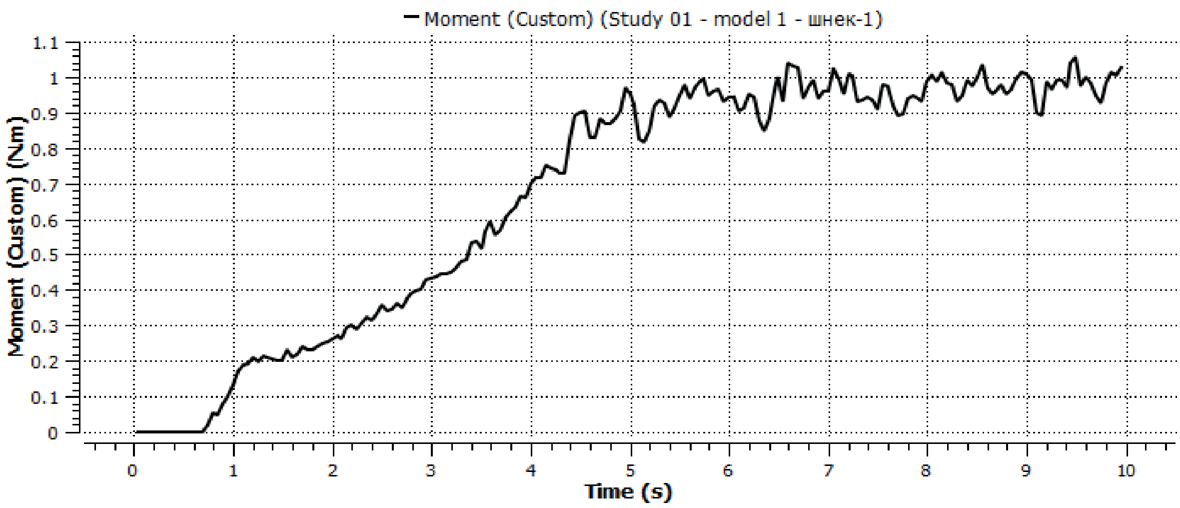

__Figure 13__ Graph of the torque dependence on time for L = 300 mm, a = 100 mm; β = 90° based on the results of computer simulation of the bulk cargo transportation process

difference of the torque values between the displacement limit value is 14 - 22% for different bulk cargoes.

Thus, it is confirmed that the vertical bulk cargo column, above the auger operating part in the loading zone, significantly affects the energy consumption, increasing its value, which causes unproductive energy losses for the performance of technological operations to capture and move such cargo in screw feeders.

Computer simulation of the bulk cargo transportation process (Figure 13) shows the duration of the process of torque stabilization due to filling with bulk cargo a part of the unloading hopper 13 (Figure 2), placed above the auger operating part and separated from loading nozzle filled with the bulk cargo, using an inserted vertical plate 17, made along the width of loading nozzle. At the same time, in this zone, intensive formation of the so-called “dead zones” is observed near the right wall-hand of the loading nozzle and in the upper part of the bulk cargo column (Figure 14).

Such bulk cargo accumulation over the part of auger operating part in the loading nozzle of the unloading hopper results in additional energy costs caused by the presence of additional resistance to the movement of such material in the operating mode due to the pressure of vertical bulk cargo column in this zone and the costs of overcoming the frictional forces between the cargo layers.

Figure 9 shows the graph of the torque dependence on the bulk cargo height in the loading nozzle. From the graph, one can see that the increase in the cargo height in the loading nozzle results in an increase in torque, which is caused by the increase in the cargo value, and as a result, an increase in its weight acting on the operating part of the screw feeder. However, a significant increase in the torque occurs up to a certain value, despite the further increase in the bulk cargo height in the loading nozzle. This is explained by the fact that at a lower height, the conditional plane of failure intersects with the free surface of the cargo in the loading nozzle. When the bulk cargo height increases and the level of the free plane of the cargo rises, the plane of failure intersects with the opposite vertical wall of the loading nozzle, which leads to the fact that a significant proportion of the bulk cargo weight is transferred to the sides of its side walls its side walls due to the friction forces between the bulk cargo and the walls of the loading nozzle.

This is also confirmed by results of the computer simulation of the transporting process of the fixed volume of bulk cargo (Figures 15 and 16). From Figure 15, one see that at the final stage of transportation, there is a cargo accumulation (in the direction of transportation) close to the right-hand wall of the loading nozzle and its movement in the direction opposite to the direction of transportation, creating conditions for a temporary increase in torque (Figure 16) due to the mixing of the material and appearance of additional resistance to its movement in the operating mode, using the vertical bulk cargo column pressure.

Displacement of the loading nozzle, relative to the auger operating part of the screw feeder with the same length of the loading zone, avoids the appearance of a bulk cargo stagnation zone (Figure 12) and reduces the torque value by approximately 5.5% (according to experimental data, this torque reduction is about 19 %).

Thus, it can be concluded that it is not reasonable to place the operating part of the screw feeders directly in the hoppers (except when it is technologically necessary), where they will be subjected to heavy loads from the weight of the material stored in these hoppers, and place them under the loading nozzle located between the hole in the bottom of the hopper and the operating part of the screw feeder. In this case, the dimensions of the loading nozzle are much smaller than the dimensions of the hopper, and this will contribute to reducing the impact of the bulk cargo weight on the auger operating part.

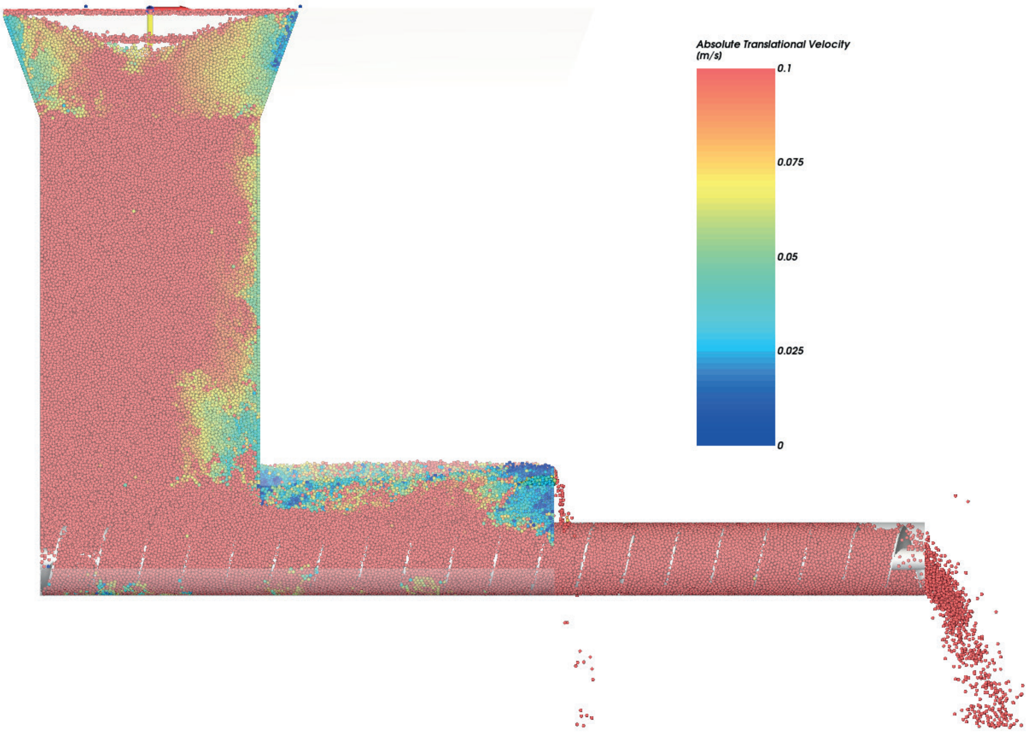

Figure 14 *Location of the stagnation zone ("dead" zone) of the bulk cargo (blue) according to the results of computer simulation of its transportation process at* L *= 300 mm,* β *= 45° and* a *= 100 mm*

Figure 15 *Computer simulation of the limited volume of the bulk cargo transportation*

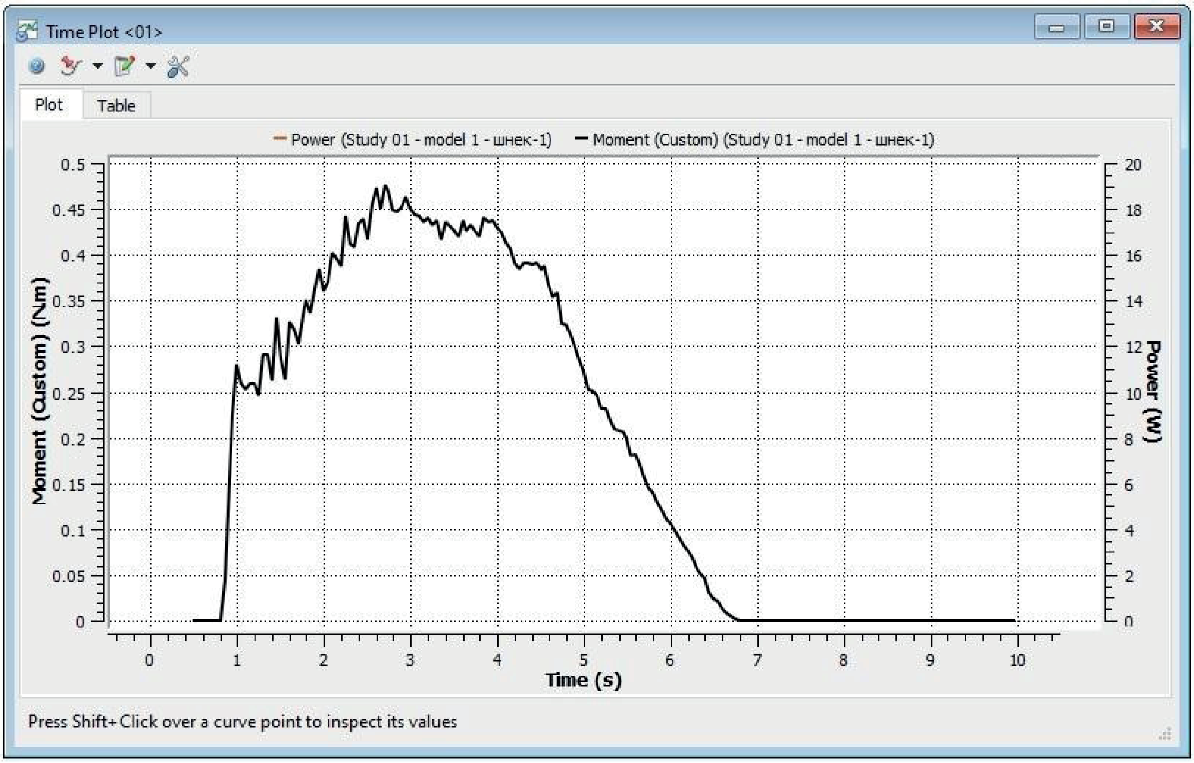

***Figure 16** Graph of the torque dependence on time for L = 300 mm, β = 90° based on the results of computer simulation of the limited volume of the bulk cargo transportation*

5 Conclusions

Vertical bulk cargo flow, displaced relative to the auger operating part of the screw feeder, improves its working conditions by significantly reducing the pressure of the vertical column of such cargo located in the hopper on the operating part, minimizes the internal friction force between the bulk cargo flow coming from the loading hopper and that involved in the process of longitudinal transportation, which reduces the energy costs for the process of bulk cargo capturing by the flights of the helical spiral. Feeding the bulk cargo to the working zone along a plane tangential to the cylindrical surface of the spiral rotation and inclined at an angle to the horizontal plane improves the uniformity of the capture of such cargo by the flights of the spiral and the smooth operation of the screw feeder, since the cargo, moving along the inclined plane, creates the same pressure on the auger operating part, which stabilizes the filling factor of the inter-flight volume of the screw tape.

Increasing the length of the loading zone, without shifting the loading nozzle relative to the auger operating part of the screw feeder, results in formation of a significant stagnation zone of the bulk cargo. To avoid the appearance of such a stagnation zone and reduce the torque value, it is reasonable to shift the loading nozzle relative to the operating part of the screw feeder with the same length as the loading zone.

Experimental investigations have shown that the displacement of the auger operating part of the screw feeder relative to its vertical axis reduces the energy costs of transportation for various bulk cargoes by 14 - 22%, as well as establishes the optimal inclination angle of the rotary wall for various cargo, which is in the range of 60-75° and provides the most favorable conditions for their supply to the capture zone.

The obtained results can be used for creation and effective application of the screw feeders, which are characterized by a variable length of the loading zone in the hopper, with the most favorable conditions for the supply of various bulk cargo to the capture zone by the screw at minimum energy costs for their transportation.

The next stage of research, in order to eliminate the phenomenon of formation of the so-called "dead zone" of the bulk cargo in the feeding nozzle of the screw feeder, is the development and study of screw operating parts with a variable inter-turn volume, where the increase in the inter-turn volume on each subsequent turn, corresponding to the pitch of the single-turn helical spiral of the screw operating part, should be constant. Only in that case, the bulk cargo will be captured by the turns of the helical spiral evenly along the entire length of the screw feeder's loading nozzle. Besides that, the developed design of the screw feeder can be used for further research of the stabilization methods of cargo volumetric mass, i.e., the weight consumption during the transportation of multicomponent materials by screw feeders by studying and determining conditions of capture in the hopper by separate turns of certain materials.

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Conflicts of 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.

References

[1] METCALF, J. R. The mechanics of the screw feeder. *Proceedings of the Institution of Mechanical Engineers* [online]. 1965, **180**(1), p. 131-146. ISSN 0020-3483. Available from: https://doi.org/10.1243/PIME_PROC_1965_180_015_02
[2] MINGLANI, D., SHARMA, A., PANDEY, H., DAYAL, R., JOSHI, J. B., SUBRAMANIAM, S. A review of granular flow in screw feeders and conveyors. *Powder Technology* [online]. 2020, **366**, p. 369-381. ISSN 0032-5910, eISSN 1873-328X. Available from: https://doi.org/10.1016/j.powtec.2020.02.066
[3] ROBERTS, A. W., MANJUNATH, K. S., MCBRIDE, W. The mechanics of screw feeder performance for bulk solids flow control. In: 4th International Conference on Bulk Materials, Storage, Handling and Transportation: 7th International Symposium on Freight Pipelines: proceedings [online] [accessed 2023-03-27]. Preprints of papers. Barton: ACT. 1992. ISBN 0858255545, p. 333-338. Available from: https://search.informit.org/doi/10.3316/informit.388068299607697
[4] PATINGE, S., PRASAD, K. Effect of parameters on the screw feeder performance using discrete element method. *Asian Journal of Convergence in Technology* [online]. 2016, **2**(3), p. 22-23 [accessed 2023-03-27]. ISSN 2350-1146. Available from: https://asianssr.org/index.php/ajct/article/view/157/216
[5] WANG, Y, LI, T, MUZZIO, F. J., GLASSER, B. J. Predicting feeder performance based on material flow properties. *Powder Technology* [online], 2017, **308**, p. 135-148. ISSN 1873-328X. Available from: https://doi.org/10.1016/j.powtec.2016.12.010
[6] VASYLKIV, V., PYLYPETS, M., DANYLCHENKO, L., RADYK, D. Formalized description and synthesis of schemes for shaping helical flights and auger billets based on the componentic methods. *Scientific Journal of TNTU* [online], 2021, **104**(4), p. 44-57. ISSN 2522-4433. Available from: https://doi.org/10.33108/visnyk_tntu2021.04.044
[7] VASYLKIV, V., PYLYPETS, M., DANYLCHENKO, L., RADYK, D. Investigation of deflections of winded screw flights and auger billets in the processes of their manufacture. *Scientific Journal of TNTU* [online]. 2021, **104**(4), p. 33-43. ISSN 2522-4433. Available from: https://doi.org/10.33108/visnyk_tntu2021.04.033
[8] ROBERTS, A. W. Predicting the volumetric and torque characteristics of screw feeders. *Bulk Solids Handling*. 1996, **16**(2), p. 233-244. ISSN 0173-9980.
[9] YU, Y., ARNOLD, P. C. Theoretical modelling of torque requirements for single screw feeders. *Powder Technology* [online], 1997, **93**(2), p. 151-162. ISSN 1873-328X. Available from: https://doi.org/10.1016/S0032-5910(97)03265-8
[10] PATERWITZ, M., GERLING, S., SCHEMBECKER, G. Challenges in tracing material flow passing a loss-in-weight feeder in continuous manufacturing processes. *International Journal of Pharmaceutics* [online]. 2021, **612**, 121304 [accessed 2022-01-25]. ISSN 2229-5518. Available from: https://doi.org/10.1016/j.ijpharm.2021.121304
[11] XU, X., SHEN, CH., LI, F., WANG, L. Design and experimental study of equal-area variable-pitch screw structure for wheat flour. *INMATEN Agricultural Engineering* [online]. 2021, **64**, p. 423-436. ISSN 2068-4215, eISSN 2068-2239. Available from: https://doi.org/10.35633/inmateh-64-42
[12] ANSI/CEMA Standard No. 350. Screw conveyors for bulk materials. 5th edition. 2019.
[13] BATES, L. Entrainment patterns of screw hopper dischargers, transaction of the ASME. *Journal of Engineering for Industry* [online]. 1969, **91**(2), p. 295-302. ISSN 1087-1357, eISSN 1528-8935. Available from: https://doi.org/10.1115/1.3591561
[14] BATES, L. *Guide to the design, selection, and application of screw feeders*. London: Wiley and Sons Ltd, 2008. ISBN 9781860582851.
[15] BORTOLAMASI, M., FOTTNER, J. Design and sizing of screw feeders. In: International Congress for Particle Technology PARTEC 2001: proceedings [online] [accessed 2023-03-27]. 2001. p. 27-29. Available from: https://mediatum.ub.tum.de/doc/1188322/fml_20131230_514_export.pdf
[16] KULKARNI, U. G., SHAH, H. P., SANAS, S. M., SHETE, A. P., KEKAN, G. H. Design and development of screw feeder. *International Journal of Advance Research, Ideas and Innovations in Technology* [online]. 2017, **3**(2), p. 1099-1102 [accessed 2023-03-27]. ISSN 2454-132X. Available from: https://www.ijariit.com/manuscripts/v3i2/V3I2-1547.pdf
[17] LIU, M., NING, W., XIAOMEI, C., YING, S., JIANGPENG, L. Design of feed screw conveyor. *Journal of Physics: Conference Series* [online]. 2020, **1601**, 062005. ISSN 1742-6588, eISSN 1742-6596. Available from: http://dx.doi.org/10.1088/1742-6596/1601/6/062005

[18] GRIMARD, J., DEWASME, L., WOUWER, A. V. Dynamic modeling and model-based control of a twin screw extruder. In: 25th Mediterranean Conference on Control and Automation (MED): proceedings [online]. 2017. ISSN 2473-3504, p. 316-321. Available from: https://doi.org/10.1109/MED.2017.7984137

[19] KARWAT, B., RUBACHA, P., STANCZYK, E. Simulational and experimental determination of the exploitation parameters of a screw conveyor. *Eksploatacja i Niezawodnosc / Maintenance and Reliability* [online]. 2020, **22**(4), p. 741-747. ISSN 1507-2711, eISSN 2956-3860. Available from: https://doi.org/10.17531/ein.2020.4.18

[20] CLEARY, P. W. DEM modelling of particulate flow in a screw feeder model description. *Progress in Computational Fluid Dynamics, an International Journal* [online]. 2007, **7**(2-4), p. 128-138. ISSN 1468-4349, eISSN 1741-5233. Available from: https://doi.org/10.1504/PCFD.2007.013005

[21] KRETZ, D., CALLAU-MONJE, S., HITSCHLER, M., HIEN, A., RAEDLE, M., HESSER, J. Discrete element method (DEM) simulation and validation of a screw feeder system. *Powder Technology* [online]. 2016, **287**, p. 131-138. ISSN 0032-5910, eISSN 1873-328X. Available from: https://doi.org/10.1016/j.powtec.2015.09.038

[22] LOPEZ, A., VIVACQUA, V., HAMMOND, R., GHADIRI, M. Analysis of screw feeding of faceted particles by discrete element method. *Powder Technology* [online]. 2020, **367**, p. 474-486. ISSN 0032-5910. Available from: https://doi.org/10.1016/j.powtec.2020.03.064

[23] PATINGE, S., PRASAD, K. Screw feeder performance prediction using discrete element method. *International Journal of Scientific and Engineering Research* [online]. 2017, **8**(3), p. 48-51 [accessed 2023-03-27]. ISSN 2229-5518. Available from: https://www.ijser.org/researchpaper/Screw-feeder-performance-prediction-using-Discrete-Element-Method-DEM.pdf

[24] BURKHARDT, G. J. Effect of pitch, radial clearance, hopper exposure and head on performance of screw feeders. *Transactions of the American Society of Agricultural Engineers* [online]. 1967, **10**, p. 685-690. ISSN 0001-2351, eISSN 2151-0059. Available from: https://doi.org/10.13031/2013.39761

[25] CARLETON, A. J., MILES, J. E. P., VALENTIN, F. H. H. A study of factors affecting the performance of screw conveyors and feeders. *Journal of Engineering for Industry* [online]. 1969, **91**(2), p. 329-333. ISSN 0022-0817. Available from: https://doi.org/10.1115/1.3591565

[26] CARSON, J. W. Designing efficient screw feeders. *Powder and Bulk Engineering*. 1987, **12**, p. 32-42. ISSN 0897-6627.

[27] FERNANDEZ, J. W., CLEARY, P. W., MCBRIDE, W. Effect of screw design on hopper drawdown of spherical particles in a horizontal screw feeder. *Chemical Engineering Science* [online]. 2011, **66**, p. 5585-5601. ISSN 0009-2509. Available from: https://doi.org/10.1016/j.ces.2011.07.043

[28] PATEL, J. N., PATEL, S. P., PATEL, S. S. Productivity improvement of screw conveyor by modified design. *The International Journal of Emerging Technology and Advanced Engineering* [online]. 2013, **3**(1). p. 492-496 [accessed 2023-03-27]. ISSN 2250-2459. Available from: https://www.ijetae.com/files/Volume3Issue1/IJETAE_0113_77.pdf

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INTERACTION OF THE TE33A DIESEL LOCOMOTIVE AND THE RAILWAY TRACK ON CURVED SECTION WITH RADIUS 290 m

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Resume

The purpose of the research was an experimental study of the dynamic processes of interaction between a TE33A diesel locomotive and a railway track when passing along a curved section with a radius of 290 m. To study the dynamic and driving properties of the rolling stock, the analysis of the experimental data obtained was carried out. When performing the study, the following results were obtained: the indicators of the frame forces of each wheel were determined when moving the TE33A locomotive along a curve with a radius of 290 m; the coefficients of the vertical dynamics of the second suspension stage when moving the TE33A locomotive along a curve with a radius of 290 m are determined; axial stresses in the rails under the influence of the TE33A locomotive on the track with rails of grades R50 and R65 are determined.

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1 Introduction

One of the decisive factors ensuring clear and rhythmic operation of the railways is the stable operation of the locomotive economy, improving the technical condition, maintenance, and use of the locomotive fleet. The high intensity of locomotive use, high weight and speed of trains require an increase in the traction and speed qualities of locomotives operating under conditions of large dynamic loads. To ensure the safety of trains, the crew of the locomotives must have sufficient reliability.

Subsequently, the need to increase the speed and power of diesel locomotives, as well as improve the conditions for fitting them into the curves, led to the appearance of such a structural element of the mechanical part as carts, on which the body frame rested and was able to turn relative to it [1].

The use of bogies in the design of the mechanical part of locomotives required a number of related technical tasks, including: resting the body on a bogie movable relative to the vertical axis, transmitting longitudinal and transverse forces in conditions of relative movements of the body and bogie and connecting bogies with each other to improve the conditions of movement in curves. To reduce the likelihood of wheel skidding, devices were provided to help equalize the loads between individual driving wheelsets and prevent a significant decrease in vertical loads on the front axles of the wheelsets of each bogie when the maximum traction force is realized when the locomotive is starting.

The design of the trolley, as a separate device, forced, in order to improve the vibration protection of the body, to introduce elastic vertical links (body stage of spring suspension), and to improve the indicators of dynamic qualities during the horizontal vibrations (smoothness and lateral force), to abandon the rigid link of the body with the trolley in the transverse direction, introducing quasi-elastic crosslink devices - the so-called «return» devices. At the same time, it turned out that the bogie frame began to perform loading functions

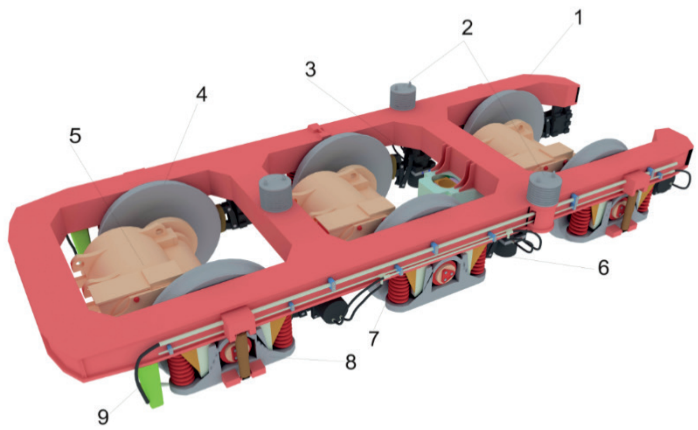

Figure 1 *General view of the three-axle trolley: 1 - trolley frame, 2 - elements of the second stage of spring suspension, 3 - the place of laying the pin, 4 - wheelset, 5 - traction electric motor, 6 - brake pad, 7 - elements of the first stage of spring suspension, 8 - axle box assembly, 9 - sand supply*

Table 1 *Specifications of the trolley*

Name of indicators	Parameter values
Load from wheelset on rail, kN	233
Design speed, km/h	120
Traction motor	5GEB30B
Number of traction motors	3
Traction drive	One-sided with support-axial suspension of TED (TM)
Gearing	One-way, spur, with UZK
Gear gear ratio	5.3125
Design pressing of brake pads on axle at pressure of 0.38 MPa, kN	136
Body support system	Three-point, supports with rubber-metal elements

unusual for its purpose, which led to a complication of the design of the bogies, an increase in their weight and, as a result, to a deterioration in the conditions for the locomotive to pass curved sections of the track [2-3]. All these ultimately led to an increase in the horizontal forces of interaction between wheels and rails, and to an increase in the wear of wheelset bands and rails.

In this work, the test object is the TE33A main freight diesel locomotive with asynchronous traction motors and electric drive. The locomotive was manufactured by Lokomotiv Kurastyru Zauyty Joint Stock Company in Astana in 2010. The axial formula of the locomotive is 30-30. Design axle load on rails (227.65 ± 2%) kN. The service weight of the diesel locomotive (138 ± 2%) tf. Design speed 120 km/h. The diesel locomotive is designed to work with freight trains and has a two-stage spring suspension (Figure 1). Static deflection of the first stage of suspension is 131.5 mm. The second suspension stage consists of one central and two side support and return supports (on the trolley). Static deflection of the central support is 13.7 mm, side supports 10.3 mm. The first stage is helical springs, the second stage is rubber-metal blocks [4]. Traction and braking forces from the bogies to the body are transmitted by a pivot. The diesel locomotive uses support-axial suspension of traction motors and motor-axial rolling bearings. The bogie frame is connected with wheelsets through jaw boxes. The main technical data are given in Table 1.

Wheelsets are formed from solid-rolled wheels pressed onto the forged axle. Each wheel pair corresponds to an individual brake unit with a cylinder and shoes, the operating parameters of the unit are automatically adjusted. Such a system is the most efficient and easy to operate and repair [5-6].

The wheelsets of the locomotive sustain and transfer their own weight, weight of the body and bogies of the locomotive to the rails [7]. When rotating, the wheel pair, interacting with the rail, realizes the clutch force of the locomotive. Each wheel pair is driven by individual traction motor 5GEB30.

Minimum dimensions for the wheel profile are given in accordance with Figures 2, 3 and 4.

The main reasons for the wear and undercutting of the ridges of the wheel pairs of locomotives are the passage of curved sections of the railway track [4]. Determination of permissible speeds and dynamic parameters of interaction between a TE33A series diesel locomotive and a railway track, when passing on a curved section with the smallest radius, is an urgent research issue.

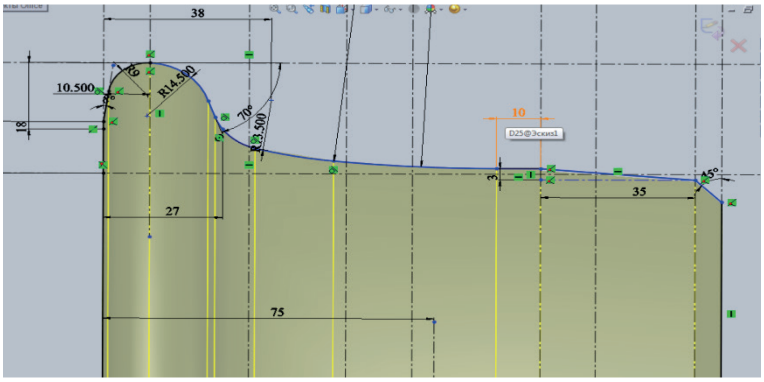

Figure 2 *The profile of the locomotive wheel TE33A with a crown thickness of 27 mm*

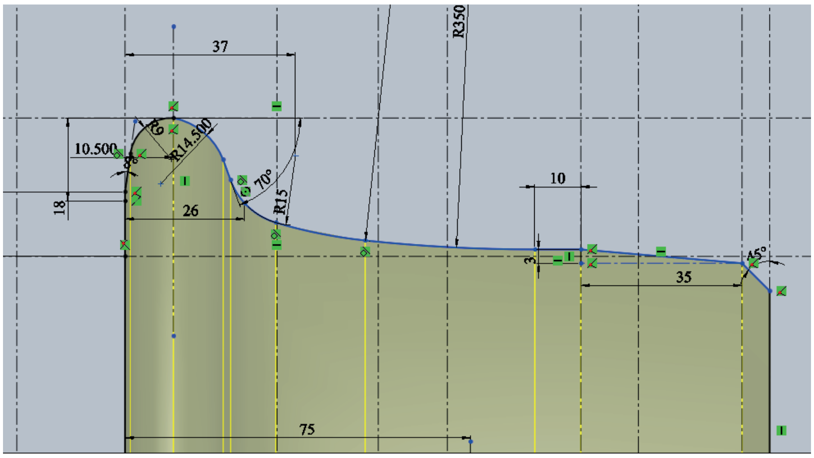

Figure 3 *The profile of the locomotive wheel TE33A with a ridge thickness of 26 mm*

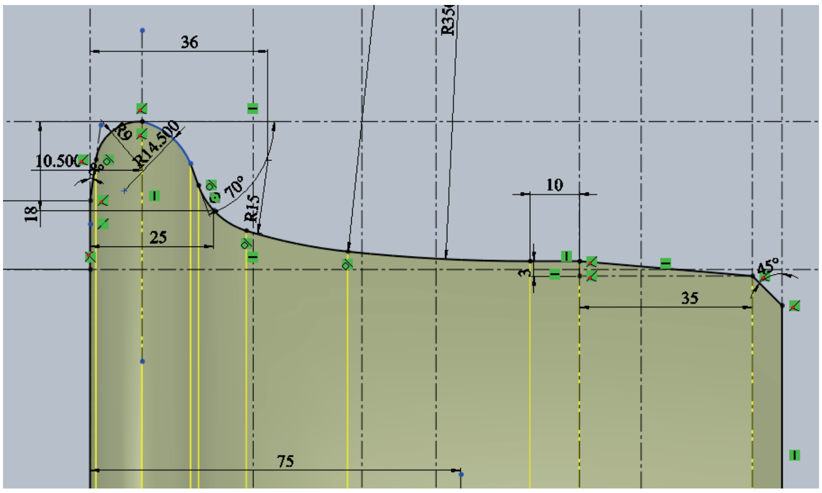

Figure 4 *The profile of the locomotive wheel TE33A with a ridge thickness of 25 mm*

To solve this issue, the following tasks have been set:

1) determination of the vertical dynamics coefficient of the first and second suspension stages;
2) identification of the coefficient of stability against wheel derailment from the railway track;
3) experimental evaluation of dynamic stress in the edges of the sole of the rail in curved sections with a radius of 290 m;
4) determination of the parameters of the frame (lateral) forces in straight and curved sections of the railway track.

2 Materials and methods

To measure the level of impact of the diesel locomotive on the track in the curved sections of the

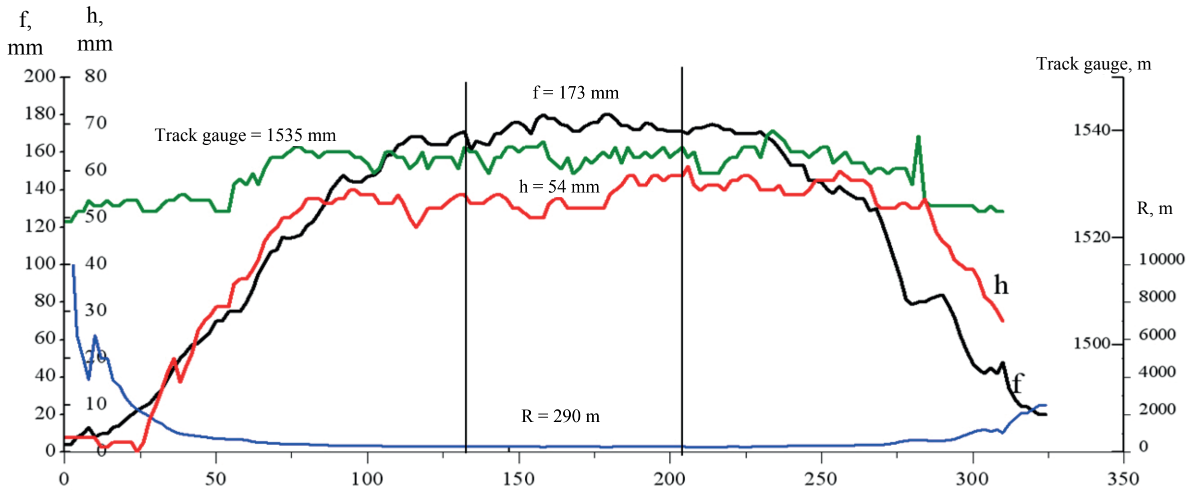

Figure 5 *Parameters of the curved section of the path of a radius of 290 m*

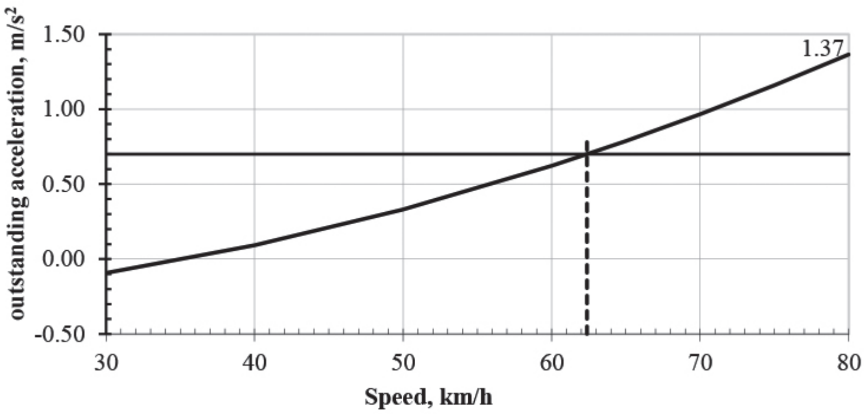

Figure 6 *Outstanding acceleration in 290 m radius curve*

track with a radius of 300-400 m, the track 3820-3821 km of the Chokpar- Alaaigyr section was selected. At the same site, the dynamic indicators of the locomotive were determined. In the section, the track is laid with rails R65 on wooden sleepers. Length of links 25 m. Ballast crushed stone [8-9]. Epura sleepers 2000 pcs/km. According to the certificate provided by the PCh-47 (track facilities), the average lateral wear of the rails is 8 mm. The number of unusable sleepers is 15 %. According to the design documents, the curve radius is 285 m. Immediately before the tests on the site, 6 unusable sleepers were replaced. According to the track measurement car, the state of the track corresponds to the “good” rating. Results of measurements of geometric dimensions of the track section are given in Figure 5.

Thus, the actual elevation of the outer rail is 54 mm, and the radius is 290 m. For this section [10-11], the dependence of the outstanding acceleration on the speed of movement is shown in Figure 6.

When testing in a 290 m radius curve, the ambient temperature was from 4 to 10 °C. The wind speed reached 14 m/s.

The races were performed at speeds of 30, 40, 50, 60 and 70 km/h.

The data for determining the estimated values of the frame forces, the vertical dynamics coefficients of the first and second suspension stages were processed using the same method as for the curve of radius 600 m [12].

The processing results are shown in Figures 7-9 and Tables 2-4.

The data shown in Figures 7-9 show that the dynamic parameters of the locomotive in the curve of radius 290 m are within the permissible limits [13-14].

Results of calculation of the safety factor against the wheel derailment from data measured in curve of radius 290 m are given in Figure 10. The minimum value of the coefficient is 1.7 at a speed of 70 km/h.

When drawing up a table of permissible speeds of movement of a diesel locomotive, an analytical expression is used in the calculations, describing the dependence of the coefficient of vertical dynamics of the first stage of suspension on the speed of movement. To form this expression, the vertical dynamics coefficients at forward travel were combined with the data at reverse travel [15]. The results of measurements in straight and curved sections of the path were included in the formed array. From the obtained variation series, the maximum probable values of the coefficient k_d were calculated for

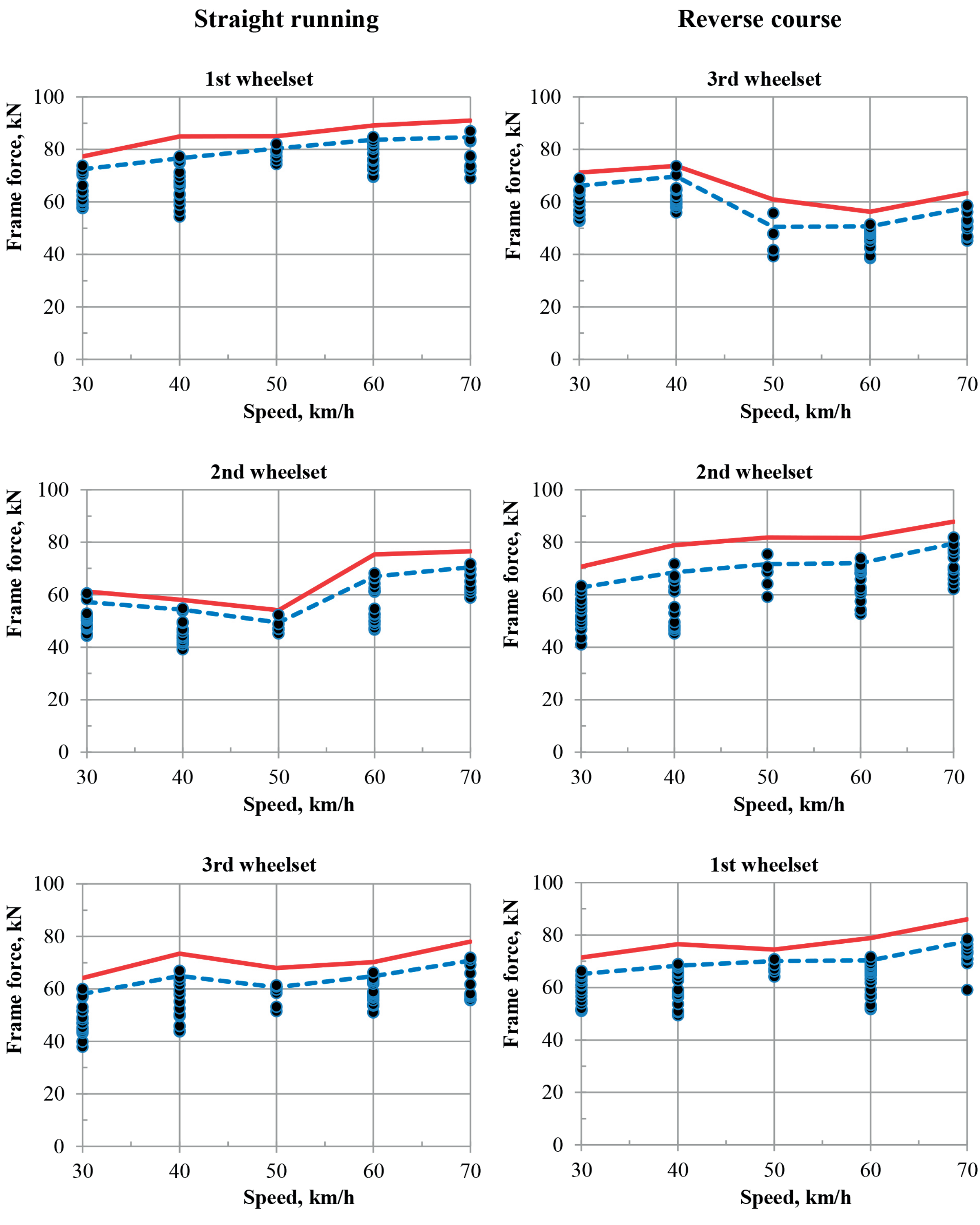

Figure 7 *Frame forces during the diesel locomotive movement TE33A in a 290 m radius curve*

each realized speed of movement. Based on least-squares data processing, this relationship can be described by the empirical formula:

$$k_d = 0.06667 + 0.00211V, \quad (1)$$

where V - speed, km/h.

Before the tests and after the completion of the tests, the diesel locomotive was inspected. As a result of visual inspection of the crew of the locomotive, it was established that before the tests and after them there was no touch of the nodes and elements in places not provided for by the design [16].

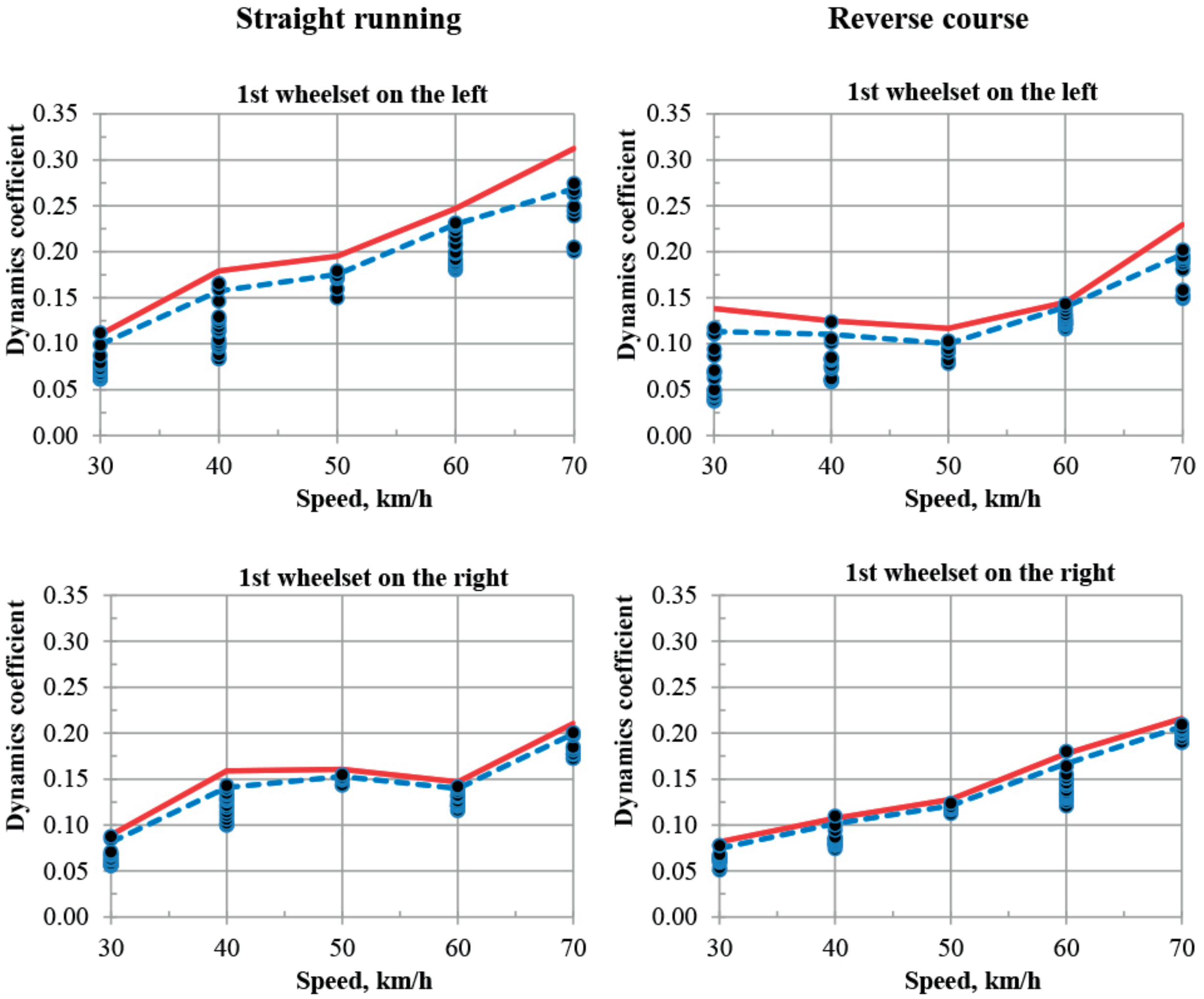

Figure 8 *Coefficient of vertical dynamics of the first stage of suspension at movement of a diesel locomotive TE33A-0023 in curve of radius 290 m*

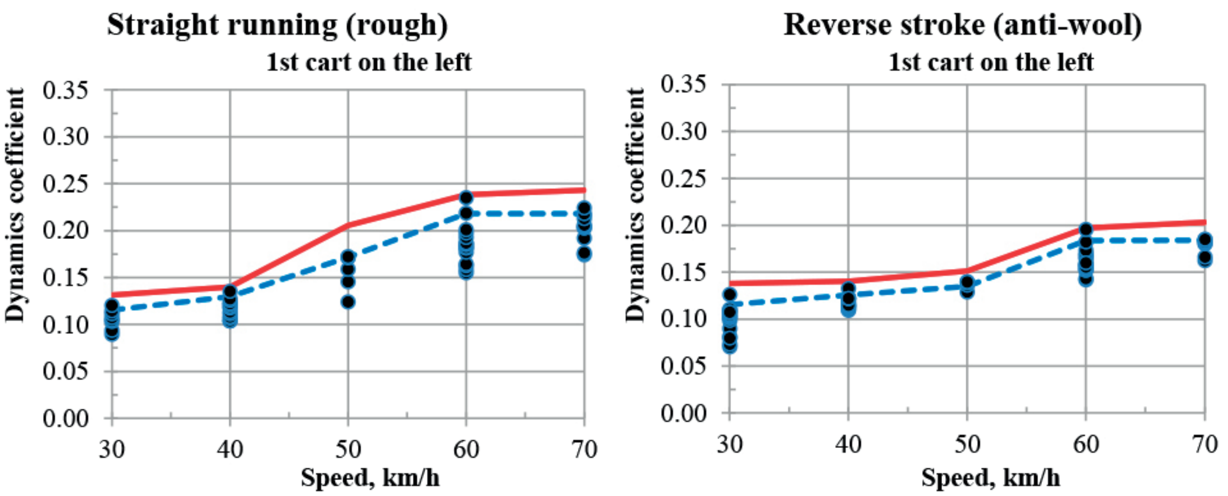

Figure 9 *Coefficient of vertical dynamics of the second stage of suspension at movement of a diesel locomotive TE33A-0023 along curve of radius 290 m*

Table 2 *Frame forces during the movement of a diesel locomotive TE33A in a curve of radius 290 m*

Speed, km/h	Maximum probable value						Maximum observed value					
	Straight running			Reverse course			Straight running			Reverse course		
	Wheelset number											
	1	2	3	1	2	3	1	2	3	1	2	3
30	77.3	70.7	64.2	71.4	61.2	71.2	72.4	62.8	58.1	65.2	57.3	66.1
40	85.0	78.9	73.4	76.5	58.0	73.8	76.7	68.6	64.9	68.3	54.3	69.8
50	85.1	81.8	68.0	74.4	54.1	60.9	80.3	71.6	60.7	70.0	49.4	50.5
60	89.2	81.6	70.2	78.9	75.4	56.3	83.7	72.1	64.8	70.4	67.0	50.6
70	91.0	87.8	78.1	86.0	76.5	63.4	84.6	79.4	70.8	77.6	70.5	57.8

Table 3 *Vertical dynamics coefficient of the first stage suspension during movement of the diesel locomotive TE33A in the curve of radius 290 m*

Meaning	Speed, km/h	Straight running		Reverse course	
		1st wheelset		1st wheelset	
		on the left	on the right	on the left	on the right
maximum probable	30	0.11	0.09	0.14	0.08
	40	0.18	0.16	0.12	0.11
	50	0.20	0.16	0.12	0.13
	60	0.25	0.15	0.14	0.18
	70	0.31	0.21	0.23	0.22
maximum observed	30	0.10	0.08	0.11	0.07
	40	0.16	0.14	0.11	0.10
	50	0.18	0.15	0.10	0.12
	60	0.23	0.14	0.14	0.17
	70	0.27	0.20	0.20	0.21

Table 4 *Coefficient of vertical dynamics of the second suspension stage during the movement of the diesel locomotive TE33A in the curve of radius 290 m*

Speed, km/h	Maximum probable value		Maximum observed value	
	Straight running on the left	Reverse course on the right	Straight running on the left	Reverse course on the right
30	0.13	0.14	0.12	0.12
40	0.14	0.14	0.13	0.13
50	0.21	0.15	0.17	0.14
60	0.24	0.20	0.22	0.18
70	0.24	0.20	0.22	0.18

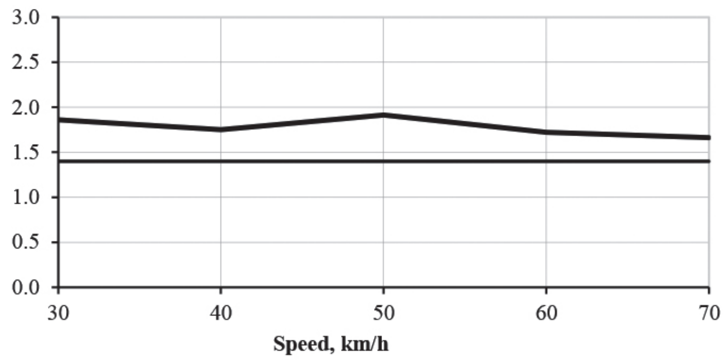

Figure 10 *Stability margin factor against the wheel derailment in 290 m radius curve*

3 Results

Allowable speeds of the diesel locomotive circulation according to the conditions of bending strength of rails are determined based on the theoretical calculations of the path for strength using the experimental data obtained during the present tests: loads from the wheel on the rail based on the results of weighing the diesel locomotive, the coefficient of vertical dynamics, characteristics of the diesel locomotive, track parameters, stress levels in the edges of the rail foot in the test areas. Calculations were performed according to the method presented in [6, 17]. When drawing up the table of permissible velocities, the requirements set forth in [18] are taken into account. The calculations used the values of the dynamic maximum vertical load from the wheel to the rail from the vertical vibrations of the overspring structure, calculated using the formula:

$$P_p^{\max} = k_d(P_w - q), \tag{2}$$

where k_d - coefficient of vertical dynamics, taken from experimental data,
P_w - load from the wheel on the rail according to the results of weighing, kN,
q - weight of unsprang parts per wheel, kN.

According to the obtained data, the maximum probable value of the maximum dynamic load from the wheel on the rail is calculated. In this case, it is assumed that the distribution of values of the maximum dynamic load from the wheel to the rail is subject to the normal law. The probability of non-exceeding the maximum dynamic load from the wheel to the rail of the obtained values is taken 0.994. Under these conditions, the maximum dynamic load from the wheel to the rail is calculated using the formula [16]:

$$P_{din}^{\max} = P_{av} + 2.5S\text{, kN}, \tag{3}$$

where P_{av} - average value of vertical load from the wheel to the rail, kN,
S - mean square deviation of dynamic vertical load from the wheel to the rail, kN.

Value S is defined as composition of average square deviations of dynamic load from wheel to the rail from oscillations of overspring structure, from inertia forces of unsprang masses when wheel passes isolated path irregularity, from inertia forces of unsprang masses arising due to continuous irregularities on surface of wheels rolling and due to presence of smooth isolated irregularities on surface of wheels [18].

The action of horizontal transverse forces and torques, created by eccentric application of vertical forces on the rail, is taken into account by introducing a transition factor from axial stresses at the bottom of the rails to edge *f*. To determine the coefficient, the maximum probable stress values in the edges of the bottom of the rails, calculated from measurements in a straight line and a curve with a radius of 600 m at a speed of 100 km/h and in a curve with a radius of 290 m at a speed of 60 km/h, are used [19].

Maximum probable values of experimental axial stresses in the rail foot are calculated as maximum probable values of the stress semi-summes in the edges of the rail foot.

The maximum equivalent load for calculating stresses in rails from bending and torsion, replacing a system of concentrated wheel loads, is formed taking into account vertical loads from both wheelsets of the bogie:

$$P_{eq}^{I} = P_{din}^{\max} + P_{av2} \cdot \mu_2, \tag{4}$$

where P_{av2} - average value of the vertical load from the wheel of the second wheel pair on the rail;
μ_2 - ordinate of the line of influence of bending moments of the rail in the section of the track located under the wheel of the second wheel pair.

Maximum design axial stresses (in MPa) in the rail bottom are calculated using the formula

$$\sigma_o^p = \frac{P_{equ}^I}{4kW}, \tag{5}$$

where k - coefficient of relative stiffness of rail base and rail, cm^{-1},
W - moment of rail resistance along the bottom of the sole, cm^3.
k and W- values for different topsides structures are shown in Table 2 [20].

The coefficient *f* in the areas under consideration is calculated using the formula

$$f = \frac{\sigma_k^e + \Delta\sigma_o}{\sigma_o^p}, \tag{6}$$

where σ_k^e - maximum probable value of edge stress in the rail base, MPa.
$\Delta\sigma_o = \sigma_o^p - \sigma_o^e$ - difference between the design and experimental axial stresses for the section of the track where the tests were carried out.

Based on the obtained values, an analytical expression is compiled describing the dependence of the coefficient *f* on the radius of the curve, from which its value is calculated for sections of the path with a different radii of curvature. Results of calculation *f* and corresponding normalized value of axial stress, determined by the formula:

$$\left[\sigma_o = \frac{[\sigma_k]}{f}\right], \tag{7}$$

are summarized in Table 5, where $[\sigma k]$ = 240 MPa - allowable stresses in the edges of the rail foot.

Figures 11 and 12 show graphs of the design axial stresses at the bottom of rails for track with different topsides structures versus speed. Lines corresponding to the level of the normalized value of axial stresses for paths with different radii of curvature are applied to the

Table 5 *Values of coefficient f and corresponding normalized values of axial stress*

Indicator	Direct	Radii of curves, m							
		1000	900	800	700	600	500	400	300
f	1.23	1.53	1.56	1.60	1.65	1.72	1.82	1.97	2.22
$[\sigma_o]$, MPa	195	157	154	150	145	140	132	122	108

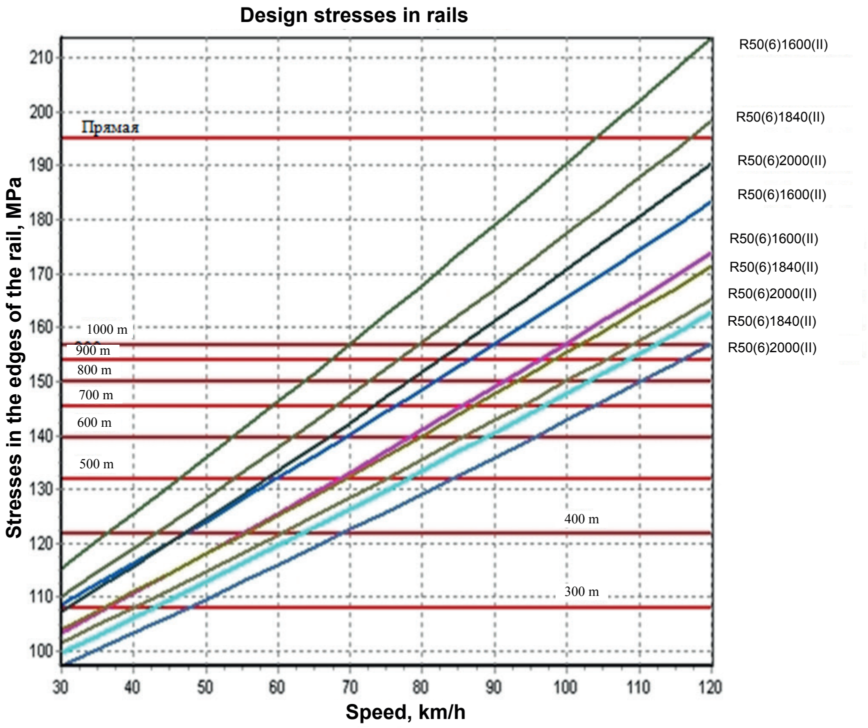

Figure 11 *Design axial stresses in rails under the influence of a diesel locomotive TE33A on the track with rails R 50*

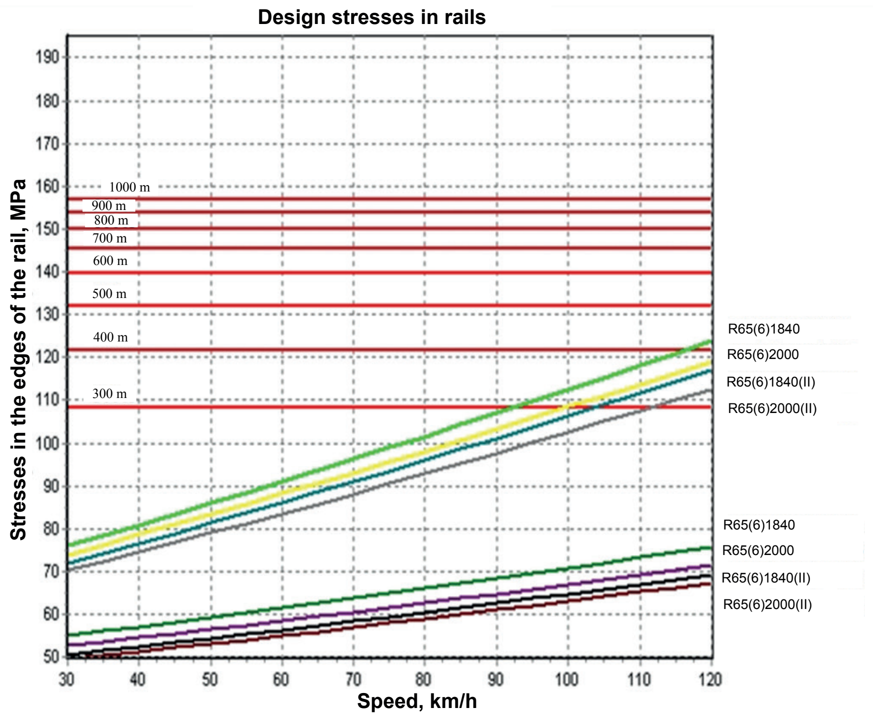

Figure 12 *Design axial stresses in rails under the influence of a diesel locomotive TE33A on the path of structure R 65*

Table 6 *Allowable diesel locomotive speeds TE33A*

Rail Type	Radius of curves, m								
	Direct	1000	900	800	700	600	500	400	300
R65(6)1840	K-120	K-120	K-120	K-120	K-120	N-115	N-105	N-95	N-80
R65(6)2000	K-120	K-120	K-120	K-120	K-120	N-115	N-105	N-95	N-80
R65(6)1840	K-120	K-120	K-120	K-120	K-120	N-115	N-105	N-95	N-80
R65(6)2000	K-120	K-120	K-120	K-120	K-120	N-115	N-105	N-95	N-80
R65(6)1840	K-120	K-120	K-120	K-120	K-120	N-115	N-105	N-95	N-80
R65(6)2000(II)	K-120	K-120	K-120	K-120	K-120	N-115	N-105	N-95	N-80
R65(6)1840(II)	K-120	K-120	K-120	K-120	K-120	N-115	N-105	N-95	N-80
R65(6)2000(II)	K-120	K-120	K-120	K-120	K-120	N-115	N-105	N-95	N-80
R50(6)1600(II)	K-120	95	95	90	80	75	65	50	35
R50(6)1840(II)	K-120	110	105	100	95	85	75	60	40
R50(6)2000(II)	K-120	120	115	105	100	90	80	65	45
R50(6)1600(II)	C-100	85	80	80	70	65	55	45	25
R50(6)1840(II)	C-100	100	95	90	85	75	65	50	35
R50(6)2000(II)	C-100	C-100	100	95	90	80	70	55	35
R50(6)1600(II)	100	65	65	60	55	50	45	35	20
R50(6)1840(II)	C-100	75	75	70	65	60	50	40	25
R50(6)2000(II)	C-100	80	80	75	70	65	55	45	30

Note 1: The letter "K" before the speed digit means the structural speed of the diesel locomotive.

Note 2: The letter "N" before the speed digit means the speed limit in the curved sections of the track by the value of the accepted allowable outstanding acceleration of 0.7 m/s2 at the elevation of the outer rail of 150 mm.

Note 3: The letter "C" after the speed digit means the speed limit by order No. 41 of the Ministry of Railways of the Russian Federation [22].

Note 4: Numerals of speed of movement without letters mean limitation of speed of movement according to conditions of the rail strength.

same figures. The abscissa of the point of intersection of these lines with the graph of the dependence of the design axial stress in the bottom of the rails on the speed corresponds to the permissible speed of the locomotive on the tracks of this type of topsides with the specified radius of curvature [13-14].

When drawing up the table of circulation rates, the inadmissibility of exceeding the outstanding acceleration in curves 0.7 m/s^2, the limitation on the ratio of lateral and vertical forces from the rail to the sleeper are taken into account. In addition, the speed of circulation of the locomotive should not exceed the structural speed provided for by the technical specifications and, according to the order of the Ministry of Transport and Communication of the Republic of Kazakhstan No. 41Ts of 12.11.01 [21], with rails R50 on gravel and sand ballast of 100 km/h. The results of studies to determine the speeds of movement of the diesel locomotive TE33A according to the criteria of the stability of the rail-sleeper grid by ballast shear, the strength of the bearing elements of the upper structure of the track and the non-exceedance of the outstanding acceleration of 0.7 m/s^2 in curves with an elevation of the outer rail of 150 mm are shown in Table 6.

4 Conclusions

According to the objectives of the study, the following results were obtained:

1) The coefficient of vertical dynamics of the first stage of suspension of the TE33A diesel locomotive in all considered modes fully complies with the established standards. The coefficient of vertical dynamics of the second stage of suspension of the TE33A locomotive in curves with a radius of 290 m to speeds with outstanding acceleration does not exceed 0.7 m/s^2, that is, it is within the permissible value.
2) The coefficient of stability margin against wheel derailment meets the requirements of NB ZhT TsT 02-98 in all considered modes. The minimum value of the coefficient was 1.7 at a speed of 70 km/h.
3) An experimental evaluation of dynamic stresses in the edges of the sole of the rail on curved sections with a radius of 290 m was performed, and the following values were obtained:

- in curved sections with a radius of 290 m with an outstanding acceleration of 0.7 m/s^2 - 198 MPa;
- with an outstanding acceleration of 1.0 m/s^2 - 221

MPa.
The values obtained correspond to acceptable standards.

4) The parameters of the frame (lateral) forces on straight and curved sections of the railway track are determined. The values of lateral forces in straight sections of the path up to the structural speed and in curved sections up to speeds with an outstanding acceleration of 0.7 m/s^2 are within the acceptable limits. However, in curves with a radius of 290 m, the values of lateral forces at all speeds are in the maximum permissible values.

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Conflicts of 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.

References

[1] ARBOLEYA, P., MOHAMED, B., GONZALEZ-MORAN, C., EL-SAYED, I. BFS algorithm for voltage-constrained meshed DC traction networks with nonsmooth voltage-dependent loads and generators. In: IEEE Power and Energy Society General Meeting: proceedings. IEEE. 2017. p. 1526-1536.

[2] KADYROV, A., ZHUNUSBEKOVA, Z., GANYUKOV, A., KADYROVA, I., KUKESHEVA, A. General characteristics for loading the working elements of drilling and milling machines when moving in the clay solution. *Communications - Scientific Letters of the University of Zilina* [online]. 2021, **23**(2), p. B97-B105. ISSN 1335-4205, eISSN 2585-7878. Available from: https://doi.org/10.26552/com.C.2021.2.B97-B105

[3] IMASHEVA, G., ABDULLAYEV, S., TOKMURZINA, N., ADILOVA, N., BAKYT, G. Prospects for the use of gondola cars on bogies of model ZK1 in the organization of heavy freight traffic in the republic of Kazakhstan. *Mechanika* [online]. 2017, **24**(1), p. 32-36. ISSN 1392-1207, eISSN 2029-6983. Available from: https://doi.org/10.5755/j01.mech.24.1.17710

[4] SAPRONOVA, S., TKACHENKO, V., FOMIN, O., GATCHENKO, V., MALIUK, S. Research on the safety factor against derailment of railway vehicles. *Eastern-European Journal of Enterprise Technologies* [online]. 2017, **6/7**(90), p. 19-25. ISSN 1729-3774, eISSN 1729-4061. Available from: https://doi.org/10.15587/1729-4061.2017.116194

[5] KOZBAGAROV, R., AMANOVA, M., KAMZANOV, N., BIMAGAMBETOVA, L., IMANGALIYEVA, A. Investigation of wear of cutting part of polygonal knife car graders in different ground conditions. *Communications - Scientific Letters of the University of Zilina* [online]. 2022, **24**(4), p. D229-D238. ISSN 1335-4205, eISSN 2585-7878. Available from: https://doi.org/10.26552/com.C.2022.4.D229-D238

[6] MIKHAILOV, E., SEMENOV, S., TKACHENKO, V., SAPRONOVA, S. Reduction of kinematic resistance to movement of the railway vehicles. *MATEC Web of Conferences* [online]. 2018, **235**, 00033. eISSN 2261-236X. Available from: https://doi.org/10.1051/matecconf/201823500033

[7] PERIN, I., WALKER, G. R., LEDWICH, G. Load sharing and wayside battery storage for improving AC railway network performance, with generic model for capacity estimation. Part 1. *IEEE Transactions on Industrial Electronics* [online]. 2019, **66**(3), p. 1791-1798. ISSN 0278-0046, eISSN 1557-9948. Available from: https://doi.org/10.1109/TIE.2018.2838066

[8] KHODAPARASTAN, M., MOHAMED, A. A., BRANDAUER, W. Recuperation of regenerative braking energy in electric rail transit systems. *IEEE Transactions on Intelligent Transportation Systems* [online]. 2019, **20**(8), p. 2831-2847. ISSN 1524-9050, eISSN 1558-0016. Available from: https://doi.org/10.1109/TITS.2018.2886809

[9] CHEN, Z., FANG, H. An alternative solution of train-track dynamic interaction. *Shock and Vibration* [online]. 2019, **2019**, 1859261. ISSN 1070-9622, eISSN 1875-9203. Available from: https://doi.org/10.1155/2019/1859261

[10] GERLICI, J., TKACHENKO, V., SAPRONOVA, S., LACK, T. Steerability research of railway vehicles. In: 24th International Conference Current Problems in Rail Vehicles PRORAIL 2019: proceedings. Vol. 1. 2019. p. 145-152.

[11] WU, Q., LUO, S., COLE, C. Longitudinal dynamics and energy analysis for heavy haul trains. *Journal of Modern Transportation* [online]. 2014, **22**(3), p. 127-136. ISSN 2662-4745, eISSN 2662-4753. Available from: https://doi.org/10.1109/10.1007/s40534-014-0055-x

[12] BAKYT, G., ABDULLAYEV, S., SULEYEVA, N., YELSHIBEKOV A., SEIDEMETOVA, Z., SADVAKASSOVA, Z. Simulation of dynamic processes of interaction of car and railway track during train passage of curved sections of the track. *Transport Problems* [online]. 2020, **15**(2), p. 45-70. Available from: https://doi.org/10.21307/tp-2020-020

[13] KADYROV, A., GANYUKOV, A., IMANOV, M., BALABEKOVA, K. Calculation of constructive elements of mobile overpass. *Current Science* [online]. 2019, **116**(9), p. 1544-1550. ISSN 0011-3891. Available from: https://doi.org/10.18520/cs/v116/i9/1544-1550

[14] ZHU, Z., GONG, W., BAI, Y. A hybrid solution for studying vibrations of coupled train-track-bridge system. *Advances in Structural Engineering* [online]. 2017, **20**(11), p. 1699-1711. ISSN 1369-4332, eISSN 2048-4011. Available from: https://doi.org/10.1177/1369433217691775

[15] LAU, A., HOF, I. Simulation of train-turnout coupled dynamics using a multibody simulation software. *Modeling and Simulation in Engineering* [online]. 2018, **2018**, 8578272. ISSN 1687-5591, eISSN 1687-5605. Available from: https://doi.org/10.1155/2018/8578272

[16] MIKHAILOV, E., SEMENOV, S., SAPRONOVA, S., TKACHENKO, V. On the issue of wheel flange sliding along the rail. In: International Conference Transbaltica: proceedings [online]. 2019. ISBN 978-3-030-38665-8, eISBN 978-3-030-38666-5, p. 377-385. Available from: https://doi.org/10.1007/978-3-030-38666-5_40

[17] JOHANSSON, A., PALSSON, B., EKHETAL, M. Simulation of wheel-rail contact and damage in switches and crossings. *Wear* [online]. 2011, **271**(1-2), p. 472-481. ISSN 0043-1648, eISSN 1873-2577. Available from: https://doi.org/10.1016/j.wear.2010.10.014

[18] SAPRONOVA, S., TKACHENKO, V., FOMIN, O., KULBOVSKIY, I., ZUB, E. *Rail vehicles: resistance to movement and handleability* [online]. Dnipro: Ukrmetalurginform STA, 2017. ISBN 978-966-921-163-7. Available from: https://www.metaljournal.com.ua/assets/MonographKyivverstka.pdf

[19] ABDULLAYEVA, A., KALABAYEVA, A., IVANOV, A., ABDULLAYEV, S., BAKYT, G. Methods for identification of complex industrial control objects on their accelerating characteristics. *Communications - Scientific Letters of the University of Zilina* [online]. 2022, **24**(3), p. B239-B246. ISSN 1335-4205, eISSN 2585-7878. Available from: https://doi.org/10.26552/com.C.2022.3.B239-B246

[20] MIKHAILOV, E., SAPRONOVA, S., TKACHENKO, V., SEMENOV, S., SMYRNOVA, I., KHOLOSTENKO, Y. Improved solution of guiding of railway vehicle in curves. In: International Conference Transport Means: proceedings. 2019. p. 916-921.

[21] Order of the Ministry of Transport and Communication of the Republic of Kazakhstan No. 41Ts of 12.11.01.

[22] KONSTANTINOV, M., WAGNER, C. Flow and thermal comfort simulations for double decker train cabins with passengers. In: 3rd International Conference on Railway Technology: Research, Development and Maintenance: proceedings. Vol. 110. 2016.

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EXPERIMENTAL STUDYING THE BELT CONVEYOR ROLLER WEAR DEPENDENCE ON THE INTENSITY OF TECHNOLOGICAL DUST ACCUMULATION IN OPEN PIT MINING

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Resume

The paper presents the research on revealing the causes of belt conveyors downtime at open-pit mining operations. By results of researches it is established that the reasons of the above mentioned problems are technological dust formed at crushing of mineral ore, further loading and unloading, and also at transporting by conveyors. Dense dust-air mixture settling on the rotating mechanisms of conveyors, gets into the bearing units and on the surfaces of friction gears, which accelerates the process of wear of parts several times.

The problem of determining the dependence of the wear of the working surface of roller bearings on the intensity of accumulation of process dust deposited on the parts and units of conveying machines has been set and solved.

The analysis has shown that one of the methods of protection of parts of conveyor equipment as a whole is removal of aggressive medium.

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1 Introduction

At present, not a single industrial enterprise can do without transport continuous machines, since this type of transport is easy to manufacture and efficient in transportation due to the low cost of moving goods. With proper operation of these devices, uninterrupted operation of production is ensured. In this regard, the most common type of conveyors is the belt conveyor, without which no industrial enterprise can do, and which, due to its simplicity of design, is the most popular and cost-effective at the present time [1].

The performance of belt conveyors depends on their reliable and trouble-free operation. The breakdown of belt conveyors is being caused by the breakdown of their elements due to increased wear and tear [2]. Prediction of occurrence of wear of elements with the help of models received by analysis of the data received in production conditions, will allow solving the problem of increasing the time of trouble-free operation of a belt conveyor [3].

One of the important elements which deterioration can strongly affect the operation of the belt conveyor is a roller support. A number of works [4-7] are dealing with the problems of roller conveyor wear. In these works the reasons of wear are analyzed, methods of diagnostics and modeling are presented. The review of the sources shows that the main reasons of roller failure are the bearing unit failure, wear of rollers surface as a result of action of abrasive particles of a settled dust. At the same time, in the absence of modern diagnostic tools at the enterprise an important source of information for studying the reasons for the conveyor elements failure could be the aggregate logs which with the use of corresponding methods of the analysis allow obtaining sufficiently acceptable scientific results.

2 Relevance

For the Republic of Kazakhstan, the most promising trend in open pit mining is the development and

Figure 1 Cyclic-flow transport of the crushing and screening complex of the «BAST» mining and processing plant [9]

widespread introduction of conveyor transport. The preliminary analysis in the Republic of Kazakhstan and abroad shows the almost complete absence of effective designs of apron conveyors. In this regard, issues of developing innovative designs of apron conveyors require a comprehensive study and providing scientific foundations in this area [8].

The conveyor pan line with rollers is an important part of the belt conveyor, the technical condition of which depends on reliability of the conveyor as a whole.

Reliability of the pan line is determined by reliability of the roller bearing rollers, since reliability of the supporting metal structures is an order of magnitude higher.

An important indicator for evaluating reliability of a roller is its service life that depends on the type, parameters of roller supports and operating conditions.

Figure 1 shows images of cyclic-flow transport of the crushing and sorting complex of the mining and processing plant of "BAST" taken during the experiments.

The task of determining the service life of the belt conveyor rollers was dealt with by L. G. Shakhmeister, V. G. Dmitriyev, V. F. Monastyrsky [10-11]. Their works show that the main cause of failure of the rollers is the bearing assembly failure, the wear of the roller bearing surface as a result of depositing abrasive particles of settled dust on them. The loads on the rollers in the course of transportation of the rock mass are determined, and based on this, formulas are proposed for calculating their service life. At the same time, the loads on the roller working surface arising from large pieces of freight are not taken into account accurately enough.

In works, there are proposed formulas for calculating the average service life of bearings and rollers of a belt conveyor. However, when describing the load on the roller bearing, the authors did not take into account the dynamic forces arising from the movement of the load along the conveyor line and due to the bending of the belt. It is shown in work [12] that with the belt speeds of more than 2 m/s, these forces are significant.

The analysis of the conveyor belt failures shows that the main reasons for the roller failure are surface wear due to abrasive wear and fatigue failure of bearing elements under the impact of dynamic loads. Consequently, the service life of one roller depends on the degree of wear of the roller shell and the service life of the bearings.

3 Statement of the problem

The purpose of this work is to determine the roller bearing wear dependence on the intensity of technological dust accumulation deposited on the surface of rotating mechanisms and belt conveyor units.

The tasks of the study are to determine empirical dependences of:

1) the roller shell wear in time;
2) dust accumulation in time;
3) the roller bearing wear dependence on the intensity of dust accumulation.

4 Technology of the freight movement at the enterprise

Figure 2 shows the transport and technological diagram of ore at the Maksut mining and processing plant. The ore mining technology begins with the geological and surveying department (position 1) that is engaged in the exploration of mineral deposits, studying ore blocks and their content. This service also gives the development trend.

Drilling and blasting, mining and transportation of ore is provided by the Interrin Research and Production Enterprise (position 2). This organization performs “overburden” of waste rock located above the ore blocks

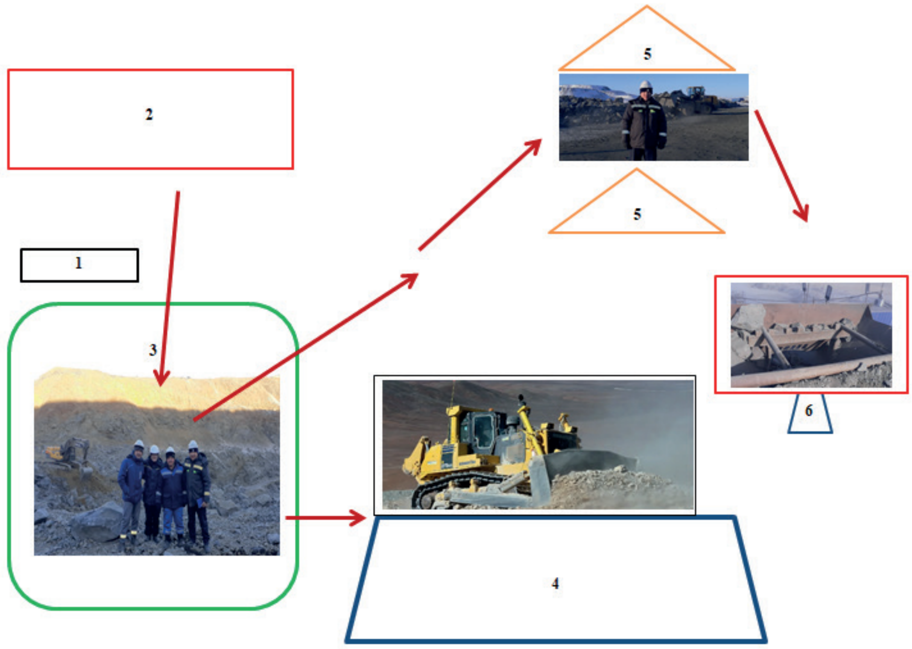

Figure 2 *Transportation-technological scheme ore transportation at Maksut mine [9]*
1 - geological and mine surveying department, 2 - dislocation of the Interrin Research and Production Enterprise, 3 - quarry, 4 - ore warehouse, 5 - rock dump, 6 - receiving hopper of the jaw crusher feeder

Figure 3 *Receiving hopper of the coarse lump crusher of the Maksut mine (position 6 of Figure 2) [9]*

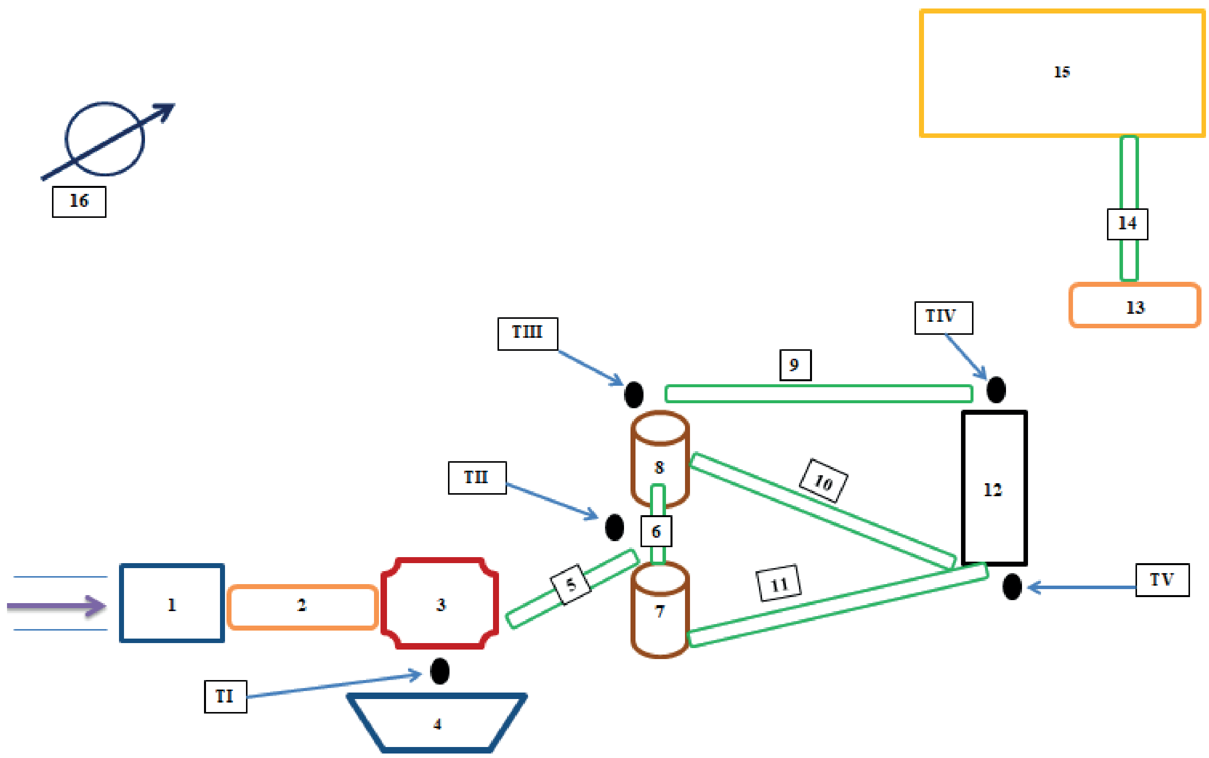

Figure 4 *A diagram of locating the equipment of the crushing and screening complex*
1-feeder hopper, 2-feeder, 3-jaw crusher, 4-crushing room operator, 5-conveyor No.1, 6-conveyor No.2, 7-cone of secondary crushing, 8-cone of secondary crushing, 9-conveyor No.3, 10-conveyor No.4, 11-conveyor No.5, 12-grinder, 13-feeder of conveyor No.6, 14-conveyor No.6, 15-building of concentrator, 16-south-east wind direction; TI- the place of dust sampling and thickness measurement, is located at the height of 5 meters from the zero mark; TII-place of sampling and measurement of dust thickness growth, located at the height of 3 meters from the zero mark; TIII-place of sampling and measurement of dust thickness growth, located at the height of 0 meters from the zero mark; TIV-place of sampling and measurement of dust thickness growth located at the height of 5 meters from the zero mark; TV-place of sampling and measurement of dust thickness growth, located at the height of 0 meters from the zero mark

in the quarry (position 3) and takes it to the rock dump (position 4) intended for storage of waste rock. After the ore blocks are cleared of waste rock, wells are drilled with a certain grid, then there follow blasting and direct ore mining.

Loading is carried out by excavators onto dump trucks with the carrying capacity of 20-50 tons that deliver the ore to the ore warehouse (position 5). It is a ramp for storing marketable ore. The volume of ore storage in the ore warehouse is 2500-3000 tons, which is enough to provide the crushing and screening complex for 10-12 days.

At the ore stockpile there is a receiving hopper (Figure 6), which is the beginning of the mineral ore crushing process. In front of the hopper there is an open area (ramp) for maneuvering a front-end loader, which delivers ore from the ore stockpile and doses ore to the receiving hopper.

Figure 3 shows the receiving hopper of the lump crusher located in the ore stockpile (position 6 of Figure 2), which is the beginning of the mineral ore crushing process. In front of the hopper there is an open area (ramp) for maneuvering the front-end loader, which delivers ore from the ore stockpile and doses ore to the receiving hopper.

The receiving hopper has sorting grates that prevent the ingress of oversized pieces with the length of more than 500 mm.

Figure 4 shows a diagram of the equipment of the crushing and screening complex.

Under the receiving hopper there is a feeder. It is a plate conveyor that doses ore into the jaw crusher by changing the speed of the load-carrying belt. Then, from the jaw crusher, the crushed ore with the fraction of 40-80 mm enters conveyor belt No. 1 and is fed through it to the loading cone of medium crushing at the level of 4500 mm. From this equipment, the crushed ore enters the grate with the cells of 30 mm, from where it enters conveyor No. 5 located below. Larger ore that has not passed through the grates enters along an inclined plate to conveyor No. 2.

On conveyor No. 5, the crushed ore enters the vibrating screen that has a sieve on the upper tier with the cells of 40 mm and 20 mm on the lower tier of screening.

From unloading conveyor No. 2, ore with the fraction of more than 30 mm is fed to the fine crushing cone at the level of 4500 mm. The slots of this cone are 15 mm

***Table 1** Downtime of conveyors Nos. 1 to 6 due to failures and repairs*

No.	Date	Unit and defect characteristics	Amount of work done to eliminate the defects	Real service life of the unit, part	Rquipment downtime, hour
1	13/03/2019	Cut on the belt	Patching - 1.5 m	3 months	5
2	23/03/2019	Wear of supporting and bearing rollers	Replacing rollers 3 pcs.	3 months	1.5
…	…	…	…	…	…
325	18/08/2021	Wear of the vertical roller	Replacing the vertical roller 2 pcs.	1 month	1

***Figure 5** Measuring technological dust in the CSC section*

but despite this, larger ore passes through these slots and therefore, it is transported on conveyor No. 3 to the vibrating screen for further screening.

The ore passed through the lower sieve of the screen enters the feeder of conveyor No. 6, through which it enters the factory for further grinding and dressing.

In the process of crushing, the ore splits at the boundaries of the mineralization of the ore body that mixing with air, rises up forming a thick captivity, eventually settling on the rotating mechanisms and equipment of the crushing and screening complex.

5 Research part

Based on the results of studying the operation of cyclic-flow transport at the Maksut mining and processing plant of the BAST JSC in the East Kazakhstan region (hereinafter referred to as GOK) carried out from September 2020 to September 2021, significant downtime of the crushing and screening complex (hereinafter CSC) was revealed due to premature wear of components and parts of conveyor equipment, which naturally led to non-fulfillment of the enterprise plan and losses. To determine the reasons for downtime of the CSC equipment, studies were carried out on the aggregate logs of six conveyors, a feeder with a jaw crusher, cones of fine and medium crushing, as well as oil stations providing a lubrication system for the mechanisms of all the CSC equipment. The results for the last 3 years are shown in Table 1.

The analysis of the aggregate logs showed that significant downtime of the CSC equipment was caused by the failure of the roller bearings of the conveyors and their replacement. The main reason for the roller bearings failure is the working surface wear due to the abrasive action of technological dust. The main measure for dust protection of equipment is irrigation of crushed material during transportation. Sticking to the conveyor belt, it enhances the abrasive effect on the roller support shell, and getting into the bearing units in the form of a liquid suspension, destroys the roller bearings. One of the measures to protect mechanisms against the aggressive impact of dust was dust cleaning, which was carried out every four days with the complete stop of the equipment.

Figure 4 shows that to study the effect of process dust on the roller bearings of the conveyors, the places

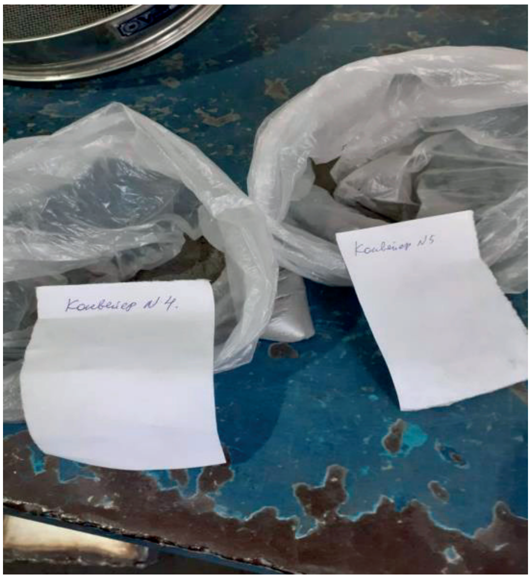

Figure 6 *Samples of technological dust from the CSC*

Figure 7 *Calibrated sieves from the Kraft Company*

Figure 8 *Blue paint marks on the conveyor rollers*

for sampling and measuring the settling dust at the CSC section marked with points T1 to T5 were installed. For the above period, every shift (the shift duration is 11 hours) measurements of dust accumulation were carried out in the most dusty areas of the CSC (Figure 5).

Measurements of settled dust were made using a measuring ruler, the measurement results were noted in the "Register of Research and Experiments" during the inter-shift shutdown of the equipment. In the most dusty areas of the CSC in Figure 4 marked with points T1 to T5, technological dust was sampled and placed in plastic bags indicating the time, date and place of sampling (Figure 6).

Then, in the research and analytical laboratory of the Mining and Processing Plant, there was determined the size of the abrasive dust particles using special calibrated sieves with the mesh range of 0.1 mm to 3 mm.

The dust settled on the conveyor structure was sieved on special calibrated sieves of "KRAFT" company, which are shown in Figure 7.

According to results of sieving it has been defined that 30% of dust consists of particles with grain size 3 mm, 25% - 2 mm, 20% - 1 mm, 25% - smaller than 0.1 mm. These samples were tested for polymetals content: Cu, Fe, Mg, Au, Ag, etc.

6 Experimental part

For the purpose of the experiment, the newly mounted rollers on the conveyor pan line were previously marked with blue paint, as shown in Figure 8.

Figure 9 *Measuring the roller shell wear*

Table 2 *Results of the study of roller wear dependence by day in heavy dusty conditions for seventeen weeks*

Operating time, 24 hours	Operating time of the roller bearings, hours	Dust accumulation thickness, mm	Roller bearing shell wear, mm
1	22	28	0
2	44	42	0.01
3	66	57	0.015
4	88	78	0.02
5	110	85	0.03
6	132	104	0.04
7*	154	118	0.04
8	176	0	0.04
…	…	…	…
119*	2618	121	3.95
120	2640	0	3.98
121	2662	45	4**

*- days when conveyor equipment is shut down and cleaned of process dust

**- values for wear of the shell requiring replacement of the roller bearing

Table 3 *Dependence of roller wear on dust thickness during operation*

Operating time, week - weeks	Number of operating hours of support rollers, - hour	Roller shell wear value, micrometers, (μm) - micrometers, (μm)
1	154	200
2	308	340
3	462	490
...	...	...
15	2156	3320
16	2331	3680
17	2464	3960

On the newly mounted roller bearings with the diameter of 108 mm, measurements of the working surface of the shell wear were carried out every shift using a ShTs-1 caliper, which are shown in Figure 9.

The readings of the instrument were recorded every shift in the Register of Research studies and experiments indicating the date and time of measurements, the wear magnitude of the working surface of the roller bearings, the condition of the rolling bearings on the roller rotation shaft.

Studying and measuring the roller wear, accumulated dust thickness and the abrasiveness of the process dust particles were carried out daily during the planned shutdown of the conveyors within seventeen weeks. The values of the survey results are shown in the Table 2 below.

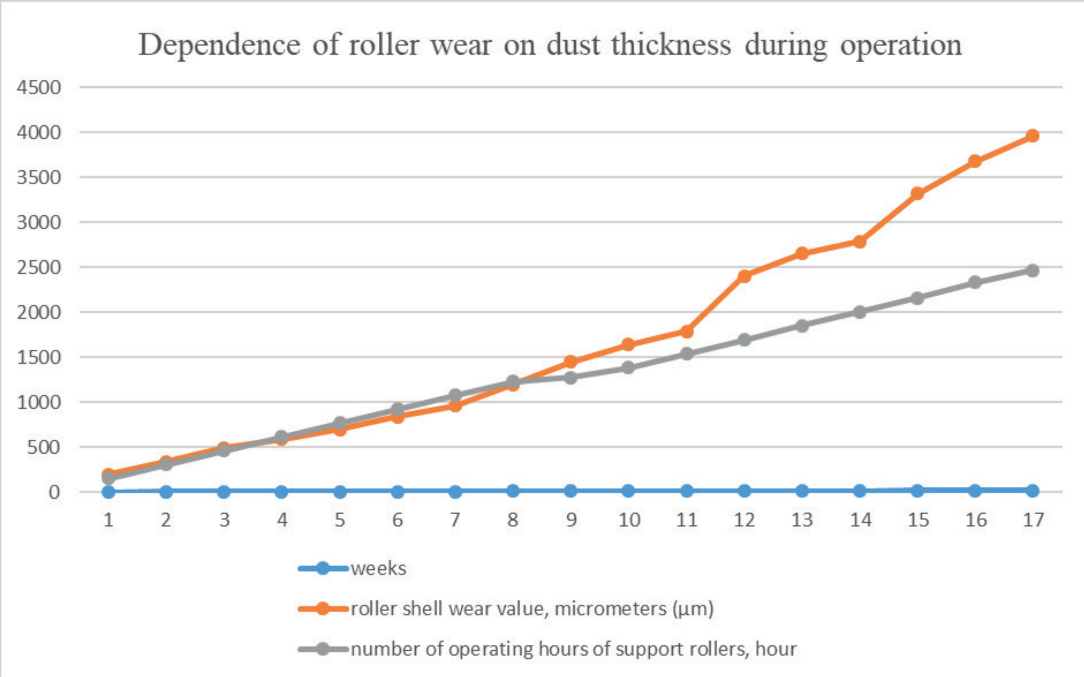

***Figure 10** Dependence of roller wear on dust thickness during operation*

***Table 4** Average values of accumulated dust layer thickness*

Day of the week after the next dust removal	The complex operating time, hours	The accumulated dust layer thickness, mm
1	22	28
2	44	42
3	66	57
4	88	78
5	110	85
6	132	104
7	154	118

According to the values in Table 3, the diagram shown in Figure 10 is constructed.

According to the data shown in Table 2, it is clear that the actual average workload of the studied rollers is 2600-2700 hours, although according to the established state standard 57841-2017 "Mine belt conveyors. Rollers" roller conveyors of the considered type (108 millimeters in diameter) with a belt speed of 2 meters per second, must work at least 8000 hours of machine time.

7 Processing the experimental results

Based on the results of shift monitoring within the period from September 2020 to September 2021, the average values of dust accumulation and roller wear were determined. They are shown in Table 2 for each conveyor.

During the operation of the crushing and screening plant conveyors, dust accumulates and is removed at intervals of once every seven days.

Based on the results of the observations, the average values of dust layer thickness by days of the week, for a period of 121 days are established.

Observations of weekly dust accumulation are shown in Table 4.

It was mentioned above that the dust collection was carried out every seven days, so the number of measurements of dust accumulation and wear of roller shells is seven.

Let us determine the empirical dependence of dust accumulation on time. The empirical dependence is defined as an exponential dependence [13]:

$$y = a \cdot e^{b \cdot x}, \qquad (1)$$

where:
x is the value of the argument (time);
y is the function value (the thickness of the layer of accumulated dust).

Numerical values of a and b are determined from the results of observations, which are shown in Table 3

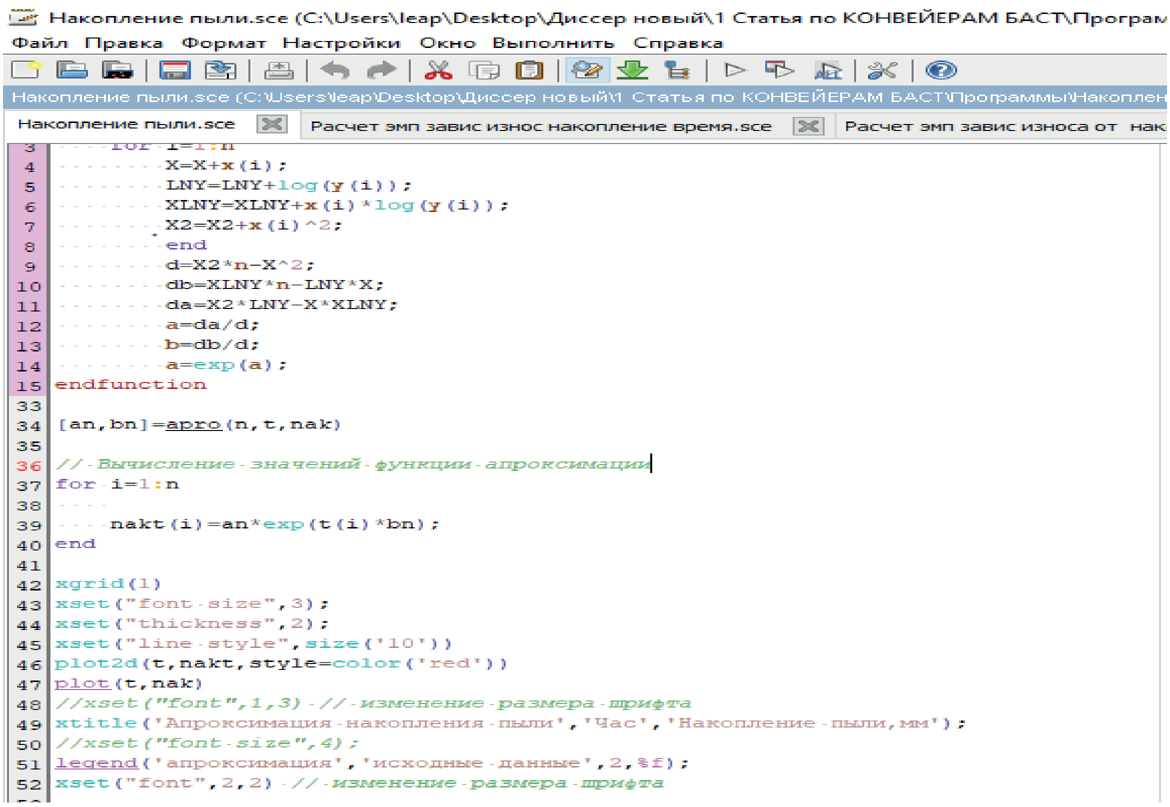

Figure 11 *Screenshot of the Scilab program environment*

Table 5 *Average values of dust thicknesses affecting the rollers and the wear rate of the rollers under the influence of the dust by day of the week*

Measurement No.	Dust accumulation, mm	Wear of the roller shell, mm
1	29.235	0.0265
2	44.35	0.0224
3	61.59	0.0211
4	73.88	0.0259
5	89.76	0.033
6	106.59	0.039
7	122.59	0.039

by the method of least squares, for which the program code in Scilab environment was developed [13]. In Table 3 average values of dust thicknesses acting on the rollers and wear rate of the rollers under the influence of the dust are shown. Observations and measurements were carried out over a period of seventeen weeks. At the end of each week all parts of each conveyor were cleaned along the entire conveyor line.

To calculate the parameters a and b of the empirical dependence (1), a programme code has been developed in the Scilab environment [14], a screenshot of the programme page is shown in Figure 11:

The first column of the Table 5 shows the days of the week, the second and third columns show the average values of the wear intensity of the rollers and the thickness of the process dust.

As a result of the calculations, an empirical time dependence of the thickness of process dust accumulation is obtained n_d, which has the form:

$$n_d = 25.75 \cdot e^{0.02096 \cdot t}, \tag{2}$$

where: t is the observation time, hour.

Graphical representation of the observation results and graph of the empirical relationship are shown in Figure 12.

The obtained empirical dependence of the working surface of roller bearing wear on time has the form:

$$Z_t = 0.705\, e^{0.0353 \cdot t}, \tag{3}$$

where: Z_t is the roller working surface wear;
t is the time of observation.

A graphical representation of the results of

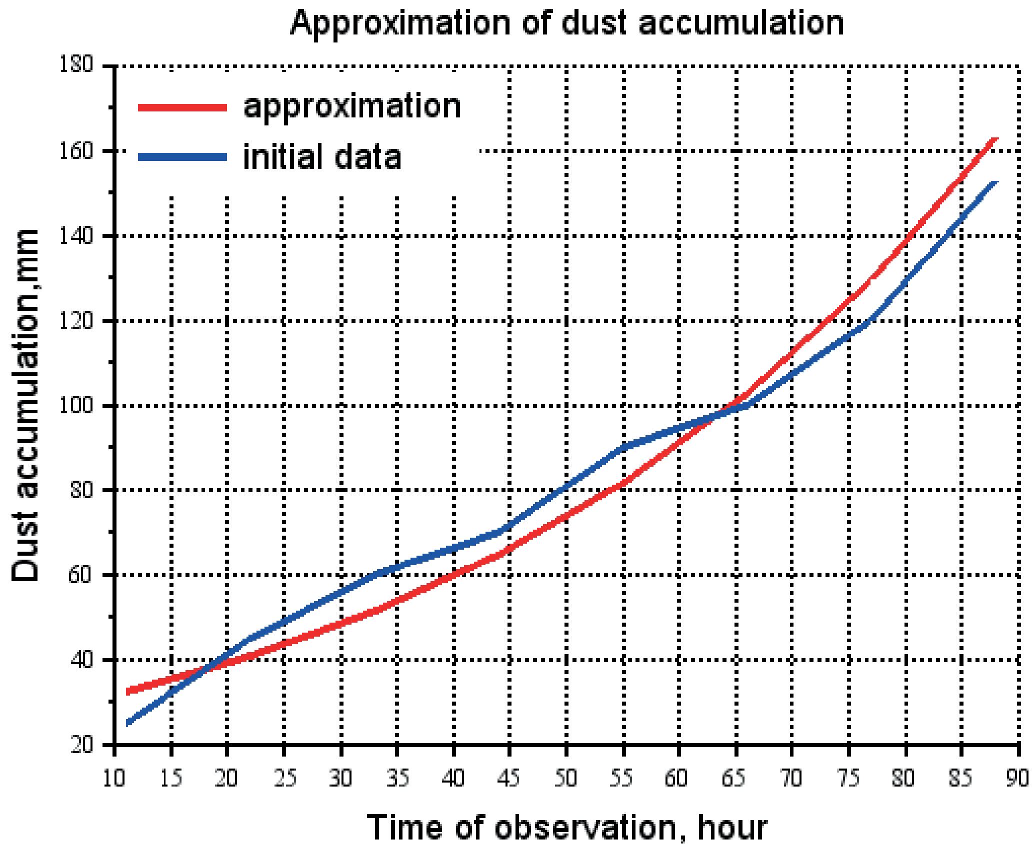

Figure 12 *The dust accumulation empirical dependence on time*

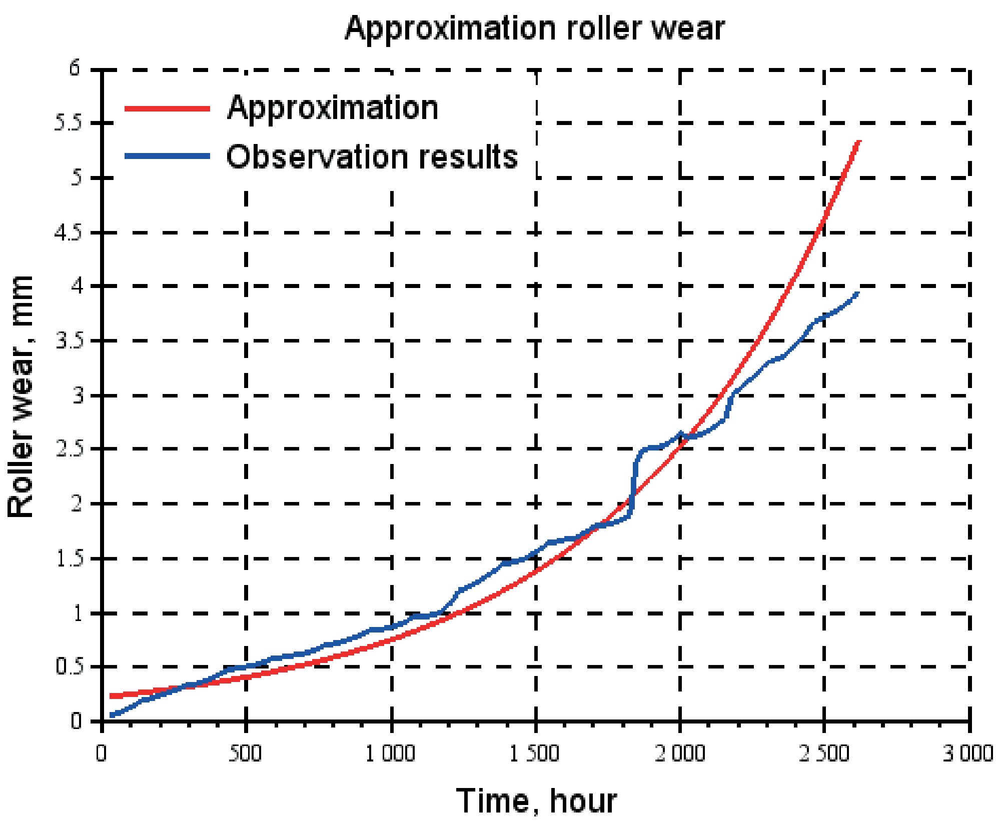

Figure 13 *The roller working surface wear dependence on time*

observations and a graph of the empirical dependence are presented in Figure 13.

The empirical dependence of the wear of the working surface of roller bearings on the intensity of accumulation of process dust, based on the type of the graph of observation data, we determine by the parabolic dependence of the form *y=ax2+bx+c*. The specific form of the parabolic empirical dependence, the coefficients of which are determined by the least squares method, is represented by the following formula:

$$z = 0.03119n_p^2 - 0.40670n_p + 3.52417 \cdot 10^{-5}, \qquad (4)$$

where: z - is the roller working surface wear, [m];
n_p - is the thickness of the accumulated technological dust layer, [mm].

A graphic representation of the results of observations and a graph of the empirical dependence of the working surface of the roller bearing wear on the intensity of the accumulation of process dust are shown in Figure 14.

8 Conclusion

Based on the results of experimental studies carried out from September 2020 to September 2021 on six MMP CSC conveyors transporting crushed ore, it was found that the rotation units and working surfaces of the roller bearings were the most vulnerable for wear. To identify a causal relationship, technical and operational documentation was studied (aggregate logs of each conveyor for the last 3 years, complaints issued to manufacturers and their representative offices in our country, manufacturer's operating manuals, reference books and other technical literature), according to the results which it was found that 40 percent of the parts and assemblies of conveyors served out the service life set by the manufacturer by 60 percent, and 30 percent of the equipment work out only for a third of the machine hours.

In the course of shift monitoring the equipment with the use of instrumentation and tools, it was found that the cause of the above problems was technological dust generated during crushing the mineral ore, loading and unloading, as well as further transportation by conveyors. A thick dust-air mixture that settles on the rotating mechanisms of conveyors reaches the bearing units and the surfaces of friction gears, which accelerates several times the process of parts wear.

The set objectives of the study have been fulfilled:

1. The dependence of dust accumulation on time is described by the empirical Equation (2).
2. Dependence of wear of the working surface of the roller bearing on time is described by the empirical Equation (3).

Dependence of wear of the working surface of the roller bearing on the intensity of accumulation

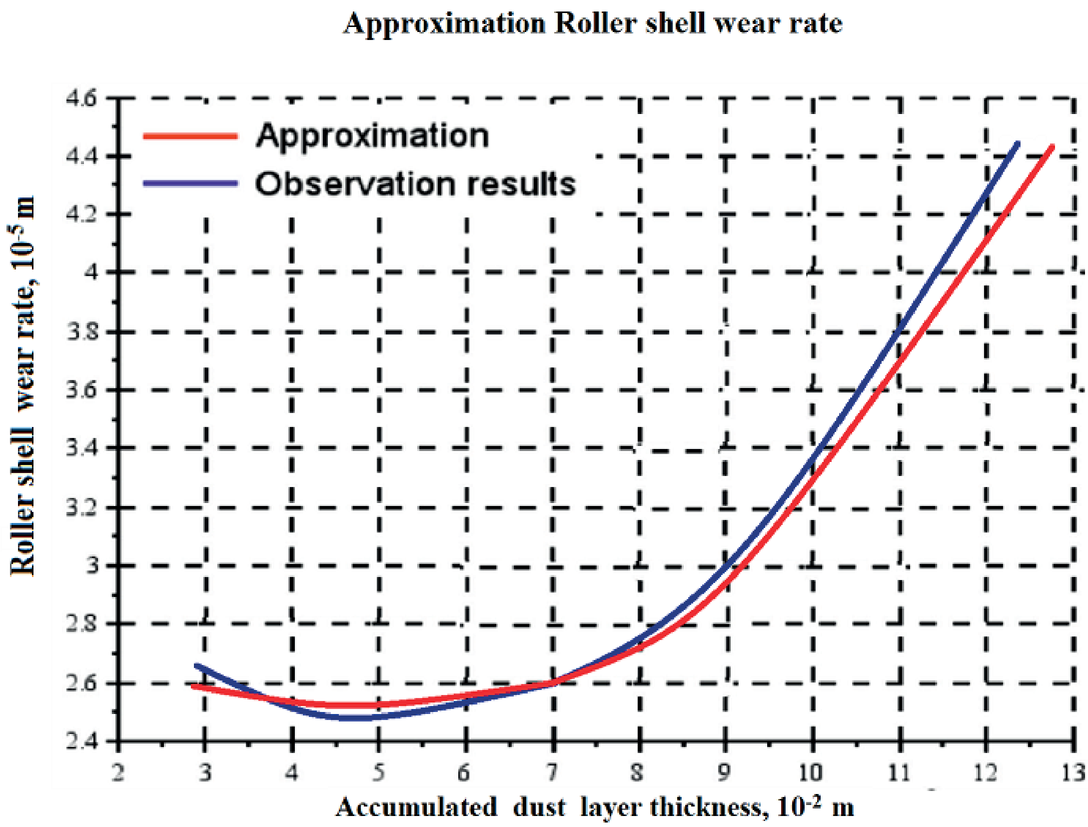

Figure 14 *The roller working surface wear empirical dependence on the intensity of the technological dust accumulation*

of process dust is described by the empirical Equation (4).

The analysis of the empirical dependences of roller bearing shell wear on dust accumulation shows that in order to achieve stable operation of cyclic-flow transport in severe conditions, it is necessary to protect the most vulnerable components and parts of the conveyor against the impact of the abrasive and aggressive environment. One of the general methods of protecting conveyor equipment is the aggressive environment removal with the further use of mineral dust as a dressed polymetal concentrate.

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Conflicts of 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.

References

[1] YARDLEY, E. D., STACE, L. R. History and economics of conveyor applications [online]. Chapt. 2. In: *Belt Conveying of Minerals*. Woodhead Publishing Series in Metals and Surface Engineering, 2008. ISBN 978-1-84569-230-8. p. 4-16. Available from: https://doi.org/10.1533/9781845694302.4

[2] HOMISIN, J., GREGA, R., KASSAY, P., FEDORKO, G., MOLNAR, V. Removal of systematic failure of belt conveyor drive by reducing vibrations. *Engineering Failure Analysis* [online]. 2019, **99**, p. 192-202. ISSN 1350-6307, eISSN 1873-1961. Available from: https://doi.org/10.1016/j.engfailanal.2019.02.028

[3] DABEK, P., KROT, P., WODECKI, J., ZIMROZ, P., SZREK, J., ZIMROZ, R. Measurement of idlers rotation speed in belt conveyors based on image data analysis for diagnostic purposes. *Measurement* [online]. 2022, **202**, 111869. ISSN 0263-2241, eISSN 1873-412X. Available from: https://doi.org/10.1016/j.measurement.2022.111869

[4] FISET, M., DUSSAULT, D. Laboratory simulation of the wear process of belt conveyor rollers. *Wear* [online]. 1993, **162-164**(B), p. 1012-1015. ISSN 0043-1648, eISSN 1873-2577. Available from: https://doi.org/10.1016/0043-1648(93)90113-Z

[5] RAVIKUMAR, S., KANAGASABAPATHY, H. MURALIDHARAN, V. Fault diagnosis of self-aligning troughing rollers in belt conveyor system using k-star algorithm. *Measurement* [online]. 2018, **133**, p. 341-349. ISSN 0263-2241, eISSN 1873-412X. Available from: https://doi.org/10.1016/j.measurement.2018.10.001

[6] ZHAO, L. Typical failure analysis and processing of belt conveyor. *Procedia Engineering* [online]. 2011, **26**, p. 942-946. ISSN 1877-7058. Available from: https://doi.org/10.1016/j.proeng.2011.11.2260

[7] YANG, M., ZHOU, W., SONG, T. Audio-based fault diagnosis for belt conveyor rollers. *Neurocomputing* [online]. 2020, **397**, p. 447-456. ISSN 0925-2312, eISSN 1872-8286. Available from: https://doi.org/10.1016/j.neucom.2019.09.109

[8] GALKIN, V. I. *Modern theory of belt conveyors of mining* enterprises. Moscow: Izvo MGGU, 2005. ISBN 978-5-98672-209-2.

[9] Photos and diagrams created during experiments at the Maksut mine of the BAST joint stock company.

[10] SHAKHMEISTER, L. G., DMITRIEV V.G. *Probabilistic methods of calculation of transporting machines*. Moscow: Mashinostroenie, 1983.

[11] MONASTYRSKY, V. F. *Bulk and roller supports dynamic efforts interactions obtaining for mine belt conveyer*. Kiev: Geo-Technical Mechanics, 2012.

[12] RUUD, P. A. *An introduction to classical econometric theory*. New York: Oxford University Press, 2000. ISBN 9780195111644.

[13] NAGAR, S. Introduction to Scilab: for engineers and scientists [online]. 2017. Available from: https://doi.org/10.1007/978-1-4842-3192-0

[14] ALEKSEEV, E. R., CHESNOKOVA, O. V., RUDCHENKO, E. A. *Scilab. Solution of engineering and mathematical problems*. Moscow: ALT Linux; BINOM. Laboratory of Knowledge, 2008.

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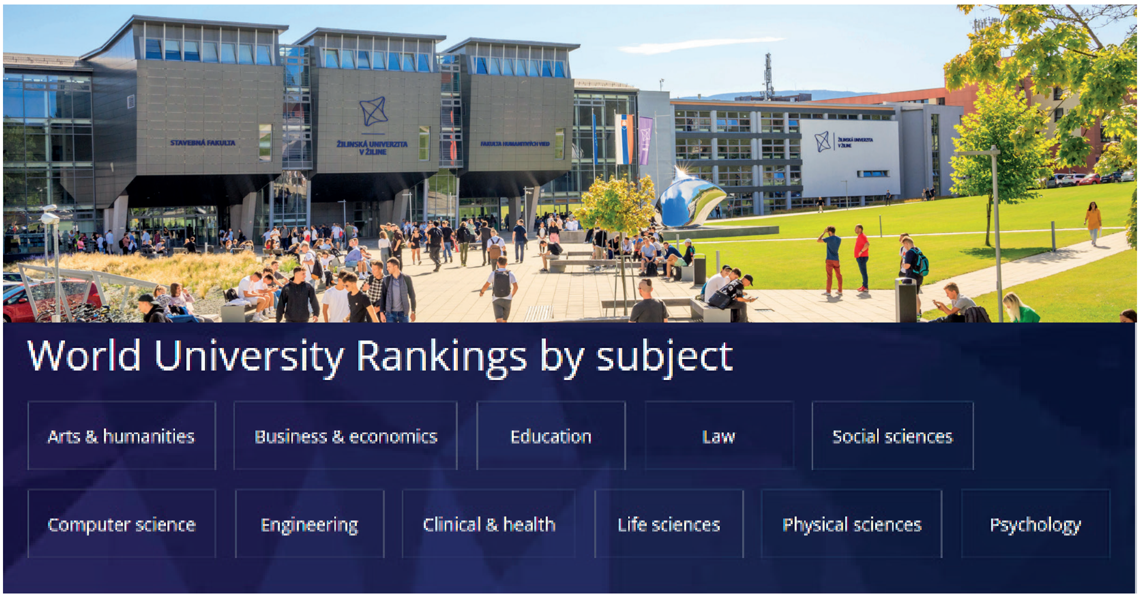

Within the eleven evaluated areas, World University Rankings by Subject 2023 ranked the University of Žilina in five categories. In the Social Sciences category, University of Žilina was ranked at 401-500 place (the evaluated faculties were FPEDAS, FBI, FRI). In the Business and Ecatomics category, University of Žilina was ranked at 401-500 place (the FPEDAS faculty was evaluated). Other evaluated areas were Technical Sciences, where University of Žilina was ranked at 1001+ place and Computer Sciences, where University of Žilina was ranked at 801+ place.

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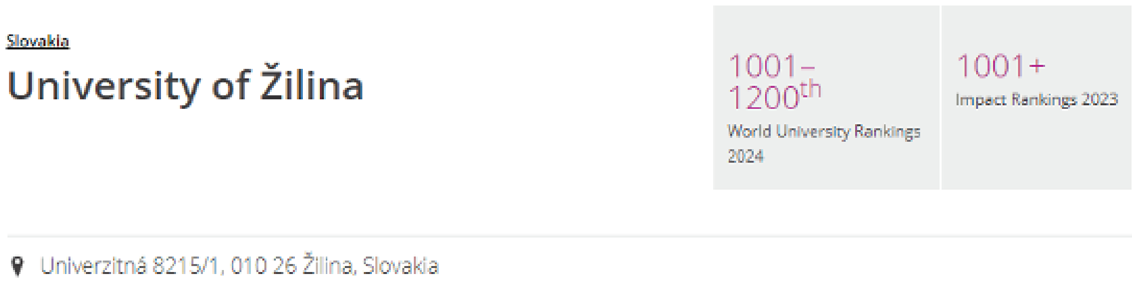

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SUPERCAPACITOR MODULE SIZING CONCERNING OPERATIONAL CONSTRAINTS OF THE POWER CONVERTER

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Resume

In this paper, the focus is given on the potential use of the supercapacitor component for peak power delivery, required during operation. Potential application use considered here is electric drive for robotic arm motorization. Automatization of industrial and manufacturing processes requires increasing demands on the use of industrial robots. The motion profiles of such system, requires within the operation peak power demand. The supply system can be composed from DC bus power supply, or combined with energy storage system. Combination with proper energy storage component, can improve energy efficiency and provide peak power for the requirements of the system operation. In this paper, design approach for supercapacitor (SC) module is presented for certain motion profile, which is defined by power requirement here. SC module design reflects input to output electrical specifications, while the most optimal configuration is being identified according to SC operation. This approach refers also to the identification of the operational performance of DC-DC bidirectional converter and its proper topological configuration.

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1 Introduction

Energy efficiency and its optimal utilization are coming more and more important, thus representing interesting point of the scientific interest. Energy sources are converted into different forms and partially stored in the grid system for power shaping or peak demand covering. There are various possibilities how to design energy storage system, while hybridization is coming more popular. Here it means, that the use of combination electrochemical cells with various properties are used for potential optimization of the operational scenarios of target application system. Each of the energy storage technology has its properties, which can be recognized also within lifetime or the value of the capacity. Even iron-based electrochemical cells have long operational life and are environmentally friendly, the energy density is not as high as for other perspective technology [1-2]. Research in this field of technology brought development of supercapacitors, which are characterized by long life operation and very high-power density. The usage of SCs as temporary energy storage for regenerative braking is growing [3-6]. The benefits of the SCs are their extended lifetime, high power density, short charge-discharge time, low input resistance, and environmental friendliness. Energy density is not comparable to the conventional and modern electrochemical cells on the other side, therefore combination of these two technologies represents attractive solutions for many applications whose operation scenarios requires the potential use of hybrid energy storage system (HESS) [7-8].

A hybrid energy storage system (HESS), which complements the beneficial qualities of each module, is the combination of the battery and SC. In this configuration, the battery's operating time is increased while the negative effects of current fluctuation are reduced. This is a crucial component for using HESS. Practically the main task of the capacitor is to cover and absorb peak power demands during the system operation. It means, that the design of supercapacitor must meet power profile of the application [9-11].

In this paper the focus is given on the optimal design of supercapacitor module for hybrid energy

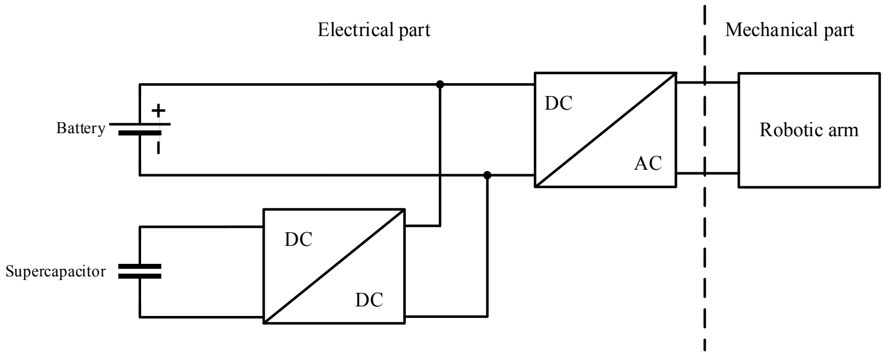


Figure 1 *Block scheme of the electrical and mechanical system*

Table 1 *Input parameter specification*

	Input Parameters		
	Electrical Parameters	minimum	maximum
V_B	Battery voltage	40 V	54.4 V
$V_{SCmodule}$	Supercapacitor voltage	16 V	32 V

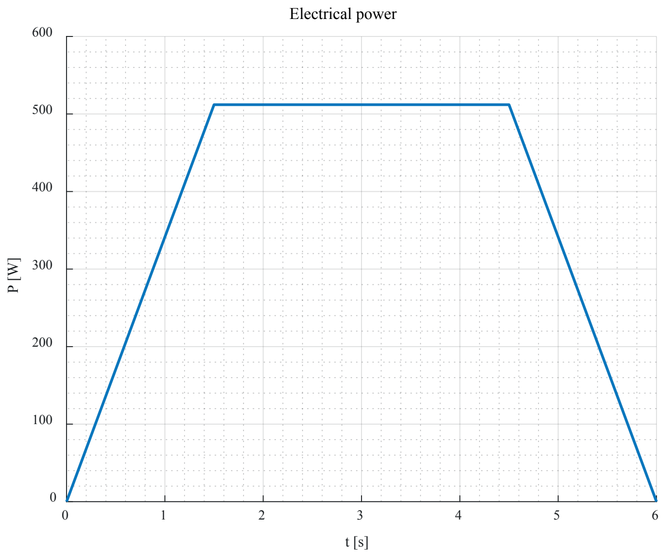


Figure 2 *Time waveform of the power for the working profile (one operational interval)*

supply/storage system. The input to output parameters of the bidirectional DC-DC power converter are defined initially, and are reflecting application properties of HESS. According to the optimization of the supercapacitor module operation, the analysis on the potential topological solution of the DC-DC converter and its duty cycle working range are presented at the end of the paper.

2 System specifications on power electronic circuit

The basic block diagram of the considered system is shown in Figure 1. It consists of a mechanical part, which is formed by a robotic arm, and an electrical part. As a main source is used a battery to maintain a constant power to the load or to charge a supercapacitor. A supercapacitor is used to deliver peak power. The bidirectional DC/DC converter connects the supercapacitor to the battery and to the inverter. The design of supercapacitor bank and selection of a bidirectional DC/DC converter topology is part of the optimization proposal of this paper.

The load is formed by the inverter and the robotic arm. The input parameters for the designing of power converters and supercapacitor bank are stated in a following Table 1.

The voltage of 40 V is for fully discharged and 54.4 V is for fully charged battery pack. The maximum voltage of the V_{SC} supercapacitor is set to 32 V. For efficient utilization of the supercapacitor bank, when

75% of the energy is assumed to be drawn, the minimum voltage value will be half of the maximum. Then the minimum value is 16 V.

The calculation of the supercapacitor capacity C_{SC} depends on the power profile of the load. The power profile is dependent on the working mode of the mechanical movement of the robotic arm. The profile of the mechanical quantities of the working cycle are shown in Figure 2. This cycle corresponds to the specific requirement during the operation of the mechanical system. It is expected here that the power delivery for this time interval (6 seconds) will be covered by the supercapacitor itself. Therefor the design must meets this power requirements.

3 Analysis of supercapacitor module configuration

The power profile specified in Figure 2 is being considered and is used for the determination of the supercapacitor parameters. From Figure 2 is seen that peak power demand is 512 W within 6 s time interval, then steady operation is expected, while required power delivery is supported by the battery system (Figure 1). Based on this, we can calculate the energy that needs to be supplied for a given peak power and will be sourced from supercapacitor module. According to the physical interpretation, the energy is an area covered by time waveform of the power profile. Therefore, when approximation of defined profile (Figure 2), we obtain two triangular time waveforms of power for the duration of 1.5 s and one rectangular waveform lasting for 3 seconds. After the peak power demand, the constant power is delivered to the load. This power is drawn from the battery.

Considering operational and lifetime conditions for the bank of supercapacitor (SC), the key optimization parameters are related to the:

- Maximal current of the supercapacitor cell.
- Ripple current of the supercapacitor cell (during charging and discharging periods).
- Heat dissipation and operational temperature.

The first criterion is affected by the supercapacitor itself, i.e. it is defined by the manufacturer. Optimization regarding maximal current can be later optimized by paralleling cells. Second criterion can be affected by selection of proper converter topology. The third criterion is a matter of design specifications of the supercapacitors bank. These parameters are considered within calculations regarding operational profiles.

Speaking about searching the optimal settings of the bank of supercapacitors, initial focus is given on the possibilities of the ripple current cancelation. Perspective topologies have been developed for this purpose, while interleaving of the power stage of the converter is main approach how to reduce ripple current. From Figure 3 is seen, that with the increase of converter stages, for certain values of the duty cycle, the ripple current reduction is possible.

Presented design approach considers that the sizing of the bank of SC is made in terms of defining the voltage variation during power delivery (Table 1). This operation refers to duty cycle variation during DC-DC converter operation, thus duty cycle range from Figure 3 can be found thus defining the current ripple amplitudes.

Two alternatives are presented here, while it is considered, that during discharging process, after the end of motion profile the voltage on the bank of SC will be 50% from V_{SCmax}. The maximum voltage level V_{SCmax} is 32 V. The voltage at the end of discharging process will be half of the voltage V_{SCmax}, i.e. $V_{SCdisch}$ = 16 V.

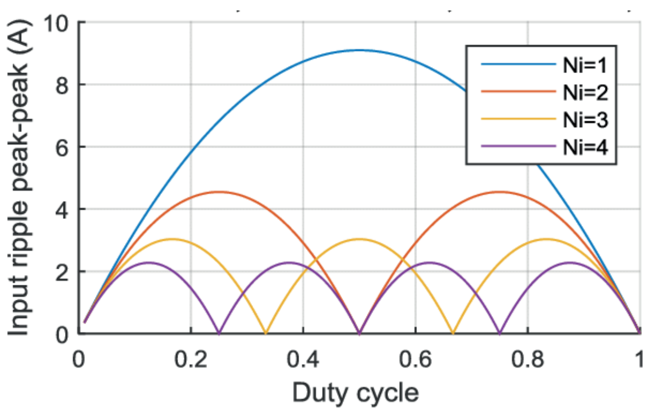
The calculation of the energy for the delivering of the peak power to the load is as follows:

A. Calculation based on average power value criterion

The formula for average power calculation considering rectangular waveform is given by next equation:

$$P_{AV} = \frac{1}{T} * P * t\,[W]. \quad (1)$$

For 1st and 3rd interval, triangular waveform is characterized, so the Equation (1) is then modified



Figue 3 *Magnitude of input ripple as a function of duty cycle for different number of interleaved stages of the DC-DC converter*

Table 2 *Possible SC module configurations*

U_{SC} [V]	C_{SC} [F]	ESR [mΩ]	I_{SCmax} [A]
2.7	5	35	10
2.7	7	31	10
2.7	8	28	12
2.7	10	27	12
2.7	12	26	14
2.7	15	23	17
2.7	20	24	20
2.7	25	20	20
2.7	30	19	25
2.7	35	20	25
2.7	40	18	30
2.7	50	15	30
2.7	60	13	30

$$P_{AVtriangle} = \frac{1}{T} \cdot \frac{P_{peak}}{2} \cdot \frac{T}{4} = \frac{P_{peak}}{8} = 64 \text{ W} . \quad (2)$$

For 2nd interval (rectangular waveform) the average power is

$$P_{AVconst} = \frac{1}{T} \times P_{peak} \times \frac{T}{2} = \frac{P_{peak}}{2} = 256 \text{ W} . \quad (3)$$

Then the total power for defined time waveform from Figure 2 is given by Equation (4).

$$P_{AVtot} = 2 \times P_{AVtriangle} + P_{AVconst} = 384 \text{ W} . \quad (4)$$

Corresponding energy of SC module is then calculated by next formula:

$$E_{SC} = P_{AVtot} \times t = 2304 \text{ J} . \quad (5)$$

B. Calculation based on energy criterion

Previous procedure considers average power calculation, while in this procedure bit different approach is presented, while it is expected that the results would be the same. General formula for energy calculation is given by Equation (6).

$$E = P \times t \ [\text{J}]. \quad (6)$$

Then the required energy for 1st and 3rd interval refers to triangular waveform in Equation (7), while rectangular part (2nd interval) of the waveform is characterized by energy requirement described by Equation (8).

$$E_{triangle} = \frac{1}{2} \times P_{peak} * t = \frac{1}{2} \times 512 \times 1.5 = 384 \text{ J} , \quad (7)$$

$$E_{const} = P_{peak} \times t = 512 \times 3 = 1536 \text{ J} . \quad (8)$$

Total energy of SC module is:

$$E_{SC} = 2 \times E_{triangle} + E_{const} = 2304 \text{ J} . \quad (9)$$

Here it is seen, that considering the parameters defined in Table 1, the energy stored within the supercapacitor module must be at least 2304 J.

C. Corresponding capacity of SC module

Continuing design of SC module, the series - parallel configuration targeting properties of the module (energy and voltage) will be analyzed.

$$C_{SC\_module} = \frac{8}{3} \frac{E_{SC}}{V_{SC\max}^2} = \frac{8 * 2304 \text{ J}}{3 * 32^2} = 6 \text{ F} . \quad (10)$$

According to the current rating of the SC module, the maximum power rating simultaneously with minimal voltage of the module during operation shall be considered. Then for maximal current value, next equation is valid:

$$I_{SC\_moduleMAX} = \frac{P_{peak}}{V_{SC\min}} = \frac{512}{16} = 32 \text{ A} . \quad (11)$$

D. SC module configuration

Important design issue for supercapacitor module configuration is related to power loss minimization, thus minimization of parasitic ESR of SC module. For prototyping purposes, the SC cell from Vishay series MAL2220 is considered as an example for module configuration. Parameters of single SC cell - series MAL 2220 [12].

Table 2, shows the main parameters of one cell from MAL2220 series, while these are key inputs for SC module configuration, i.e. capacitance, ESR and maximum current of one cell.

To achieve the required voltage of the SC module (32V), it is necessary to configure 12 SC cells in series even any of the component from MAL2220 series is considered. On the other side, if required value of the capacity of SC module (6F) must be met, the situation differs for individual single cell components from Table 2. These variations are summarized in Table 3.

From the available combinations of SC modules

***Table 3** Parameters of different SC modules*

Cell capacity [F]	Nr. of parallel cell	Final capacity [F]	ESR [mΩ]	$I_{SCmoduleMAX}$ [A]
5	15	6.25	28	150
7	11	6.41	33.8	110
8	9	6	37.33	108
10	8	6.66	40.5	96
12	6	6	55.2	84
15	5	6.25	55.2	85
20	4	6.66	72	80
25	3	6.25	80	60
30	3	7.5	76	75
35	3	8.75	80	75
40	2	6.66	108	60
50	2	8.33	90	60
60	2	10	78	60

(Table 3), we consider the SC module solution with the lowest ESR to achieve minimal losses (12S15P with total capacity 6.25F and ESR 28mΩ).

Now, knowing the module configuration, the maximum available energy considering capacity of the module should be recalculated Equation (12) together with minimum available energy calculation referring defined minimal voltage value of SC module in Equation (13). It is a starting point for maximum power loss value identification of the SC module operated under power profile defined by Figure 2.

$$E_{SC\_module\_\max} = \frac{1}{2} \times C \times V^2_{SC\max} = \frac{1}{2} \times 6.25 \times \times 32^2 = 3200 \text{ J}, \tag{12}$$

$$E_{SC\_module\_min} = \frac{1}{2} \times C \times V^2_{SCmin} = \frac{1}{2} \times 6.25 \times \times 16^2 = 800 \text{ J}. \tag{13}$$

Because maximum current of SC module will be sourced at minimum voltage value, then considering result from Equation (12) and Equation (9) and by reinterpretation of the capacitor energy formula, the Equation (14) identifies the minimum voltage, which will be reached during module operation under defined power profile.

$$V_{SCmodule_{min}} = \sqrt{\frac{2 \times (E_{SC\_module\_\max} - E_{SC})}{C}} = \sqrt{\frac{2 \times (3200 - 2304)}{6}} = 16.933 \text{ V}. \tag{14}$$

Maximum current of SC module (max power/ voltage of SC module minimal) during operation will be:

$$I_{SC\_module\_MAX} = \frac{P_{peak}}{V_{SC\min}} = \frac{512}{16.933} = 30.24 \text{ A} . \tag{15}$$

The existence of the ESR parameter will reflect within voltage drop of module itself in Equation (17). Calculation of voltage drop considering ESR effect:

$$ESR_{SCmodule} = \frac{Nr_{serial} \times ESR_{1cell}}{Nr_{paralel}} = \frac{12 \times 35\, m\Omega}{15} = 28\, m\Omega, \tag{16}$$

$$\Delta V_{ESR} = ESR_{SCmodule} \times I_{SCmoduleMAX} = 28\, m\Omega \times 30.24 \text{ A} = 0.847 \text{ V}. \tag{17}$$

Now, with regard to evaluated voltage drop reflecting module operation, the minimal voltage on the supercapacitor is given by Equation (18).

$$V_{SCmodule\_\min\_ESR} = V_{SCmodule} \times \Delta V_{ESR} = 16.933 - 0.847 = 16.086\text{V}. \tag{18}$$

Based on this analysis, it is seen, that considering all critical aspects which can affect minimal value of the voltage of SC module, its voltage shall not drop below 16 V.

Finaly power losses can be evaluated using Equation (19).

$$SC_{\text{mod}\_loss} = I^2_{SC\_module\_MAX} \times ESR_{SCmodule} = 30.24^2 \times 0.028 = 25\text{W}. \tag{19}$$

4 Evaluation of the operational region regarding ripple cancelation of interleaved bidirectional converter

As was mentioned within introductory part of this paper, the use of proper topology of bidirectional converter (Figure 4) may affect operational life of supercapacitor.

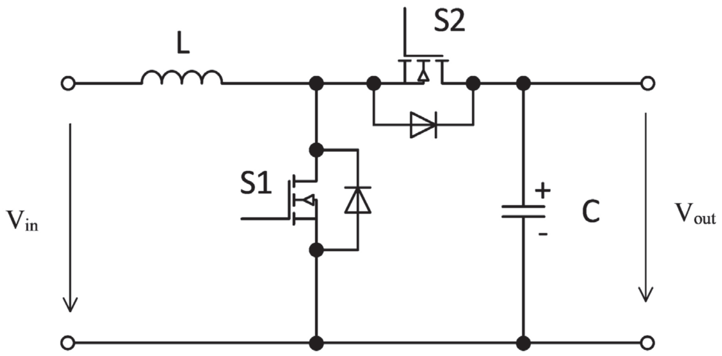


Figure 4 *Principal schematic of bidirectional boost converter*

Table 4 *Defined operational voltage ranges for bidirectional boost converter*

Input/output voltages	Profile 1
$V_{SCmodule}$	32 V - 16.09 V
V_{DCbus}	40 V - 54.4 V

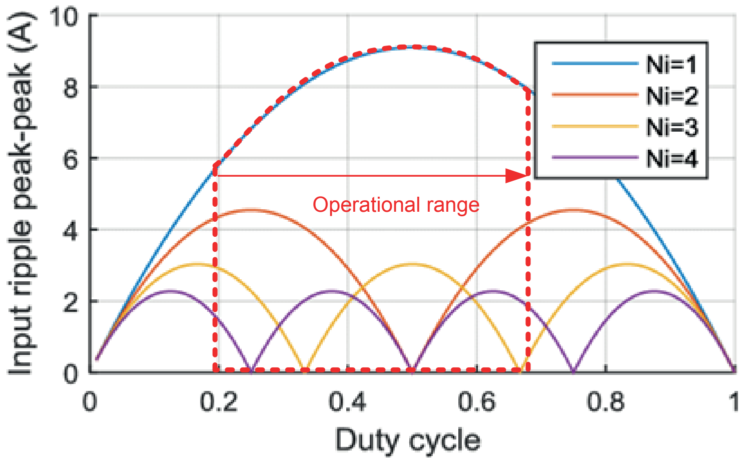


Figure 5 *Operational range of the duty cycle for n-interleaved boost converter*

Interleaved topologies enable to reduce current ripple, which is one of the parameters that markedly affects lifetime of capacitors [13-15]. At this point, the analysis of operational properties of SC module (voltage levels vs. Power demand) will be provided according to duty cycle variation, which results in current ripple cancelation possibilities of interleaved converters (Figure 3). Because DC bus voltage from Figure 1 is higher than voltage of the SC module, the boost topology operation will be considered for bidirectional DC/DC converter.

For the standard boost type of converter (including interleaved), the relationship between input (SC module voltage) to output voltage (DC bus voltage) ratio is defined by duty cycle as follows:

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-D} \rightarrow D = 1 - \frac{V_{in}}{V_{out}}. \quad (20)$$

The operational duty cycle (D) range for boundary states is established. The SC module voltage VSCmodule serves as the boost converter's input voltage, while VDCbus serves as the device's output voltage.

Considering boost mode, the duty cycle can vary within the values, which are affected by the maximum and minimum voltages at the input and output of the converter. For values indicated in Table 4, duty cycle is within interval:

- Low limit of D = from 32 V to 40 V (D = 0.2),
- High limit of D = from 16.09 V to 54.4 V (D = 0.7).

Summarizing achieved results, it is now possible to indicate what would be the ripple current cancelation possibility, when calculated duty cycle values are considered (Figure 5). The results shown below, are clearly indicating that the possibility for SC module operation is possible by using interleaved bidirectional DC-DC converter, while for certain duty cycle range 3-leg and 4-leg represents the best possibility.

5 Conclusion

In this paper, the hybrid energy storage system was introduced as a potential solution for peak power demands. The target application here was focused on possible use of such concept within the electric drive systems for robotic arm motorization. The input to output parameters specification is referring to standard industrial use, while power profile defining the peak demands was defined as well. The main aim of the study was to find optimal solution of design of supercapacitor module, which is responsible for covering energy demands during peak power operation. It refers to proper sizing according to energy, and minimal voltage requirement during discharging process. This is important when we are speaking about effective utilization of supercapacitor module designed from single cells. After energy sizing, the sample part of single cell was defined, while optimal configuration of series and parallel strings have been evaluated according to parasitic resistance reduction. When the proper configuration was selected, the analysis on the operational properties was performed, while power loss generation was calculated as well. Finally, in order to present possible solution to optimize operational performance of the SC module targeting improvements related to operational life, interleaved solution of bidirectional converter have been mentioned in regard to the current ripple reduction on SC module. The analysis of duty cycle operation range was performed and ripple current reduction was represented by the operational characteristics of interleaved bidirectional converters. The study shows several outcomes, i.e. it represents the idea of optimal SC module sizing, while the possibility for lifetime optimization is given as well through duty cycle range identification.

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Conflicts of 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.

References

[1] SAHIN, M. E., BLAABJERG, F., SANGWONGWANICH, A. A Comprehensive review on supercapacitor applications and developments. *Energies* [online]. 2022, **15**, 674. eISSN 1996-1073. Available from: https://doi.org/10.3390/en15030674

[2] SLADECEK, V., KUCHAR, M., PALACKY, P. LiFePo battery charger with controlled rectifier. In: 18th International Scientific Conference on Electric Power Engineering EPE 2017: proceedings [online]. IEEE. 2017. eISBN 978-1-5090-6406-9. Available from: https://doi.org/10.1109/EPE.2017.7967351

[3] SMITH, S. C., SEN, P. K., KROPOSKI, B. Advancement of energy storage devices and applications in electrical power systems. In: 2008 IEEE Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century: proceedings [online]. IEEE. 2008. ISSN 1932-5517, ISBN 978-1-4244-1905-0, p. 1-8. Available from: https://doi.org/10.1109/PES.2008.4596436

[4] LIU, S., WEI, L., WANG, H. Review on the reliability of supercapacitors in energy storage applications. *Applied Energy* [online]. 2020, **278**, 115436. ISSN 0306-2619, eISSN 1872-9118. Available from: https://doi.org/10.1016/j.apenergy.2020.115436

[5] SLADECEK, V., NEBORAK, I., PALACKY, P. Optimisation of electric drive setting in battery-powered locomotive. In: 15th International Scientific Conference on Electric Power Engineering EPE 2014: proceedings [online]. IEEE. 2014. eISBN 978-1-4799-3807-0. Available from: https://doi.org/10.1109/EPE.2014.6839448

[6] PIERSON, J. R., JOHNSON, R. T. The battery designer's challenge - satisfying the ever-increasing demands of vehicle electrical systems. *Journal of Power Sources* [online]. 1991, **33**(1-4), p. 309-318. ISSN 0378-7753, eISSN 1873-2755. Available from: https://doi.org/10.1016/0378-7753(91)85069-9

[7] JING, W., LAI, C.H., WONG, W. S. H., WONG, M. L. D. Battery-supercapacitor hybrid energy storage system in stand-alone DC microgrids: a review. *IET Renewable Power Generation* [online]. 2017, **11**(4), p. 461-469. eISSN 1752-1424. Available from: https://doi.org/10.1049/iet-rpg.2016.0500

[8] SIMCAK, M., SPANIK, P. Comparison of control methods for power stage of battery management systems with 4 cells. In: 21st International Scientific Conference on Electric Power Engineering EPE 2020: proceedings[online]. IEEE. 2020. eISBN 978-1-7281-9479-0. Available from: https://doi.org/10.1109/EPE51172.2020.9269209

[9] CAMARA, M. B., GUALOUS, H., GUSTIN, F., BERTHON, A. Design and new control of DC/DC converters to share energy between supercapacitors and batteries in hybrid vehicles. *IEEE Transactions on Vehicular*

Technology [online]. 2008, **57**(5), p. 2721-2735. ISSN 0018-9545, eISSN 1939-9359. Available from: https://doi.org/10.1109/TVT.2008.915491

[10] VASTA, E., LUCIFORA, A., TORNELLO, L. D., FOTI, S., CACCIATO, M., PERNACI, CH., DE CARO, S., SCELBA, G. State of charge estimation of battery energy storage systems in low voltage electric drive applications for hybrid and electric vehicles. In: 2022 IEEE Energy Conversion Congress and Exposition ECCE: proceedings [online]. IEEE. 2022. eISBN 978-1-7281-9387-8, p. 1-7. Available from: https://doi.org/10.1109/ECCE50734.2022.9947619

[11] VASTA, E., GRECO, D., SCELBA, G., CACCIATO, M., DE BENEDETTI, M. M., LANUZZA, L., EBERHARDT, O., DUGO, D., SAMINARA, G. Design of a battery testing system with software/hardware interface. In: 2022 ELEKTRO: proceedings [online]. IEEE. 2022. eISBN 978-1-6654-6726-1, p. 1-6. Available from: https://doi.org/10.1109/ELEKTRO53996.2022.9803500

[12] Electrical double layer energy storage capacitors power and energy versions - VISHAY, 220 EDLC ENYCAP [online]. Available from: https://www.mouser.com/datasheet/2/427/220edlc_enycap-1762440.pdf

[13] TURZYNSKI, M., BACHMAN, S., JASINSKI, M., PIASECKI, S., RYŁKO, M., CHIU, H.-J., KUO, S.-H., CHANG, Y.-C. Analytical estimation of power losses in a dual active bridge converter controlled with a single-phase shift switching scheme. *Energies* [online]. 2022, **15**, 8262. eISSN 1996-1073. Available from: https://doi.org/10.3390/en15218262

[14] TURZYNSKI, M., CHRZAN, P. J., KOLINCIO, M., BURKIEWICZ, S. Quasi-resonant DC-link voltage inverter with enhanced zero-voltage switching control. In: 2017 19th European Conference on Power Electronics and Applications EPE'17 ECCE Europe: proceedings [online]. IEEE. 2017. eISBN 978-90-75815-27-6, p. P.1-P.8. Available from: https://doi.org/10.23919/EPE17ECCEEurope.2017.8099289

[15] KINDL, V., ZAVREL, M. ,TYRPEKL, M., SIKA, J. Analysis of coupling elements for wireless power transfer with primary side compensation. In: 2022 20th International Conference on Mechatronics - Mechatronika ME: proceedings [online]. IEEE. 2022. eISBN 978-1-6654-1040-3, p. 1-7. Available from: https://doi.org/10.1109/ME54704.2022.9983352

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THE ARCHITECTURE OF THE ON-BOARD POWER SYSTEM OF A MORE ELECTRIC AIRCRAFT

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Resume

Currently, various systems and devices for on-board equipment of modern aircraft are undergoing extensive transformations, particularly in terms of powering electrified aircraft. The main goal of authors of this article was to conduct an analysis of the selected electrified aircraft architecture in the scope of the HVDC system, among architectures in the 540 V voltage range (± 270 VDC) and 350 V, creating a mathematical model and making the necessary tests and simulation studies on the developed model. In the above aspect, article presents selected test results of a proposed system consisting of aircraft generators with changing speeds, which power the bidirectional transistor converters operating in parallel. On the other hand, the energy, generated by generators equipped with a rectifier systems feeds a 0.4/15 kV booster transformer operating at idle. In the final part of the work, based on simulation studies (analysis, mathematical model, tests), important insights are presented and practical conclusions are formulated.

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1 Introduction

Nowadays, modern planes are primarily designed in a context that takes into account the longest possible crossing of distances between various points located on the globe, hence in recent years a new trend has appeared to increase the efficiency and effectiveness of on-board electric systems of the most advanced aircrafts.

Additionally, taking into account the number of innovative avionics systems, including radio receivers on board of a modern aircraft, there was a need to increase the power of the classic electrical network of the aircraft, which in turn resulted in significant energy consumption, including in particular in the field of more/all electric aircraft MEA/AEA (More/All Electric Aircraft). Taking into account the requirements for the production of more useful power by on-board sources of the aircraft's electrical network, the standard of the more electric aircraft MEA/AEA was developed, which is now being implemented to an increasing number of constructed aircrafts [1-3].

In the design process, the main factor determining the efficiency of the developed standard was dictated primarily by improving the operational reliability of on-board electrical equipment, which in turn led to increased reliability of the entire aircraft. In conclusion, the concept of MEA has proven its worth in the following factors: efficiency of the entire aircraft, increase in its reliability and reduction in fuel consumption, and thus reduced the operating costs, as well [4-6].

In addition, the flexibility and economy of the aircraft have increased. The main power components that significantly affect the operation of the electricity network in accordance with the MEA trend are on-board sources in the form of synchronous permanent magnet generators PMSG (Permanent Magnets Synchronous Generator), switchable reluctance starters/generators SR S/G (Synchronous Reluctance Starter/Generator) by using a starter/generator unit, powered by voltage of 270 VDC and AS S/G (Alternating Synchronous Starter/Generator).

The above on-board power sources are the key components of an autonomous system for generation, division and distribution of electricity. The complete electricity generating system, in accordance with the concept of a more electric aircraft, consists of: constant speed drive CSD (Constant Speed Drive), integrated drive generator IDG (Integrated Drive Generator) and a component responsible for producing constant rotational speed at variable frequency VSCF (Variable Speed Constant Frequency). Analyzing individual power generation systems, it should be noted that the VSCF system is characterized by greater efficiency compared to the CSD/IDG system, because the subunits associated with the VSCF system can be deployed in various places on the aircraft as opposed to the CSD/IDG system, where its mechanical elements, including the electro-hydraulic transmission must be close to the engine [7-8].

In addition, in the event of a power system failure, replacement or repair in the case of the VSCF system is problem-free, which translates into proper maintenance of the electrical network operation during the flight. The electrical network of the aircraft requires the supply of DC and alternating AC; therefore, it is necessary to use devices that convert AC voltage and AC current into DC values. Usually, passive rectifiers, made of semiconductor diodes or active switching elements, such as thyristors, are most often used. Both elements generate additional harmonic signals, which reduce the efficiency of the generator. Undesired signals, in the form of harmonics, can be eliminated by using the passive filters or active filters [9-10].

This paper presents a complete simulation model, mapping the actual on-board electrical network model in the field of power electronics systems PES (Power Electronics Systems) meeting the requirements of the more electric aircraft (MEA/AEA) concept.

The simulation model was created for advanced aircraft power supply systems in the scope of on-board power source (generator), performing work based on the method of creating rotational speed and variable frequency of the VSCF system. The output power of the on-board electricity network is 90 kVA per transmission channel of the power supply network (in aircraft compliant with the MEA there are two) [11-12].

In the developed model, it was assumed that experimental tests will be carried out for various combinations of end devices (the so-called loads), alternating AC and direct DC. In the case of avionic systems supplied with DC current, it should be remembered to maintain a constant value of useful power and continuous maintenance of DC current.

The undesirable harmonic signals and noise appearing in the system were eliminated by using a high-pass filter HPF (High-pass Filter), which was placed behind the generator system [13-15].

2 Analysis and mathematical model of selected components of the on-board power system architecture according to the concept of a more electric aircraft

By entering the analysis process and creating a mathematical description (model) of selected key components of the on-board autonomous power system, in accordance with the MEA trend, it should be noted that the basic elements of the considered system are the generator or integrated starter/generator unit in the scope of the EPS system and alternating current converter to direct current AC/DC for the PES system.

In addition, in the case of analyzing on-board electro-energetic networks of modern aircraft, two types of AC networks should be considered. The first of these is a network based on an alternating current AC generator with a fixed (stabilized) frequency of 400 Hz (in the case of conventional aircraft) or on an integrated unit in the form of an AC starter/generator with variable (non-stabilized frequency) of 360-900 Hz (in the case of electrified aircraft), which changes at a speed proportional to the angular velocity of the main engine shaft.

Additionally, it should be added that the above type of electro-energetic power network is usually based on a 3-phase 200 V network (classic civil and military aircraft) and a 3-phase 115 V network (Airbus) or 230 V network (Boeing), for advanced civil and military aircraft compatible with the MEA concept.

The second type of network is the electro-energetic power network based on electromechanical or electronic converters requiring, due to their design solution, high frequency and voltage [16-18].

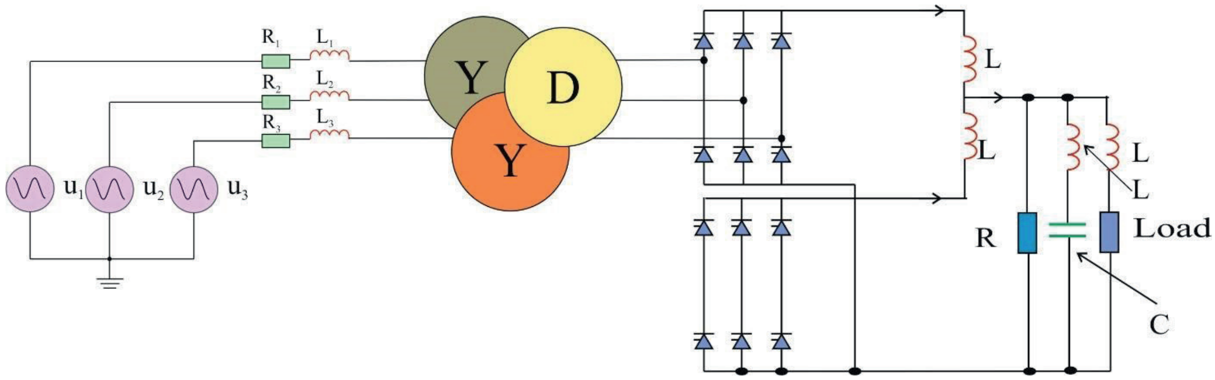

***Figure 1** A block diagram of a TRU system using a 12-pulse rectifier*

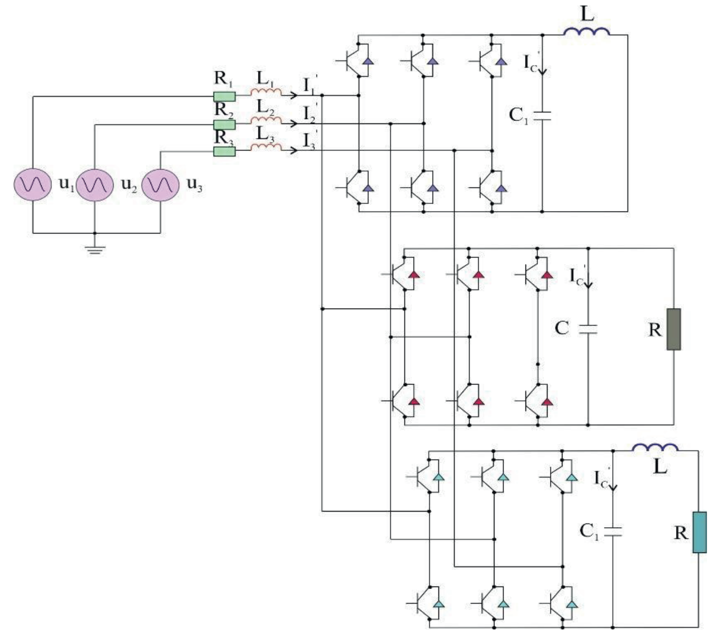

Figure 2 *Method of controlling the DC voltage for different types of loads*

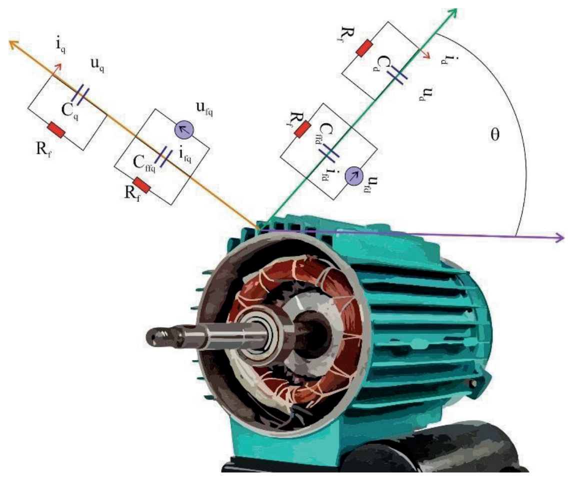

Figure 3 *Block diagram of the generator with an additional electrical circuit*

2.1 Analysis of on-board power sources in accordance with the MEA/AEA concept

The complete airplane power system includes an internal combustion engine, an electric starter and various types of generators, which are treated as integrated drive units. In addition to the specified components, responsible for the process of electricity generation and conversion, there is also a rectifier unit, useful power controllers, pneumatic actuators, anti-icing systems and various elements of systems and subsystems, having an indirect impact on the operation of the aircraft's on-board electrical network.

The general block diagram of the on-board electricity network in the scope of the PES system, compatible with the MEA concept, is shown in the Figure 1.

Subsequently in the analysis, it should be noted that due to switching on the start-up system, the AC voltage and current generation process is performed, which are then converted into DC values. This system is characterized by maintaining the final power at the output of the generating system. In the next range, an electric engine, operating in the variable rotational speed range provides the required value of the input power to the generator.

This operation is carried out as a result of maintaining a constant value of the rotational speed at the output of the generator. The output voltage, obtained at the PMSG synchronous generator output, is shaped by a frequency in the range from 400 to 800 Hz.

The main components, responsible for implementation of the AC conversion operations into DC current, are multi-pulse rectifier circuits in the form of 6-, 12- and 24-pulse rectifiers. The simulation tests used a rectifier built of 12 semiconductor diodes. In total, all the components in the system form transformer-rectifier devices in the form of TRU (Transformer Rectifier Unit), the general diagram of which for different types of loads is shown in Figure 2 [19-22].

The TRU system is characterized by a high power factor, with minimal distortion of harmonic voltage and current signals THD (Total Harmonic Distortion) at 13%. As a result, power losses occurring in the rectifier are negligible. Furthermore, the rectifier circuit is supplied through a three-phase transformer connected in the star-star-delta *Y/Y/D* configuration (Figure 1).

The method of connecting the transformer ensures supplying the voltage shifted in phase by an angle of 30° for the 12-pulse rectifier. The output voltage on the TRU rectifier (270 VDC) is regulated by the generator current and the electromagnetic field generated by the generator by means of the feedback proportional controller PI (Proportional-Integral Controller).

The capacitor, present in the rectifier system, serves to smooth the DC end voltage. All the types of loads supplied with DC current are connected to an adjustable 270 VDC power bus through special DC/DC converters, which is illustrated in the Figure 3.

In simulation tests, it was assumed that the maximum DC load value is 5.6 [kW], and the voltage transfer process is controlled by the PI controller. All the DC/DC converters in the system are of a conventional type, which are based on IGBT (Insulated Gate Bipolar Transistor) elements [23-26].

2.2 A mathematical model of AC/DC conversion for different positions of permanent magnets of an electric machine

The structure of the on-board autonomous power system architecture, compatible with the MEA concept in the mathematical modelling process, was considered in the form of a simplified model, which includes key components responsible for generating the on-board electricity, i.e. a PMSG (Permanent Magnet Synchronous Generator) and a rectifier system responsible for the conversion process of alternating voltage AC to direct DC, which in the aviation application is transformer-rectifier unit TRU (Transformer Rectifier Unit).

The basic component, subjected to the analysis, is the arrangement and position of the rotor in the stator at the moment of shaping the magnetic field. The stator circuits are considered to be a system of two axes through which electric current flows. The components responsible for generating the magnetic field were modelled by appropriate connection of resistive and capacitive elements. Thanks to this approach, the proposed solution significantly improves the efficiency of the entire system, control of the useful and reactive power balance, as well as effectively performs the power division operation, depending on the current load on board of the modern aircraft.

In addition, a system for dividing and distributing electricity, together with AC/DC converters, allows more freedom in the field of more efficient power control in AC and DC circuits. This process is expressed based on the equations presented later in this article. The presented model takes into account the direct relationship between the sides of AC and DC, responsible for AC voltage and AC power generation, as well as the DC voltage and current [27-28].

In the mathematical analysis process, the assumption was made that the electric generator would be treated as a synchronous machine with permanent magnets of an arcuate shape. This type of construction is referred to as SMPMSG (Surface Mounted Permanent Magnet Synchronous Generator). The analyzed generator uses permanent magnets with rare earth dopants, NdFeB type (very strong neodymium magnets) [29-30].

These magnets are mounted on the inner side of the rotor yoke, which simultaneously acts as the hull of an external generator. The number of magnetic poles of the generator was determined in the design process in accordance with the mathematical expression $2p = 40$. In addition, in order to further simplify the design of the synchronous generator, it was assumed that in the stator winding the number of grooves per pole and phase was equal to $q = 1$. The nominal frequency of the generator is $f_N = 400$ Hz, as a typical frequency in aerospace applications.

The rotor is supplied with the DC voltage, which generates a specific electric field, responsible for induction of electric charge in the circuit. The intensity of the electric field, and the rotational speed occurring in the electrical machine PMSM (Permanent Magnet Synchronous Machine), are expressed in terms of the capacitance of the capacitor in the DC circuit.

The following figure shows a block diagram of the analyzed synchronous generator with a defined electric circuit based on permanent magnets. For the electric circuit, the current equation in the synchronous generator stator circuit can be represented as:

$$\begin{aligned} i_d &= \frac{dQ_d}{dt} - Q_q\frac{d\theta}{dt} - \frac{u_d}{R}, \\ i_q &= \frac{dQ_q}{dt} - Q_d\frac{d\theta}{dt} - \frac{u_q}{R}, \\ i_0 &= \frac{dQ_0}{dt} - \frac{u_d}{R}, \end{aligned} \tag{1}$$

where: i_d, i_q, i_0 are the current in the axes d, q and 0, respectively, Qd, Qq are the electric charge present in the electric circuit in the axes d, q and 0, respectively and R is the resistance included in the generator electrical circuit.

In addition, the parameters u_d, u_q, u_0- determine the voltage values in the stator circuit. The sizes with the lower index f refer to the electric field appearing in the analyzed system. The electric charge flowing in the electric circuit of the synchronous generator at any time is determined b:

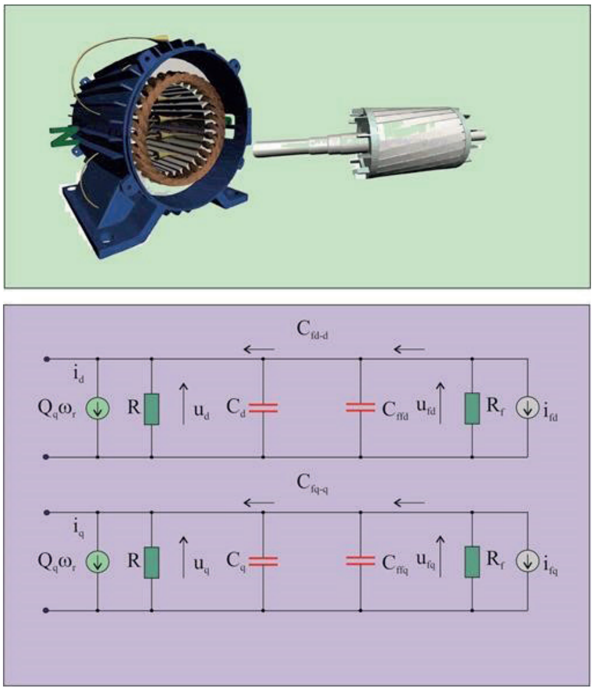

Figure 4 *Substitute diagram of electric circuit of the PMSG synchronous generator*

$$\begin{aligned}
&Q_d = -C_d u_d + C_{fd-d} u_{fd} i_d = \\
&= \frac{dQ_d}{dt} - Q_q \frac{d\theta}{dt} - \frac{u_d}{R}, \\
&Q_d = -C_d u_d + C_{fd-d} u_{fd} Q_q = -C_q u_q + \\
&+ C_{fq-q} u_{fq} Q_0 = -C_0 u_0, \\
&Q_q = -C_q u_q + C_{fq-q} u_{fq} i_q = \\
&= \frac{dQ_q}{dt} - Q_q \frac{d\theta}{dt} - \frac{u_q}{R}, \\
&Q_0 = -C_0 u_0 i_0 = \frac{dQ_0}{dt} - \frac{u_d}{R},
\end{aligned} \tag{2}$$

where: C_{fd-d} and C_{fq-q} are equivalent capacities between the rotor and the stator in the d–q axes, respectively, in turn, by $C_{fq-q}v_{fq}$ is the value of the electric charge transferred from the rotor to the stator was defined.

Next, the current equations for the rotor for the d–q axis were determined as [31-33]:

$$\begin{aligned}
&i_{fd} = \frac{dQ_{fd}}{dt} - \frac{u_{fd}}{R_f}, \\
&i_{fq} = \frac{dQ_{fq}}{dt} - \frac{u_{fq}}{R_f},
\end{aligned} \tag{3}$$

where: quantities Q_{fd} and Q_{fq} - were determined by the following relationships:

$$\begin{aligned}
&Q_{fd} = C_{ffd} u_{fd} - \frac{3}{2} C_{fd-d} u_d, \\
&Q_{fq} = C_{ffq} u_{fq} - \frac{3}{2} C_{fq-q} u_q,
\end{aligned} \tag{4}$$

where: C_{ffd}, C_{ffq} describe the rotor capacities in the d–q axes.

In the next stage of mathematical considerations, an attempt was made to normalize variable quantities that characterize the work of a synchronous generator, such as: frequency of voltage operation and current.

The mentioned parameters were related to the stator transformation relative to the d–q axes during the synchronous machine operation. The complete equations, describing the physical phenomena occurring during the operation of the synchronous generator, the block diagram of which is depicted in the Figure 4, are as follows:

$$\begin{aligned}
&i_d = \frac{dQ_d}{dt} - Q_q \omega - \frac{u_d}{R}, \\
&i_q = \frac{dQ_q}{dt} - Q_d \omega - \frac{u_q}{R}, \\
&i_0 = \frac{dQ_0}{dt} - \frac{u_0}{R}, \\
&i_{fd} = \frac{dQ_{fd}}{dt} + \frac{u_{fd}}{R}, \\
&i_{fq} = \frac{dQ_{fq}}{dt} + \frac{u_{fq}}{R_f},
\end{aligned} \tag{5}$$

where:

$$\begin{aligned}
&Q_d = -C_d u_d + C_{fd-d} u_{fd}, \\
&Q_q = -C_q u_q + C_{fq-q} u_{fq}, \\
&Q_0 = -C_0 u_0, \\
&Qf_d = C_{ffd} u_{fd} + C_{fd-d} u_d, \\
&Qf_q = C_{ffq} u_{fq} + C_{fq-q} u_q,.
\end{aligned} \tag{6}$$

Simplified substitute scheme of a synchronous generator is shown in Figure 4 with an additional circuit improving the control of the power generated by the apparatus, using for this purpose the phase locked loop PLL (Phase Locked Loop).

An arc-shaped permanent magnet generator, placed in the stator, was modelled in the Matlab/Simulink programming environment and a series of simulations were performed, out of which one of the most optimal solutions was chosen for the on-board electrical network of a more electric aircraft in accordance with the MEA concept [34-35].

3 The results of simulation tests of the proposed architecture of the on-board power system according to the concept of MEA/AEA

The correctness of the constructed model has been verified by comparing the simulation results to the mathematical model presented in the previous subsection. Analogical symmetrical disturbances were introduced in individual harmonics of voltages and currents in both models and the time waveforms were compared.

Figure 5 shows the waveforms for a three-phase short circuit in point 2.1 (Figure 1), and Figure 6 for a step change of the voltage setpoint. The waveforms for both models show good compatibility. Models of voltage and current regulation systems, for various generators, are presented in publications [36-38].

In the next stage of testing, the analysis process was carried out in terms of the key characteristics and the effect of frequency variation on the main parameters and performance of an on-board power generation source, such as an AC generator, and an analysis of the effect of frequency variation on behaviour and performance of the generator was carried out (Figures 7-18).

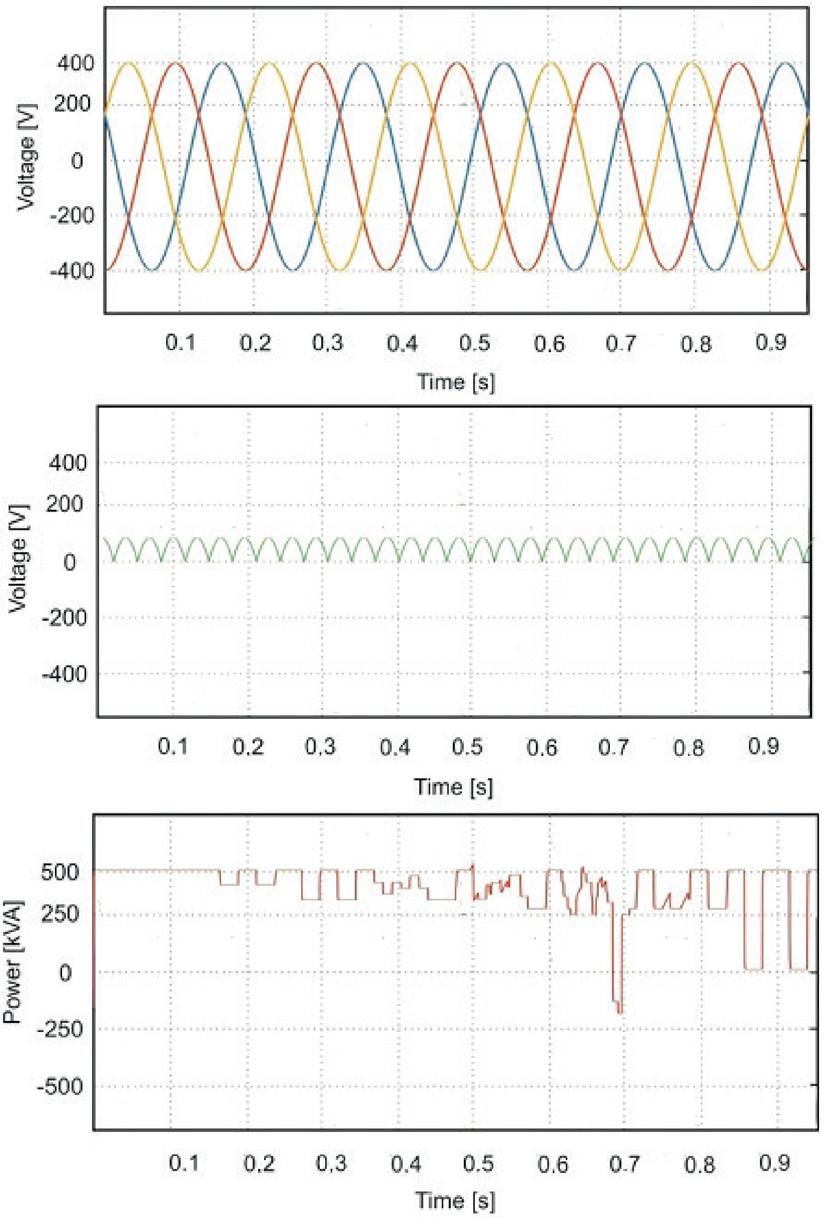

Figure 5 *Waveforms of voltage components and power of an on-board aircraft power source for a coil load and a resistor in accordance with the concept of MEA*

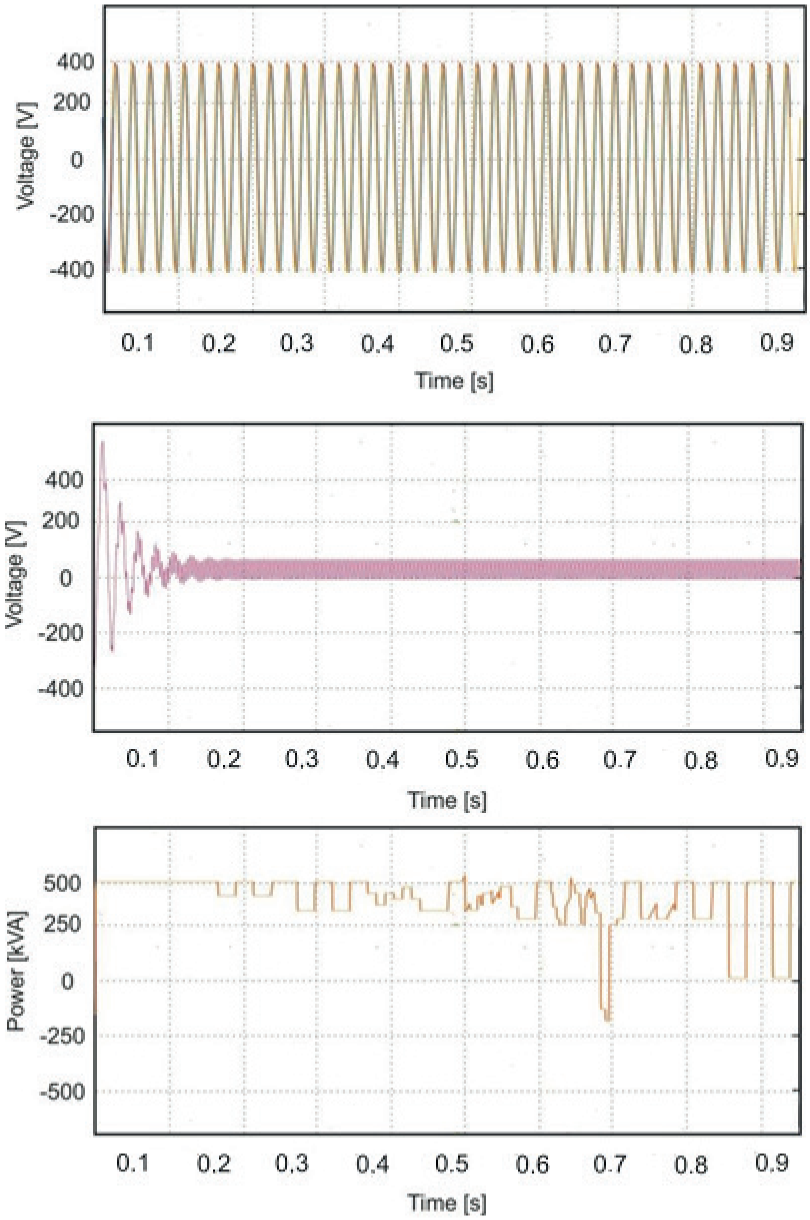

Figure 6 *Waveforms of voltage and power components of an on-board aircraft power source for load of coil, resistor and capacitor in accordance with the MEA concept*

From the below waveforms of Figures 7-12 (for 400 Hz frequency) and Figures 13-18 (for 800 Hz frequency), respectively, it can be seen that the tested generator in the AAES system of an electrified aircraft, according to the MEA trend, during the single operation with a linear receiver R, for a rotor speed of 1000 rpm, gives off electrical power P = 20 kW at the phase-to-phase voltage V_{LL} and current I = 5.1 A. It should be noted that such conditions would occur, among others, in the case of direct connection of the generator with operating avionic equipment of a modern aircraft.

In many practical applications, the synchronous generator is connected to a 3-phase 12-pulse rectifier, which can be the case, for example, when using the generator to power the DC loads, charge batteries or when operating the generator with a rigid network via a frequency converter. It should be noted here that the 12-pulse rectifier is a resistive load, however, non-linear in nature, in turn, both the current and voltage at the output terminals of the generator operating with a diode rectifier are significantly distorted, as can be observed in selected graphs (Figures 11-13 and Figure 15).

In addition, due to additional harmonics in the spatial-temporal distribution of induction in the gap and additional harmonics in the current, in a generator operating with a rectifier there are additional losses in the magnetic circuit and increased losses in the windings, which results in significantly lower efficiency of the generator and higher temperature rises in the electric machine compared to operation on a resistive linear load with the same input power.

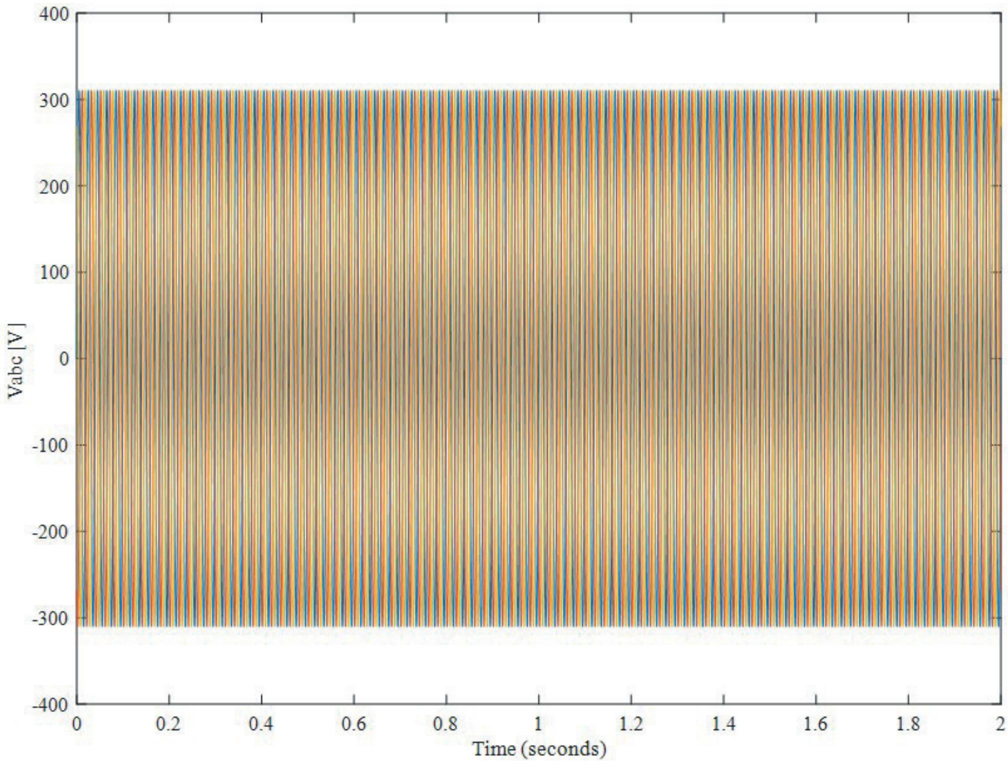

Figure 7 *Voltage waveforms of the 3-phase on-board aircraft power source according to the MEA concept*

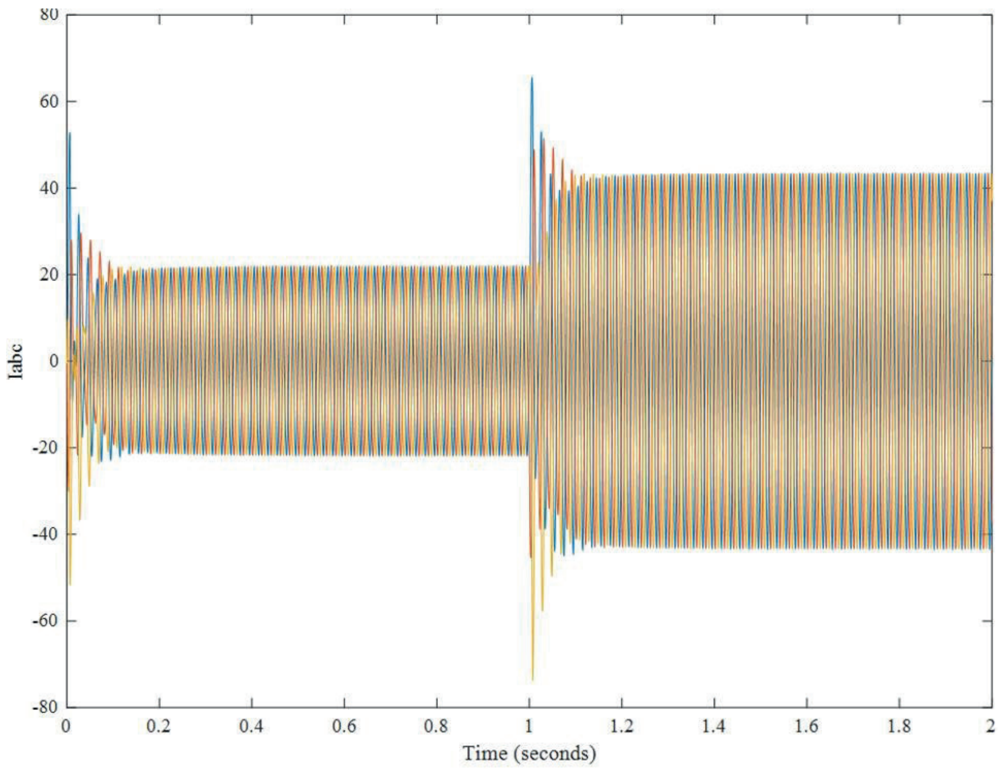

Figure 8 *Current waveforms of the 3-phase on-board aircraft power source according t o the MEA concept*

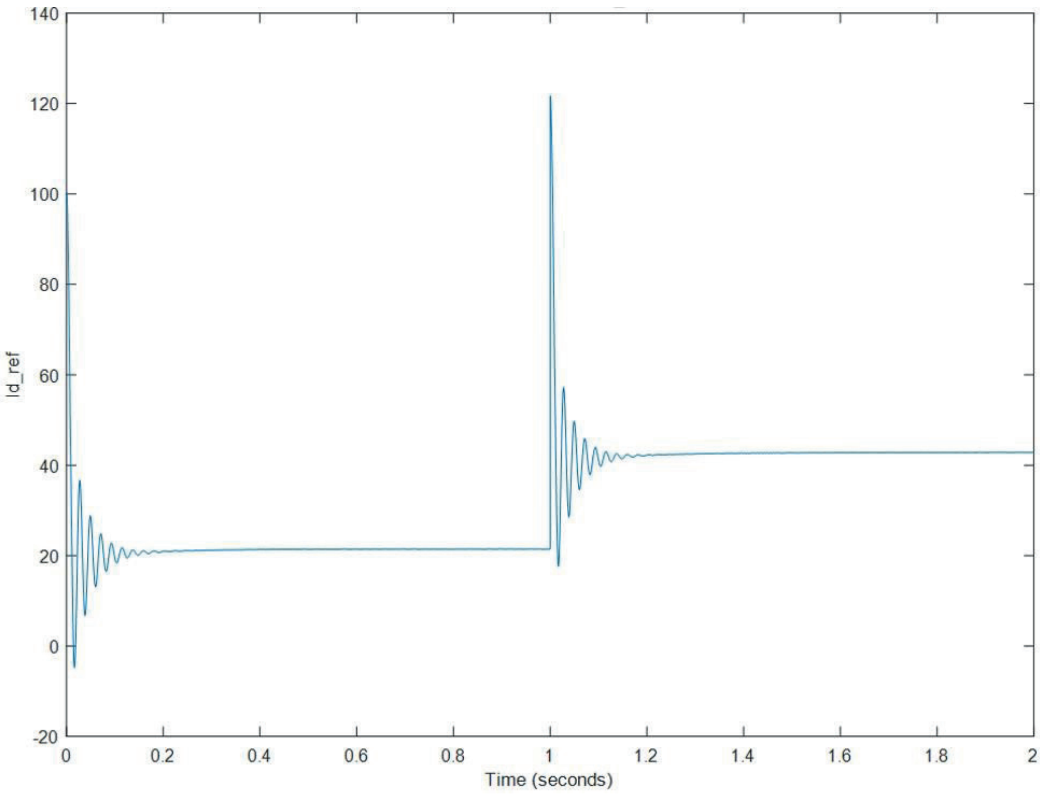

Figure 9 *Current waveform of the 3-phase AC generator in the d–axis of rotor position*

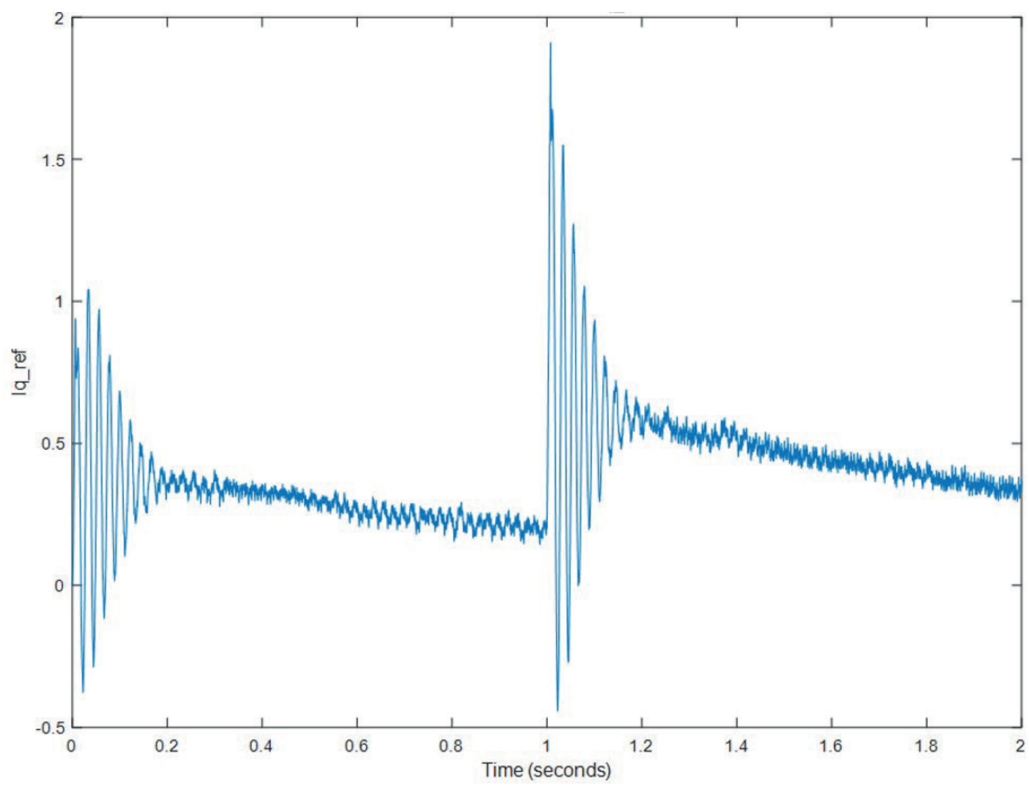

Figure 10 *Current waveform of the 3-phase AC generator in the q–axis of rotor position*

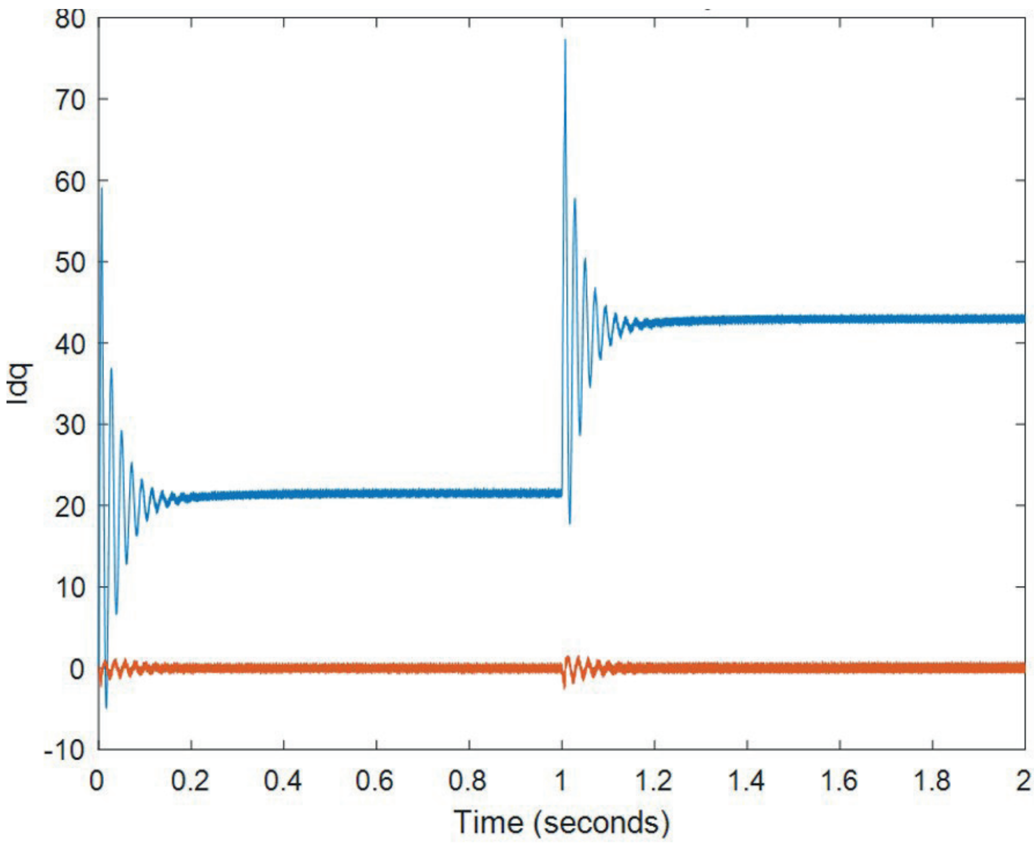

Figure 11 *Current waveform of the 3-phase AC generator in the d–q axis of rotor position*

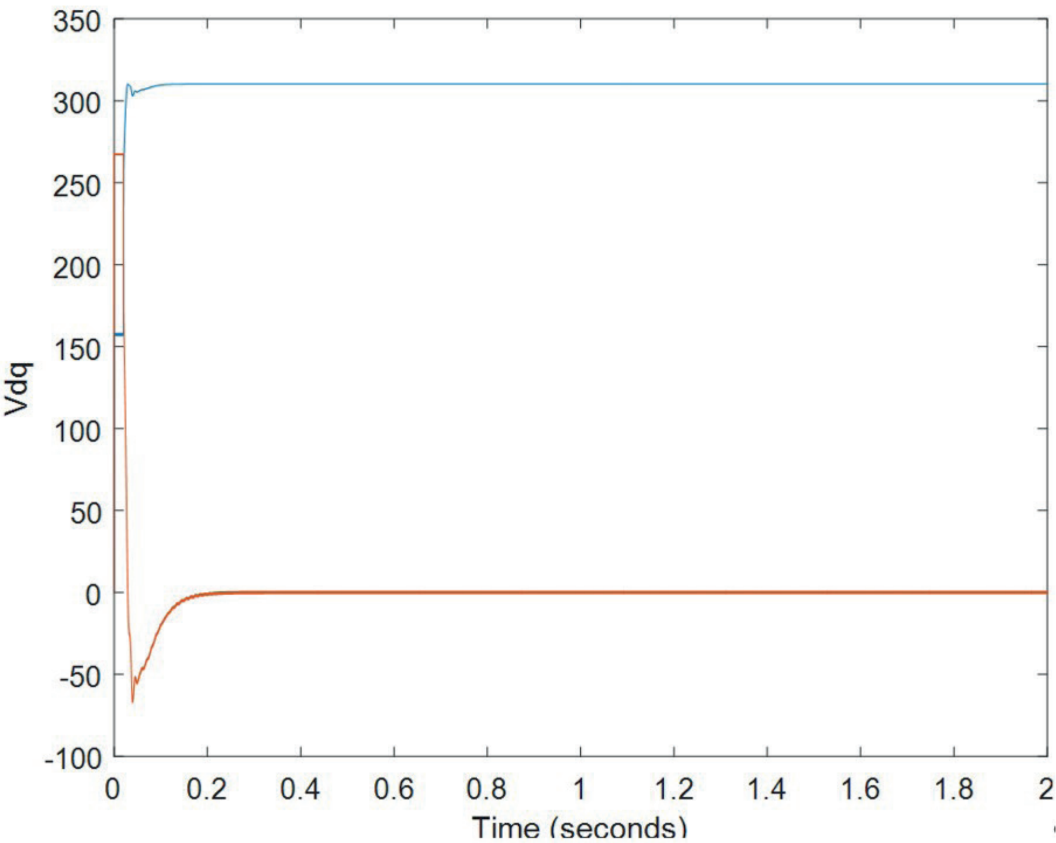

Figure 12 *Voltage waveform of the 3-phase generator in the d–q axis of rotor position*

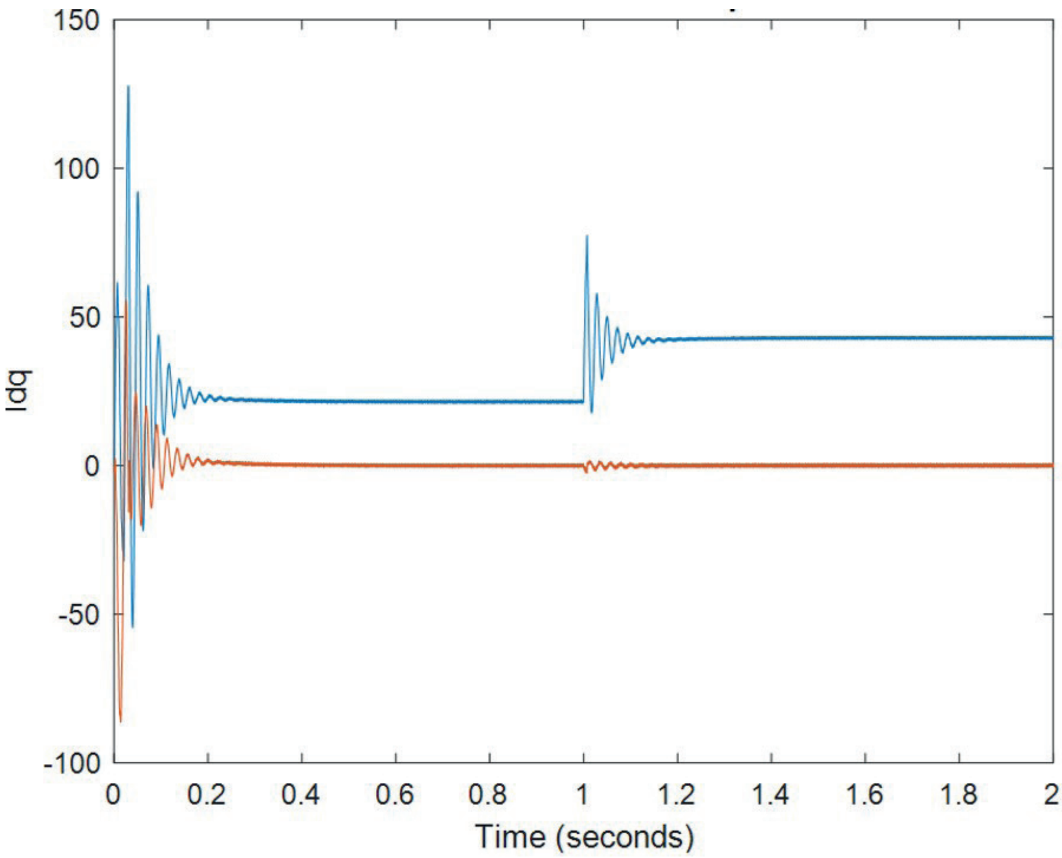

Figure 13 *Current waveform of the 3-phase generator in the d–q axis of rotor position*

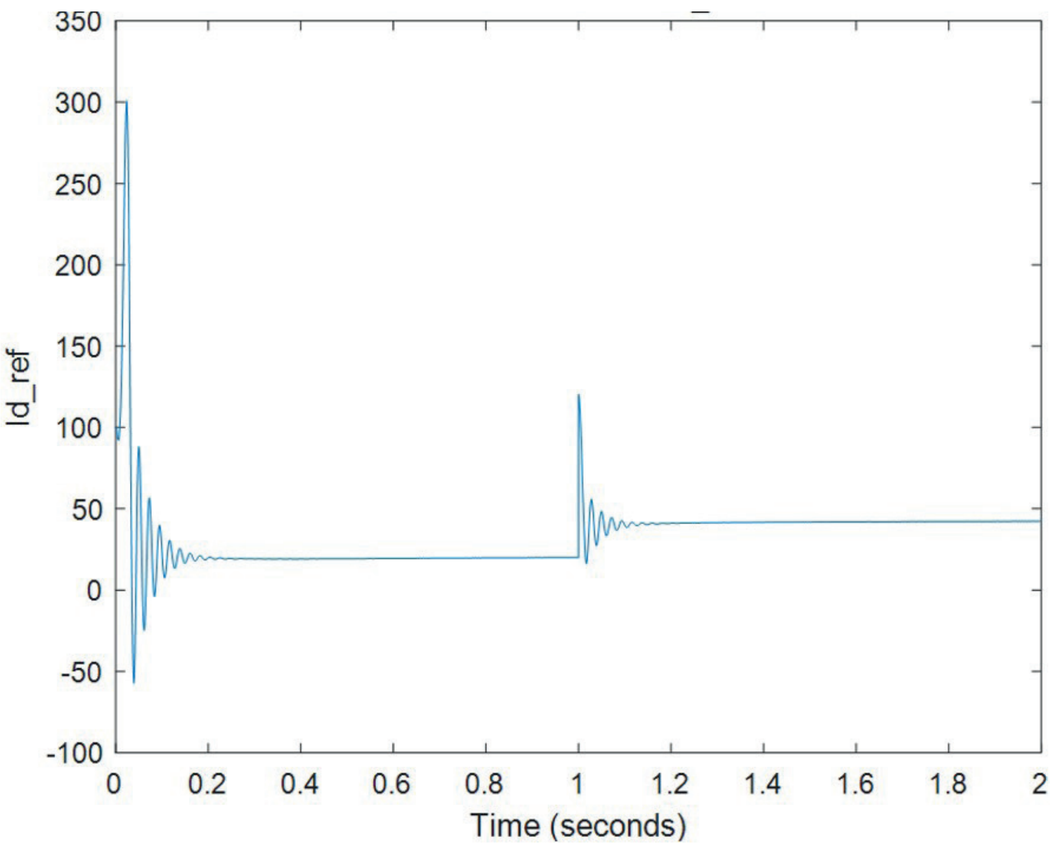

Figure 14 *Current waveform of the 3-phase AC generator in the d–axis of rotor position*

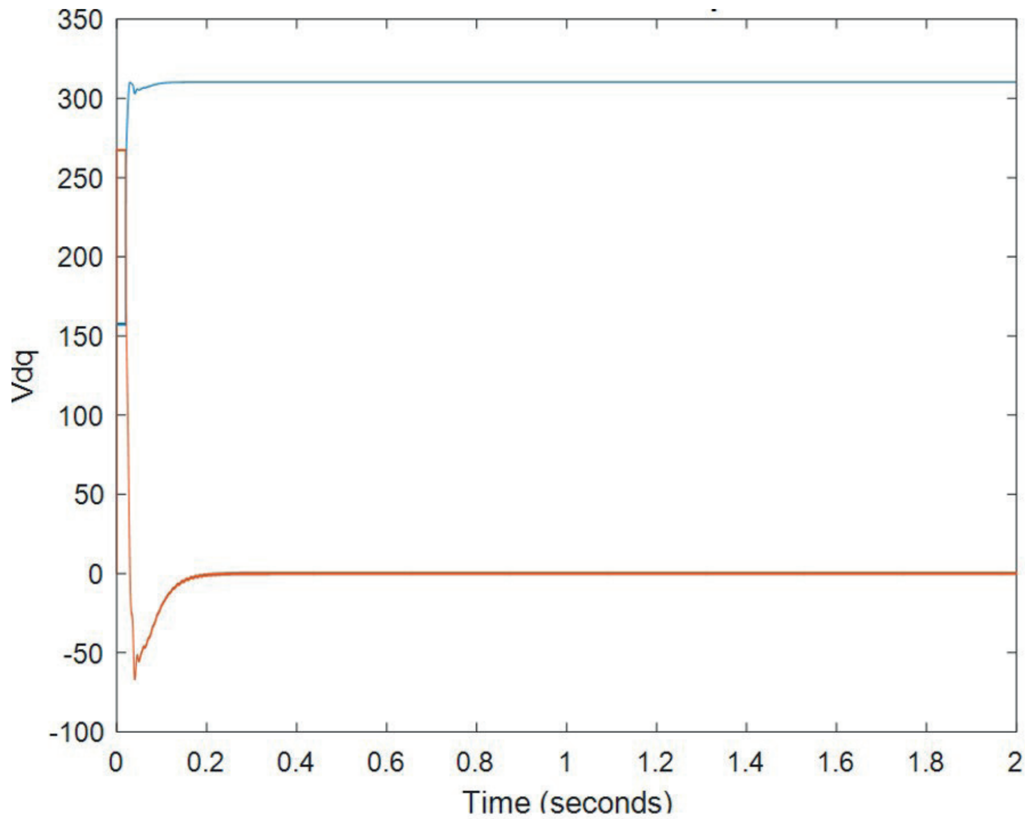

Figure 15 *Voltage waveform of the 3-phase AC generator in the d–q axis of rotor position*

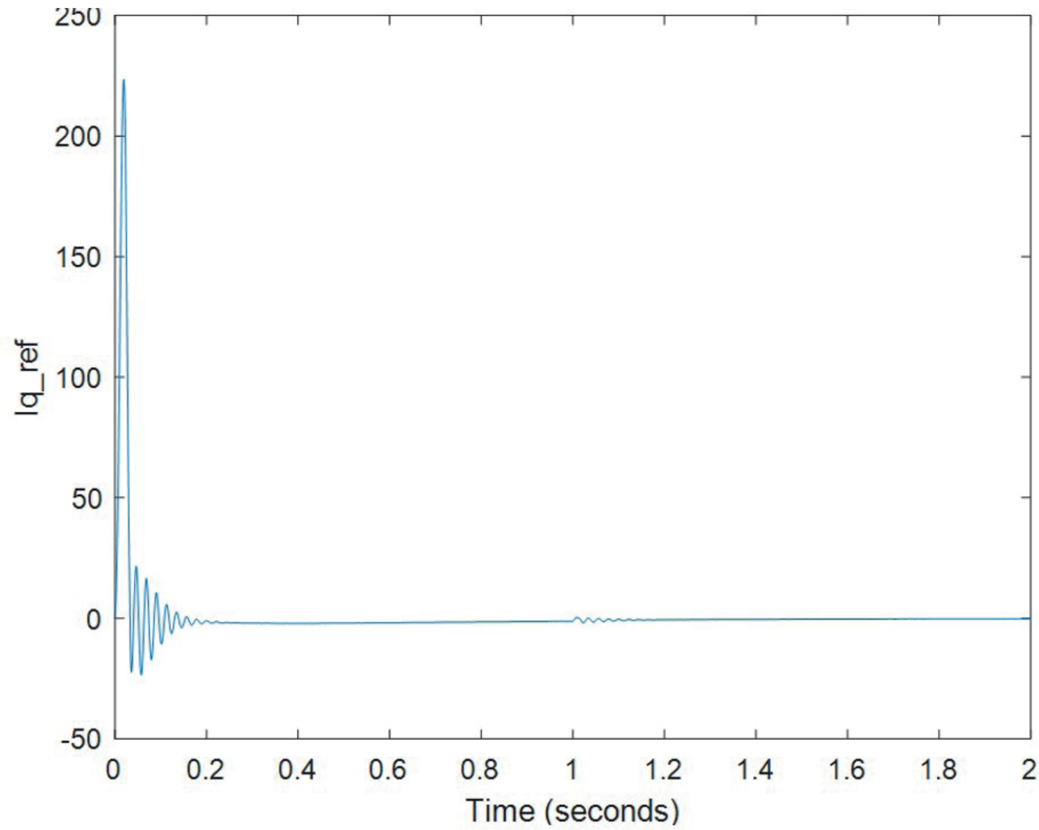

Figure 16 *Current waveform of the 3-phase AC generator in the q–axis of rotor position*

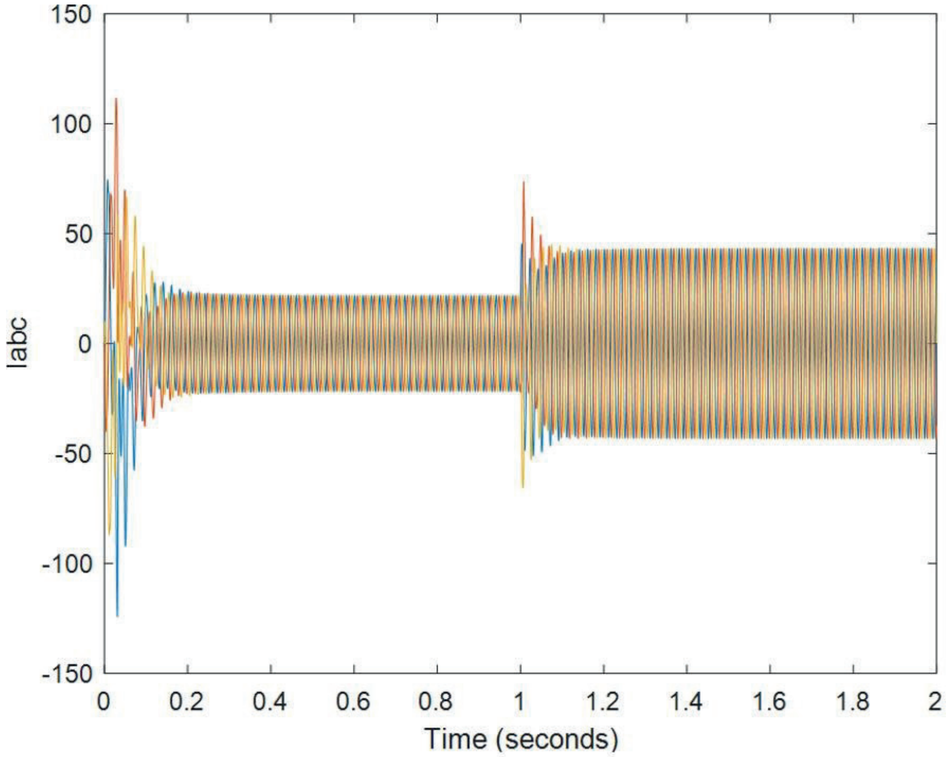

Figure 17 *Current waveforms of the 3-phase on-board aircraft power source according to the MEA concept*

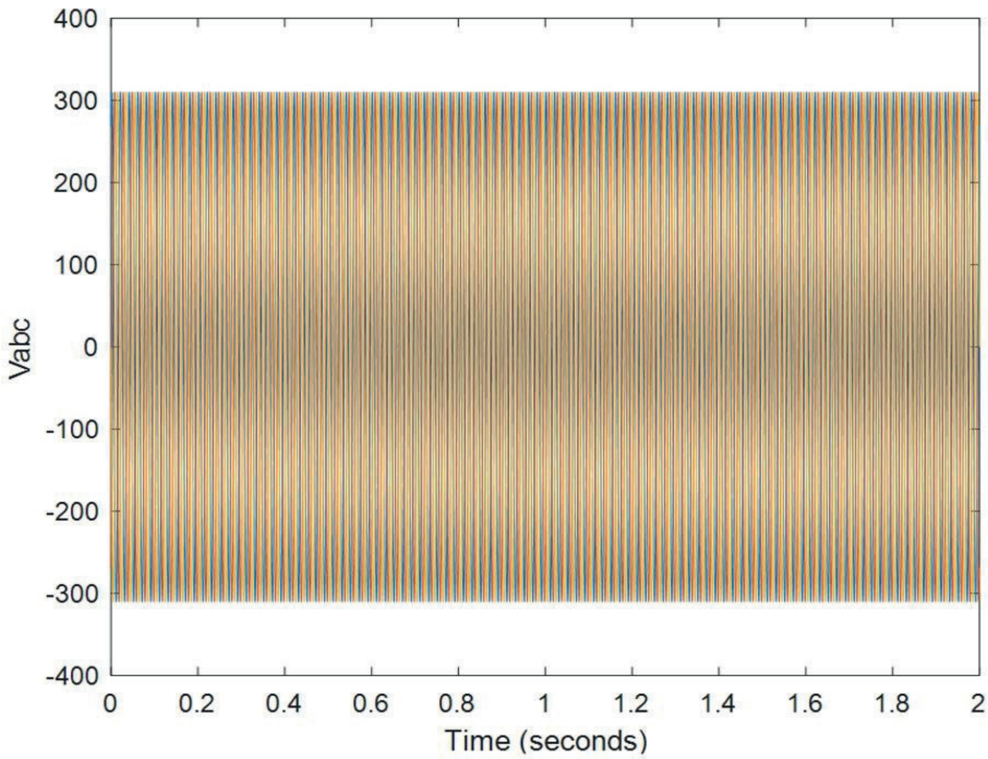

Figure 18 *Voltage waveforms of the 3-phase on-board aircraft power source according to the MEA concept*

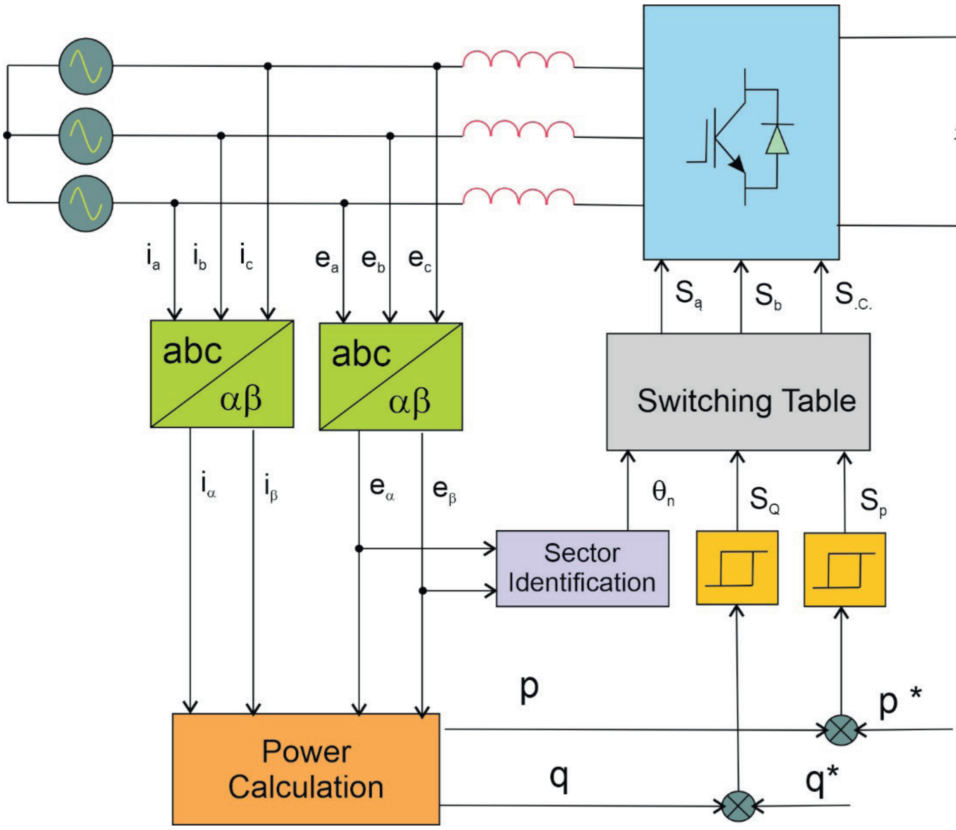

Figure 19 Scheme of the control system of a self-excited synchronous generator

4 The results of simulation studies of the control system

For the purposes of the tests, the control systems of two different types of generators were programmed in such a way that the first generator on the switchgear rails is switched on via a 24-pulse generator converter. When the generator is switched on the converter buses, it has the priority of the leading generator, i.e., the amplitude and frequency of the voltage produced by it takes precedence and applies to the entire aircraft power grid. On the other hand, the control system, connected to the bidirectional converter of the second synchronous generator until it is switched on the rails, works in the so-called "island" manner.

Operation in this mode involves the process of regulating the amplitude of the voltage and frequency of the mains converter of the synchronous generator to specific values that allow it to be synchronized with the voltage on the rails of the system. At the moment when the voltage and frequency of the mains converter of the generator to be connected, and the generator already connected to the rails, are equal, the synchronization system signals that the second generator is ready to be connected to the rails. After switching to parallel operation, it becomes impossible to maintain the regime of island operation, since in such an operating algorithm it is not possible to efficiently distribute active and reactive power between the operating generators.

In the presented control system, information on the value of the rotational speed and the current rotor position angle comes from the measurement of sinusoidal voltages at the output of the generator (u_a, u_b, u_c). By studying the transitions of the voltage values through zero, information about the frequency and speed of the generator as illustrated in Figure 19 in Chapter 3. For this reason, there is no need for additional computational means in the form of software simulators or machine state observers.

The operation of the power electronic system with a synchronous generator is briefly presented below. For a synchronous converter generator to be switched on and controlled, the capacitors of the intermediate circuit of the converter must be pre-charged. In turn, for this to be possible, a switch controlled by a sufficiently high value of the DC voltage U_{DC} must turn on.

In the system under consideration, the contactor turns on when the rotational speed of the synchronous generator reaches a value of about 885 rpm. As the rotational speed of the generator increases, the DC voltage of the DC link, denoted as U_{DC}, also increases. Through an appropriate control algorithm executed in the processor, it is possible to raise the DC voltage to about 690 V from the moment the contactor that charges the capacitors of the intermediate circuit is switched on. It should be noted that an important advantage of the circuit in question is the absence of pre-charging of capacitors from external sources.

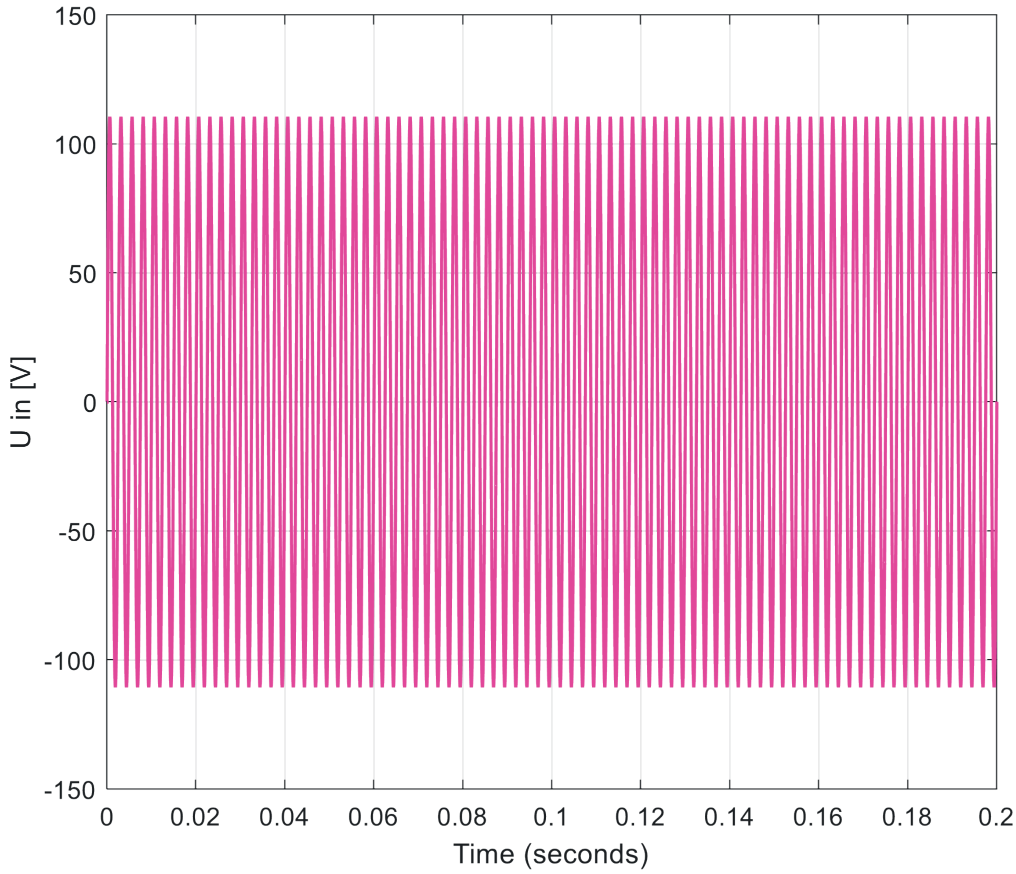

Figure 20 *Voltage waveform on the generator before switching on the control signal*

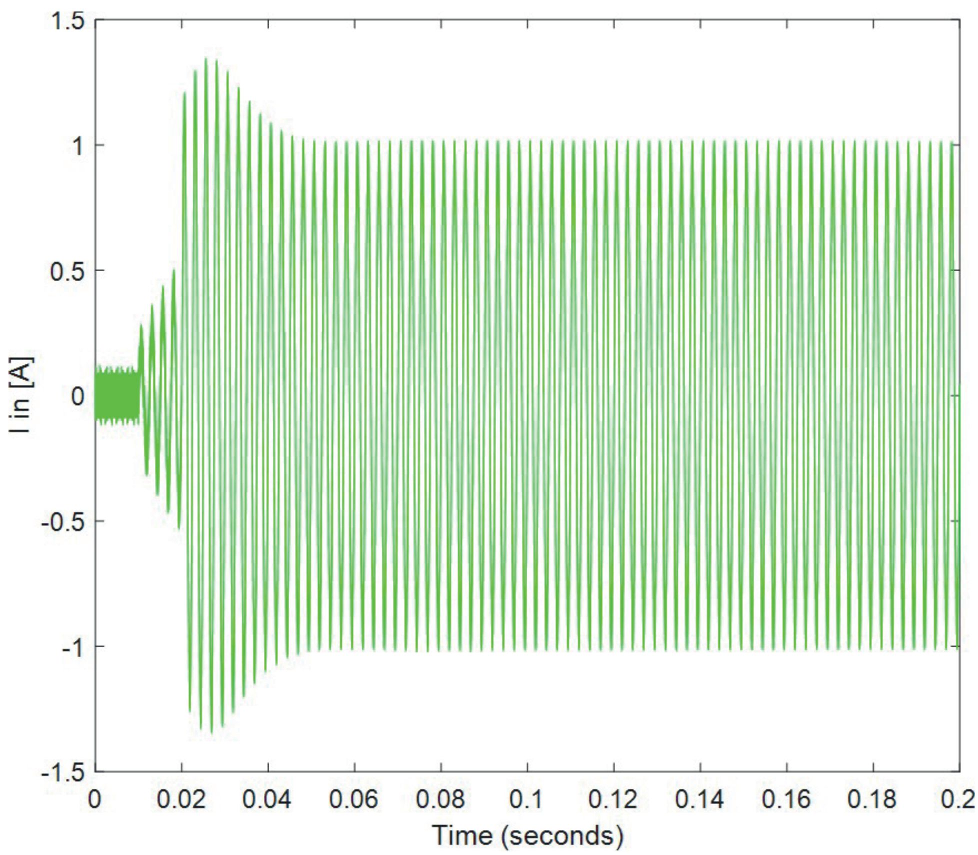

Figure 21 *Current waveform on the generator before switching on the control signal*

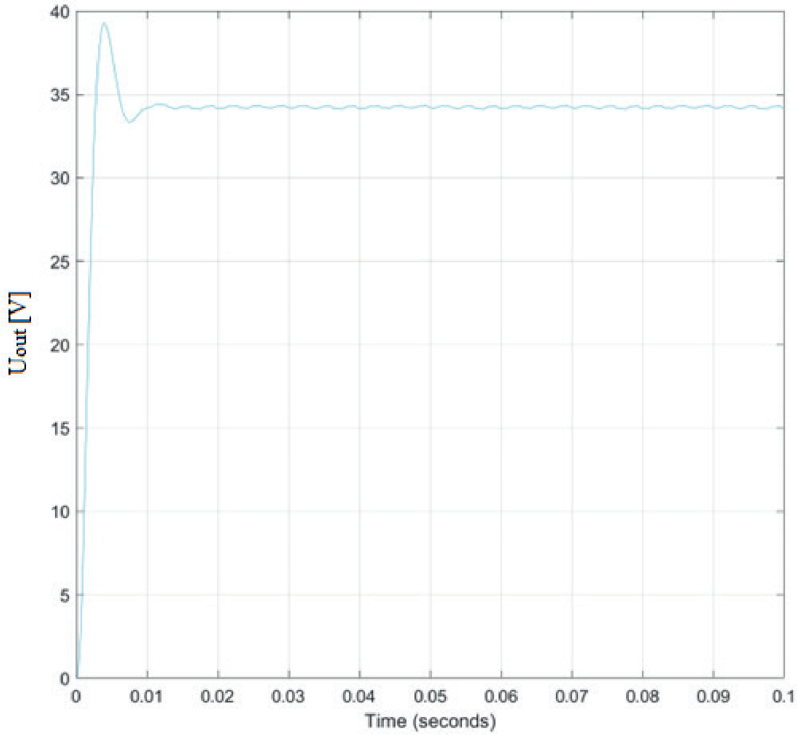

Figure 22 *Voltage DC waveform at the input of the converter with control signal*

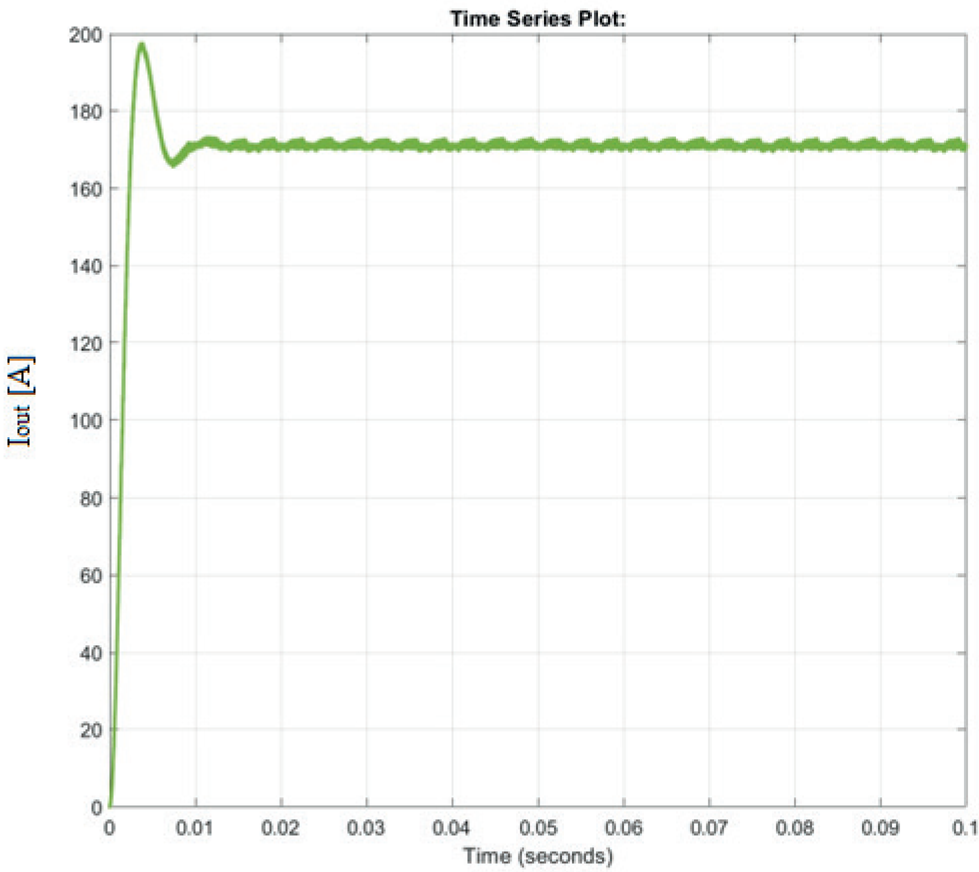

Figure 23 *DC current waveform at converter input with control signal*

4.1 Control of converter operation

Converters, transferring the energy from the intermediate circuit capacitors of the power grid converter, provide two modes of operation. In the case of a single generator operation, the converter has the task of controlling and regulating the voltage amplitude and frequency. When there is a need to switch on and synchronize another generator for parallel operation, the algorithm changes. The frequency of the converter of the connected generator is automatically adjusted to equalize its value with the frequency of the generator (or generators) switched on the buses.

The same happens with the amplitude of the output voltage, that is, when the synchronization conditions are met, the generator switch is turned on and the generator-converter system begins to work in parallel with other sources connected to the network. In the case of switching on, the algorithm controlling the operation of the converter changes under the influence of the signal informing about switching on the buses, and the system begins to work in the program implementing active and reactive power distribution. For the correct operation of the power distribution controllers, continuous information about the frequency of the network voltage is necessary. In the presented solution, a software-based PLL (Phase Locked Loop) circuit was used for frequency control. As a result of the PLL algorithm, the signal processor obtains information about the frequency and phase angle of the voltage, which makes it possible to regulate the amplitude and phase shift values of the output voltage.

Figures 21-23 show that there are uneven loads in generators with the total active and non-active power, and thus also current, both in the states of dynamic load changes and in static states. It should be noted that from the above-mentioned waveforms it is not possible to determine small differences in the values of the AC voltage and current waveforms on the input side of the rectification system. The values of the current at the input of the rectification system (Figure 23) are determined by the control program executed by a specialized Matlab/Simulink software module in real time, in parallel operation of both aircraft generators. The generator carrying out the procedure of distributing the power for the various loads of the aircraft's electrical network takes on a predetermined value of the load, while the remainder (if any) is protected by the second generator.

In this way, it is shown that the requirements of the current regulations for asymmetrical loads are so vague that by meeting the regulations on the permissible value of the ratio of the symmetrical component of the order opposite to the rated current, it is possible to force different current spreads in the windings of the generator. Those distributions cause the occurrence of different values of power losses in the windings, and thus different heating of the windings.

Due to the fact that during the three-phase loads on a generator the value of the ratio $I_d/I_n = 0.1$ depends on many variables, when connecting a load, it is difficult to predict at what values of currents in individual windings the required value of this ratio will be obtained.

5 Conclusions

The developed model of the generator with the excitation and voltage regulation system makes it possible to conduct tests and analyses any asymmetrical states of the generator and excitation system (Figures 1-4). This is a new solution, previously not used in studies of excitation systems.

In this respect, a discrete model of the control system, with the real sampling time and full mapping of measurement systems, was applied. The developed model of the system, based on diodes, allows the mapping of real waveforms in excitation systems (Figures 5-6).

The generator described in the article was made in the Matlab/Simulink programming environment, and simulation studies of the generator for various states of operation are currently underway. It should be noted that the preliminary test results indicate the correctness of the adopted solutions, both in terms of the obtained electrical parameters of the generator and its mechanical design.

From the simulations carried out can be observed that changing the frequency of the generator results in minimizing the tapping torque, which is an unfavorable phenomenon that causes current pulsations when changing the rotor position, and thus interferes with its operation, which was successfully reduced to about 2.5% of the rated torque.

The preliminary results of the tests carried out in this article also indicate the correctness of the calculated power waveforms in the aircraft's electrical network. The investigated efficiency of the generator, when operating with a 12-pulse rectifier and with a generated power of 20 kW, is about 81%. It should be noted that in the case of using the solution in the form of a 6-phase armature winding (2x3 phases), an additional increase in the rated power of the generator of about 3.4% was obtained, and the power losses in the armature winding are reduced by the same amount.

In turn, each of the three-phase windings eliminates the third harmonic in the line-to-line voltage, while the three-phase system, formed from the transformation of the 2x3-phase system, eliminates the fifth and seventh harmonics of the voltage.

In addition, it should be noted that a hybrid excitation generator, when operating alone, has the ability to smoothly stabilize the voltage with changes in load power. In addition, the alternator, when operating on the power grid, can be synchronized with the grid like any machine with electromagnetic excitation, and during the steady-state operation has the ability to continuously regulate the reactive power transferred to the grid. The excitation winding of the generator is characterized by the low copper mass, thus the power loss in the excitation winding is small.

The proposed power electronic system worked stably and, what should be emphasized, was characterized by the high speed of operation and regulation, in the case of abrupt changes occurring in the circuit. The 15 kV quality of the voltage produced by the transformer on the converter side, measured with a higher harmonic content tester, showed that the THD (Total Harmonic Distortion) averaged 2.3% with a value of 2.4% of the input voltage. The output voltage, measured on the converter side, came from measurements with voltage transformers, that is, it was smoothed, which resulted in an improved voltage shape.

The presented system allows free distribution of active and reactive power and long-term cooperation of electricity sources, such as electric generators of various types operating at variable speeds. The developed method of switching on the transformer made it possible to significantly simplify the system and allowed the replacement of electrical components by program code, which increased the reliability of the entire system. Further work will include studies of the stability of the presented systems under rapid load changes across the power range.

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Conflicts of 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.

References

[1] MOIR, I., SEABRIDGE, A. *Military avionics systems* [online]. West Sussex: John Wiley and Sons, Ltd., 2006. ISBN 9780470016329, eISBN 9780470035467. Available from: https://doi.org/10.1002/0470035463.fmatter
[2] ABDEL-FADIL, R., EID, A., ABDEL-SALAM, M. Electrical distribution power systems of modern civil aircrafts. In: 2nd International Conference on Energy Systems and Technologies: proceedings [online]. 2013. Available from: http://www.afaqscientific.com/icest2013/22-Eid76.pdf
[3] SETLAK, L., KOWALIK R. Model and simulation of permanent magnets synchronous machine (PMSM) of the electric power supply system (EPS), in accordance with the concept of a more electric aircraft (MEA). *ITM Web of Conferences* [online]. 2018, **16**, 03004. eISSN 2271-2097. Available from: https://doi.org/10.1051/itmconf/20181603004
[4] FORSYTH, A., ABDEL-HAFEZ, A. A review of more-electric aircraft. 13th International Conference on Aerospace Sciences and Aviation Technology ASAT - 13: proceedings [online]. 2009. Available from: https://doi.org/10.21608/ASAT.2009.23726
[5] BROMBACH, J., LUCKEN, A., NYA, B., JOHANNSEN, M., SCHULZ, D. Comparison of different electrical HVDC-architectures for aircraft application. In: Electrical Systems for Aircraft, Railway and Ship Propulsion ESARS: proceedings [online]. IEEE. 2012. ISBN 978-1-4673-1370-4, eISBN 978-1-4673-1371-1. Available from: https://doi.org/10.1109/ESARS.2012.6387380
[6] LUCKEN, A., BROMBACH, J., SCHULZ, D. Design and protection of high voltage DC on-board grid with integrated fuel cell system on toward optimized electrical networks electric aircraft. In: Electrical Systems for Aircraft, Railway and Ship Propulsion ESARS: proceedings [online]. IEEE. 2012. ISBN 978-1-4673-1370-4, eISBN 978-1-4673-1371-1. Available from: https://doi.org/10.1109/ESARS.2010.5665245
[7] MOIR I., SEABRIDGE, A. *Aircraft systems: mechanical, electrical, and avionics subsystems integration*. 3rd ed. West Sussex: John Wiley and Sons, Ltd., 2008. ISBN 978-0-470-05996-8.
[8] EMANDI, K., EHSANI, M. Aircraft power systems: technology state of the art, and the future trends. *Aerospace and Electronic Systems Magazine* [online]. 2000, **15**(1), p. 28-32. ISSN 0885-8985, eISSN 1557-959X. Available from: https://doi.org/10.1109/62.821660
[9] MLOT, A., LUKANISZYN, M., KORKOSZ, M. Influence of an end-winding size on proximity losses in a high-speed PM synchronous motor. In: 2015 Selected Problems of Electrical Engineering and Electronics WZEE: proceedings [online]. IEEE. 2015. Available from: https://doi.org/10.1109/WZEE.2015.7394026
[10] RAGHUVANSHI, S., SINGH, N. Comparative analysis of 36, 48, 60 pulse AC-DC controlled multipulse converter for harmonic mitigation. *International Journal of Advanced Research in Computer Engineering and Technology (IJARCET)*. 2014, **3**(4). ISSN 2278-1323.
[11] MOHAN, N., UNDERLAND, T. M., ROBBINS, W. P. *Power electronics: converters, application, and design*. West Sussex: John Wiley and Sons, 1989. ISBN 0-471-58408-8.

[12] KAZMIERKOWSKI, M. P., BLAABJERG, F., KRISHNAN, R. *Control in power electronics*. Academic Press Series in Engineering. USA: Elsevier Science, 2002. ISBN 0-12-402772-5.

[13] SETLAK, L., KOWALIK, R. Mathematical modelling and simulation of selected components on-board autonomous power supply system (ASE), in accordance with the concept of a more electric aircraft (MEA). In: 18th International Scientific Conference on Electric Power Engineering EPE: proceedings [online]. IEEE. 2017. eISBN 978-1-5090-6406-9. Available from: https://doi.org/10.1109/EPE.2017.7967337

[14] ZHAO, X., GUERRERO, J. M., WU, X. Review of aircraft electric power systems and architectures. In: IEEE 2014 International Energy Conference ENERGYCON: proceedings [online]. eISBN 978-1-4799-2449-3. Available from: https://doi.org/10.1109/ENERGYCON.2014.6850540

[15] ERRAMI, Y., OUASSAID, M. Modelling and control strategy of PMSG based variable speed wind energy conversion system. In: International Conference on Multimedia Computing and Systems ICMCS: proceedings [online]. 2011. ISBN 978-1-61284-730-6, eISBN 978-1-61284-730-6. Available from: https://doi.org/10.1109/ICMCS.2011.5945736

[16] MOUNI, E., TNANI, S., CHAMPENOIS, G. Comparative study of three modelling methods of synchronous generator. In: IEEE 32nd Annual Conference on Industrial Electronics: proceedings [online]. 2006. eISBN 978-1-5090-9155-3, p. 1551-1556. Available from: https://doi.org/10.1109/IECON.2006.347987

[17] BOZHKO, S., WU, T., TAO, Y., ASHER, G. M. More-electric aircraft electrical power system accelerated functional modelling. In: International Power Electronics and Motion Control Conference: proceedings [online]. 2010. ISBN 978-1-4244-7856-9, eISBN 978-1-4244-7855-2. Available from: https://doi.org/10.1109/EPEPEMC.2010.5606894

[18] ROBOAM, X. New trends and challenges of electrical network embedded in “more electrical aircraft”. In: Proceedings of the IEEE International Symposium on Industrial Electronics ISIE’11: proceedings [online]. IEEE. 2011. ISBN 978-1-4244-9310-4, eISBN 978-1-4244-9312-8, p. 26-31. Available from: https://doi.org/10.1109/ISIE.2011.5984130

[19] SETLAK, L., KOWALIK R. Modern technological solutions in generation, transmission and distribution of electricity in “conventional” vs. “more electric” aircrafts. In: 2017 Progress in Applied Electrical Engineering PAEE: proceedings [online]. IEEE. 2017. eISBN 978-1-5386-1528-7. Available from: https://doi.org/10.1109/PAEE.2017.8009008

[20] ABDEL-HAFEZ, A. Power generation and distribution system for a more electric aircraft - a review. In: *Recent advances in aircraft technology*. AGARWAL, R. (ed.). China: In-Tech, 2012. ISBN 978-953-51-0150-5, p. 289-308.

[21] ABU-RUB, H., MALINOWSKI, M., AL-HADDAD, K. *Power electronics for renewable energy systems. Transportation, and industrial applications* [online]. 1st ed. John Wiley and Sons, Ltd., 2014. ISBN 9781118634035, eISBN 9781118755525. Available from: https://doi.org/10.1002/9781118755525

[22] GONG, G., DROFENIK, U., KOLAR, J. W. 12-pulse rectifier for more electric aircraft applications. In: IEEE International Conference on Industrial Technology ICIT: proceedings [online]. 2003. ISBN 0-7803-7852-0. Available from: https://doi.org/10.1109/ICIT.2003.1290816

[23] ERRAMI, Y., OUASSAID, M. Modelling and control strategy of PMSG based variable speed wind energy conversion system. In: International Conference on Multimedia Computing and Systems ICMCS: proceedings [online]. IEEE. 2011. ISBN 978-1-61284-730-6, eISBN 978-1-61284-732-0. Available from: https://doi.org/10.1109/ICMCS.2011.5945736

[24] SETLAK, L., KOWALIK, R. Model study and simulation of selected components of on-board power supply system ASE in the range of EPS and PES systems of a modern aircraft, compatible with the concept of more electric aircraft. In: IAENG Transactions on Engineering Sciences: Special Issue for the International Association of Engineers Conference`s 2016: proceedings [online]. Vol. II. 2018. ISBN 978-981-3230-76-7, eISBN 978-981-3230-78-1, p. 344-359. Available from: https://doi.org/10.1142/9789813230774_0025

[25] AREERAK, K-N., BOZHKO, S. V., ASHER, G. M., THOMAS, D. W. P. Stability analysis and modelling of AC-DC system with mixed load using DQ-transformation method. In: 2008 IEEE International Symposium on Industrial Electronics: proceedings [online]. IEEE. 2008. ISBN 978-1-4244-1665-3. Available from: https://doi.org/10.1109/ISIE.2008.4676898

[26] MONROY, A. O., LE-HUY, H., LAVOIE, C. Modelling and simulation of a 24-pulse transformer rectifier unit for more electric aircraft power system. Electrical Systems for Aircraft, Railway and Ship Propulsion ESARS: proceedings [online]. IEEE. 2012. ISBN 978-1-4673-1370-4, eISBN 978-1-4673-1372-8. Available from: https://doi.org/10.1109/ESARS.2012.6387383

[27] WU, B., NARIMANI, M. *High-power converters and AC drives* [online]. Hoboken, New Jersey: IEEE Press, John Wiley and Sons, Inc., Publication, 2006. ISBN 9781119156031, eISBN 9781119156079. Available from: https://doi.org/10.1002/9781119156079

[28] SKVARENINA, T. L., PEKAREK, WASYNCZUK, S. O., KRAUSE, P. C. Simulation of a more-electric aircraft power system using an automated state model approach. In: Intersociety Energy Conversion Engineering

Conference: proceedings [online]. IEEE. 1996. p. 133-136. ISBN 0-7803-3547-3. Available from: https://doi.org/10.1109/IECEC.1996.552859

[29] SETLAK, L., KOWALIK, R. Mathematical model and simulation of selected components of the EPS of the aircraft, providing the operation of on-board electrical equipment and systems in accordance with MEA/AEA concept. In: 2017 Progress in Applied Electrical Engineering PAEE: proceedings [online]. IEEE. 2017. eISBN 978-1-5386-1528-7. Available from: https://doi.org/10.1109/PAEE.2017.8009007

[30] MAKAROV, D., KHARITONOV, S., ZINOVIEV, G., SIDOROV, A.V. Variable frequency generation system for aircraft. In: 2014 IEEE Energy Conversion Congress and Exposition: proceedings [online]. IEEE. 2014. ISSN 2329-3721, eISSN 2329-3748. Available from: https://doi.org/10.1109/ECCE.2014.6953496

[31] LATAWIEC, K., STANISLAWSKI, R., LUKANISZYN, M., CZUWARA, W., RYDEL, M. Fractional-order modelling of electric circuits: modern empiricism vs. classical science. In: 2017 Progress in Applied Electrical Engineering PAEE: proceedings [online]. IEEE. 2017. eISBN 978-1-5386-1528-7. Available from: https://doi.org/10.1109/PAEE.2017.8008998

[32] SETLAK, L., KOWALIK, R., REDO, W. The study of permanent magnets synchronous machine (PMSM) of the autonomous electric power supply system (ASE), compatible with the concept of a more electric aircraft (MEA). *ITM Web of Conferences* [online]. 2018, **16**, 03001. eISSN 2271-2097. Available from: https://doi.org/10.1051/itmconf/20181603001

[33] WHEELER, P., CLARE, J., BOZHKO, S. Regeneration in aircraft electrical power systems. In: SAE Power Systems Conference: proceedings. SAE. 2010.

[34] SETLAK, L., KOWALIK, R., REDO, W. Mathematical models and simulation of key multi-pulse rectifiers in field of autonomous electric power supply system, using Matlab/Simulink programming environment compatible with the concept of a more electric aircraft (MEA). In: 2017 European Conference on Electrical Engineering and Computer Science EECS: proceedings [online]. IEEE. 2017. eISBN 978-1-5386-2085-4. Available from: https://doi.org/10.1109/EECS.2017.75

[35] MALDONADO, M. A., KORBA, G. J. Power management and distribution system for a more-electric aircraft (MADMEL). *Aerospace and Electronic Systems Magazine* [online]. 1999, **14**(12), p. 3-8. ISSN 0885-8985, eISSN 1557-959X. Available from: https://doi.org/10.1109/62.811084

[36] WEIMER, J. A. Electrical power technology for the more electric aircraft. In: 12th AIAA/IEEE Digital Avionics Systems Conference: proceedings. IEEE. 1993. p. 445-450.

[37] YANG, Z., QU, J., MA, J., SHI, X. Modeling and simulation of power distribution system in more electric aircraft. *Journal of Electrical and Computer Engineering* [online]. 2015, **2015**, 847624. Available from: https://doi.org/10.1155/2015/847624

[38] SETLAK, L., KOWALIK, R. Analysis, mathematical model and simulation of selected components of advanced technological solutions of HVDC architecture of modern aircraft compatible with the concept of MEA/AEA. In: The World Congress on Engineering and Computer Science 2017: proceedings. 2017. ISBN 978-988-14047-5-6, p. 327-332, 2017.


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EXPLORING THE TRAFFIC CONGESTION AND IMPROVING TRAVEL TIME RELIABILITY MEASURES IN HETEROGENEOUS TRAFFIC ENVIRONMENTS: A FOCUS ON DEVELOPING COUNTRIES

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Resume
Traffic congestion is a pervasive issue that affects urban areas worldwide. This study investigates congestion on urban roads in an Indian smart city. Video graphic technique was employed to collect data across various traffic volumes. Travel time for different vehicle categories was estimated, and the travel time reliability congestion index was assessed. Multiple linear regression modelling was utilized to assess the attributes influencing congestion. Traffic signal synchronization and enforcement of traffic regulations, decentralization of important offices, and regulating roadside activities received strong recommendations from the majority of inhabitants. For improving the functionality and accessibility, related to the urban road network, these attributes should be enforced. The research intended to assess the functional effectiveness of urban roads using travel time reliability measures.

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1 Introduction

Traffic congestion is a genuine concern for road users all over the world. The traffic congestion usually occurs when the existing roadway is not able to satisfy the vehicle flow demand [1-5]. Congestion has emerged as one of the biggest problems of contemporary society in any metropolis for decades without a perfect and efficient solution [2]. Unlike other global problems, like hunger, poverty, illiteracy, etc., traffic congestion is directly experienced by millions of people travelling on roads around the world everyday [3-6]. Due to the congestion, serious patients, medicines and medical equipment are not transported during emergencies, which leads to loss of human lives [7-9]. Congestion increases the undesirable waiting time beyond a certain threshold, leading road users to feel unnecessary stress and pursue unsafe driving behaviour [10-14]. Various factors have been attributed to the inception of road congestion on urban roads. While the foremost reason is regarded as the unavailability of infrastructure to satisfy the demand placed on it, many other external factors also lead to traffic congestion. Those consist of various traffic phenomena and occurrences, like the sudden vehicle breakdown and crashes, presence of construction zones, inclement weather, and other traffic incidents [15-18]. According to [19], the traffic congestion leads to highly worrisome stress in drivers and leads them to perform aggressive and unsafe driving behaviour, which could result in undesirable occurrences such as road accidents which may turn catastrophic too.

Many studies have been conducted to study and analyze the traffic congestion on roads. Further, attempts have been made to alleviate the congestion on urban roads [20]. Most of the studies on congestion pertained to the developed countries of North America and Europe [5, 9-11], whereas, the congestion studies in developing countries have been quite limited. Congestion pricing has been suggested by many researchers in the past [3, 21-24]. Similarly, many macroscopic models have been considered by researchers to analyze the traffic congestion. Similarly, even though studies by [25-26] have suggested that fuzzy logic and multiple regression analysis are better in modelling the driver's behaviour to understand congestion and road accidents, the studies were conducted in European countries and could not be validated for developing countries. Moreover, due to an exponential increase in population resulting in overloading of streets, the problem of congestion keeps on increasing. Traffic composition and driving behaviour are the major concern in developing countries [27-31]. In developing countries, mixed traffic conditions further augment to this problem.

The existing transportation framework is facing challenges due to the increasing human resources and vehicles, making it insufficient to handle the current situation. In India, there is limited investigation conducted regarding congestion, and the presence of heterogeneous environments adds to the complexity. This research centers on travel time reliability congestion index to assess the operational efficiency of the road network and proposes feasible congestion reduction strategies.

2 Literature methodology

Reputable journals and conferences, related to traffic engineering, indexed in Scopus, Web of Science, Google Scholar, and Science Citation Index, were carefully chosen for the study focusing on traffic congestion impacts and its mitigation measures. Using the specific keywords such as "congestion index", "traffic congestion impacts" and "congestion mitigation measures," relevant articles were thoroughly explored from the collected research papers. Articles pertaining to congestion index, congestion impacts and mitigation measures were extracted after a prolonged period of observation, and the remaining articles were excluded.

3 Summary of literature

Traffic congestion can be examined in terms of its causes, impacts, prediction techniques, and mitigation measures. The discussion of various congestion causes highlights that the travel time reliability measures are frequently employed by researchers in the field of traffic congestion. The majority of researchers have utilized the travel time reliability measures to analyze the traffic congestion behaviour. The main focus of the study was on traffic congestion problems and their mitigation measures.

4 Research methodology

A well-designed research methodology is crucial for generating reliable and valid results, ensuring that the research findings would meaningfully contribute to the body of knowledge in a particular field. The current study utilized the study approach presented in Figure 1.

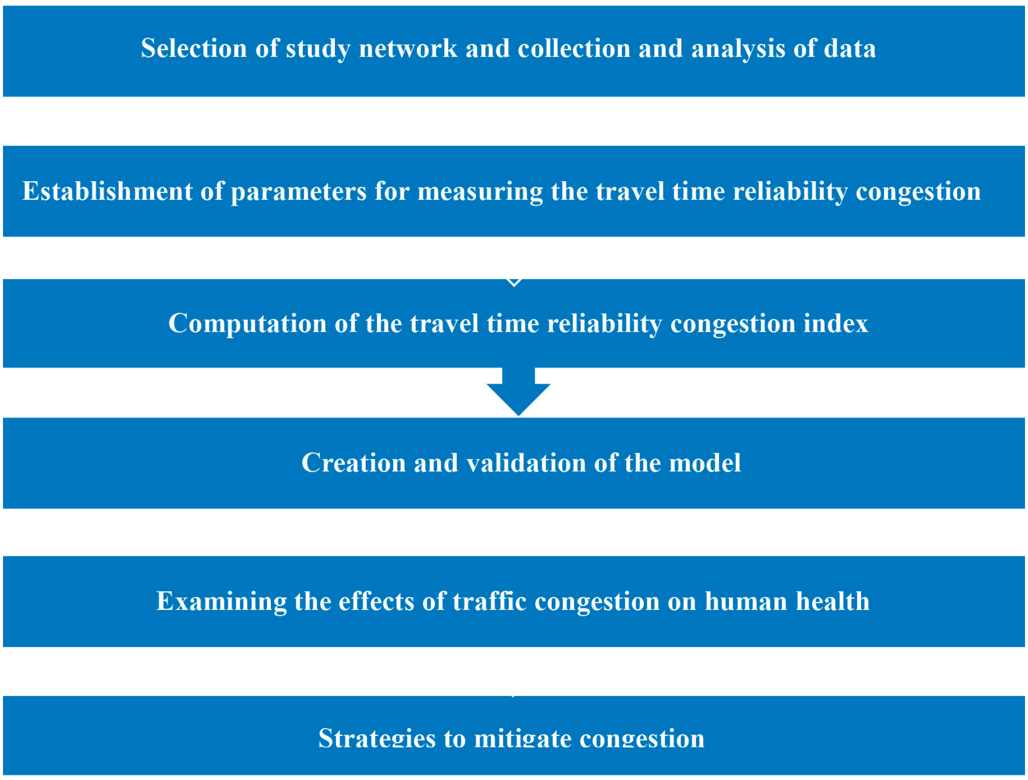

Figure 1 *Flowchart depicting the methodology*

5 Study area characteristics

The present study focuses on the arterial road network. Tiruchirappalli, situated in the state of Tamilnadu in the southern region, is the fourth largest municipal corporation and urban conglomeration within the state, located along the Kaveri River. The research is centered around the Tiruchirappalli city, renowned for its historical and traditional significance in India. Moreover, the city holds significance as a prominent educational center with prestigious institutions like Anna University, Bharathidasan University, Indian Institute of Management (IIM), National Institute of Technology (NIT), Indians Institute of Information Technology (IIIT), and Tamil Nadu National Law School (NLS).

Selecting the appropriate study area is crucial for establishing an efficient and congestion-free road network. It involves considering factors, such as existing transport infrastructure, traffic behaviour, and other research requirements. This study primarily examines the urban roads to evaluate the congestion index and

Table 1 *Information regarding the roads selected for the study*

No.	Road Name	Road Class	Lane Configuration	Length (m)
1.	Thillainagar main road	Arterial	4 lane undivided	1000
2.	Palakkarai	Arterial	2 lane undivided	650
3.	Puthur EVR	Arterial	4 lane divided	750
4.	Bishop	Arterial	2 lane undivided	1050

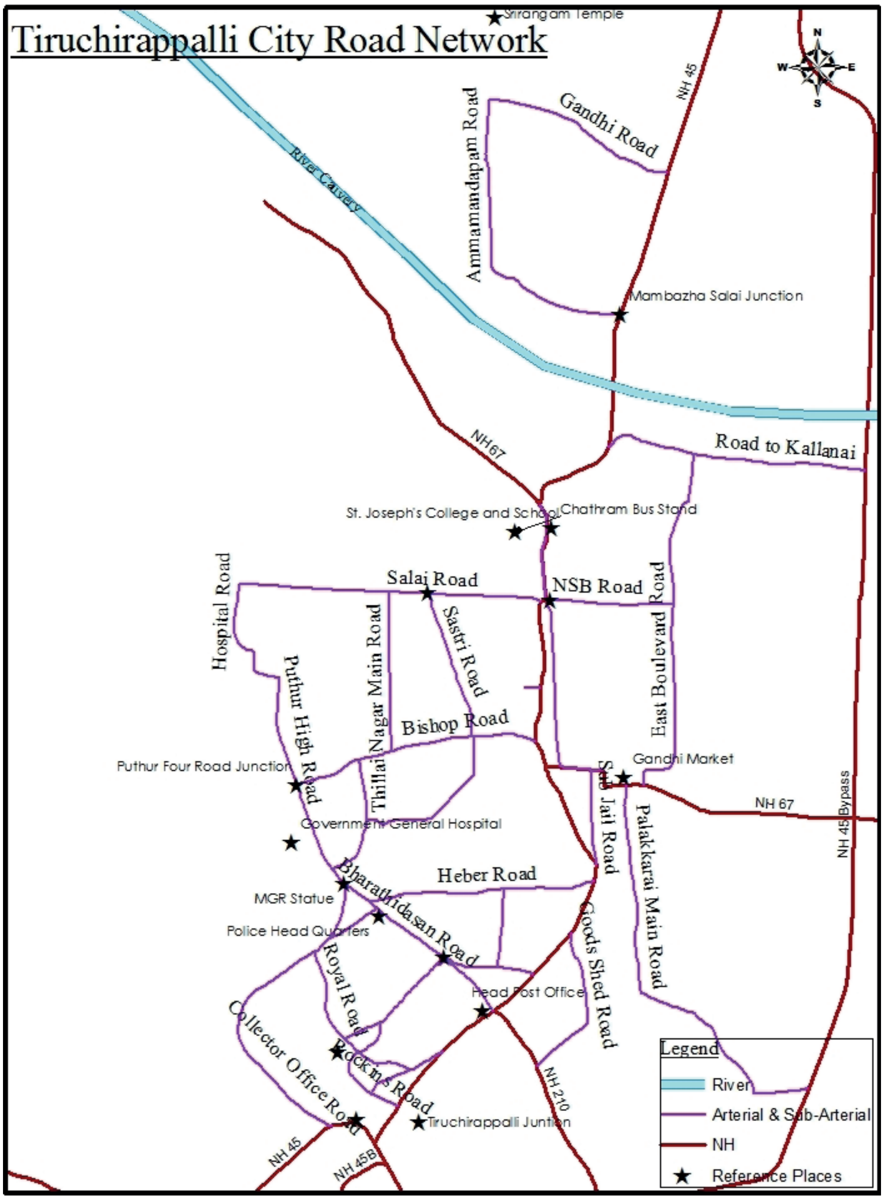

Figure 2 *Tiruchirappalli city road network*

analyze fluctuations in travel time for diverse types of vehicles in Tiruchirappalli district. The following roads have been chosen for the study:

1. Thillainagar main road,
2. Palakkarai road,
3. Puthur EVR road and
4. Bishop road.

All the roads are so chosen and studies have been conducted at midblock sections where no intersections are present within 200 m of upstream and downstream of the road stretch. Further, the stretches are selected in such a way that the side friction due to parking or any other food stalls are not affecting the vehicular movement. Thillainagar main road in Tiruchirappalli city connects Thennur Junction and Salai Junction, spanning a length of 1000 m. The road intersects with 11 other roads. It is a four-lane single carriageway with footpaths and on-street parking on both sides. The section under study, measuring 100 m, lies between the 3rd cross and 5th cross.

Palakkarai road, situated between Chatram and Railway Junction in Tiruchirappalli, is a two-lane single carriageway covering a distance of 650 m. The road features unpaved shoulders, each with a width of 1 m. Heavy vehicles like buses and trucks are not allowed on this route in the direction of Chatram.

Puthur EVR road, situated between Puthur Junction and MGR statue in Tiruchirappalli city, spans a length of 750 m. It is a four-lane dual carriageway with footpaths on both sides. On-street parking is permitted towards the Puthur Junction to MGR statue.

Bishop road, also known as Thennur High Road, is a commercial route linking Thennur Junction and Puthur Junction in Tiruchirappalli city. The road extends for 1050 m and is a two-lane single carriageway with on-street parking on both sides. It lacks footpaths but has paved shoulders on either side. The detail geometric features of the selected roads are provided in Table 1 and Figure 2 shows the aerial view of the selected road networks.

6 Data collection and extraction

Data collection and extraction are crucial steps in the research process, particularly in studies and projects that require empirical data for analysis. These steps involve gathering relevant information from various sources and organizing it for further analysis and interpretation. Data collection and extraction are fundamental steps in any research or analysis process. Thorough and careful data collection, combined with appropriate extraction and management, are crucial for obtaining the meaningful and accurate results in research studies. In the research, data were collected using video recording methods and manually extracted using the assistance of Avidemux software. Avidemux is a video editing software where videos can run in required frames per second (fps) or the frames in which it is recorded. It helps in minimizing the error during the data extraction since the videos can be run with interval of as low as 0.04 seconds (25 fps).

6.1 Travel time

Travel time is a fundamental aspect of transportation planning, management, and decision-making that directly impacts the efficiency, safety, and convenience of travel for individuals. Travel time refers to the duration taken to travel from one point to another, usually measured in minutes, hours, or any time unit. It is a critical factor in transportation and logistics as it directly affects the efficiency of movement and the overall travel experience.

6.2 Travel time reliability measures

Travel time reliability pertains to the regularity and predictability of travel times on a given route or transportation network. It is an essential aspect of transportation planning and management, as it directly impacts the efficiency and convenience of travel for commuters and goods. The travel time reliability measures are valuable for transportation planners and policymakers to identify congested areas, evaluate the impact of traffic management strategies, and prioritize infrastructure improvements to enhance overall travel experience and efficiency. Travel time reliability is a different approach from the V/O (Volume-to-Capacity) ratio, which mainly focuses on expanding roadways to accommodate existing traffic demand. However, the travel time reliability measures are centered around various performance indicators, such as mobility, serviceability, accessibility, and well-planned management of the existing transportation system.

6.3 Travel time reliability congestion index (TTRCI)

Travel time reliability congestion index is an indicator that assesses the level of congestion and the consistency of travel times on a given road or transportation network. It is used to assess the influence of congestion on travel time variability and reliability for commuters and goods. The index takes into account factors such as the variance in travel times, the probability of encountering delays, and the predictability of travel times.

$$\begin{aligned}&Travel\ time\ reliability\ congestion\\&index\,(TTRCI) = 95th\ percentile\ travel\ time -\\&Average\ Travel\ time / Average\ travel\ time\end{aligned} \tag{1}$$

Table 2 *Travel time reliability congestion index (%) of the selected roads*

Roadway	Direction	Travel time reliability congestion index (%)
Thillainagar main road	Upward	26
	Downward	28
Palakkarai road	Upward	36
	Downward	33
Puthur EVR road	Upward	26
	Downward	28
Bishop road	Upward	36
	Downward	33

The Travel time reliability congestion index is a measure of the additional travel time that commuters need to add to their expected travel time to ensure on time arrival at their destination with a certain level of confidence. It is calculated by dividing the difference between the 95th percentile travel time and the mean travel time by the mean travel time.

Four sites were chosen as the study areas, and a traffic volume measurement was conducted at the time of both morning peak hours (from 7:30 A.M. to 10:30 A.M.) and morning off-peak hours (from 12:30 P.M. to 3:30 P.M.) using the video graphic survey techniques along the designated road segments.

The congestion index for the selected roads have been calculated in both directions of movement, as shown in Table 2. A higher percentage of congestion Index suggests that more time is required for vehicles to traverse a specific road section, indicating a higher degree of congestion on that road. This variation in congestion index is influenced by factors such as the type of vehicles and lane characteristics. A smaller congestion Index indicates better serviceability and less congestion on the road.

A higher travel time reliability congestion index indicates greater variability and unpredictability in travel times, leading to less reliable and consistent travel experiences. Conversely, a lower index suggests a more reliable transportation system with consistent and predictable travel times, resulting in smoother and more efficient journeys for travellers. Transportation planners and policymakers use this index to identify congestion hotspots, prioritize infrastructure improvements, and implement traffic management strategies to enhance overall travel time reliability and alleviate congestion-related issues.

7 Travel time reliability congestion index model

The travel time reliability congestion index model is a quantitative method used to assess the level of congestion and the reliability of travel times on a road or transportation network. This model incorporates various factors, including traffic volume, speed, and variability in travel times, to calculate the congestion index. The aim of this model is to provide a numerical value that represents the level of congestion and travel time predictability experienced by commuters and goods.

The present study aimed to develop a travel time reliability congestion index model by analyzing the different factors contributing to traffic congestion. The primary elements affecting the travel time reliability were identified as vehicle speed, traffic volume and travel time. The focus of the travel time reliability congestion index model was on predicting the congestion levels. To assess the model validity, observed travel times during the peak hour from 9:00 AM to 10:00 AM were compared to the estimated values, aiming for minimal percentage of error.

7.1 Model estimation

Model estimation is the process of determining the parameters or coefficients of a mathematical or statistical model based on observed data. The goal of the model estimation is to find the best-fitting values for the model's parameters so that the model can accurately represent the relationship between the variables in the data. Proper model estimation requires careful consideration of the model's assumptions, data quality, and appropriate estimation techniques to ensure reliable and meaningful results.

Regression analysis is a common method used in model estimation, particularly for predicting numerical outcomes, where the correlation between the dependent and independent variables is explored to create a regression model. The research aimed to create a multiple linear regression models, with travel time reliability congestion index as the dependent variable, and speed, traffic volume, travel time as the independent variables. However, before initiating regression, the independent variables are subjected to Pearson correlation to determine whether the variables are mutually exclusive or dependent. The obtained R-values are provided in Table 3.

As can be seen from Table 3, R-values between the independent variables suggest that Travel time is dependent on speed with a value of 0.733. However,

Table 3 *Pearson correlation table*

Pearson Correlation Value	Actual Travel Time	Speed	Traffic Volume
Actual Travel Time	1	-.733	-.508
Speed	-.733	1	.604
Traffic Volume	-.508	.604	1

Table 4 *Regression model for determining TTRCI*

Equation	R-Square
$TTRCI = 12.414 + (0.024 * TV) - (0.028 * TT)$	0.948
$TTRCI = 28.537 + (0.348 * S) - (0.093 * TT)$	0.404

where: $TTRCI$ = Travel time reliability congestion index,
S = Speed of vehicle in km/h,
TT = Travel time in s,
TV = Volume in PCU/h.

Table 5 *The percentage of error during the validation method*

Time of day (AM)	Observed travel time reliability congestion index	Estimated travel time reliability congestion index	Error percentage, %
9:00 – 9:10	28.49	28.00	1.72
9:10 – 9:20	30.13	29.90	0.76
9:20 – 9:30	36.10	37.16	-2.93
9:30 – 9:40	35.62	34.76	2.41
9:40 – 9:50	33.98	34.18	-0.59
9:50 – 10:00	28.13	27.71	1.49

other variables are not dependent on each other strongly. Therefore, the mutually independent variables are traffic volume and speed or, traffic volume with travel time. Therefore, the two equations have been modelled to determine the TTRCI and best between them can be utilized to assess the congestion. Table 4 shows the two models with R-square values.

Equations in Table 4 shows that TTRCI can be more accurately determined from Traffic Volume and Travel time, since the equation has much better R-square value of 0.948. Further, it is also convenient to calculate both the independent variables easily on field. The formulated equation is applicable when the travel time is greater than 10 seconds and the traffic volume exceeds 650 PCU/h.

7.2 Model calibration and validation

Model calibration involves making adjustments of the parameters or coefficients of a model to improve its accuracy and fit with the observed data. It is a crucial step in the model development process, especially for predictive models and simulations, where the goal is to ensure that the model‘s predictions align well with the real-world data.

During the model calibration, the model‘s parameters are fine-tuned using optimization techniques, such as minimizing the difference between the model‘s predictions and the actual observed values. The objective is to ensure that the model is as accurate as possible and captures the underlying patterns and relationships present in the data. It ensures that the model’s predictions are reliable, and that the model can be confidently used for decision-making and forecasting purposes. The proper model calibration is essential to avoid biases and inaccuracies in model predictions and improve the model’s overall usefulness and effectiveness. Table 5 showcases the error percentage during model validation.

Model validation is a critical step in the model development process to assess the performance, accuracy, and generalization ability of the model. It involves evaluating how well the model‘s predictions align with real-world data and checking whether the model can effectively make accurate predictions for the new, unseen data. Model validation helps to ensure that the model is robust and reliable and can be confidently used for decision-making and future predictions. It helps to build confidence in the model’s performance and assists in selecting the best model among different alternatives. The proper model validation is crucial for using models effectively in decision-making processes and applications across various domains.

To validate the proposed travel time reliability congestion index model, the congestion index evaluated by the model was compared to the congestion index acquired through the field data. Separate field data

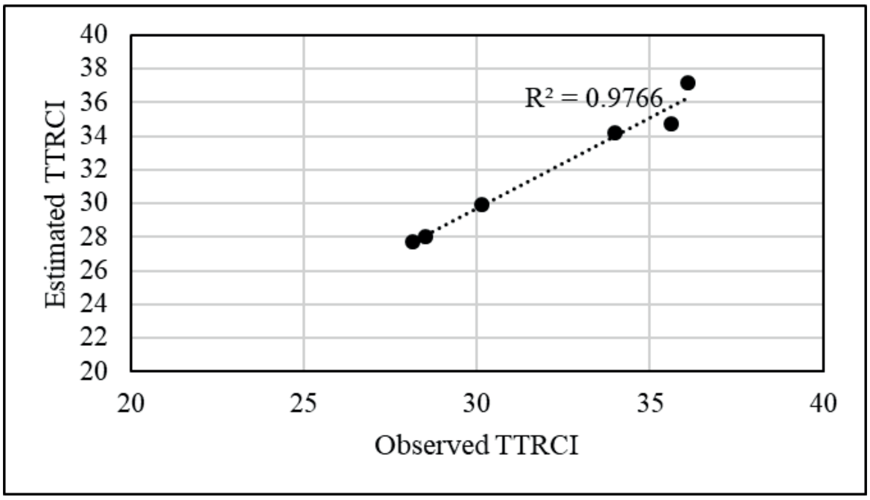

Figure 3 *The variability between observed travel time and estimated travel time*

were gathered from multiple locations of arterial road, different from the location where the model was developed. This ensured that the model's equation is not limited to a specific location and can be applied to estimate congestion index at different locations.

Table 5 presents the comparison between the travel time reliability congestion index of all the vehicle categories estimated using the proposed model and the observed congestion index collected from the field data. The results indicate that the values derived

Table 6 *Parameters influencing human health*

Parameters	Explanation	Order
Air pollution	Congested traffic is a major source of air pollution in urban areas. Traffic congestion results in the emission of pollutants like nitrogen oxides (NOx), particulate matter (PM), volatile organic compounds (VOCs), and carbon monoxide (CO) from vehicles. Prolonged exposure to these pollutants can cause respiratory issues, worsen asthma and other respiratory conditions, and elevate the chances of cardiovascular diseases.	Order I
Exposure to harmful substances	People who spend significant time in congested traffic are exposed to higher levels of harmful substances, such as diesel exhaust, which contains toxic compounds and carcinogens.	Order I
Noise pollution	Traffic congestion generates high levels of noise pollution, which can lead to stress, sleep disturbances, and hearing impairment. Chronic exposure to noise pollution has also been linked to cardiovascular issues and mental health problems.	Order I
Physical inactivity	In congested areas, people often spend more time sitting in vehicles or waiting in traffic, leading to a sedentary lifestyle. Lack of physical activity is associated with a higher risk of obesity, diabetes, and other chronical conditions.	Order III
Mental health impact	The stress and frustration caused by traffic congestion can negatively impact the mental health, leading to anxiety, irritability, and decreased overall well-being.	Order II
Road traffic accidents	Congestion can increase the likelihood of the road traffic accidents, leading to injuries and fatalities. Drivers may experience increased stress and impatience, which can contribute to risky driving behaviour.	Order II
Delayed emergency services	Congestion can impede the timely arrival of emergency services, affecting the ability to respond to accidents and medical emergencies promptly.	Order I
Environmental impact	Traffic congestion can lead to more idling vehicles, increasing fuel consumption and leads to increased greenhouse gas emissions, contributing to climate change and environmental degradation.	Order II
Unequal exposure	Low-income neighbourhoods and marginalized communities often experience higher levels of traffic congestion and pollution, leading to health disparities and environmental injustice.	Order III

from the proposed model closely match the observed field values, with percentage error varying from 0.53 to 2.93 %. This indicates that the proposed model is effective in predicting the travel time reliability congestion index. Figure 3 helps in understanding the same in form of a pictorial representation. The validation process demonstrates that the proposed travel time reliability congestion index model is reliable and capable of accurately predicting travel times at different locations of arterial road. The travel time reliability congestion index model is a valuable tool for assessing the performance of transportation systems and understanding the impact of congestion on travel times. It aids in the optimization of traffic flow, enhances the overall travel experience, and contributes to more efficient and reliable transportation networks.

8 The impact of traffic congestion on human health

Traffic congestion can have significant impacts on human health, both directly and indirectly. The health effects of traffic congestion are diverse and can affect individuals in various ways. The study aims to investigate the influence of congestion on human health by gathering data from both field locations and workplaces. Some of the key parameters influencing human health are categorized as provided in Table 6.

Addressing the traffic congestion and its impact on human health requires a comprehensive approach, including promoting sustainable transportation options like public transit, cycling, and walking, implementing traffic management strategies, and reducing reliance on

Table 7 *Strategies to alleviate the traffic congestion*

Parameters	Description	Priority level
Improved public transportation	Enhancing public transportation systems, such as buses, trains, and subways, to provide reliable and efficient alternatives to the private car travel. This approach can incentivize individuals to opt for public transit, thereby decreasing the volume of vehicles on the road	Level 3
Congestion pricing	Implementing tolls or fees that vary, based on the level of congestion, time of day, or location to manage demand and encourage travel during the off-peak hours.	Level 3
Carpooling and ride sharing	Encouraging commuters to share rides by carpooling or using the ride share services, which can decrease the volume of vehicles on the road and decrease the overall congestion.	Level 2
Active transportation	Encouraging walking and cycling as feasible transportation alternatives for short trips, which can help reduce the vehicle traffic and improve public health.	Level 1
Traffic signal synchronization and enforcement of stringent traffic regulations	Optimizing the traffic signal timing to facilitate smoother traffic flow and reduce the stop-and-go congestion.	Level 1
Smart traffic management	Implementing intelligent transportation systems and traffic management technologies to monitor traffic conditions and adjust signal timings in real-time based on traffic flow.	Level 4
Expanded road infrastructure	Adding lanes, building new roads, or improving existing roadways to increase the capacity and accommodate growing traffic demands.	Level 4
Flexible work hours	Encouraging telecommuting and flexible work schedules to reduce the number of commuters during the peak hours.	Level 2
Park and ride facilities	Establishing park-and-ride facilities near the transit hubs to encourage commuters to park their cars and use public transportation for the rest of their journey.	Level 3
Transportation education and awareness campaigns	Raising public awareness about the impacts of congestion and promoting sustainable transportation options through educational campaigns.	Level 2
Decentralization of important offices	By moving important offices to multiple locations, the burden on transportation networks and public services in the central area can be alleviated, reducing the traffic congestion and overcrowding.	Level 1
Regulating roadside activities	By effectively managing the roadside activities, authorities can create a more efficient and streamlined transportation system, reducing congestion and improving overall mobility for commuters.	Level 1

private vehicles. Additionally, urban planning that gives priority to green spaces and creating pedestrian friendly environments, can assist to mitigate the adverse health effects of traffic congestion. The present study attempted to identify the parameters, which are affecting majority of inhabitants and categorized them as order I. Similarly, other factors are categorized as order II and order III.

9 Suggested approaches to mitigate congestion

Congestion mitigation refers to the actions and strategies implemented to alleviate or reduce the traffic congestion in transportation systems. These measures aim to improve the flow of traffic, enhance transportation efficiency, and minimize the negative impacts of congestion on commuters, businesses, and the environment. The central objective of this study was to enhance the existing traffic infrastructure with minimal costs and effort. Various congestion reduction strategies were considered as a part of this effort. Valuable input was obtained from the diverse perspectives, including the general public, specialists, experts, educators, engineers, and street vendors. The grouping of approaches to alleviate the traffic congestion has been presented in Table 7.

The present study prioritized the upgrading of the existing traffic framework with minimal costs consideration, rather than focusing on building new infrastructures. The study utilized a priority level approach, based on feedback gathered from various sources. Elements ranked lower (Level 1) require immediate implementation for more significant impact. Among the elements, active transportation (promoting walking and cycling as viable transportation options for short trips, which can help reduce the vehicle traffic and improve public health), traffic signal synchronization and Enforcement of stringent traffic regulations**,** decentralization of important offices, and regulating roadside activities, received the strong recommendations from the majority of inhabitants. For improving efficiency and accessibility, pertaining to urban road network, those aforementioned approaches should be promptly executed. The increasing number of motorcycles has rendered non-motorized vehicles obsolete. Proper execution of these elements needs to be taken seriously and accomplished at the earliest opportunity. A combination of these congestion mitigation strategies, tailored to specific urban environments and transportation systems, can help alleviate the traffic congestion, improve mobility, and create more sustainable and efficient transportation networks.

10 Conclusions and recommendations

Traffic congestion has become increasingly problematic on urban road networks for so many decades all over the world. In developing countries, like India, where the mixed traffic conditions prevail, the traffic congestion scenarios get further complicated. Congestion not only affects the overall economy, but negatively affects health, environment and traffic safety, as well. Due to the increase in vehicular traffic in recent times, congestion mitigation strategies have become a point of hot discussions for traffic engineers, researchers, and practitioners alike.

The main focus of the present research was on analyzing the traffic congestion and its adverse effects. Data was collected from the specific roadways in the Indian traffic scenario to propose strategies for mitigating congestion. The extent of congestion varied based on vehicle categories and lane distribution. The study evaluated the extent of congestion and analyzed its negative impact on various factors. It was found that congestion prediction in the Indian environment is challenging, and complete elimination is not feasible, particularly due to the increasing number of the two-wheeler and four-wheeler, particularly passenger cars.

The travel time reliability congestion index was utilized to assess the congestion extent on the chosen road network. The heavy traffic congestion forces residents to spend more time on the road, resulting in adverse effects on the country's overall economy. Moreover, the traffic congestion negatively impacts the environment and human health. A travel time reliability congestion index model was developed, taking into account various factors that influence travel time reliability. The observed percentage error was around 5%, indicating that the general model is suitable and statistically significant in estimating travel time reliability congestion index. During the congested periods, motorists are required to frequently operate the brake and clutch, leading to increased fuel consumption and reduced performance and longevity of a vehicle. As a result, vehicle operating costs are closely linked to congestion. Addressing the traffic congestion and its impact on human health requires a comprehensive approach, including promoting sustainable transportation options like public transit, cycling, and walking, implementing the traffic management strategies, and reducing reliance on private vehicles. Additionally, prioritizing green spaces and creating pedestrian friendly environments in urban planning can help to mitigate the adverse health effects of traffic c ongestion.

Among the elements, promoting walking and cycling as viable transportation options for the short trips, which can help reduce vehicle traffic and improve public health, Traffic signal synchronization and enforcement of stringent traffic regulations, decentralization of important offices, and regulating roadside activities received strong recommendations from the majority of inhabitants. For improving the functionality and accessibility of the urban road network, these aforementioned approaches should be promptly executed.

The study highlighted the importance of adopting a holistic approach, combining the technological innovations with appropriate policy interventions, to effectively manage and alleviate the traffic congestion. In developing countries such as India, the presence of a diverse and heterogeneous traffic environment further complicates the situation. Enormous traffic congestion can sometimes lead to life and death situations, with consequences that cannot be underestimated. It is crucial to establish effective coordination among different organizations, from research and planning to execution and practical implementation, to effectively address the traffic congestion. With ongoing research, collaboration, and implementation of sustainable strategies, it is possible to create more efficient, accessible, and liveable urban environments for future generations.

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Conflicts of interest

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References

[1] PADIATH, A., VANAJAKSHI, L., SUBRAMANIAN, S. C., MANDA, H. Prediction of traffic density for congestion analysis under Indian traffic conditions. In: 12th International IEEE Conference on Intelligent Transportation Systems: proceedings [online]. IEEE. 2009. ISBN 978-1-4244-5519-5, p. 78-83. Available from: https://doi.org/10.1109/ITSC.2009.5309716

[2] CHIDAMBARAM, B., ZIKOS, D. Congestion mitigation measure in Hyderabad - a midnight summer dream? In: South Asia Chronicle. Sudasien Seminar. Vol. 2. Berlin: Humboldt University, 2012. ISBN 978-3-86004-286-1, p. 58-92.

[3] SUMI, L., RANGA, V. Intelligent traffic management system for prioritizing emergency vehicles in a smart city. *International Journal of Engineering* [online]. 2018, **31**(2), p. 278-283. ISSN 1025-2495, eISSN 1735-9244. Available from: https://doi.org/10.5829/ije.2018.31.02b.11

[4] LYMAN, K., BERTINI, R. L. Using travel time reliability measures to improve regional transportation planning and operation. *Transportation Research Record: Journal of the Transportation Research Board* [online]. 2008, **2046**(1), p. 1-10. ISSN 0361-1981, eISSN 2169-4052. Available from: https://doi.org/10.3141/2046-01

[5] PALMA, A. D., LINDSEY, R. Traffic congestion pricing methodologies and technologies. *Transportation Research Part C: Emerging Technologies* [online]. 2011, **19**(6), p. 1377-1399. ISSN 0968-090X, eISSN 1879-2359. Available from: https://doi.org/10.1016/j.trc.2011.02.010

[6] ZHILI, L., CHUNYAN, L., CHENG, L. Traffic impact analysis of congestion charge in mega cities. *Journal of Transportation Systems Engineering and Information Technology* [online]. 2009, **9**(6), p. 57-61. ISSN 1570-6672. Available from: https://doi.org/10.1016/S1570-6672(08)60088-4

[7] MCGROARTY, J. Recurring and non-recurring congestion: causes, impacts, and solutions. USA: University of Cincinnati, 2010.

[8] MAHMUD, K., GOPEAND, K., CHOWDHURY, S. M. Possible causes and solutions of traffic jam and their impact on the economy of Dhaka City. *Journal of Management and Sustainability* [online]. 2012, **2**(2), p. 112-135. ISSN 1925-4725, eISSN 1925-4733. Available from: https://doi.org/10.5539/jms.v2n2p112

[9] JIA, H., TAN, Y., FU, X. Study on evaluation method of urban traffic congestion based on fuzzy comprehensive evaluation. In: 2012 3rd International Conference on Digital Manufacturing and Automation: proceedings [online]. IEEE. 2012. ISBN 978-1-4673-2217-1, p. 819-822. Available from: https://doi.org/10.1109/ICDMA.2012.192

[10] RAO, A. M., RAO, K. R. Measuring urban traffic congestion - a review. *International Journal for Traffic and Transport Engineering* [online]. 2012, **2**(4). ISSN 2217-544X, eISSN 2217-5652. Available from: http://doi.org/10.7708/ijtte.2012.2(4).01

[11] YANG, S. On feature selection for traffic congestion prediction. *Transportation Research Part C: Emerging Technologies* [online]. 2013, **26**, p. 160-169. ISSN 0968-090X, eISSN 1879-2359. Available from: https://doi.org/10.1016/j.trc.2012.08.005

[12] WEN, H., SUN, J., ZHANG, X. Study on traffic congestion patterns of large city in China taking Beijing as an example. *Procedia - Social and Behavioral Sciences* [online]. 2014, **138**(0), p. 482-491. ISSN 1877-0428. Available from: https://doi.org/10.1016/j.sbspro.2014.07.227

[13] PETROVSKA, N., STEVANOVIC, A. Traffic congestion analysis visualisation tool. In: 2015 IEEE 18th International Conference on Intelligent Transportation Systems: proceedings [online]. IEEE. 2015. eISBN 978-1-4673-6596-3, p. 1489-1494. Available from: https://doi.org/10.1109/ITSC.2015.243
[14] HE, F., YAN, X., LIU, Y., MA, L. A traffic congestion assessment method for urban road networks based on speed performance index. *Procedia Engineering* [online]. 2016, **137**, p. 425-433. ISSN 1877-7058. Available from: https://doi.org/10.1016/j.proeng.2016.01.277
[15] SAMAL, S. R., DAS, A. K. Evaluation of traffic congestion parameters under heterogeneous traffic condition: a case study on Bhubaneswar City. In: *Transportation research* [online]. MATHEW, T., JOSHI, G., VELAGA, N., ARKATKAR, S. (eds.). Lecture Notes in Civil Engineering, Vol. 45. Singapore: Springer, 2020. ISBN 978-981-32-9041-9, eISBN 978-981-32-9042-6, p. 675-684. Available from: https://doi.org/10.1007/978-981-32-9042-6_53
[16] SAMAL, S. R., KUMAR, P. G., SANTHOSH, J. C., SANTHAKUMAR, M. Analysis of traffic congestion impacts of urban road network under Indian conditions. *IOP Conference Series: Materials Science and Engineering* [online]. 2020, **1006**(1), 012002. ISSN 1757-899X. Available from: https://doi.org/10.1088/1757-899X/1006/1/012002
[17] SAMAL, S. R., MOHANTY, M., SANTHAKUMAR, S. M. Adverse effect of congestion on economy, health and environment under mixed traffic scenario. *Transportation in Developing Economies* [online]. 2021, **7**(2), p. 1-10. ISSN 2199-9287, eISSN 2199-9295. Available from: https://doi.org/10.1007/s40890-021-00125-4
[18] SAMAL, S. R., MOHANTY, M., SELVARAJ, M. S. Assessment of traffic congestion under Indian environment - a case study. *Communications - Scientific Letters of the University of Zilina* [online]. 2022, **24**(4), D174-D182. ISSN 1335-4205, eISSN 2585-7878. Available from: https://doi.org/10.26552/com.C.2022.4.D174-D182
[19] ISA, N., YUSOFF, M., MOHAMED, A. A review on recent traffic congestion relief approaches. In: 2014 4th International Conference on Artificial Intelligence with Applications in Engineering and Technology: proceedings [online]. IEEE. 2014. eISBN 978-1-4799-7910-3, p. 121-126. Available from: https://doi.org/10.1109/ICAIET.2014.29
[20] DUBEY, P. P., BORKAR, P. Review on techniques for traffic jam detection and congestion avoidance. In: 2015 2nd International Conference on Electronics and Communication Systems ICECS: proceedings [online]. IEEE. 2015. eISBN 978-1-4799-7225-8, p. 434-440. Available from: https://doi.org/10.1109/ECS.2015.7124941
[21] ALMATAR, K. M. Traffic congestion patterns in the urban road network: (Dammam metropolitan area). *Ain Shams Engineering Journal* [online]. 2023, **14**(3), 101886. ISSN 2090-4479, eISSN 2090-4495. Available from: https://doi.org/10.1016/j.asej.2022.101886
[22] BAYRAKTAR, E., KORKMAZ, B. N., ERARSLAN, A. U., CELEBI, N. Traffic congestion-aware graph-based vehicle rerouting framework from aerial imagery. *Engineering Applications of Artificial Intelligence* [online]. 2023, **119**, 105769. ISSN 0952-1976, eISSN 1873-6769. Available from: https://doi.org/10.1016/j.engappai.2022.105769
[23] SEROK, N., HAVLIN, S., BLUMENFELD LIEBERTHAL, E. Identification, cost evaluation, and prioritization of urban traffic congestions and their origin. *Scientific Reports* [online]. 2022, **12**(1), 13026. eISSN 2045-2322. Available from: https://doi.org/10.1038/s41598-022-17404-8
[24] BABAEI, A., KHEDMATI, M., JOKAR, M. R. A., TIRKOLAEE, E. B. Sustainable transportation planning considering traffic congestion and uncertain conditions. *Expert Systems with Applications* [online]. 2023, **227**, 119792. ISSN 0957-4174, eISSN 1873-6793. Available from: https://doi.org/10.1016/j.eswa.2023.119792
[25] CUBRANIC-DOBRODOLAC, M., SVADLENKA, L., CICEVIC, S., TRIFUNOVIC, A., DOBRODOLAC, M. Using the interval type-2 fuzzy inference systems to compare the impact of speed and space perception on the occurrence of road traffic accidents. *Mathematics* [online]. 2020, **8**(9), 1548. eISSN 2227-7390. Available from: https://doi.org/10.3390/math8091548
[26] CUBRANIC-DOBRODOLAC, M., SVADLENKA, L., CICEVIC, S., DOBRODOLAC, M. Modelling driver propensity for traffic accidents: a comparison of multiple regression analysis and fuzzy approach. *International Journal of Injury Control and Safety Promotion* [online]. 2020, **27**(2), p. 156-167. ISSN 1745-7300, eISSN 1745-7319. Available from: https://doi.org/10.1080/17457300.2019.1690002
[27] SKOVAJSA, J., PRIBYL, O., PRIBYL, P., SCERBA, M., JANOTA, A. Evaluation of a mobile highway management system at roadwork zones. *International Journal of Engineering* [online]. 2022, **35**(5), p. 900-907. ISSN 1025-2495, eISSN 1735-9244. Available from: https://doi.org/10.5829/ije.2022.35.05b.06
[28] REN, C., WANG, Z., YIN, C., XU, H., WANG, L., GUO, L., LI, J. Boundary guidance strategy and method for urban traffic congestion region management in internet of vehicles environment. *Journal of Advanced Transportation* [online]. 2023, **2023**, 4866326. ISSN 0197-6729, eISSN 2042-3195. Available from: https://doi.org/10.1155/2023/4866326
[29] BAO, Z., OU, Y., CHEN, S., WANG, T. Land use impacts on traffic congestion patterns: a tale of a northwestern Chinese city. *Land* [online]. 2022, **11**(12), 2295. eISSN 2073-445X. Available from: https://doi.org/10.3390/land11122295

[30] SALEEM, M., ABBAS, S., GHAZAL, T. M., KHAN, M. A., SAHAWNEH, N., AHMAD, M. Smart cities: fusion-based intelligent traffic congestion control system for vehicular networks using machine learning techniques. *Egyptian Informatics Journal* [online]. 2022, **23**(3), p. 417-426. ISSN 1110-8665, eISSN 2090-4754. Available from: https://doi.org/10.1016/j.eij.2022.03.003

[31] RAZA, A., ALI, M. U., ULLAH, U., FAYAZ, M., ALVI, M. J., KALLU, K. D., ZAFAR, A., NENGROO, S. H. Evaluation of a sustainable urban transportation system in terms of traffic congestion - a case study in Taxila, Pakistan. *Sustainability* [online]. 2022, **14**(19), 12325. eISSN 2071-1050. Available from: https://doi.org/10.3390/su141912325

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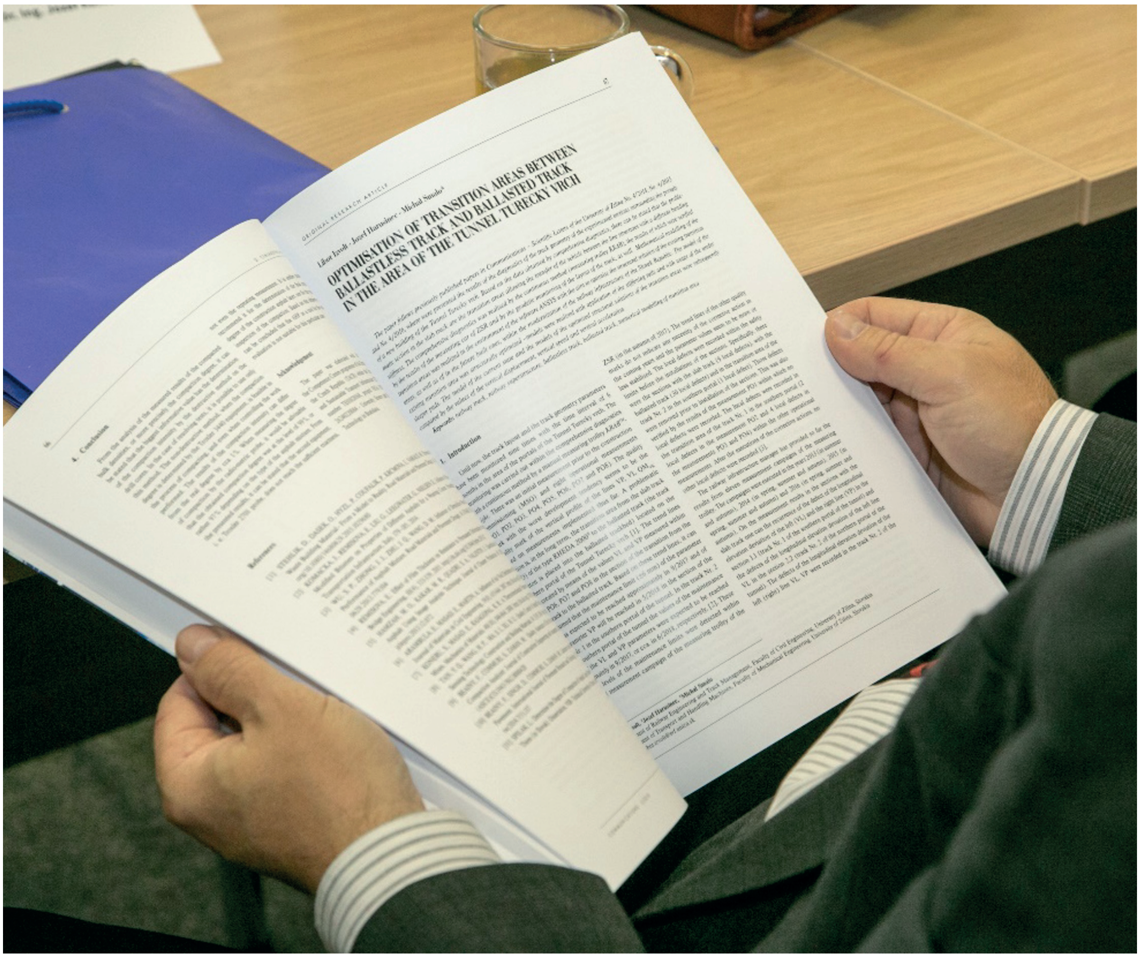

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ACCIDENT RESPONSE ANALYSIS OF SIX DIFFERENT TYPES OF DISTRACTED DRIVING

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Resume

The study analysed the driving performance and visual impairment of 92 participants under six different distraction scenarios. Using a car simulator and by simulating two real-world roads, a variety of data was collected, including driver behavior and vehicle-related data. According to a statistical analysis conducted during and before the distraction on road 1, females significantly increased speed more than males when using a hand-held call (=scenario #3), hands-free call (=scenario #4), text (=scenario #6), and voice command text (=scenario #7). The Kruskal-Wallis H test was performed on gender, age, vehicle speed, throttle, and offset from the center of the road subcategories, while selecting the more correlated variable with each type of distraction. Finally, the generalized linear regression model was used to provide a significant relationship between the frequency of distraction and highly correlated independent variables.

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1 Introduction

Driving while distracted is anything that diverts the driver's attention from the main task of driving, which is one of the most important factors leading to crashes and fatalities [1]. The 2010 to 2019 U.S. crash data showed nearly 3,000 people died each year in crashes associated with distracted driving [2-4]. Different studies have indicated that talking to passengers, using a cell phone, eating, drinking, and taking off or putting on clothes can distract drivers behind the wheel and lead to accidents and fatalities [5-7]. Although several activities are referred to as the source of distraction in multiple studies, cell phone related activities (calling and texting both hands-free and hand-held) are the riskiest task that may result in distraction for drivers [8-11].

This study aims to investigate six different distractions commonly associated with driving including "eat and drink", "hand-held calls", "hands-free call", "taking off and putting on clothes", "texting", and "voice command text" on drivers' performance and visual impairment. The behavior of 92 participants before, during, and after the distraction was studied using a real-world network including two types of roads (a freeway and an urban arterial road). As a part of the first step of data collection, the gender, age, speed of the vehicle, number of brakes, throttle, offset from the center of the road, acceleration, and deceleration, pushing severity during acceleration, and eye gaze movement from on the road to the out-of-the-road were collected. Using Pearson correlation [12] and factor analysis [13] tests, the highly correlated variables were identified in the second step. For the final step, a new statistical method in the state-of-the-art (Kruskal-Wallis H test) was applied to find the key variable affecting distraction.

The findings of this study can provide insight into policymaking, legislation, education and training, safety guidelines, and car manufacturing standards. The remainder of this article is structured as follows: Section 2: Literature Review, Section 3: Research Methodology, Section 4: Data Analysis, Section 5: Statistical Model Analysis and Discussion, Section 6: Conclusion, and Section 7: References.

2 Literature review

Urban traffic congestion and the probability of incidents are increasing at alarming rates due to an increase in vehicles [14]. Engaging in distractions while driving is the act of diverting the driver's attention from the driving duties. Activities may include communicating or interacting with passengers, texting, browsing the web, eating, drinking, and reaching for devices are prevalent types of driving distractions. Human error causes 94% of all traffic accidents, according to a report by the National Highway Traffic Safety Administration (NHTSA) [15]. Distracted driving is among the most important factors contributing to crashes every year [16]. According to the published report by NHTSA [3], approximately 9% of fatal crashes, 15% of injury crashes, and 15% of crashes reported by the police are caused by distracted driving. In addition, a total of 3142 people were killed and 424,000 people were injured in motor vehicle crashes caused by distracted driving. Cell phone usage is a common distraction for motor vehicle drivers [17]. According to the NHTSA data from 2017, about 5.3% of drivers use their cell phones while driving [18] and among different age groups, younger drivers are more likely to use cell phone while driving [19] since a significant percentage of this group of drivers are interested in texting while driving [20]. Driving while using a cell phone (e.g., to talk, send text messages, or watch videos) can impact many aspects of driving performance, such as reaction time, speed, and decision-making [21-22]. Additionally, using a cell phone while driving can lead to missing enough distances to the front vehicle, braking, headway adaption, missing lane changes, lane position variability, and can lead to a lack of appropriate perception reaction time [23-25]. Cell phone-related crashes in the U.S. killed 385 people and injured 3300 people in 2018 [26]. Additionally, a recent study during the Covid-19 pandemic highlighted that hands-free cell phone use (64 %), GPS use (75 %), and eating and drinking were the most reported distracting behaviors among drivers [27].

The causes and consequences of distractions have been studied in a variety of studies [28-30]. From different types of distraction, hand-held calls, hands-free calls, texting, and voice message text were taken into account as key reasons of distraction since drivers had a reduction in their awareness of the situation [31] and cause more road edge excursions [32]. The study conducted by Harbluk et al. [7] showed that drivers pay less attention to traffic lights at intersections when using mobile phones. Drews et al. [33] showed that in the secondary task condition, drivers react more slowly to the braking lights and demonstrate less control of a vehicle in forward and lateral movements. Owens et al. [34] indicated that sending and receiving text messages while driving lead to increase the time in which eyes are off the road, increase in the mental demand, and steering measures degradation. In another study, He et al. [35] investigated the texting while driving, and the scholars found that texting behind the wheel leads to higher workloads for drivers and more lane excursions. Furthermore, they [35] demonstrated that the impact of vocal texting on driving performance was less than that of manual texting, but it still impaired drivers compared to undistracted driving.

In terms of hand-held calls distraction, Knapper et al. [36] indicated that this secondary task can lead to a significant decrease in vehicle speed. Moreover, holding a phone and entering directions lead to more time eyes off the road and reduced lateral control. Haque and Washington [37] investigated the braking behavior of young drivers in hand-held calls. The results of their study revealed that participants reduced their speed faster and more abruptly.

In terms of hands-free calls distraction, Yan et al. [38] investigated the effects of hands-free calling on braking reaction time, speed variation, the fluctuation of car-following distance, and car-following headway. The results revealed that hands-free calling impaired driving performance considerably. In another study, Alosco et al. [32] demonstrated that hands-free calls impaired driving performance at the same level as eating. The scholars found that when participants were distracted by hands-free calls, they crossed more center lines, were involved in more crashes, and were involved in more pedestrian strikes when compared to when participants were not distracted. Zhao et al. [39] highlighted that drivers who frequently use hands-free calls behind the wheel change their speed more quickly and accelerate at a faster rate. Their braking maneuvers were also harder and they spent more time in the left lane.

In terms of eating and drinking distractions, Alosco et al. [32] found that distracted drivers were more likely to miss the stop signs when eating. Irwin et al. [40] discovered that eating had significant negative effects on Standard Deviation of Lane Positioning (SDLP), lane departure from the road center, and auditory reaction time. Wang et al. [25] specified that high speed has a negative effect on SDLP and trajectory offset (TO), so when speed was increased, SDLP and TO increased.

In terms of putting on or taking off clothing while driving, Bailey et al. [41] found that putting on or taking off clothes distraction is very risky for 57.7% of their research sample size, and it is somewhat risky for 29.6% of the sample. In another research, Honowski [42] specified that putting on or taking off clothing while driving can negatively affect a driver's reaction time.

The state-of-the-art highlighted the negative impact of different types of distracted driving on driver's behavior. In the same line with previous studies, the aim of our study is to examine six different types of distractions integrally and to identify the highly correlated independent variables (driver behavior or vehicle characteristics) with the percentage of distractions using a new statistical test (Kruskal-Wallis H test).

Figure 1 *Morgan State University's driving simulator (a) and Tobii Pro Glasses2 eye-tracking system (b)*

3 Research methodology

3.1 Data collection

A driving simulator (FORUM8 Company's fixed driving simulator with three 40-inch monitors) was used to collect driving performance data from a simulated network of the Baltimore Metropolitan Area (BMA) in Maryland, USA. A real-world network, including two freeway and urban arterial roads, were simulated. I-695 is a 51.46-mile full beltway that extends around Baltimore, Maryland. A portion of I-695 with 3.3 miles (=5.31 km), with four lanes and a 55 mph speed limit was studied so that this section is one of the crowded sections of I-695 in Baltimore city. Total of 92 participants were recruited via flyers distributed manually, online, and through social media at Morgan State University and in the Baltimore metro area. The flyer included contact information, a summary of the study requirements, and details about the monetary compensation for driving the simulator. A valid driver's license was required for participants, and they received $15 an hour for their participation. During the pre-drive interview, we asked the participants whether they wore eyeglasses or if they used hands-free devices in general. As a part of the driving experience, participants were also asked to wear a hands-free device and a jacket or sweater to simulate different distractions. Water and candy were provided to distract them while drinking and eating. After filling out a pre-survey questionnaire, participants drove for about two hours in different simulated scenarios, and then submitted a post-survey questionnaire afterward. As a way of determining the drivers' general behavior, we asked them whether they multitask while driving or not. The results showed that 96% of participants prefer to concentrate on only driving rather than doing anything else. The participants were instructed to adjust their cell phone's volume to a loud ringer before beginning each scenario and to have it handy at all times. In addition, a graphical "Collision" text and a special sound of collision were displayed on the screen when a collision occurred between the vehicles. An eye-tracking system (Tobii Pro Glasses2) was worn by participants to capture gaze frequency and duration. The eye-tracking system can record eye movement by using two sensors mounted on the glasses and is equipped with one central camera which records events in the driving process. Then, by using the Tobii Analyzer tools, all recordings were analyzed. Figure 1 shows the driving simulator and Tobii Pro Galsses eye-tracking system used in this study.

In pre-survey questionnaire, the personal information of a participant, including gender, age, ethnicity, type of driving license (lerner's permit, class A, and class C), and driving experience, were asked and made sure all the questions were answered correctly by all participants. Furthermore, using different technologies e.g., social media during driving, they were asked to specify the general behavior of participants while driving. After filling out the pre-survey form, the participants were asked to drive 7 scenarios including "without distraction (basic scenario)", and six scenarios with distraction including "eating and drink", "hand-held calls", "hands-free call", "taking off and putting on clothes", "texting", and "voice command text". Each distraction scenario was performed at a specific distance from the initial position of the network. The participants had no clue what "hand-held calls", "hands-free calls", "texting", or "voice command texts" were about. To minimize the error of data collection, all participants drove in the simulated network to get familiar with the driving simulator and the network (base scenario - without distraction). The driving simulator and eye tracking system recorded participants' driving performance and eye movement per second for behavioral and gaze analysis. In road 1 (freeway), the distraction was done in km 00+880 from the initial position of the network. In road 2 (urban arterial), the distraction was done in km 00+480 from the initial position of the network. On both roads, distraction points have been identified based on the presence of the real-world natural barriers that cause drivers to be distracted. It is worth mentioning that there were no differences in the content of distractions between the two routes. Detailed descriptions of each scenario are provided in Table 1.

Table 1 *The description of the scenarios*

Scenario ID	Description
1 (Basic scenario)	Without Distraction: driving in the normal condition
2	Eat and Drink: The participant should drink water and eat candy
3	Hand-Held Calls: During the data collection, the observer called the participant's phone number, which the participant had to answer by keeping the phone near his or her ear. A 20-second phone call was taken.
4	Hands-Free Call: During the data collection, the observer called the participant's phone number, which the participant had to answer by hands-free device. A 20-second phone call was taken.
5	Taking off and on putting Clothes: During the data collection, the observer asked the participant to take off and put on his/her jacket
6	Texting: An observer sent a short message by SMS during the data collection, and participants were required to read it, then respond by typing a text. It is recommended that 20 seconds be allowed for viewing, reading, and responding. However, the time interval of viewing, reading and responding is different between participants.
7	Voice Command Text: An observer sent a message by SMS during the data collection, and participants were required to respond by sending a voice command text. In scenario #7, to record and send a voice message, participants had to unlock their cell phones, press the record icon, and press the send icon.

Figure 2 *Simulated network with different road classes and distraction locations*

Every participant experienced different types of distractions randomly without any special order or learning effect. It is worth mentioning that in both phone calls and text distractions, the same content and context were used. During the phone call, participants were asked about their first and family names, as well as their dates of birth. Participants in the text distraction scenario were asked to respond with the name of their high school. Based on the recorded data, variables related to the participants' driving performance were selected for this study, including speed, throttle, brake, offset from road center, steering wheel velocity, and lane changing. Additionally, during the data collection the participant's behavior with a secondary task, which engaged their attention physically, visually, and cognitively that can affect their driving behavior, was monitored. Figure 2 shows the simulated network and 2 distraction points in the simulated network.

3.2 Pre-survey data analysis

Descriptive analysis of pre-survey data reveals that about 43% of participants were female, and 57% of participants were male. Based on the "age" group of the participants, 16% between 18 to 20 years old, 45%

Table 2 *Distraction experience of the participant in the Pre-survey*

	Talk on the phone (hand-held or hands-free), %	Facebook %	Snapchat %	Twitter %	Instagram %	Other Social media (Whats app, Telegram, etc.), %
Never	23	75	63	84	63	87
Rarely	24	15	15	9	15	9
Sometimes	43	8	18	4	15	3
Always	10	2	3	3	7	1

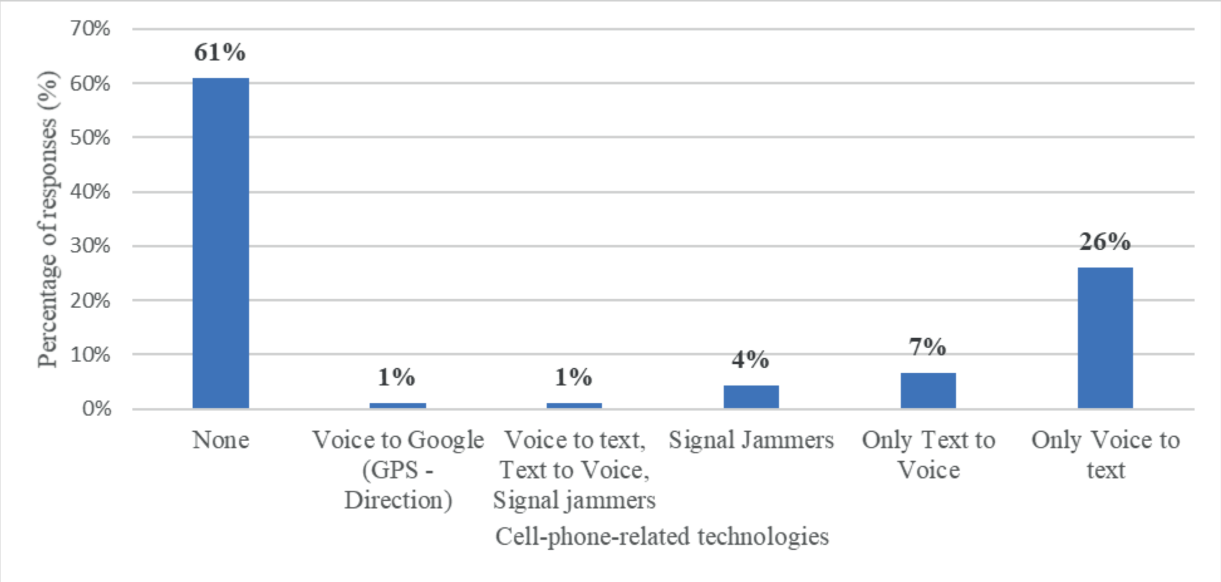


Figure 3 *Cell-phone-related technologies declared by participants*

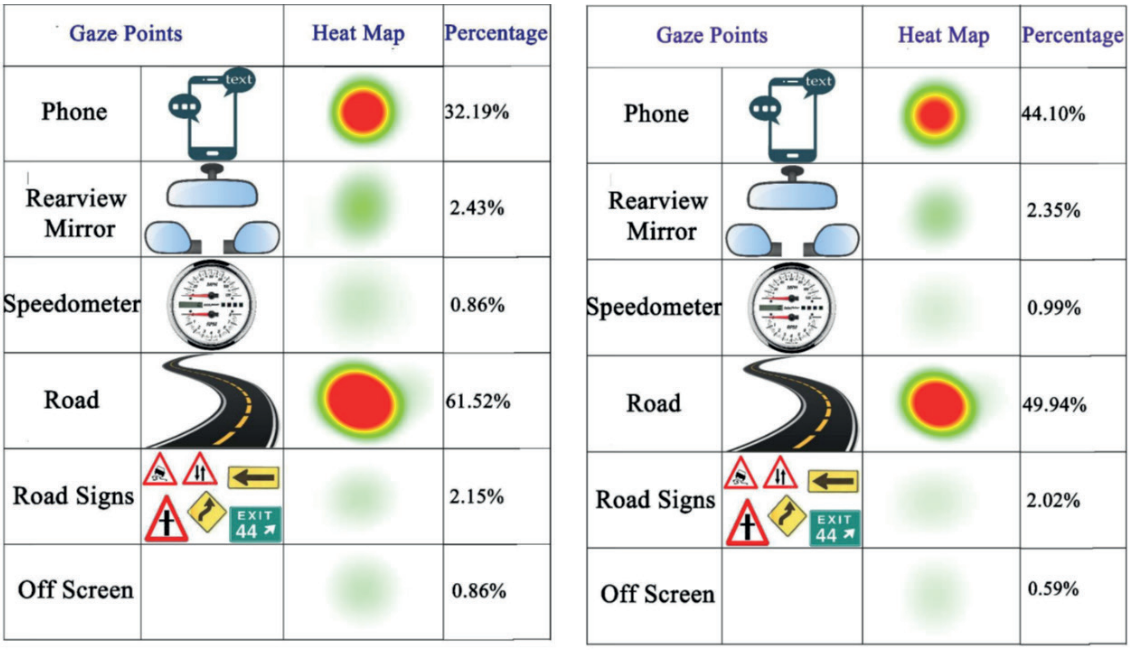
between 21 to 25 years old, 16% between 26 to 30 years old, 10% between 31 to 35 years old, 3% between 35 to 45 years old, 9% between 36 to 40 years old, and 1% more than 40 years old.

The "ethnicity" of the participants specified that 13% Asian/Pacific Islander, 59% black of African American, 2% Hispanic or Latino, 1% native American or American Indian, 12% White, and 13% from the other races.

Participants with previous driving experience were invited to participate in the study. The "driving experience" specified that 6% of participants with learner's permit, 3% of participants with commercial vehicles license (class A), and 90% of the participants with permanent license for all regular vehicles (class C). Furthermore, to designate the milage of driving by participants in the real world, the participants were asked to declare the approximate mileage of driving. The results of driving mileage highlighted that 48% of participants drove a car less than 100 miles, 25% of participants with 100 to 200 miles, 11% of participants with 201 to 300 miles, 10% of participants with 301 to 400 miles, and 7% of participants with more than 400 miles. The 92 participants were selected randomly, so that they can represent a significant percentage of society's behavior. As a goal of this study, the distraction experience of participants was asked by talking to phone (hand-held or hands-free), checking Facebook during driving, checking Snapchat during driving, checking Twitter during driving, checking Instagram during driving, or checking the other social media e.g., Whats app or Telegram during driving. The results of the pre-survey questionnaire on distraction experience are shown in Table 2.

In addition, participants were asked about different cell-phone-related technologies they usually use. Cell-phone-related technologies declared by participants are shown in Figure 3.

A previous comprehensive analysis of distraction dataset [43] indicated that there was a meaningful difference between %driving performance such as speed, throttle, brake, steering wheel velocity, offset from the center of the road, and lane change in the majority of distraction scenarios compared to the base scenario (no distraction). On the same line with the state-of-the-art, our research collected more than 60 variables, including vehicle characteristics, driver characteristics, and road characteristics. Then, Pearson correlation test [44] and factor analysis [13, 45] were used to specify the highly correlated variables to distraction driving. Finally, the highly correlated variables were utilized for statistical analysis of distraction driving. It is worth mentioning that %SPSS software was used for statistical analysis.



a: voice command to text scenario **b**: typing a text message scenario

Figure 4 *Heat maps in gaze fixations analysis- a: voice messaging scenario (Scenario #7), b: texting scenario (=Scenario #6)*

3.3 Eye-tracking analysis

By using an eye-tracking system, the gaze fixations of participants were analyzed when they were exposed to text distraction scenarios (=scenarios #6 and #7). The heat maps of these two scenarios are presented in Figure 4, with red being the scenario with the highest gaze fixations and green being the scenario with the lowest gaze fixations.

Eye-tracker data analysis as shown in Figure 4 revealed that in the voice messaging scenario (=scenario #7), about 62% of gaze fixations were on the road and approximately 32% of gaze fixations were on the phone while recording a voice message. On the other hand, in the typing text message scenario (=scenario #6), the gaze fixations on the road were about 50% and roughly 44% of all gaze fixations were on the phone while driving. This is an alarming change of behaviour with 37% more gaze fixations on the phone than the voice messaging scenario that can easily result in a collision. Since texting and voice command messages are two of the most frequently used types of distraction, the paper did not use eye-tracking analysis in scenarios #2 to #5. Moreover, the limitation of cloud space for recording eye-tracking videos forced the authors to exclude eye-tracking from the remaining scenarios.

3.4 Hypotheses

After collecting the data and identifying the personal information of participants, a Pearson correlation test and factor analysis were used to identify the variables highly correlated with different types of distractions. Hereupon, the variables including age, gender, ethnicity, household income, driving experience, number of vehicles in the household, mileage of driving, speed of vehicle, throttle, offset from the center of the road, and the number of brakes were investigated. A Pearson correlation test and factor analysis specified that age, gender, speed of the vehicle, throttle, and offset of a vehicle from the road center are highly correlated with different types of distraction. Hence, three following hypotheses were provided to investigate speed, throttle, and offset before, during, and after the distraction.

Hypothesis #1, Vehicle Speed: Different studies investigated the speed changes of distracted drivers [46-50]. Trespalacios et al. [46] considered as an average 30 s for speed adaptation behaviour of distracted drivers. Strayer et al. [47] suggested, compared to single-task conditions (i.e., driving only), when drivers use cell phones, their reactions are 18% slower, their following distance is 12% greater, and they take 17% longer to recover lost speed after braking than when they do not use cell phones. Based on observations of 2 million seconds in 7394 baselines (no events), 1237 near crashes, and 617 crashes, Arvin and Khattak [48] suggested a 15-second interval as the time interval during which the distracted driving occurs. Arvin and Khattak also proposed the time interval of 6.66 seconds in crash/near crash events (CNC), and 4.74 seconds in no events for cellphone-oriented distractions, an average of 3.19 seconds and 2.17 seconds in CNC and no events for object-oriented distractions, and an average of 5.51 seconds and 4.42 seconds in CNC and no events for Activity-oriented distractions, respectively. Caird et al.

[49] found that drivers on the phone were distracted for an average of 27 seconds, which was significantly longer than the average distraction time of 19 seconds for drivers who were not on the phone. Finally, Wu and Xu [50] suggested cell phone distractions take 6.63 seconds to detect, talking or singing distractions take 4.90 seconds, focusing on objects takes 3.53 seconds, eating or drinking distracts for 8.67 seconds, changing devices in vehicles distracts for 3.59 seconds, and other distractions take 1.67 seconds. According to the state-of-the-art proposed time intervals for speed and to increase the accuracy of study, a 15 second time interval for before distraction, a 15 second time interval for during the distraction, and a 15 second time interval for after distraction were investigated.

Hypothesis #2, Throttle: The throttle is defined as an input on the accelerator pedal. For a more accurate throttle analysis, similar to the study by Jeihani et al. [51], a 16 second time interval for before distraction, 16 seconds during the distraction, and 16 seconds after distraction were evaluated.

Hypothesis #3, Offset from the road center: Offset from the road center is defined as the distance between the vehicle's position and the center of the road. Wang et al. [25] after examining 1200 distracted driving segments determined that an 8.27-second average trajectory offset was appropriate. In another study, Peng et al. [52] suggested 4 to 5 seconds for analyzing the longitudinal and lateral offsets. Hereupon, based on in-person observing the behavior of participants during the data collection and to increase the accuracy of analysis, similar to throttle analysis, 16 seconds before distraction, 16 seconds during the distraction, and 16 seconds after distraction were analyzed.

After identifying the variables that are highly correlated, the Kruskal-Wallis H test was used to identify the independent variables representative of each distraction type.

4 Data analysis

4.1 Road 1 (freeway road)

A 3.3-mile stretch of I-695 from Exit 27 to the Exit 3 corridor was considered as road #1. The I-695 is a 51.46-mile full beltway that extends around Baltimore, Maryland. Road 1 includes a two-way road with four lanes in each direction. A distraction was done in road 1 at km 0+880 from the network's initial position.

The analysis includes the "weighted average" so that the three weighted average values of all the data records per second, including before, during, and after distraction were obtained. That means one average value for before distraction, one average value for during distraction, and one average value for after distraction were calculated.

To accurately assess participants' driving behavior in all seven scenarios, they were categorized by gender and age. That means the speed, throttle, and offset from the road center were evaluated for male and female participants and based on their age groups. To report the changes of speed, throttle, and offset, two comparison sets including "during distraction with before distraction (during-before)", and "after distraction with during distraction (after-during)" were designed. If the weighted average value in during distraction was higher than before distraction, it means the speed, throttle, and offset were increased in the "during-before" set. Similarly, if the weighted average value in after distraction was higher than during distraction, it means the speed, throttle, and offset were increased in the "after-during" set. Table 3 shows the percentage of increasing or decreasing speed, throttle, and offset for male participants in "during-before" set.

As shown in Table 3, for instance in "eat and drink" scenario (=scenario #2), 100% of male participants preferred to increase the speed during the distraction toward before distraction. Furthermore, 13% and 30% of male participants preferred to increase throttle and offset from the center of the road, respectively, in scenario #2. As an average for 7 scenarios, 96%, 13%, and 19% of male participants increased the speed, throttle, and offset, respectively. According to the results of male participants, although a significant percentage of male participants increased speed during distractions, however, 87% and 81% decreased throttle and offset, respectively. It means that during the distraction, increasing speed cannot enhance pushing harder on accelerator of male participants' distance from the center of the road. Table 4 shows the percentage of increasing or decreasing speed, throttle, and offset for male participants in "after-during" set.

As shown in Table 4, male participants behaved completely different after distraction. The throttle and offset were increased on average across seven scenarios, while the speed after distraction increased less than during-before set. By using the same methodology of male participants, Table 5 shows the percentage of increasing or decreasing speed, throttle, and offset for female participants in the "during-before" set.

As can be seen in Table 5 and as a comparison with the results of Table 3, female participants increased their speed in scenarios #3, #4, #6, and #7 more than male participants. The throttle was increased more in scenarios #2, #3, #4, and #5 towards the male participants. The offset from the road center for female participants was increased more in scenario #3. Table 6 shows the percentage (%) of female participant in "after-during" distraction set.

As can be seen in Table 6, in scenarios #2, #3, #4, and #5, female participants' speed increased towards the male participants after distraction. The throttle was increased in scenarios #2, #3, and #4 towards the male participants after distraction. Additionally, female participants preferred to increase the distance from the

Table 3 *The percentage (%) of male participant in "during-before" distraction set on road #1*

Scenario/Variable	Speed		Throttle		Offset from the center of road	
	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)
No distraction (#1)	100	0	9	91	9	91
Eat and Drink (#2)	100	0	13	87	30	70
Hands held call (#3)	95	5	19	81	16	84
Hands-free call (#4)	95	5	16	84	16	84
Take off and on clothes (#5)	91	9	9	91	18	82
Text (#6)	93	7	7	93	24	76
Voice Commands text (#7)	98	2	17	83	19	81
Average of 7 scenarios	96.0	4.0	12.9	87.1	18.9	81.1

Table 4 *The percentage (%) of male participant in "after-during" distraction set on road #1*

Scenario/Variable	Speed		Throttle		Offset from the center of road	
	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)
No distraction (#1)	53	47	84	16	80	20
Eat and Drink (#2)	57	43	78	22	78	22
Hands held call (#3)	51	49	74	26	60	40
Hands-free call (#4)	56	44	77	23	63	37
Take off and on clothes (#5)	59	41	86	14	86	14
Text (#6)	71	29	95	5	57	43
Voice Commands text (#7)	64	36	76	24	67	33
Average of 7 scenarios	58.7	41.3	81.4	18.6	70.1	29.9

Table 5 *The percentage (%) of female participant in "during-before" distraction set on road #1*

Scenario/Variable	Speed		Throttle		Offset from the center of road	
	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)
No distraction (#1)	100	0	3	97	5	95
Eat and Drink (#2)	100	0	15	85	20	80
Hands held call (#3)	100	0	22	78	19	81
Hands-free call (#4)	100	0	21	79	16	84
Take off and on clothes (#5)	75	25	15	85	10	90
Text (#6)	100	0	0	100	14	86
Voice Commands text (#7)	100	0	14	86	14	86
Average of 7 scenarios	96.4	3.6	12.9	87.1	14.0	86.0

center of the road after distraction in scenarios #2, #3, and #6 towards the male participants. As a conclusion of male and female participants on road 1 before, during, and after distraction, the following results are obtained.

A comparison of the "during-before" distraction set among females and males participants revealed the following consequences: Female participants increased the speed more than male participants in hand-held call (=scenario #3), hands-free call (=scenario #4), text (=scenario #6), and voice command text (=scenario #7). Throttle results showed that the value of throttle was increased more for female participants in scenarios eat and drink (=scenario #2), hand-held call (=scenario #3), hands-free call (=scenario #4), and take off and put on clothes (=scenario #5). In addition, female participants increased the offset from the center of the road in scenario hand-held call (=scenario #3) toward the male participants.

Table 6 *The percentage (%) of female participant in "after-during" distraction set on road #1*

Scenario/Variable	Speed		Throttle		Offset from the center of road	
	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)
No distraction (#1)	54	46	82	18	69	31
Eat and Drink (#2)	65	35	85	15	80	20
Hands held call (#3)	65	35	81	19	65	35
Hands-free call (#4)	61	39	82	18	63	37
Take off and on clothes (#5)	60	40	65	35	65	35
Text (#6)	49	51	74	26	71	29
Voice Commands text (#7)	57	43	60	40	66	34
Average of 7 scenarios	58.7	41.3	75.6	24.4	68.4	31.6

Table 7 *The percentage (%) of male participants in "during-before" distraction set on road #2*

Scenario/Variable	Speed		Throttle		Offset from the center of road	
	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)
No distraction (#1)	49	51	20	80	40	60
Eat and Drink (#2)	30	70	9	91	35	65
Hands held call (#3)	30	70	26	74	47	53
Hands-free call (#4)	44	56	40	60	37	63
Take off and on clothes (#5)	9	91	5	95	59	41
Text (#6)	45	55	21	79	50	50
Voice Commands text (#7)	51	49	28	72	51	49
Average of 7 scenarios	36.9	63.1	21.3	78.7	45.6	54.4

A comparison of the "after-during" distraction set among females and males participants revealed the following consequences: Female participants increased the speed more than male participants in without distraction (=scenario #1), eat and drink (=scenario #2), hand-held call (=scenario #3), hands-free call (=scenario #4), take off and put on clothes (=scenario #5). Throttle results showed that the value of throttle was increased more for female participants in scenarios eat and drink (=scenario #2), hand-held call (=scenario #3), and hands-free call (=scenario #4). In addition, female participants increased the offset from the center of the road in scenarios eat and drink (=scenario #2), hand-held call (=scenario #3), and text (=scenario #6) toward the male participants.

Based on a comparison of "age" and considering that 45% of male and female participants were between the ages of 21 and 25, 43% of female participants with age group 21-25 years old in without distraction (=scenario #1), 45% in eat and drink scenario (=scenario #2), 43% in hand-held call (=scenario #3), 44% in hands-free call (=scenario #4), 45% in take off and put on clothes (=scenario #5), 43% in text (=scenario #6), and 43% in voice commands text (=scenario #7) increased the vehicle speed. In terms of throttle, 15% of female participants with age group 21-25 years old increased throttle in eat and drink scenario (=scenario #2), 8% in hand-held call (=scenario #3), 10% in hands-free call (=scenario #4), 5% in take off and on clothes (=scenario #5). In terms of offset, 5% of female participants with age group 21-25 years old preferred to keep distance from the center of the road in without distraction (=scenario #1), 5% in eat and drink scenario (=scenario #2), 11% in hand-held call (=scenario #3), 5% in hands-free call (=scenario #4), 10% in take off and on clothes (=scenario #5), 6% in text (=scenario #6), and 9% in voice commands text (=scenario #7).

4.2 Road 2 (urban arterial road)

An urban arterial road including three lanes in each direction was simulated as shown in Figure 2. In accordance with the real-world road characteristics with 3.8 miles (=6.11 km), a 35 mph speed limit was simulated. Furthermore, the distraction was done at km 0+480 from the road's initial position. The same methodology as explained for road 1 was applied to study the behavior of male and female participants before, during, and after the distraction. To report the

***Table 8** The percentage (%) of male participants in "after-during" distraction set on road #2*

Scenario/Variable	Speed		Throttle		Offset from the center of road	
	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)
No distraction (#1)	38	62	87	13	78	22
Eat and Drink (#2)	39	61	91	9	65	35
Hands held call (#3)	40	60	88	12	63	37
Hands-free call (#4)	47	53	84	16	70	30
Take off and on clothes (#5)	59	41	91	9	55	45
Text (#6)	40	60	88	12	64	36
Voice Commands text (#7)	42	58	86	14	65	35
Average of 7 scenarios	43.6	56.4	87.9	12.1	65.7	34.3

***Table 9** The percentage (%) of female participants in "during-before" distraction set on road #2*

Scenario/Variable	Speed		Throttle		Offset from the center of road	
	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)
No distraction (#1)	62	38	20	80	42	58
Eat and Drink (#2)	50	50	20	80	30	70
Hands held call (#3)	58	42	45	55	53	47
Hands-free call (#4)	45	55	37	63	39	61
Take off and on clothes (#5)	40	60	15	85	55	45
Text (#6)	49	51	29	71	43	57
Voice Commands text (#7)	54	46	34	66	46	54
Average of 7 scenarios	51.1	48.9	28.6	71.4	44.0	56.0

***Table 10** The percentage (%) of female participants in "after-during" distraction set on road #2*

Scenario/Variable	Speed		Throttle		Offset from the center of road	
	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)
No distraction (#1)	32	68	92	8	85	15
Eat and Drink (#2)	25	75	85	15	80	20
Hands held call (#3)	22	78	89	11	74	26
Hands-free call (#4)	47	53	89	11	66	34
Take off and on clothes (#5)	40	60	85	15	75	25
Text (#6)	23	77	94	6	63	37
Voice Commands text (#7)	23	77	80	20	71	29
Average of 7 scenarios	30.3	69.7	87.7	12.3	73.4	26.6

changes of speed, throttle, and offset, two comparison sets including "during distraction with before distraction (during-before)", and "after distraction with during distraction (after-during)" were designed. Table 7 shows the percentage of increasing or decreasing speed, throttle, and offset for male participants in "during-before" set.

According to Table 7, male participants preferred to decrease the vehicle speed in scenarios #2, #3, #4, #5, and #6. In most scenarios, including scenarios #2, #3, #4, #5, #6, and #7, the throttle was decreased. While the male participants increased their speed, the offset was decreased in scenarios #2, #3, and #4, which indicated that they could control the vehicle. Table 8 shows the behavior of male participants in "after-during" set on road 2.

As can be seen in Table 8, a significant percentage of male participants decreased the speed, increased the throttle, and increased the offset after distraction. To analyze the behavior of female participants, Tables 9 and 10 show the percentage (%) of female participants in "during-before" and "after-during" sets, respectively.

Table 9 shows that female participants decreased their speed during the distraction more than the male participants. In terms of throttle and offset, female participants exhibited the same behavior as male participants in "during-before" set. Table 10 shows the percentage of female participants in "after-during" distraction set on road #2.

According to Table 10, female participants decreased their speed more than male participants after distraction. Additionally, female participants increased the offset more than male participants. In regards to the throttle after distraction, the same behavior was observed as in the case of male participants.

As a conclusion of male and female participants on road 2 before, during, and after the distraction, the following results are obtained.

During distraction, in scenarios #2, #3, #4, #5, #6, and #7, female participants increased their speed more than male participants. In scenarios #2, #3, #5, #6, and #7, female participants increased throttle more than male participants. Moreover, female participants keep their distance from the center of the road when distracted with a hand-held call (=scenario #3) or a hands-free call (=scenario #4).

Female participants exhibited conservative driving behavior after distractions, as they did not increase vehicle speed in all the distraction scenarios. In scenarios #3, #4, and #6, female participants increased the throttle more than male participants. Additionally, female participants in scenarios #2, #3, #5, and #7 kept a greater distance from the center of the road than male participants.

Based on a comparison of "age" and considering that 45% of male and female participants were between the ages of 21 and 25, 25% of female participants with age group 21-25 years old in without distraction (=scenario #1), 25% in eat and drink scenario (=scenario #2), 24% in hand-held call (=scenario #3), 24% in hands-free call (=scenario #4), 20% in take off and on clothes (=scenario #5), 23% in text (=scenario #6), and 23% in voice commands text (=scenario #7) preferred to increase the speed. In terms of throttle, 5% of female participants with age group 21-25 years old increased throttle in eat and drink scenario (=scenario #2), 21% in hand-held call (=scenario #3), 16% in hands-free call (=scenario #4), 10% in take off and on clothes (=scenario #5), 17% in text message (=scenario #6), and 9% in voice command text message (=scenario #7). In terms of offset, 15% of female participants with age group 21-25 years old preferred to keep the distance from the center of the road in without distraction (=scenario #1), 20% in eat and drink scenario (=scenario #2), 21% in hand-held call (=scenario #3), 13% in hands-free call (=scenario #4), 15% in take off and on clothes (=scenario #5), 17% in text (=scenario #6), and 20% in voice commands text (=scenario #7).

5 Statistical model analysis and discussion

To determine if highly correlated variables (gender, age, speed, throttle, and offset) influence different types of distraction, the Kruskal-Wallis H test [53] was used. As a rank-based nonparametric test, the Kruskal-Wallis H test can be used to determine if there is a statistically significant difference between the two or more groups of an independent variable on a continuous or ordinal dependent variable [54]. The distraction of the participant is a dependent variable in our research that includes Likert scales (e.g., distracted, somewhat distracted, not distracted). In the context of distracted, the participant is completely distracted by those six types of distraction. Participants that were somewhat distracted were able to control their vehicles vigilantly despite distractions. A participant who was not distracted was completely attentive during the distraction. Each participant's distraction level was measured by how long they spent distracted from the road to the off-road. It is important to note that the Kruskal-Wallis H test is only reported for scenarios #2 through #7 when the participants were distracted during the roads.

Generally, four hypotheses are investigated for Kruskal-Wallis H test [55] including: 1) The dependent variable should be measured on an ordinal or continuous scale; 2) Independent variables should consist of two or more categorical groups (in this paper age and gender categories for speed, throttle, and offset); 3) Observations should be independent, which means there should be no relationship between observations within and between groups; 4) The distributions in each group have the same shape, which means they are also equally variable. According to the fourth hypothesis, the Kruskal-Wallis H test is used to compare the medians of dependent variables when distributions have the same shape. In the case of different distribution shapes, the Kruskal-Wallis H test can be used to compare the mean ranks.

5.1 Scenario #2 (=eat and drink) on "road 1" and "road 2"

The results of Kruskal-Wallis H test for eat and drink type of distraction showed "offset" variable can reject the null hypothesis (=the mean ranks of the groups are the same). Hereupon, offset from the road center is the best variable for eat-and-drink distractions on the road 1. According to the Kruskal-Wallis H test results for eat-and-drink distraction on road 2, "age" is the best variable to reject the null hypothesis.

***Table 11** The result of Kruskal-Wallis H test on road 1 and road 2*

Type of distraction	Independent-Samples Kruskal-Wallis Test Summary		
		Road 1 (Offset)	Road 2 (Age)
Eat and drink distraction	Total N	92	92
	Test Statistic	8.97	11.06
	Asymptotic Sig.(2-sided test)	.034	.0293
		Road 1 (Offset)	Road 2 (Offset)
Hand-held call distraction	Total N	92	92
	Test Statistic	6.743	4.746
	Asymptotic Sig.(2-sided test)	.009	.029
		Road 1 (Offset)	Road 2 (Throttle)
Hands-free call distraction	Total N	92	92
	Test Statistic	4.884	13.824
	Asymptotic Sig.(2-sided test)	.027	.0403
		Road 1 (Age)	Road 2 (Speed)
Take off and put on clothes distraction	Total N	92	92
	Test Statistic	12.27	11.63
	Asymptotic Sig.(2-sided test)	.0131	.0281
		Road 1 (Offset)	Road 2 (Offset)
Text distraction	Total N	92	92
	Test Statistic	15.221	17.785
	Asymptotic Sig.(2-sided test)	.000	.002

***Table 12** The result of Kruskal-Wallis H test for voice command distraction on road 1 and road 2*

Independent-Samples Kruskal-Wallis Test Summary			
	Road 1		Road 2 (Offset)
	(Throttle)	(Offset)	
Total N	92	92	92
Test Statistic	6.323	12.456	12.723
Asymptotic Sig.(2-sided test)	.012	.001	.002

5.2 Scenario #3 (=hand-held call) on "road 1" and "road 2"

According to Kruskal-Wallis H test results for hand-held call distraction on road 1 and road 2, "offset" is the best variable to reject the null hypothesis.

5.3 Scenario #4 (=hands-free call) on "road 1" and "road 2"

The results of Kruskal-Wallis H test for hands-free call distraction on road 1 highlighted that "offset" is the best variable to reject the null hypothesis. The results of Kruskal-Wallis H test for hands-free call distraction on road 2 specified that "throttle" is the best variable to reject the null hypothesis.

5.4 Scenario #5 (=take off and put on clothes) on "road 1" and "road 2"

Based on the Kruskal-Wallis H test results for take off and put on clothes distraction on road 1, "age" was deemed the best variable for rejecting the null hypothesis. Furthermore, "speed" was selected as the best independent variable to reject the null hypothesis on road 2.

5.5 Scenario #6 (=text) on "road 1" and "road 2"

Based on the Kruskal-Wallis H test results for text distraction on road 1, "offset" was identified the best variable for rejecting the null hypothesis. A value of zero for the offset error on road 1 was obtained.

Table 13 *The highly correlated independent variables from Kruskal-Wallis H test*

Scenario	Description of the scenario	Road 1	Road 2
#2	Eat and drink	Offset	Age
#3	Hand-held call	Offset	Offset
#4	Hands-free call	Offset	Throttle
#5	Take off and on clothes	Age	Speed
#6	Text message	Offset	Offset
#7	Voice command text	Throttle, Offset	Offset

Table 14 *The generalized linear regression models for the frequency of distracted participants*

Scenario	Road #1	Road #2
#2	Frequency of distraction = 200.85 -0.032*Speed + 58.54*Offset -0.092*Throttle + 11.55*Gender + 4.43*Age	Frequency of distraction = 74.22 +1.34*Speed + 3.45*Offset +45.88*Throttle + 8.67*Gender + 3.39*Age
#3	Frequency of distraction = 103.54 +0.16*Speed + 84.13*Offset +17.55*Throttle + 6.03*Gender -1.88*Age	Frequency of distraction = 44.51 +1.05*Speed + 54.03*Offset +1.42*Throttle + 7.05*Gender + 2.46*Age
#4	Frequency of distraction = 50.78 +1.96*Speed + 15.84*Offset -6.09*Throttle + 9.17*Gender -0.302*Age	Frequency of distraction = 42.96 +1.05*Speed + 1.51*Offset +55.25*Throttle + 7.5*Gender +2.52*Age
#5	Frequency of distraction = 119.53 +1.91*Speed + 1.76*Offset +90.15*Throttle + 0.84*Gender +5.21*Age	Frequency of distraction = 87.67 +1.69*Speed + 3.46*Offset +61.95*Throttle + 9.03*Gender +3.81*Age
#6	Frequency of distraction = 156.67 -0.115*Speed + 16.22*Offset +1.89*Throttle + 0.27*Gender -3.33*Age	Frequency of distraction = 42.97 +1.008*Speed + 54.42*Offset +1.39*Throttle + 7.51*Gender +2.55*Age
#7	Frequency of distraction = 143.002 +0.261*Speed + 15.88*Offset +22.69*Throttle + 1.08*Gender -1.87*Age	Frequency of distraction = 50.16 +1.23*Speed + 66.96*Offset +1.51*Throttle + 7.53*Gender +2.51*Age

Accordingly, the variable offset on road 1 can reject the null hypothesis with a great accuracy. Similarly, the "offset" variable was selected as the best independent variable to reject the null hypothesis on road 2.

5.6 Scenario #7 (=voice command text) on "road 1" and "road 2"

According to Kruskal-Wallis H test results on road 1, two independent variables including "throttle and offset" were capable of rejecting the null hypothesis. In road 2, the variable "offset" was considered as an independent variable that could reject the null hypothesis.

Asymptotic Significant error in Tables 11 and 12 shows the error value of the test that should be less than 5% confidence interval. Table 11 shows that the significant error is always less than the confidence interval, indicating that the statistical analysis is highly accurate. Considering the two highly correlated independent variables for voice command distraction on road 1, this type of distraction was not mentioned in Table 11. The results of voice command distraction are shown in Table 12.

As a discussion of the statistical analysis and for different categories of distraction, Table 13 shows highly correlated independent variables from the Kruskal-Wallis H test.

To identify a statistical relationship between the distraction type (distracted, somewhat distracted, and not distracted) and the highly correlated independent variables, the generalized linear regression models were developed. The model with the lowest significant error (< 5%) was reported for all independent variables. Table 14 shows twelve linear regression models on roads #1 and #2.

6 Conclusions

Public safety is at risk due to distracted driving. Since 2005, the distracted driving fatalities have increased dramatically due to the dramatic rise in texting volume. As technology advances, motor vehicle drivers are increasingly exposed to distractions. Injuries and fatalities may occur when the driver's attention is diverted from on the road to out-of-the road. Cell phone use is one of the most common distractions for motor vehicle drivers. In addition to the cell phone use, other distractions e.g., eating or drinking, taking off or putting on clothes, reading, using a navigation system, grooming while driving, distractions from kids or other passengers, distraction by pets, adjusting climate control while driving, playing with the radio, reaching driver's wallet while driving, and looking at a traffic accident or an eye-catching billboard (rubbernecking) were taken into account as the major distraction ways of vehicle drivers. In this study, a real-world network, including the two different roads (a freeway and an urban arterial), was simulated to examine the behavior of vehicle drivers during distraction. After in-person monitoring of both roads and based on the location of physical barriers on the road, the location of billboards and the points with a high probability of crashes, one point on each road were considered to distract the drivers. A car simulator was used to model the network, and 92 participants from inside and outside of the university were recruited to drive 7 scenarios including without distraction, distraction by eating and drinking, distraction by hand-held call, distraction by hands-free call, distraction by taking off or putting on clothes, distraction by texting a message, and distraction by sending a voice command text. Various age groups of participants were invited to address different driving behaviors. In addition, participants with prior driving experience were invited. Participants were asked to complete a pre-survey questionnaire before starting the scenarios. Participant's personal information was collected in a pre-survey questionnaire. The participants then drove the scenarios in each 2 hours' sessions. Participants were asked to complete a post-survey questionnaire after completing the scenarios to identify their experience with the car simulator. An initial database was collected from the car simulator and highly correlated distracted driving variables were identified using the Pearson correlation and factor analysis tests. Using the Pearson correlation and factor analysis tests, variables such as gender, age, vehicle speed, throttle, and vehicle offset from the center of the road were identified as highly correlated variables.

After reviewing the state-of-the-art, three hypotheses were developed to analyze speed, throttle, and offset before, during, and after the distraction. Literature review and personal observation of participants' behavior during the distraction on the road led to the time intervals for before, during, and after distraction. In the state-of-the-art, Kruskal-Wallis H tests has been less used. Hereupon, this gap in the literature was addressed in our research. This paper presents the following findings and contributions:

As a conclusion of male and female participants on road 1 in "during-before" distraction sets, females significantly increased speed more than males when using a hand-held call (=scenario #3), hands-free call (=scenario #4), text (=scenario #6), and voice command text (=scenario #7). Among the scenarios, there was an increase in throttle value for female participants in eat and drink (=scenario #2), hand-held call (=scenario #3), hands-free call (=scenario #4), and taking off and on clothes (=scenario #5). Female participants also increased their offset from the center of the road in scenario hand-held call (=scenario #3) compared to male participants. In "after-during" distraction sets, in the scenarios without distraction (=scenario #1), eating or drinking (=scenario #2), hand-held calling (=scenario #3), hands-free calling (=scenario #4), and taking off and putting on clothes (=scenario #5), female participants increased their speed more than male participants. In scenarios eat and drink (=scenario #2), hand-held call (=scenario #3), and hands-free call (=scenario #4), throttle value increased more for female participants. Additionally, female participants increased the offset from the center of the road in scenarios eat and drink (=scenario #2), hand-held call (=scenario #3), and text (=scenario #6).

As a conclusion of male and female participants on road 2 in "during-before" distraction sets, Female participants increased their speed more than male participants in scenarios #2, #3, #4, #5, #6, and #7. Female participants increased throttle more than male participants in scenarios #2, #3, #5, #6, and #7. In addition, female participants keep their distance from the center of the road when distracted by a hand-held call (=scenario #3) or a hands-free call (=scenario #4). In "after-during" distraction sets, female participants drove conservatively, not increasing vehicle speed after distractions. Female participants increased the throttle more than male participants in scenarios #3, #4, and #6. Furthermore, female participants in scenarios #2, #3, #5, and #7 keep a greater distance from the center of the road than male participants.

The highly correlated variable for each type of distraction was specified by Kruskal-Wallis H test analysis. As shown in Table 13, In scenarios #2, #3, #4, #6, and #7, "offset" was identified as a highly correlated variable when the participant drove on a freeway road (road 1). Likewise, age and throttle were found in scenarios #5 and #7 respectively as highly correlated variables when the participant drove on a freeway road (road 1). On road 2 (an urban arterial road), age (in scenario #2), offset (in scenarios #3, #6, and #7), throttle (in scenario #4), and speed (in scenario #5) were specified as highly correlated variables with distracted driving. Additionally, the statistical relationship of distracted participants in terms of highly correlated independent variables were specified by using linear regression models.

Sending a text, eating or drinking, applying makeup, working with a cell phone, texting, and using hand-held calls are all of these tasks that negatively affect the quality of driving. Drivers are responsible for keeping themselves, their passengers, and other road users safe by concentrating on the road. Visual distractions (eyes off the road), manual distractions (hands off the wheel), and cognitive distractions (mental diversion) are all main activities that lead to distracted driving. Legislation, public awareness campaigns, and technological solutions have all been implemented to combat distracted driving. Many jurisdictions prohibit handheld phone use and texting while driving. Public campaigns aim to raise awareness about distraction dangers. As well as alerting drivers to potential hazards, advanced driver assistance systems (ADAS) also provide safety features. Evaluating the efficacy of these interventions provides insights into their limitations and potential for improvement. Advancements in technology offer practical ways for mitigating distracted driving including driver-monitoring systems that use cameras and sensors to detect signs of distraction. These systems provide issue warnings or intervene if a driver appears distracted. Additionally, improved voice recognition and gesture control interfaces can reduce manual interactions and lead to traffic safety. Education programs and cognitive training can enhance drivers' ability and attention on driving tasks. These interventions aim to foster safer driving behaviors by cultivating a sense of responsibility and self-regulation. Incorporating human-centered design principles in vehicle and interface design can play a fundamental role in minimizing distraction. Providing the user-friendly interfaces can efficiently reduce the cognitive load on drivers, allowing them to focus on the road, and enhance traffic safety. By analyzing patterns of distraction and identifying high-risk situations, interventions can be tailored to specific contexts and individual behaviors. Stricter and rigorous implementation of regulations addressing distracted driving, combined with elevated fines and penalties, can be an enforcement tool to reduce the distracted driving. However, stricter, and rigorous distracted driving laws should be investigated based on the equity concepts so that this approach takes into account the equitable demands of the community. As a practical solution to eliminate the negative consequences of distracted driving, efficient approaches are suggested, including providing comprehensive education, integrating road safety modules into school curricula and driver education programs, and addressing the safe driving habits. These programs can extremely foster an environment where distraction is socially unacceptable. To improve the situation and eliminate weak points that lead to crashes caused by distracted driving, a multifaceted approach should be implemented. By combining the legislative efforts, technological innovations, and education, a holistic strategy can be developed to create safer road environments. Pulling over for a few seconds in cases if the driver plans to eat or drink, implementing navigation systems e.g., GPS before heading to the destination, familiarizing with the vehicle's controls especially any infotainment system with touch screens, setting up the radio stations or streaming music before start the vehicle, pulling over in the cases of taking a call, sounding off the notifications that distract driver's attention while driving, and limit the time looking away from the road or taking the hands off the wheel are practical ways that improve traffic safety while driving.

Some limitations of the study worth mentioning are including more distraction ways, different types of weather condition, more participants and developing models such as distracted prediction or recognition, machine or deep learning models, multilevel models, or hierarchical models. Policymaking, legislation, education, training, safety guidelines, and car manufacturing standards can benefit from the findings of this study. In the U.S., the distracted driving laws have been enacted in many states. Teen drivers should be prohibited from texting while driving, hands-free laws should be implemented, and passengers under the age of 18 should not be allowed to ride along with them. A graduated driver licensing system (GDL) provides new drivers with lower-risk driving experience by gradually granting them driving privileges. Various states have installed rumble strips on highways to alert drowsy, distracted, or otherwise inattentive drivers. Certain types of crashes can be reduced by these rumble strips.

As a future work, the authors are interested in working on machine or deep learning models, k-means clustering, and logistic regression.

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Conflicts of 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.

References

[1] OVIEDO-TRESPALACIOS, O., KING, M., VAEZIPOUR, A., TRUELOVE, V. Can our phones keep us safe? A content analysis of smartphone applications to prevent mobile phone distracted driving. *Transportation Research Part F: Traffic Psychology and Behaviour* [online]. 2019, 60, p. 657-668. ISBN 1369-8478, eISBN 1873-5517. Available from: https://doi.org/10.1016/j.trf.2018.11.017

[2] FLAHERTY, M. R., KIM, A. M., SALT, M. D., LEE, L. K. Distracted driving laws and motor vehicle crash fatalities. *Pediatrics* [online]. 2020, 145(6), e20193621. ISSN 0031-4005, eISSN 1098-4275. Available from: https://doi.org/10.1542/peds.2019-3621

[3] NHTSA. Distracted driving 2019. U.S. DOT, 2021.

[4] BRAITMAN, K. A., BRAITMAN, A. L. Patterns of distracted driving behaviors among young adult drivers: exploring relationships with personality variables. *Transportation Research Part F: Traffic*

Psychology and Behaviour [online]. 2017, 46, p. 169-176. ISBN 1369-8478, eISBN 1873-5517. Available from: https://doi.org/10.1016/j.trf.2017.01.015

[5] KLAUER, S. G., GUO, F., SIMONS-MORTON, B. G., OUIMET, M. C., LEE, S. E., DINGUS, T. A. Distracted driving and risk of road crashes among novice and experienced drivers. *The New England Journal of Medicine* [online]. 2014, 370(1), p. 54-59. ISSN 0028-4793. Available from: https://doi.org/10.1056/NEJMsa1204142

[6] AHANGARI, S., JEIHANI, M., ARDESHIRI, A., RAHMAN, M., DEHZANGI, A. Enhancing the performance of a model to predict driving distraction with the random forest classifier. *Transportation Research Record* [online]. 2021, 2675(11), p. 612-622. ISSN 0361-1981, eISSN 2169-4052. Available from: https://doi.org/10.1177/03611981211018695

[7] HARBLUK, J. L., NOY, Y. I., TRBOVICH, P. L., EIZENMAN, M. An on-road assessment of cognitive distraction: impacts on drivers' visual behavior and braking performance. *Accident Analysis and Prevention* [online]. 2007, 39(2), p. 372-379. ISSN 0001-4575, eISSN 1879-2057. Available from: https://doi.org/10.1016/j.aap.2006.08.013

[8] ENGELBERG, J. K., HILL, L. L., RYBAR, J., STYER, T. Distracted driving behaviors related to cell phone use among middle-aged adults. *Journal of Transport and Health* [online]. 2015, 2(3), p. 434-440. ISSN 2214-1405, eISSN 2214-1413. Available from: https://doi.org/10.1016/j.jth.2015.05.002

[9] TISON, J., CHAUDHARY, N., COSGROVE, L. National phone survey on distracted driving attitudes and behaviors. United States. National Highway Traffic Safety Administration: 2011.

[10] OVERTON, T. L., RIVES, T. E., HECHT, C., SHAFI, S., GANDHI, R. R. Distracted driving: prevalence, problems, and prevention. *International Journal of Injury Control and Safety Promotion* [online]. 2015, 22(3), p. 187-192. ISSN 1745-7300, eISSN 1745-7319. Available from: https://doi.org/10.1080/17457300.2013.879482

[11] GLIKLICH, E., GUO, R., BERGMARK, R. W. Texting while driving: A study of 1211 US adults with the Distracted Driving Survey. *Preventive Medicine Reports* [online]. 2016, 4, p. 486-489. eISSN 2211-3355. Available from: https://doi.org/10.1016/j.pmedr.2016.09.003

[12] SEDGWICK, P. Pearson's correlation coefficient. *The Bmj* [online]. 2012. 345, e4483. eISSN 1756-1833. Available from: https://doi.org/10.1136/bmj.e4483

[13] KLINE, P. *An easy guide to factor analysis* [online]. London: Routledge, 2014. eISBN 9781315788135. Available from: https://doi.org/10.4324/9781315788135

[14] ANSARIYAR, A., TAHMASEBI, M. Investigating the effects of gradual deployment of market penetration rates (MPR) of connected vehicles on delay time and fuel consumption. *Journal of Intelligent and Connected Vehicles* [online]. 2022, 5(3), p. 188-198. ISSN 2399-9802. Available from: https://doi.org/10.1108/JICV-12-2021-0018

[15] SINGH, S. Critical reasons for crashes investigated in the national motor vehicle crash causation survey. Washington, DC: NHTSA's National Center for Statistics and Analysis, 2015.

[16] Distracted driving research and statistics - EndDD [online]. 2022. Available from: https://www.enddd.org/research-stats/?gclid=Cj0KCQiArsefBhCbARIsAP98hXRhp3r87l8q40kH2VER1lR9Stjhsa70Ms0qb-P_e4nVufqbokioSLMaAjUNEALw_wcB

[17] PICKRELL, T. M. Driver electronic device use in 2013. United States: National Highway Traffic Safety Administration, 2015.

[18] SCHROEDER, P., WILBUR, M., PENA, R. National survey on distracted driving attitudes and behaviors-2015. United States: National Highway Traffic Safety Administration, 2018,

[19] JEIHANI, M., JAVID, R., SADEGHVAZIRI, E. Educating the public about distracted driving and evaluating distraction-prevention technologies. Baltimore, MD: National Transportation Center, Morgan State University, 2022.

[20] HOFF, J., GRELL, J., LOHRMAN, N., STEHLY, C., STOLTZFUS, J., WAINWRIGHT, G., HOFF, W. S. Distracted driving and implications for injury prevention in adults. *Journal of Trauma Nursing* [online]. 2013, 20(1), p. 31-34. ISSN 1078-7496, eISSN 1932-3883. Available from: https://doi.org/10.1097/JTN.0b013e318286616c

[21] CHAUDHARY, N. K., CASANOVA-POWELL, T. D., COSGROVE, L., REAGAN, I., WILLIAMS, An Evaluation of NHTSA distracted driving demonstration projects in Connecticut and New York. Washington, DC: National Highway Traffic Safety Administration, 2012.

[22] JANNUSCH, T., SHANNON, D., VOLLER, M., MURPHY, F., MULLINS, M. Smartphone use while driving: an investigation of young novice driver (YND) behaviour. *Transportation Research Part F: Traffic Psychology and Behaviour* [online]. 2021, 77, p. 209-220. ISBN 1369-8478, eISBN 1873-5517. Available from: https://doi.org/10.1016/j.trf.2020.12.013

[23] HOSKING, S. G., YOUNG, K. L., REGAN, M. A. The effects of text messaging on young drivers. *Human Factors* [online]. 2009, 51(4), p. 582-592. ISSN 0018-7208, eISSN 1547-8181. Available from: https://doi.org/10.1177/0018720809341575

[24] STAVRINOS, D., JONES, J. L., GARNER, A. A., GRIFFIN, R., FRANKLIN, C. A., BALL, D., WELBURN, S. C., BALL, K. K., SISIOPIKU, V. P., FINE, P. R. Impact of distracted driving on safety and traffic flow. *Accident*

Analysis and Prevention [online]. 2013, 61, p. 63-70. ISSN 0001-4575, eISSN 1879-2057. Available from: https://doi.org/10.1016/j.aap.2013.02.003

[25] WANG, C., LI, Z., FU, R., GUO, Y., YUAN, W. What is the difference in driver's lateral control ability during naturalistic distracted driving and normal driving? A case study on a real highway. *Accident Analysis and Prevention* [online]. 2019, 125, p. 98-105. ISSN 0001-4575, eISSN 1879-2057. Available from: https://doi.org/10.1016/j.aap.2019.01.030

[26] WU, P., SONG, L., MENG, X. Temporal analysis of cellphone-use-involved crash injury severities: calling for preventing cellphone-use-involved distracted driving. *Accident Analysis and Prevention* [online]. 2022, 169, 106625. ISSN 0001-4575, eISSN 1879-2057. Available from: https://doi.org/10.1016/j.aap.2022.106625

[27] JAVID, R., SADEGHVAZIRI, E., JEIHANI, M. The effect of COVID-19 on distracted driving: a survey study. *medRxiv* [online]. 2022. ISSN 0346-251X. Available from: https://doi.org/10.1101/2022.12.26.22283062

[28] HAIGNEY, D. E., TAYLOR, R. G., WESTERMAN, S. J. Concurrent mobile (cellular) phone use and driving performance: task demand characteristics and compensatory processes. *Transportation Research Part F: Traffic Psychology and Behaviour* [online]. 2000, 3(3), p. 113-121. ISBN 1369-8478, eISBN 1873-5517. Available from: https://doi.org/10.1016/S1369-8478(00)00020-6

[29] HORBERRY, T., ANDERSON, J., REGAN, M. A., TRIGGS, T. J., BROWN, J. Driver distraction: the effects of concurrent in-vehicle tasks, road environment complexity and age on driving performance. *Accident Analysis and Prevention* [online]. 2006, 38(1), p. 185-191. ISSN 0001-4575, eISSN 1879-2057. Available from: https://doi.org/10.1016/j.aap.2005.09.007

[30] YANNIS, G., LAIOU, A., PAPANTONIOU, P., CHRISTOFOROU, CH. Impact of texting on young drivers' behavior and safety on urban and rural roads through a simulation experiment. *Journal of Safety Research* [online]. 2014, 49, 25.e1-31. ISSN 0022-4375, eISSN 1879-1247. Available from: https://doi.org/10.1016/j.jsr.2014.02.008

[31] SCHROEDER, B. L., SIMS, V. K. Texting behind the wheel and beyond: a look at problematic habits. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* [online]. 2014, 58(1), p. 1376-1380. ISSN 2169-5067, eISSN 1071-1813. Available from: https://doi.org/10.1177/1541931214581287

[32] ALOSCO, M.L., SPITZNAGEL, M. B., HALL FISCHER, K., MILLER, L, A., PILLAI, V., HUGHES, J., GUNSTAD, J. Both texting and eating are associated with impaired simulated driving performance. *Traffic Injury Prevention* [online]. 2012, 13(5), p. 468-475. ISSN 1538-9588, eISSN 1538-957X. Available from: https://doi.org/10.1080/15389588.2012.676697

[33] DREWS, F. A., YAZDANI, H., GODFREY, C. N., COOPER, J. M., STRAYER, D. L. Text messaging during simulated driving. *Human Factors* [online]. 2009, 51(5), p. 762-770. ISSN 0018-7208, eISSN 1547-8181. Available from: https://doi.org/10.1177/0018720809353319

[34] OWENS, J. M., MCLAUGHLIN, S. B., SUDWEEKS, J. Driver performance while text messaging using handheld and in-vehicle systems. *Accident Analysis and Prevention* [online]. 2011, 43(3), p. 939-947. ISSN 0001-4575, eISSN 1879-2057. Available from: https://doi.org/10.1016/j.aap.2010.11.019

[35] HE, J., CHOI, W., MCCARLEY, J. S., CHAPARRO, J. S:, WANG, CH. Texting while driving using Google Glass™: promising but not distraction-free. *Accident Analysis and Prevention* [online]. 2015, 81, p. 218-229. ISSN 0001-4575, eISSN 1879-2057. Available from: https://doi.org/10.1016/j.aap.2015.03.033

[36] KNAPPER, A. S., HAGENZIEKER, M. P., BROOKHUIS, K. A. Do in-car devices affect experienced users' driving performance? *IATSS Research* [online]. 2015, 39(1), p. 72-78. ISSN 0386-1112, eISSN 0386-1112. Available from: https://doi.org/10.1016/j.iatssr.2014.10.002

[37] HAQUE, M. M., WASHINGTON, S. The impact of mobile phone distraction on the braking behaviour of young drivers: a hazard-based duration model. *Transportation Research Part C: Emerging Technologies* [online]. 2015, 50, p. 13-27. ISSN 0968-090X, eISSN 1879-2359. Available from: https://doi.org/10.1016/j.trc.2014.07.011

[38] YAN, W., XIANG, W., WONG, S. C., YAN, X., LI, Y. C., HAO, W. Effects of hands-free cellular phone conversational cognitive tasks on driving stability based on driving simulation experiment. *Transportation Research Part F: Traffic Psychology and Behaviour* [online]. 2018, 58, p. 264-281. ISBN 1369-8478, eISBN 1873-5517. Available from: https://doi.org/10.1016/j.trf.2018.06.023

[39] ZHAO, N., REIMER, B., MEHLER, B., D'AMBROSIO, L. A., COUGHLIN, J. F. Self-reported and observed risky driving behaviors among frequent and infrequent cell phone users. *Accident Analysis and Prevention* [online]. 2013, 61, p. 71-77. ISSN 0001-4575, eISSN 1879-2057. Available from: https://doi.org/10.1016/j.aap.2012.07.019

[40] IRWIN, C., MONEMENT, S., DESBROW, B. The influence of drinking, texting, and eating on simulated driving performance. *Traffic Injury Prevention* [online]. 2015, 16(2), p. 116-123. ISSN 1538-9588, eISSN 1538-957X. Available from: https://doi.org/10.1080/15389588.2014.920953

[41] BAILEY, C., O'CONNELL, K., OTTO, R., GENTILE, H., AREY, A., PAYNE, E. Distracted driving perceptions, behaviors, and knowledge among young adults. *The Health Education Monograph Series*. 2012, 29(2), p. 13-18. ISSN 0073-1455, eISSN 2692-1553.

[42] HANOWSKI, R. J. Towards developing a US-EU common distracted driving taxonomy: updating a naturalistic driving data coding approach. Virginia: Virginia Tech Transportation Institute, 2011.

[43] AHANGARI, S., JEIHANI, M., SALAHSHOUR, B., NDEGWA, M. A comprehensive analysis of distracted driving using a driving simulator. *International Journal for Traffic and Transport Engineering* [online]. 2020, 10(2), p. 252-265. ISSN 2325-0062, eISSN 2325-0070. Available from: http://dx.doi.org/10.7708/ijtte.2020.10(2).10

[44] BENESTY, J., CHEN, J., HUANG, Y., COHEN, I. Pearson correlation coefficient. In: *Noise reduction in speech processing* [online]. Vol. 2. Berlin, Heidelberg: Springer, 2009. ISBN 978-3-642-00295-3, eISBN 978-3-642-00296-0, p. 1-4. Available from: https://doi.org/10.1007/978-3-642-00296-0_5

[45] ANSARIYAR, A., LAALY, S. Statistical analysis of connected and autonomous vehicles (CAVs) effects on the environment in terms of pollutants and fuel consumption. In: 2022 International Conference on Frontiers of Artificial Intelligence and Machine Learning FAIML 2022: proceedings [online]. IEEE. 2022. p. 151-156. Available from: http://dx.doi.org/10.2139/ssrn.4377719

[46] OVIEDO-TRESPALACIOS, O., HAQUE, M., KING, M., WASHINGTON, S. Effects of road infrastructure and traffic complexity in speed adaptation behaviour of distracted drivers. *Accident Analysis and Prevention* [online]. 2017, 101, p. 67-77. ISSN 0001-4575, eISSN 1879-2057. Available from: https://doi.org/10.1016/j.aap.2017.01.018

[47] STRAYER, D. L., DREW, F. A. Profiles in driver distraction: effects of cell phone conversations on younger and older drivers. *Human Factors* [online]. 2004, 46(4), p. 640-649. ISSN 0018-7208, eISSN 1547-8181. Available from: https://doi.org/10.1518/hfes.46.4.640.56806

[48] ARVIN, R., KHATTAK, A. J. Driving impairments and duration of distractions: assessing crash risk by harnessing microscopic naturalistic driving data. *Accident Analysis and Prevention* [online]. 2020, 146, 105733. Available from: https://doi.org/10.1016/j.aap.2020.105733

[49] CAIRD, J.K., WILLNESS, CH. R., STEEL, P., SCIALFA, CH. A meta-analysis of the effects of cell phones on driver performance. *Accident Analysis and Prevention* [online]. 2008, 40(4), p. 1282-1293. ISSN 0001-4575, eISSN 1879-2057. Available from: https://doi.org/10.1016/j.aap.2008.01.009

[50] WU, J., XU, H. The influence of road familiarity on distracted driving activities and driving operation using naturalistic driving study data. *Transportation Research Part F: Traffic Psychology and Behaviour* [online]. 2018, 52, p. 75-85. ISBN 1369-8478, eISBN 1873-5517. Available from: https://doi.org/10.1016/j.trf.2017.11.018

[51] JEIHANI, M., AHANGARI, S., HASSAN POUR, A., KHADEM, N., BANERJEE, S. Investigating the impact of distracted driving among different socio-demographic groups [online]. Final report. Maryland: Morgan State University, 2019. Available from: http://hdl.handle.net/11603/18672

[52] PENG, Y., BOYLE, L. N., LEE, J. D. Reading, typing, and driving: how interactions with in-vehicle systems degrade driving performance. *Transportation Research Part F: Traffic Psychology and Behaviour* [online]. 2014, 27, p. 182-191. ISBN 1369-8478, eISBN 1873-5517. Available from: https://doi.org/10.1016/j.trf.2014.06.001

[53] MACFARLAND, T.W., YATES, J. M. Kruskal–Wallis H-test for one-way analysis of variance (ANOVA) by ranks. In: *Introduction to nonparametric statistics for the biological sciences using R* [online]. Cham: Springer, 2016. ISBN 978-3-319-30633-9, eISBN 978-3-319-30634-6, p. 177-211. Available from: https://doi.org/10.1007/978-3-319-30634-6_6

[54] VARGHA, A., DELANEY, H. D. The Kruskal-Wallis test and stochastic homogeneity. *Journal of Educational and behavioral Statistics* [online]. 1998, 23(2), p. 170-192. Available from: https://doi.org/10.3102/10769986023002

[55] OSTERTAGOVA, E., OSTERTAG, O., KOVAC, J. Methodology and application of the Kruskal-Wallis test. *Applied Mechanics and Materials* [online]. 2014, 611, p. 115-120. eISSN 1660-9336. Available from: https://doi.org/10.4028/www.scientific.net/AMM.611.115

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TRENDS IN TRAFFIC ACCIDENTS OF FIREFIGHTING VEHICLES AND THEIR EVALUATION

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Resume

The Fire Rescue Service of the Czech Republic is a security force whose primary task is to protect the lives and health of the population from fire and other emergency and critical situations. Members of the Fire Rescue Service of the Czech Republic need special firefighting appliances for performing these public services. The first-response firefighting vehicles are professionally denominated as firefighting vehicles. These vehicles are used to transport units of firefighters, fire extinguishers and a technical equipment to a scene of an intervention. Traffic accidents occur occasionally while an emergency drive. Traffic accidents always have a negative economic impact on a fire protection unit and can endanger its operational capacity in the short term. This paper summarizes results of a traffic accidents analysis of a major group of emergency firefighting vehicles - water tenders.

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1 Introduction

Authors of this paper have been monitoring and evaluating traffic accidents of firefighting vehicles type water tenders (hereinafter referred to as WT) for a long time. Those vehicles usually go as the first to a site of an intervention in the Czech Republic. First analysis of traffic accidents, conducted by the authors, focused on a period from 2011 to 2016. Results of this analysis were published in 2018 [1]. During 2017 - 2019, the trend of a total number of traffic accidents involving firefighters was increasing, unfortunately. Results of the second follow-up analysis were published in 2020 [2]. Selected aspects of traffic accidents of firefighting water tenders during years 2020, 2021 and 2022 were analysed and described in this paper, with an aim to highlight main trends and economic consequences of traffic accidents of firefighting vehicles. The paper focuses on an evaluation of causes and effects of the traffic accidents using a Generic Error-Modelling System.

2 Problem formulation

Two previous analyses [1-2] were based on an evaluation of traffic accidents (hereinafter referred to as TAs) published annually by the Police of the Czech Republic [3]. Lately published assessment was summarised in a document "Road Accident Yearbook 2020" [4]. In 2020, there were 94,794 of investigated accidents, 460 people had died and a material damage amounted to 6,016 mil. CZK (245.6 mil. EUR according to the CNB exchange rate from February 23, 2022, 1 EUR = 24.50 CZK). While studying this document, the authors focused on TAs caused by truck drivers. This group included trucks with and/or without a trailer and with a semi-trailer. Drivers of these trucks caused 10,052 Tas, within them 66 people died. The analysis [4] highlights that the highest number of TAs was in the lightest weight vehicle class up to 3.5 t, i.e., 4,368 TAs and 28 persons killed, and then in the weight class above 12 t, where it was 3,462 TAs and 25 persons killed.

Furthermore, following characteristics have been found in the overall statistics of TAs, which were used as a starting point for the analysis.

Main causes of traffic accidents caused by truck drivers. Situations when a driver did not fully pay attention to driving (2,427 TAs), an incorrect turning or reversing (1,385 TAs) and an avoidance without a sufficient lateral distance (911 TAs) were the major causes of truck drivers' TAs.

The length of driving experience of drivers of all motor vehicles. Regardless of the length of driving experience, the most frequent cause of TAs was an incorrect driving that means the driver was not fully engaged in driving. For the driving practice up to 1 year there were 5,283 TAs, of which 2,692 TAs caused by the incorrect driving. In a group of driving experience from 1 to 2 years there were 3,040 TAs, of which 1,658 caused with the same reason as above mentioned. Drivers with the practice from 3 to 5 years caused 5,318 TAs in total, of which 2,899 appeared again due to the incorrect way of driving. In a group of drivers experienced from 6 to 10 years there were 8,136 TAs, of which 4,762 arose for the same reason - the incorrect driving. In the group with a longer than 10 years practice there were 25,363 TAs in total, in which 15,603 accidents occurred due to the incorrect driving.

The age of the driver responsible for the TA. There, the following numbers were recorded in the statistics: 11,523 TAs happened in the age group 21 to 29 years, drivers aged 30 to 39 years caused 11,114 TAs, drivers aged 40 to 49 years caused 11,881 TAs and 8,417 TAs happened in the age group 50 to 59 years.

Based on detected results, three hypotheses have been laid down and then verified.

- Hypothesis No. 1: The incorrect driving is the most frequent cause of all TAs.
- Hypothesis No. 2: Drivers with the driving experience of 6 to 10 years cause most TAs.
- Hypothesis No. 3: Drivers younger than 29 years cause most TAs.

These hypotheses formed a direction of the study of firefighting trucks' TAs. The study focused both on the cause of the accidents, and the age of the drivers responsible for the accident. None of these hypotheses was confirmed by results of previous analyses [1-2]. The most common cause of culpable accidents of water tenders was the incorrect avoidance (36%) in years 2011 - 2022. In terms of economic consequences, however, the greatest material damage occurred in TAs caused by an excessive speed (75 %). Most of TAs involving units of the Fire Rescue Service of the Czech Republic (hereinafter referred to as FRS CR) were caused by drivers in the age from 30 to 39 years, next age group was from 40 to 49 years. Therefore, the analysis was extended with a study of an influence of a length of the driving experience.

The current analysis focused on causes, economic consequences, and trends in the TAs of firefighting water tenders. Trends in an accident rate, number of emergencies, a mileage of firefighting trucks and their changes were monitored in the period 2011 to 2022.

3 Methodology

A solution procedure and methods used were the same as in the previous analyses [1-2]. Sources of primary data have been taken from the so-called "Reports of Firefighting Vehicles Traffic Accident". These reports have been processed by machinery service technicians at regions, territorial departments, and individual fire stations according to the Code of Mechanical Service [5]. The analysis was based on following criteria for selecting the TAs:

- A traffic accident character - an accident caused by firemen.
- A purpose of a ride - an emergency.
- A type of a firefighting vehicle - a water tender.

Filled forms "Reports of Firefighting Vehicles Traffic Accident" (hereinafter referred to as RTA) have been centrally collected at the Directorate General of the Fire Rescue Service of the Czech Republic (hereinafter referred to as DG FRS CR). They have been processed by the MS Excel software. Data from these reports were then analysed by the authors of the paper. Elementary filtering functions in MS Excel software were used to sort records according to the above criteria. A total of 394 records of TAs were assessed for the period 2011 - 2022. Statistical yearbooks issued annually by DG FRS CR [6] were used for comparing the trend of the number of incidents in relation to the mileage of firefighting vehicles.

4 Evaluation of the traffic accident statistics

Results of the TAs analysis, carried out according to the criteria mentioned above and trends in the number of emergencies relative to the mileage of firefighting vehicles, are shown in Tables 1 and 2, and Figures 1 to 5 [6].

4.1 Causes of traffic accidents

The first steps in solving the task have been focused on filtering the TAs by the cause. An overview of water tenders TAs frequency, sorted by the cause, is summarized in Table 1. Figure 1 shows the share of individual causes for the referred period 2011 - 2022. 163 accidents (36% of all TAs) occurred due to the wrong bypassing - the incorrect overtaking of another vehicle.

***Table 1** Causes of traffic accidents*

Causes of traffic accidents	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
not keeping a safe distance	4	6	5	2	3	3	5	6	5	2	5	6
speeding	5	3	8	9	6	4	10	5	4	2	6	6
wrong bypassing	5	6	11	13	10	10	20	17	23	13	20	15
not giving way	1	0	0	1	1	2	3	0	4	4	1	0
dangerous reversing and turning	9	8	11	6	6	8	9	10	7	8	8	19
other	2	0	3	5	3	1	1	2	7	4	3	11

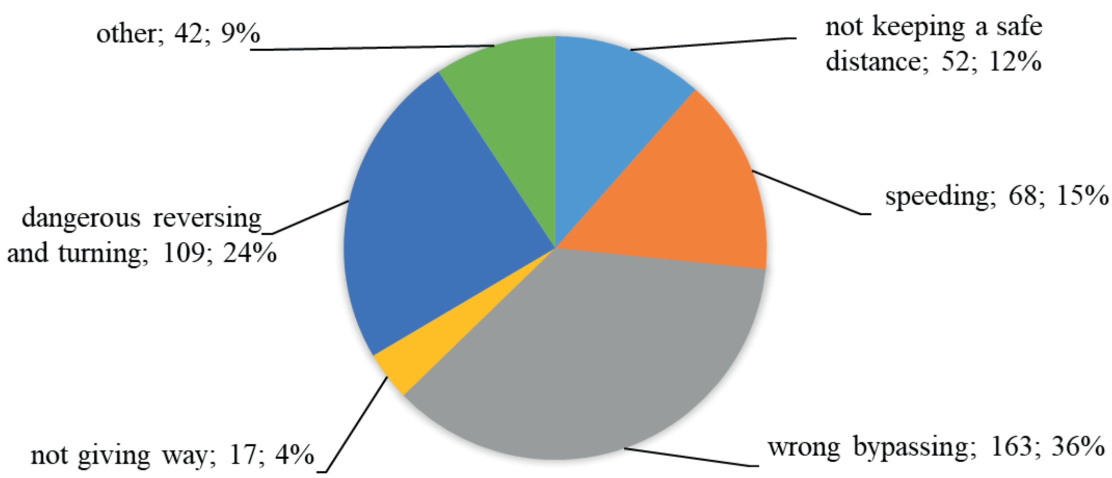

***Figure 1** Shares of traffic accident causes, years 2011 - 2022*

***Table 2** Damage to firefighting water tenders by the cause of traffic accident*

Damage in thousands of EUR	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
not keeping a safe distance	1.6	11.4	12.9	0.0	0.2	0.4	5.1	5.0	51.0	0.0	2.9	5.4
speeding	45.3	183.7	174.1	518.5	549.3	1.4	219.3	329.5	94.7	177.8	696.0	300.5
wrong bypassing	2.0	1.1	26.5	0.8	1.4	11.9	299.5	152.8	17.5	39.8	9.7	5.6
not giving way	4.1	0.0	0.0	2.9	4.9	4.1	4.3	0.0	20.4	66.9	2.0	0.0
dangerous reversing and turning	6.9	2.4	2.0	1.0	3.2	15.5	5.0	11.3	1.6	2.7	2.8	16.6
other	1.4	0.0	0.8	1.8	2.4	1.6	1.2	1.6	2.2	6.9	0.3	11.3

4.2 Value of damage in traffic accidents

Another part of the analysis was the evaluation of the amount of damage to firefighting vehicles during accidents caused by the driver-firefighter. Table 2 summarizes the damage to firefighting vehicles, sorted by the cause of the Tas, during 2011 - 2022. Amounts of the damage were converted from CZK into EUR according to the Czech National Bank exchange rate from February 23, 2022 (1 EUR = 24.50 CZK).

In 2021, previous peaks of damage from 2014 and 2015 were surpassed. That was due to three serious accidents of firefighting vehicles in November and December 2021, which resulted in the total damage of 16.5 million CZK (673.5 thousand EUR). Those accidents were caused by speeding. Excluding these three TAs, the year 2021 would have been very successful from the perspective of the financial damage. Figure 2 shows different causes of traffic accidents, the amount of damage in thousands of EUR and in percent during the monitored period.

The most serious cause of accidents in terms of the amount of damage was speeding. Accidents occurred due to speeding reached 78% of the total amount of

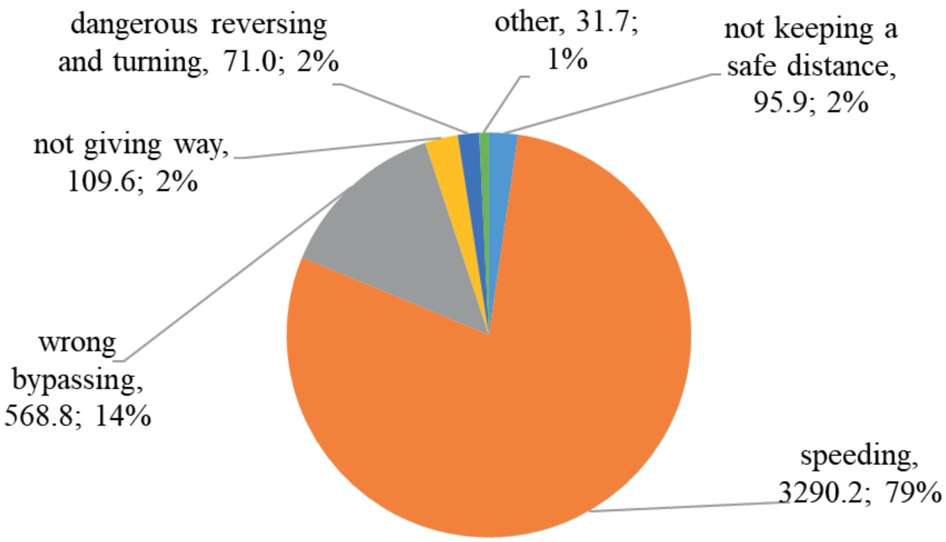

***Figure** 2 Damage to firefighting vehicles by the cause of traffic accident in 2011 - 2022*

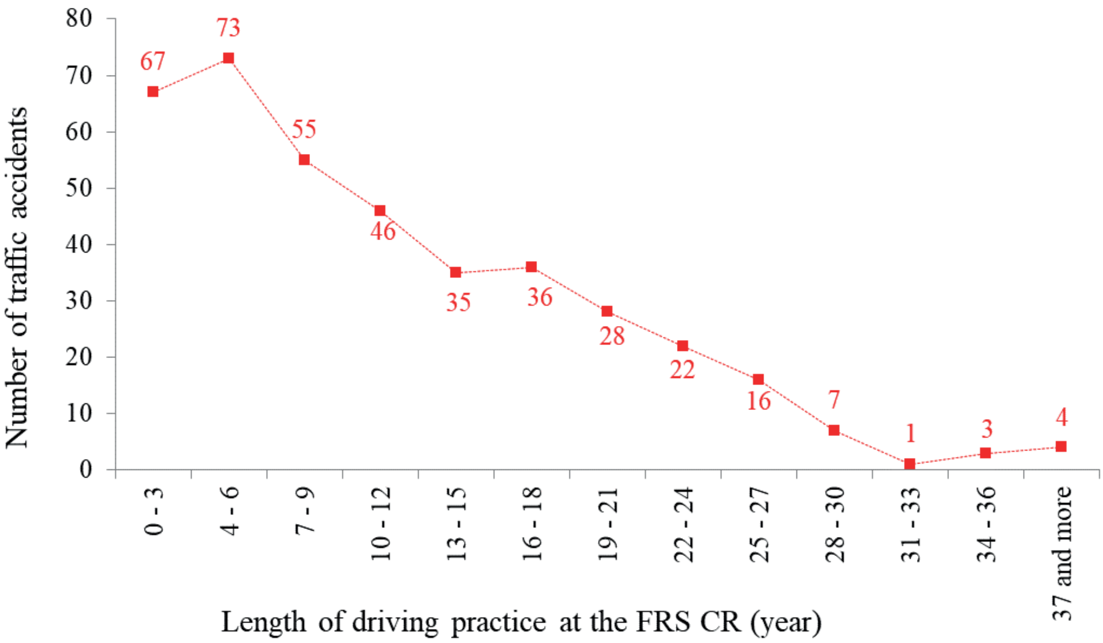

***Figure 3** Number of traffic accidents in relation to the truck driver's practice*

damage, but only 16% of the total number of accidents. Speeding, as the only cause from the whole spectrum of 6 categories of causes, significantly influenced the overall result. That fact could confirm the Pareto rule 80/20 [7].

4.3 The length of drivers' experience

Third part of the analysis was focused on the TAs with respect to the length of a truck drivers experience. The driving experience was evaluated in two categories:

- the experience in driving firefighting vehicles at the FRS CR.
- overall experience in driving trucks (i.e., the driving practice before joining the FRS CR plus the driving experience at the FRS CR).

To picture the trends, and to illustrate the relationship between the duration of the driving practice and the number of TAs, 3-year intervals of the practice length have been set. Relations between the number of TAs and the duration of the driving practice are shown in Figure 3, for the referred period 2011 - 2021.

Drivers with the experience at the FRS CR up to 6 years belong to the most critical group with the greatest numbers of accidents. For drivers with the experience of

7 years or more there can be seen a significant decrease in the number of road accidents. Drivers with the length of driving practice at the FRS CR from 0 to 9 years caused 50% of the TAs in the monitored period. In intervals 13 - 15 and 16 - 18 years of experience in driving at the FRS CR, the number of accidents was almost equal. For drivers with more than 19 years experience, there is a second positive break - there can be seen a permanent decrease in the number of road accidents. The lowest numbers of TAs (1 - 4) have been found in each 3-year interval after exceeding outreaching 31 years of driving practice at the FRS CR.

Unfortunately, our findings have confirmed the data from the previous analysis. Most accidents were registered for drivers with the driving experience at the FRS CR between 4 and 6 years.

4.4 Number of emergencies and a mileage of firefighting water tenders

In the next part of the analysis, the annual statistics of emergencies [6] and evaluated TAs were compared. Figure 4 shows both the total numbers of emergencies, and numbers of culpable TAs of water tenders (in total 394) for each year of the monitored period. To complete the information, the number of all the registered TAs without distinguishing the type of vehicle was 712 for the monitored period. For the referred period, there was, on average, one TA per 3,435 emergencies. That part of the analysis was followed by an analysis of the number of emergencies and the distance covered by firefighting vehicles. In statistical yearbooks [6] mileages were reported only for fires and technical accidents. These two types of emergencies reached 69% of all emergencies in 2011 to 2021. Resulting trends are summarised in Figure 5. The average mileage per one emergency was 7.76 km. In relation to the total number of emergencies, the average mileage per an accident was approximately 26,659 km. Both variables were higher between 2019 and 2021 compared to the results of previous analyses for the years 2011 - 2018.

Finally, one sad finding emerged from the analysis of TA statistics in 2020 - 2021: four fire fighters and one civil person were killed in analysed TAs and three water tender vehicles were destroyed in 2021. The damage to these three firefighting trucks was estimated at 16.5 million CZK (673.5 thousand EUR). Speeding was identified as the cause of all the three serious road accidents. The road surface was wet in two cases, one TA occurred while driving on an icy road. The crashed vehicles were driven by fire fighters with the driving experience at the FRS CR in the length of 5, 23 and 29 years.

Furthermore, the analysis resulted in a requirement to include an actual speed before the moment of the accident to the "Report of a traffic accident" forms for improving the analysis of TAs at the Fire Rescue Service of the Czech Republic. That information has been permanently recorded in the navigation systems GINA from GINA software Ltd., Brno [8] and Rescue Navigator from Point.X Ltd., Prague [9], which have been installed in fire vehicles of the Fire Rescue Service of the Czech Republic. Their disadvantage is the real-time recording of the vehicle position with a frequency of 1 record per 5 seconds (0.2 Hz). The second type of devices, which were

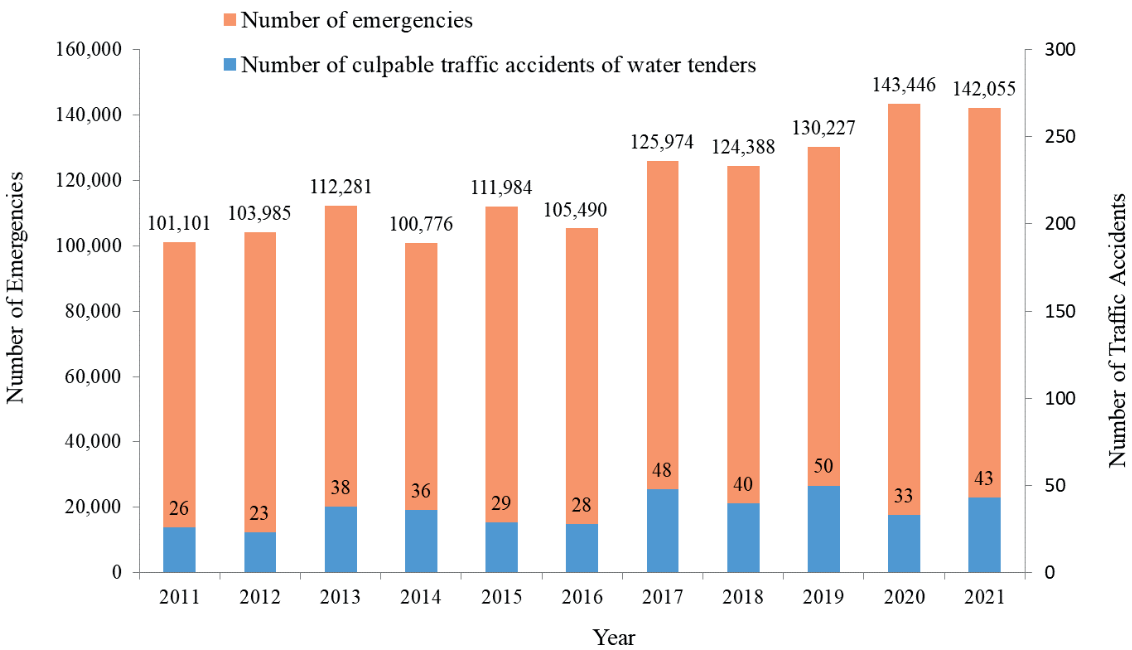

***Figure 4** Trends of emergencies and traffic accidents in 2011 - 2021*

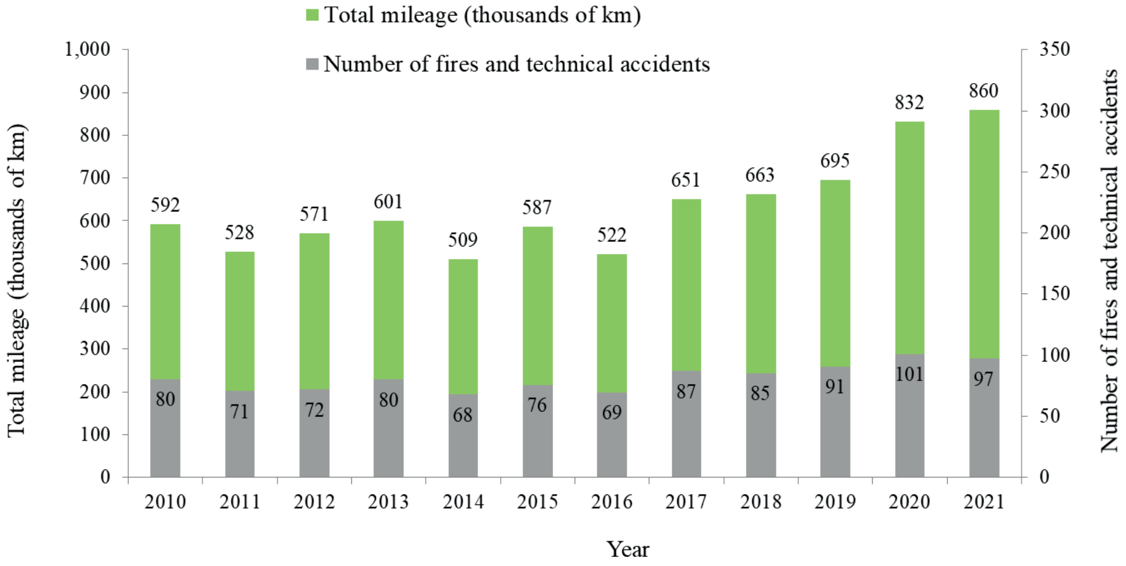

Figure 5 *Number of fires and technical types of emergencies and the mileage in 2011 - 2021*

installed in most of fire vehicles in the last 5 years, were on-board cameras, which recorded the journey in front of the vehicle. In the case of types equipped with a GPS module, a record of the vehicle's position is made at a frequency of 1 Hz (1 record per a second). If a dual set of cameras is used in the vehicle, then the second camera is placed in the cab of the vehicle and records the driver's driving activity. This real-time vehicle position data, including the audio and video footage of the journey before the TA occurred, could already be used to analyse the cause of the TA more in detail.

5 Cause and effect analysis of traffic accidents using the generic error-modelling system

Causes of Tas, involving firefighting vehicles, were investigated in the framework of the specific research projects "Verification of the Driving Characteristics of Water Tender Type Vehicles" No. SP2021/58 [10] and "Stress Load of Drivers" No. SP2022/49 [11]. In both projects, one of the defined sub-objectives always was the analysis of TAs of fire protection units of the FRS CR with a focus on a fire-fighting vehicle of the type of water tender. The TAs analysis was always focused on accidents caused while emergency driving. Here, the firefighter-driver of a vehicle was exposed to an increased mental and physical stress, compared to normal work activities at the fire station. From the RTA forms [5], information on individual TAs incurred on fire vehicles was listed with the level of culpability: culpable TA and TA with complicity. The information was entered into MS Excel. Then, the data not reported by the FRS CR in the statistical document "Analysis of traffic accidents in fire protection units" were filtered out. As a part of a previous specific research project "Verification of driving characteristics of water tender type vehicles", it was demonstrated that vehicles drive faster in a left-hand curve than in a right-hand curve of the same radius. Based on the findings of the second specific research project "Stress load of drivers", TAs were evaluated with a focus on the damaged side of the vehicles.

5.1 Questions for the analytical survey

To evaluate the TAs of WT vehicles in detail, the researchers outlaid several following questions.

- What are the most common locations for TAs?
- At what times?
- In what driving mode?
- At what speed?
- In what weather conditions?
- What is the frequency of financial damage by amount?
- What is the most common type of error?

Individual TAs sites were divided into on-road and off-road with a further division into left and right turn, straight section and downhill.

The TAs time was divided by a daytime into day (sunrise to sunset), day/night (sunset to civil twilight), night (civil twilight to civil dawn), and night/day (civil dawn to sunrise) parts, as in the day/night and night/day parts of the daytime an optical spatial perception change [12-13].

The driving mode was divided according to the purpose of driving into emergency and other, and further into start, finish, steady state, parking, rest.

The speed of the vehicle at the time of the accident could not be assessed, this information was not included in the RTA form in most cases.

In terms of meteorological conditions, the road surface was divided into dry, wet, and low adhesion (this term includes ice and snow on the road). It was also indicated what the visibility was when the TA occurred. To assess the road surface, temperatures above and below 0 °C were given. For the accident assessment, most frequent financial damages during each TA were filtered in MS Excel.

Most common errors were evaluated according to the Generic Error-Modelling System (hereinafter referred to as GEMS) [14], to classify human errors. This model is divided into three performance levels:

- Skill-based errors, usually errors of inattention or misplaced attention;
- Rule-based errors, for instance choosing an inappropriate rule, incorrect view on the state, overzealous pattern matching, frequency gambling, and/or insufficient rules;
- Knowledge-based errors. These are incomplete and/ or inaccurate understanding of the system, bias, overconfidence, and cognitive load.

5.2 Evaluation of the accident rate of water tenders from reports of firefighting vehicles traffic accident

Firefighters - drivers of firefighting vehicles at FRS CR caused or partially caused 368 TAs for the assessed period 2012-2021. Of that, it was possible to trace only 268 TAs for which the complete RTA forms with all the necessary data were provided.

The data evaluated showed that 93.3% of the TAs were culpable and 6.7% were with complicity (hereafter referred to as culpable TAs). While emergency driving, 56.3% of TAs were caused by the drivers, as shown in Table 3. 15.3% of TAs occurred while arriving at the scene of an incident, while crossing at the intervention site or departing from the intervention site. On the return journey from the intervention, 7.1% of TAs occurred.

Table 4 shows a magnitude of the total damage incurred with a distribution:

- small TAs - the damage up to 100,000 CZK (up to 4,082 EUR), with no injuries,
- large TAs - the damage above 100,000 CZK and up to 1 million CZK (from 4,082 to 40,816 EUR), with a slight injury.
- serious TA - a severe or fatal injury, the damage over 1 mil. CZK (above 40,816 EUR).

In the evaluated period, 30 people were slightly injured, 8 people were seriously injured and 2 people were killed in culpable TAs, including accidents with a complicity.

Table 5 shows the number of culpable Tas, according to their severity, depending on the type of driving. Most large and serious culpable accidents occurred during the emergency drives.

Table 3 *Number of culpable traffic accidents by a driving mode*

Driving mode		Number of TAs	Percentage (%)
Emergency driving		151	56.3
At the intervention site	Arrival at the site of an intervention, stopping the vehicle, crossing at the scene	29	10.8
	Reversing, departing from the intervention site	12	4.5
Return journey from the intervention site		19	7.1
Other rides		57	21.3

Table 4 *Severity of the traffic accident*

Size of the total damage at the TA	Number of TAs	Percentage (%)
Small	207	77.2
Large	40	14.9
Serious	21	7.8

Table 5 *Number of culpable TAs by the driving mode and the severity of the TA*

Driving mode		Severity of the TA		
		Small	Large	Serious
Driving to an intervention		105	26	20
At the intervention	Arrival at the site of an intervention, stopping the vehicle, crossing at the scene	25	4	0
	Reversing, departing from the intervention site	12	0	0
Return journey from the intervention site		18	1	0
Other rides		47	9	1

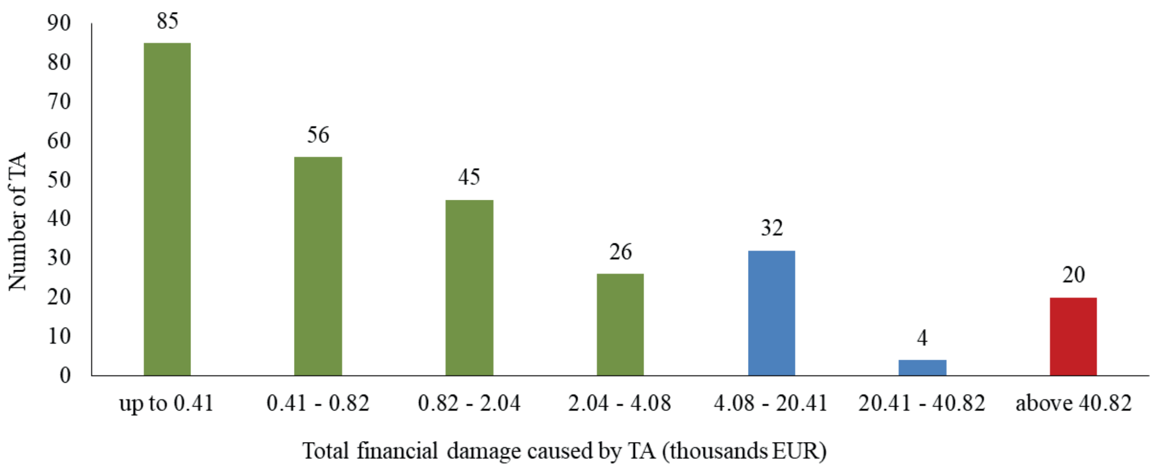

***Figure 6** Total financial damage caused by traffic accidents*

***Table 6** Generic Error-Modelling System*

Errors:	Number of TAs	Percentage (%)
Skill based	231	86.19
Rule based	24	8.96
Knowledge based	13	4.85

***Table 7** Number of traffic accidents of FRS CR vehicles depending on the road type*

Type of the road surface	Number of TAs	Percentage (%)
Roadways - asphalt	251	93.7
Paved surface - outside the road (parking lot, company complex)	7	2.6
Terrain - off the road	10	3.7

***Table 8** Number of traffic accidents depending on the manoeuvre and the communication section*

Communication section	Manoeuvre	Number of TAs
Direct section	Driving forward	114
	Overtaking	2
	Reversing	53
	Avoidance manoeuvre	38
	Turning	2
Right-hand turn	Turning right	15
	Reversing	2
Left-hand turn	Turning left	14
	Avoidance manoeuvre	2
Left-hand turn, Descent	Left turn, descent	3
Crossroads	Passing through the crossroads	4
	Avoidance manoeuvre	2
	Turning	1
	Driving forward	1
Decline	Driving forward	5
	Rest	2
Rugged terrain	Driving forward	2
	Reversing	2
	Turning	2
Rest	Rest	2

Figure 6 shows the total financial damage converted into thousands of EUR distinguished by colour (green - small damage, blue - large damage, red - serious damage).

Table 6 identifies the most common probable error types according to the GEMS, based on the available data.

Table 7 shows numbers of TAs generated in the period under review. From the available data, a following distribution of TAs by type of communication was made:

- 93.7% of TAs happened on roads,
- 3.7% of TAs occurred on an off-road on unpaved terrain.

Here it should be added that less than 1% of all evaluated emergencies occurred on the off-road terrain according to the route characteristics at Fire station Znojmo in August 2018 [15].

Table 8 shows numbers of accidents, depending on the road section and the manoeuvre, during the TA. Most of the TAs were caused by the WT drivers on the straight road in forward driving, reversing, and evasive manoeuvres. The next frequent group of TAs was the passage through right-hand and left-hand curves.

From the characteristics of the routes of the evaluated emergencies at Fire stations Brno - Lidicka, Znojmo, Zlin, Valasske Mezirici, Ostrava - Fifejdy and Novy Jicin within the analysis in the period 2018 and 2019 [15], the share of vehicle movements in curved road sections as potential critical points was identified. The average distance driven through the curved sections to the intervention site was 4%.

5.2.1 Road surface affecting the limit speed of the vehicle

Using Meteoblue climate diagrams [12] which are available for all the locations on Earth, and are based on hourly weather model simulations over a 30-year period, a summation of precipitation amounts was performed. On average, there were 208 dry days per year in the Czech Republic, 157 days with precipitation, 17 of which are snow days.

The condition of the road affecting the speed limit of the vehicle is shown in Table 9. 45.9% of the accidents caused during the study period occurred on low adhesion road surfaces. Drivers caused 12.3% of TAs on wet surfaces and 41.8% of TAs on dry surfaces.

5.2.2 Temperature effect on the adhesion between the tyre and the road surface

The Czech Republic had 101 frost days per year on average [12]. Table 10 shows that in 22.4% of TA cases,

Table 9 *Road surface affecting the limit speed of the vehicle*

Condition of the roadway	Number of TAs	Percentage (%)
Dry	112	41.8
Wet	33	12.3
Low-adhesion	123	45.9

Table 10 *Temperature effect on the adhesion between the tyre and the road surface*

Outer temperature	Number of TAs	Percentage (%)
above 0 °C	208	77.6
under 0 °C	60	22.4

Table 11 *Lighting conditions*

Lighting conditions		Number of TAs	Percentage (%)
Good visibility	Day	180	67.2
Reduced visibility	Day/Night	6	2.2
	Night/Day	5	1.9
	Night	46	17.2
	Adverse conditions	31	11.6

Table 12 *Traffic accidents depending on the daytime and the traffic density*

Time of the day	Number of TAs	Percentage (%)
Day, from 7:00 a.m. to 6:00 p.m.	192	71.64
Night, from 6:00 p.m. to 7:00 a.m.	76	28.36

Table 13 *Causes of traffic accidents*

Cause of TA	Number of TAs	Percentage (%)
Incorrect estimation of the lateral distance	101	37.69
Speeding	53	19.78
Incorrect estimation of the distance behind the vehicle	47	17.54
Incorrect estimation of the distance in front of the vehicle	19	7.09
Crossing the intersection at red lights	12	4.48
Inattention	11	4.10
Driving on an unpaved roadside	8	2.99
Errors of non-driving personnel	4	1.49
Incorrect approach to an elevated obstacle	3	1.12
Not using the anti-running wedge	3	1.12
Incorrect starting	2	0.75
Low visibility	2	0.75
Other	2	0.75
The technical factor	1	0.37

a low temperature could decrease a tyre adhesion on the road.

5.2.3 Lighting conditions

Table 11 shows lighting conditions when the road accidents occurred, according to the available data, divided into good and reduced visibility. Reduced visibility is a situation where the road users on the road cannot distinguish clearly enough other vehicles, persons, animals or objects on the road [16]. A good visibility means the time of day from sunrise to sunset. A reduced visibility means the period between day and night and night and day, as well as night, and adverse conditions:

- day/night: from sunset to civil twilight,
- night: from civil dusk to civil dawn,
- night/day: from civil dawn to sunrise,
- adverse conditions: fog, snow, heavy rain, smoke, heavy dust stirring.

Table 11 shows that 32.8% of accidents occurred in a low visibility and 67.2% of accidents occurred in a good visibility.

5.2.4 Traffic accidents depending on the daytime and the traffic density

According to the graph of daily variation of traffic intensities [17], the highest traffic density is from 7:00 a.m. to 6:00 p.m. (marked as the day), while in the early evening, evening, night, and early morning hours, i.e., from 6:00 p.m. to 7:00 a.m., the traffic intensity is low (marked as the night). Based on that, the TAs have been divided according to the daytime in Table 12. 66.32% of the analysed emergencies took place during the day and 33.68% at night [14]. In terms of a mileage [14], 66.81% emergencies took place per day and 33.19% per night. Depending on the daytime, more TAs occur during the day (71.64%) than at night (28.36 %).

Table 14 *Recommendations for education and training based on the most common traffic accidents*

Recommended training and precautions	Number of TAs	Percentage (%)
Estimation of a lateral distance	89	38.5
Estimating the distance behind the vehicle	49	21.2
Estimating the distance in front of the vehicle	27	11.7
Driving on low adhesion road surfaces	20	8.7
Avoidance manoeuvre	16	6.9
Safe speed training for cornering on different surfaces and practical training	14	6.1
Emphasis on increasing attention	7	3.0
Off-road driving	6	2.6
Starting and approaching an elevated obstacle	3	1.3

5.2.5 Causes of traffic accidents

From the analysis of the available data, Table 13 summarises the number of accidents based on their probable cause.

5.3 Evaluation of the findings using the generic error-modelling system

Evaluated data show that the firefighter-drivers caused or were complicit in 67% of TAs while driving to the intervention, arriving at the intervention site and moving to the next intervention (see Table 3).

Most of the large and serious TAs were connected with the emergencies. According to the distribution of TAs by daytime, 72% of TAs occur in heavy traffic during the day between 7:00 a.m. and 6:00 p.m. (see Table 12).

When evaluating the accidents depending on the type of manoeuvre, it was found that most TAs occurred on the straight road section (almost 78 %), and 114 TAs (43%) in the forward direction (see Table 8).

21% of TAs occurred when reversing, 93% of which were on the straight section. During the evasive manoeuvres, drivers caused 16% of TAs, 91% of which were on the straight and often clear section of the road (see Table 8).

The analysis showed that, according to GEMS, most TAs were skill-based, up to 86% (see Table 6).

6 Conclusions

During the description of single parts of the analysis of culpable TAs of firefighting vehicles type water tenders during 2011 - 2021, partial conclusions were also presented. Total of 394 TAs were analysed with the total damage of 102.3 million CZK (4.18 mil. EUR). Results of the research can be summarised in following findings.

The most frequent cause of TAs was wrong bypassing - 148 TAs (37 %). That increased by 1% in 2020 - 2021.

The greatest deal of damage to firefighting vehicles was caused by speeding - 73.3 mil. CZK (3 mil. EUR) in 54 TAs (78 %). There was an increase of 3% in 2020 - 2021.

When assessing the impact of the length of experience in driving firefighting vehicles at FRS CR, the greatest number of road accidents was caused by drivers with less than 6 year experience. The number of TAs decreased with drivers who had more than 6 years driving experience.

From evaluation of the emergency statistics, it was calculated that there was one TA per 3.435 emergencies. In terms of the mileage, that was 26.7 thousand km per one TA. These figures had a slightly increasing trend in years 2020 -2021.

From evaluation of the available data, it appeared that the firefighter-drivers caused 67% of the TAs while emergency driving, arriving at, and crossing at the intervention site. Most of the large and serious TAs were related to emergency. When distributed accidents by the daytime, more TAs occurred in the heavy traffic during the day (72 %). Most of the TAs occurred on a straight segment of the road (78 %).

The analysis shows that, according to the Generic Error-Modelling System, most accidents were skill-based (86 %). For this reason, it would be advisable to deepen the current firefighters-drivers training with specific activities such as estimating a lateral distance, estimating the distance in front of, and behind the vehicle, evasive manoeuvres (see Table 14).

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Conflicts of 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.

References

[1] JANOSIK, L., JANOSIKOVA, I., COCHLAR, M., JEMELIK, S. Economic aspects of firefighting vehicles safe driving within EU civil protection. In: 4th International Conference on European Integration: proceedings. Part 1. 2018. p. 556-565.

[2] JANOSIK, L., JANOSIKOVA, I., COCHLAR, M., POLEDNAK, P., SUDRYCHOVA, I. Economic consequences of firefighting trucks risky emergency driving. In: 5th International Conference on European Integration: proceedings [online]. 2020. ISBN 978-80-248-4455-8, eISBN 978-80-248-4456-5, p. 330-337. Available from: https://doi.org/10.31490/9788024844565

[3] Police of the Czech Republic. Statistical yearbooks 2020 [online] [accessed 2021-04-10]. (in Czech). Available from: https://www.policie.cz/clanek/statistika-nehodovosti-900835.aspx

[4] Directorate of the traffic police service of the Police Presidium of the Czech Republic. Road accident yearbook for 2020 [online] [accessed 2022-02-10]. (in Czech). Available from: https://www.policie.cz/clanek/statistika-nehodovosti-900835.aspx?q=Y2hudW09Mw%3d%3d
[5] Fire Rescue Service of the Czech Republic. Instruction of the Director General of the Fire Rescue Service of the Czech Republic and the Deputy Minister of the Interior dated December 10, 2018 which issued the Machinery Services Regulations of the Fire Rescue Service of the Czech Republic. Collection of internal acts of the Director General of the Fire Rescue Service of the Czech Republic and the Deputy Minister of the Interior No. 56 (in Czech). Prague: 2018.
[6] Ministry of the Interior - General Directorate Fire Rescue Service of the Czech Republic. 2022. Statistical yearbooks of the Fire Rescue Service of the Czech Republic [online] [accessed 2023-04-10]. Available from: https://www.hzscr.cz/clanek/statistical-yearbooks.aspx
[7] Pareto principle - Wikipedia [online] [accessed 2023-03-21]. Available from: https://en.wikipedia.org/wiki/Pareto_principle
[8] Premium mapping system - GINA: Products [online] [accessed 2023-03-21]. 2023. Available from: https://www.ginasoftware.com/premium-mapping-system
[9] Products - POINT. X [online] [accessed 2023-03-21]. 2023. Available from: https://www.pointx.cz/products.html
[10] SUDRYCHOVA, I. Final report of the specific research project No. SP2021/58 - Verification of the driving characteristics of water tender type vehicles (in Czech). Ostrava: VSB - Technical university of Ostrava, 2022.
[11] SUDRYCHOVA, I. Final report of the specific research project No. SP2022/49 - Stress load of drivers (in Czech). Ostrava: VSB - Technical university of Ostrava, 2023.
[12] Meteoblue: Observed historical climate and weather data - Switzerland: meteoblue [online] [accessed 2022-09-21]. 2022. Available from: https://www.meteoblue.com/en/weather/historyclimate/climateobserved/ostrava_czechia_3068799
[13] Czech Republic - sunrise and sunset - Meteogram.cz [online] [accessed 2022-10-03]. 2022. (in Czech). Available from: https://www.meteogram.cz/vychod-zapad-slunce/
[14] Generic Error-Modelling System - SKYbrary [online] [accessed 2022-10-03]. 2022. Available from: https://skybrary.aero/articles/generic-error-modelling-system-gems
[15] Summary research report of the project "Safe driving of firefighting equipment to intervention" - VH20182021035. 2018-2021 (in Czech). Ostrava: VSB - Technical university of Ostrava, 2021.
[16] Act No. 361/2000 Coll., on road traffic and on amendments to certain acts (in Czech). Prague: Collection of Acts. Volume 2000, Number of 361.
[17] BARTOS, L., MARTOLOS, J. *Determination of traffic intensity on roads* (in Czech). Pilsen: EDIP, 2012. ISBN 978-80-87394-06-9.

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Development of Euroregion Beskydy XVII
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GISday 2023
Date and venue: 16. 11. 2023, Žilina (SK)
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Progress in Applied Surface, Interface and Thin Film Science and Solar Renewable Energy News
Date and venue: 20. – 22. 11. 2023, Slovakia (SK)
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