## OPERATION AND ECONOMICS



## MECHANICAL ENGINEERING

Milos Hitka - Silvia Lorincova - Martina Lipoldova - Zaneta Balazova - Denisa Debnarova

# DIFFERENCES IN THE LEVEL OF WORKERS' MOTIVATION IN REPAIR AND MAINTENANCE SERVICE ENTERPRISE IN THE RAIL TRANSPORT

*The time when the only job of a manager was to delegate work to employees is over. At the present time, an ability to motivate employees is considered an essential skill for managers. It is complex and systematic effort of a manager to create a working environment and atmosphere supporting the inner needs and interests of employees affecting their behaviour and stimulating the performance positively. Differences in the level of workers' motivation in repair and maintenance service enterprise in the rail transport was defined using the sample set of almost 1,000 respondents and ANOVA and Duncan test. Following the results, it can be stated that the structure of motivation factors, as well as their importance, changed significantly in repair and maintenance service enterprise in the rail transport over the observation period.*

***Keywords:*** *human resource management, employee motivation, rail transport, ANOVA, Duncan test*

## 1 Introduction

The entrepreneurial environment is influenced by globalisation of these days [1-2]. Because of tough competition preferred in the market economy, businesses are forced to improve enterprise effectiveness [3-4]. The pressure is put on developing effective strategies to succeed in a highly competitive environment [5-7]. If enterprises do not want to stagnate, they have to place the emphasis on modernisation, improving the quality, the effectiveness of activities in order to maintain and improve their competitiveness on the market [8-11]. This way, human resource management is a strategic and logical approach to managing the most valuable asset the companies possess, i.e. people hired by enterprises, contributing to their viability and competitiveness [12-15].

## 2 Literature review

One of the most serious problems of managers in the business environment is employee motivation [16-18]. Employee motivation affects the work results directly [19-22]. It results in enterprise effectiveness and development [23-25]. It is a process reflecting the intensity, movement and efforts of an individual resulting in a goal directed behaviour of employees [26-27]. Motivation can be understood as a sequence of reactions when requirements and goals, causing some pressure, occur as a result of feelings and needs [28].

Motivation is one of the most important elements in human resource management. In order to affect employees positively, managers must recognise employees' needs and ways of effective motivation. That can lead to motivation programme covering the needs of enterprises, as well as employees. The presumption that motivation is only about money is not correct. Following the research [29-31], it can be stated that the effect of money on motivation is decisive, however the issue is much more complex because of various employees' goals, needs and goal directed behaviour, as well [32]. Their gender, age, education, status, family background, experience and abilities, etc. are different, therefore they can be motivated by different factors. Some employees want to be successful, recognised, expect career advancement, other employees consider relationships, working conditions, job position or job security to be more important [33-35]. For others working environment, management, training and professional development, salary, workplace, team work and relationship to co-workers [36], or healthy working conditions, career opportunity, supportive boss, unambiguous and definite goals, competitive compensation, interesting job, high prestige, good performance evaluation, pleasant working atmosphere, peaceful private life, competent leadership, appreciation, participation in decision-making and fringe benefits can be important, as well [37]. The aim of the paper is to define the differences in the level of workers' motivation in repair and maintenance service enterprise in the rail transport.

## 3 Methodology

The level of motivation was investigated using the data collected in the questionnaire asking about thirty motivation factors. Data were processed in the programme

**Milos Hitka*, Silvia Lorincova, Martina Lipoldova, Zaneta Balazova, Denisa Debnarova**
Technical University in Zvolen, Slovak Republic
*E-mail of corresponding author: hitka@tuzvo.sk

STATISTICA 12. The differences in the level of blue-collar workers' motivation in repair and maintenance service enterprise in the rail transport were defined using the statistical analysis. The research did not differentiate employees by occupation, but focused on object research as a whole and followed the development of changes in motivation factors according to years 2003, 2009, 2016, 2019 and 2020. Position of the rail transport within the transport system in Slovakia is very specific. It is considered supporting, mass and ecological means of transport [38].

The research was carried out in repair and maintenance service enterprise in the rail transport over the years 2003, 2009, 2016, 2019 and 2020. Total of 968 respondents participated in the research. Composition of the sample set is given in Table 1.

Taro Yamane method was used to verify representativeness of the basic sampling unit [39]:

$$n = \frac{N}{1 + N(e)^2}, \tag{1}$$

where:
n - size of the sample set,
N - size of the basic sampling unit (population)
e - permissible error/ level of precision.

Following the results, the representativeness of sampling units could be stated.

ANOVA test and Duncan test were conducted at the level of significance $\alpha$ = 5% and 95% confidence to determine the hypothesis is true [40]. Following hypotheses were tested:

*$WH_1$: we suppose that the workers' motivation in repair and maintenance service enterprise in the rail transport will be different in structure.*

*$WH_2$: we suppose that the workers' motivation in repair and maintenance service enterprise in the rail transport will be different in terms of importance.*

## 4 Results and discussion

In the first step, the level of motivation in repair and maintenance service enterprise in the rail transport was defined. Results are presented in Table 2.

Due to the fact that the level of motivation in enterprises has changed over time, subsequently, the order of importance of motivation factors in the year 2020 was defined. Five most important motivation factors (career advancement, atmosphere in the workplace, good work team, self-actualization, job security) were investigated in more detail. Results are presented in Table 3 and Table 4.

Effect of years on the motivation factor "career advancement" is presented in Figure 1. The most significant decrease occurred in the year 2009 when there was a crisis in the Slovak economy and the employee motivation decreased in general. This effect was observed in the case of all the investigated motivation factors. Statistically significant differences were noticed in the year 2020, comparing to all the other years, besides 2003 when the effect on the career advancement was the same.

Effect of years on the motivation factor "atmosphere in the workplace" is shown in Figure 2. As in the case of the previous motivation factor, there were significant differences in the year 2009 in comparison to all investigated years (Table 5). Significant differences were confirmed also in the year 2019, comparing to all the investigated years.

Results of statistical testing of the third most important motivation factor "good work team" are presented in Table 6 and Figure 3. The importance of the investigated motivation factor has increased since the year 2016. Effect of the years 2009 and 2020 was statistically significant in comparison to other investigated years.

Importance of the motivation factor "self-actualization" is illustrated in Figure 4. In the years 2003, 2016 and 2019, approximately similar level of the motivation factor was observed, i.e. there was no significant effect of the years. On the other hand, statistically significant effects were confirmed in the year 2009 and 2020 (Table 7).

Statistically significant differences in the motivation factor "job security" observed in the years 2009 and 2020 are presented in Table 8 and Figure 5. At the same time, there were the most significant differences in the evaluation of the mentioned motivation factor.

Following the obtained results, it can be stated that there were statistically significant differences in perceiving the most important motivation factors (career advancement, atmosphere in the workplace, good work team, self-actualization, job security) in the investigated years (2003, 2009, 2016, 2019 and 2020).

Figures of arithmetic means and reliability (Figures 1 - 5) show that there was a significant decrease in selected motivation factors in the year 2009, especially due to the fact that the year 2009 was considered special because of a dramatic decline in economy by approximately 5%. Slovak economy suffered the consequences of a decline in global demand resulting in a decrease in industrial production, in demand for transport services, in wholesale revenues and subsequent fall in demands in retails and services, as a result of making the staff redundant. Mentioned changes in economy affected running of the repair and maintenance service enterprise in the rail transport when the financial and economic crisis in 2009 resulted in differences in requirements for the level of employee motivation. During the following years, the differences can be due to fluctuation in motivation needs of employees, not only in terms of the order of importance, but in terms of statistical significance of differences in individual factors, as well. Those differences were caused especially by the enterprise requirements for the number of staff during the individual years, resulting from the production needs, when the total number of employees changed in time. Forasmuch as the job of a human resource manager is based on communication with employees and these changes were not discussed with them, the level of motivation factors must have changed. Following the mentioned facts, it can be stated that changes in communication between

***Table 1** Composition of the sample set*

| Year | 2003 | 2009 | 2016 | 2019 | 2020 |
|---|---|---|---|---|---|
| Number of respondents | 240 | 190 | 181 | 197 | 160 |
| Total number of workers | 357 | 300 | 275 | 347 | 243 |

***Table 2** Average values of motivation factors*

| Motivation factor | 2003 | 2009 | 2016 | 2019 | 2020 |
|---|---|---|---|---|---|
| Atmosphere in the workplace | 4.77 | 3.29 | 4.69 | 4.44 | 4.87 |
| Good work team | 3.88 | 3.94 | 3.79 | 4.07 | 4.77 |
| Fringe benefits ($13^{th}$, $14^{th}$ salary) | 4.39 | 3.01 | 4.25 | 4.21 | 4.57 |
| Physical effort at work | 4.16 | 3.91 | 3.95 | 3.85 | 4.27 |
| Job security | 3.99 | 3.19 | 4.07 | 3.79 | 4.60 |
| Communication in the workplace | 3.68 | 3.09 | 3.23 | 3.91 | 4.55 |
| Name of the company | 4.22 | 3.71 | 4.38 | 3.79 | 4.35 |
| Opportunity to apply one's own ability | 4.95 | 3.31 | 4.58 | 4.26 | 4.53 |
| Workload and type of work | 4.19 | 4.36 | 4.33 | 3.86 | 4.33 |
| Information about performance result | 3.57 | 3.11 | 3.61 | 3.62 | 4.48 |
| Self-actualization | 4.00 | 3.79 | 3.86 | 3.85 | 4.63 |
| Work environment | 4.02 | 3.29 | 3.96 | 3.74 | 4.33 |
| Employee performance | 3.81 | 2.57 | 3.72 | 3.81 | 4.37 |
| Career advancement | 4.10 | 3.71 | 3.85 | 3.68 | 4.90 |
| Competences | 4.01 | 3.00 | 3.98 | 3.55 | 4.13 |
| Prestige | 3.86 | 4.10 | 3.76 | 3.53 | 4.20 |
| Supervisor' s approach | 3.96 | 3.03 | 3.95 | 3.84 | 4.55 |
| Individual decision-making | 3.61 | 3.40 | 3.33 | 3.65 | 4.47 |
| Working hours | 4.44 | 2.63 | 4.09 | 3.78 | 4.53 |
| Social benefits | 3.94 | 3.03 | 3.68 | 3.62 | 4.33 |
| Fair appraisal system | 3.94 | 2.83 | 3.67 | 3.91 | 4.55 |
| Stress | 4.18 | 3.21 | 4.38 | 4.07 | 4.48 |
| Mental effort | 4.16 | 3.67 | 4.04 | 3.75 | 4.27 |
| Mission of the company | 4.49 | 3.50 | 4.41 | 4.11 | 4.30 |
| Region development | 2.87 | 3.30 | 2.92 | 3.18 | 4.23 |
| Education and personal growth | 4.52 | 3.19 | 4.00 | 4.13 | 4.35 |
| Company relation to the environment | 3.66 | 3.29 | 3.77 | 3.70 | 4.28 |
| Free time | 3.15 | 3.60 | 3.43 | 3.46 | 4.12 |
| Recognition | 4.41 | 3.07 | 4.50 | 3.87 | 4.42 |
| Basic salary | 3.25 | 3.16 | 3.69 | 3.56 | 4.48 |

managers and employees are essential for motivation factors being relatively stable.

An enterprise is a place where activities linked with its success are carried out [41-42]. All the areas of management must be in the centre of attention [43-45]. In order to succeed, an enterprise must be led by a competent person – manager [46-48]. He/she must have powers of concentration for employees as the human resources are according to actual trends, the greatest asset possessed by an enterprise [49]. Motivating staff to achieve goals is one of the most serious problems the managers have to face in the business environment [22, 24, 50-51]. The issue of employee motivation is considered to be one of the most important facts in the area of human resource management. It reflects a general approach of people to work and their willingness to work. Internal order of employees' needs and their personalities are the decisive factors, therefore the research on employee motivation and their satisfaction or dissatisfaction is required in order to suggest effective measures associated with motivation [52-53]. Not only the situation and the environment, but also factors like the age, gender, education, affecting the needs of an individual, must be taken into account. Personal, mental, financial as well as social factors cause the changes in employee motivation. According to Nadeem et al. [54], there are lots of variables affecting the level of motivation. The opinion of Ryan and Deci [55] is the same. They think that the levels of employee motivation differ.

Following results presented here, it can be stated that significant changes in the structure of motivation factors, as well as changes in the importance of motivation factors, occurred in the investigated enterprise over time. Five most important motivation factors (career advancement, atmosphere in the workplace, good work

***Table 3*** *ANOVA test for five most important motivation factors*

| Variance analysis | SS effect[1] | DF effect[2] | PS effect[3] | SS error[4] | SV error[5] | PS error[6] | F[7] | p[8] |
|---|---|---|---|---|---|---|---|---|
| Career advancement | 92.80863 | 4 | 23.20216 | 408.9283 | 512 | 0.798688 | 29.05034 | 0.000 |
| Atmosphere in the workplace | 343.6109 | 4 | 85.90272 | 320.1961 | 513 | 0.624164 | 137.6285 | 0.000 |
| Good work team | 111.5843 | 4 | 27.89607 | 240.9563 | 513 | 0.469700 | 59.39120 | 0.000 |
| Self-actualization | 113.4335 | 4 | 28.35837 | 297.5800 | 513 | 0.580078 | 48.88717 | 0.000 |
| Job security | 208.3348 | 4 | 52.08371 | 305.3273 | 513 | 0.595180 | 87.50917 | 0.000 |

*Notes: [1]SS effect - sum of squares, [2]SV effect- degree of freedom, [3]PS effect - intergroup variance, [4]SS error- sum of squares, [5]SV error - degree of freedom, [6]PS error - within group variance, [7]F - F-test, [8]p - level of significance (5%)*

***Table 4*** *Duncan test for the motivation factor Career advancement*

| Year | 2003 | 2009 | 2016 | 2019 | 2020 |
|---|---|---|---|---|---|
| 2003 | | 0.000003* | 0.050843 | 0.001898* | 0.368147 |
| 2009 | 0.000003* | | 0.000011* | 0.000009* | 0.000004* |
| 2016 | 0.050843 | 0.000011* | | 0.208377 | 0.006050* |
| 2019 | 0.001898* | 0.000009* | 0.208377 | | 0.000078* |
| 2020 | 0.368147 | 0.000004* | 0.006050* | 0.000078* | |

*Note: Single asterisk (*) indicates statistically significant differences at the level of significance α = 5%*

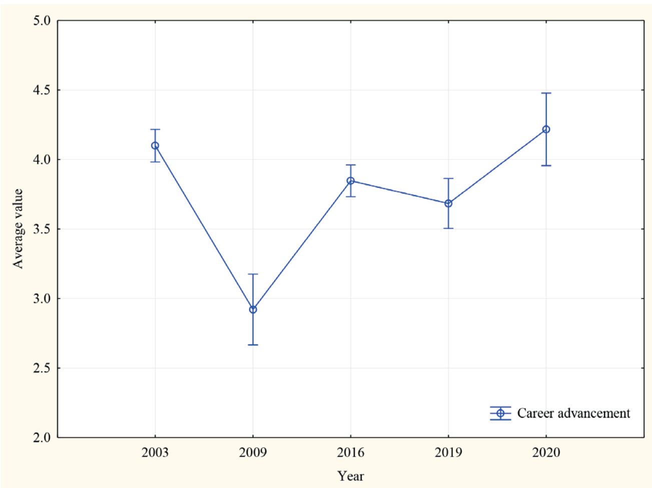


***Figure 1*** *Arithmetic means and confidence interval for the motivation factor Career advancement*

***Table 5*** *Duncan test for the motivation factor Atmosphere in the workplace*

| Year | 2003 | 2009 | 2016 | 2019 | 2020 |
|---|---|---|---|---|---|
| 2003 | | 0.000003* | 0.497061 | 0.004742* | 0.405392 |
| 2009 | 0.000003* | | 0.000011* | 0.000009* | 0.000004* |
| 2016 | 0.497061 | 0.000011* | | 0.024314* | 0.154783 |
| 2019 | 0.004742* | 0.000009* | 0.024314* | | 0.000327* |
| 2020 | 0.405392 | 0.000004* | 0.154783 | 0.000327* | |

*Note: Single asterisk (*) indicates statistically significant differences at the level of significance α = 5%*

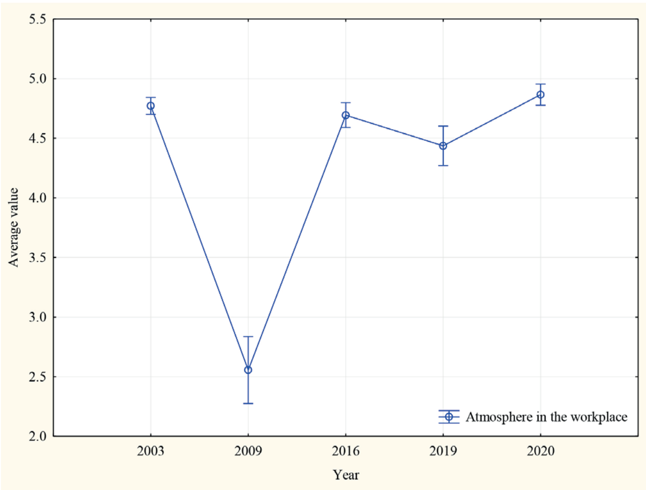


***Figure 2*** *Arithmetic means and confidence interval for the motivation factor Atmosphere in the workplace*

***Table 6*** *Duncan test for the motivation factor Good work team*

| Year | 2003 | 2009 | 2016 | 2019 | 2020 |
|---|---|---|---|---|---|
| 2003 | | 0.000011* | 0.387662 | 0.055939 | 0.000011* |
| 2009 | 0.000011* | | 0.000009* | 0.000003* | 0.000004* |
| 2016 | 0.387662 | 0.000009* | | 0.007652* | 0.000003* |
| 2019 | 0.055939 | 0.000003* | 0.007652* | | 0.000009* |
| 2020 | 0.000011* | 0.000004* | 0.000003* | 0.000009* | |

*Note: Single asterisk (*) indicates statistically significant differences at the level of significance α = 5%*

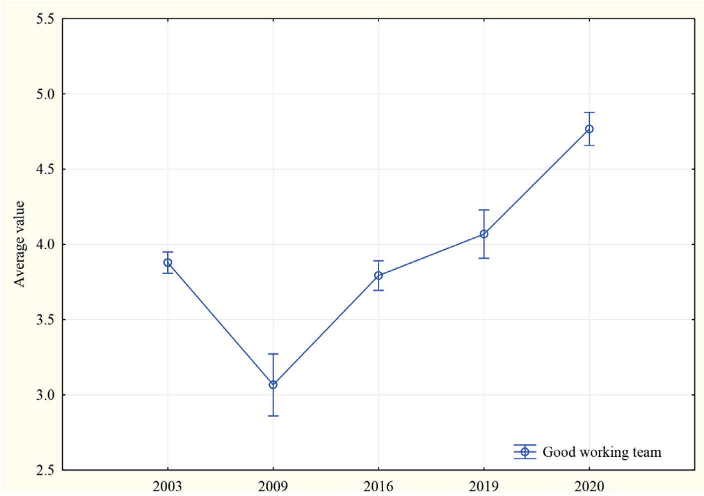


***Figure 3*** *Arithmetic means and confidence interval for the motivation factor Good work team*

***Table 7*** *Duncan test for the motivation factor Self-actualization*

| Year | 2003 | 2009 | 2016 | 2019 | 2020 |
|---|---|---|---|---|---|
| 2003 | | 0.000003* | 0.191458 | 0.190006 | 0.000009* |
| 2009 | 0.000003* | | 0.000011* | 0.000009* | 0.000004* |
| 2016 | 0.191458 | 0.000011* | | 0.929945 | 0.000011* |
| 2019 | 0.190006 | 0.000009* | 0.929945 | | 0.000003* |
| 2020 | 0.000009* | 0.000004* | 0.000011* | 0.000003* | |

*Note: Single asterisk (*) indicates statistically significant differences at the level of significance α = 5%*

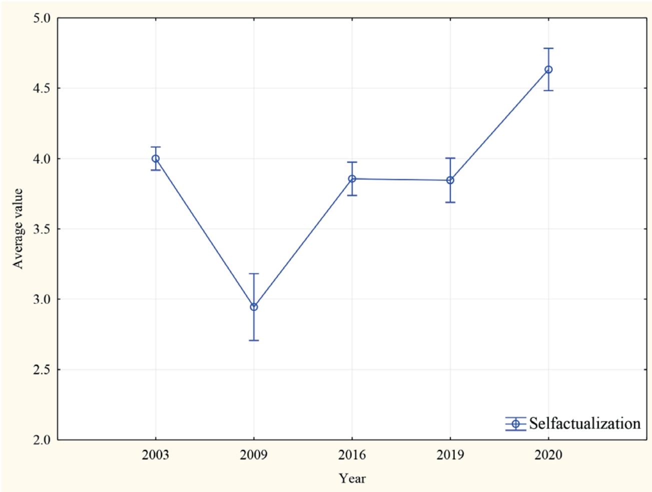


***Figure 4*** *Arithmetic means and confidence interval for the motivation factor Self-actualization*

***Table 8*** *Duncan test for the motivation factor Job security*

| Year | 2003 | 2009 | 2016 | 2019 | 2020 |
|---|---|---|---|---|---|
| 2003 | | 0.000011* | 0.439757 | 0.087749 | 0.000011* |
| 2009 | 0.000011* | | 0.000003* | 0.000009* | 0.000004* |
| 2016 | 0.439757 | 0.000003* | | 0.017696* | 0.000011* |
| 2019 | 0.087749 | 0.000009* | 0.017696* | | 0.000003* |
| 2020 | 0.000011* | 0.000004* | 0.000011* | 0.000003* | |

*Note: Single asterisk (*) indicates statistically significant differences at the level of significance α = 5%*

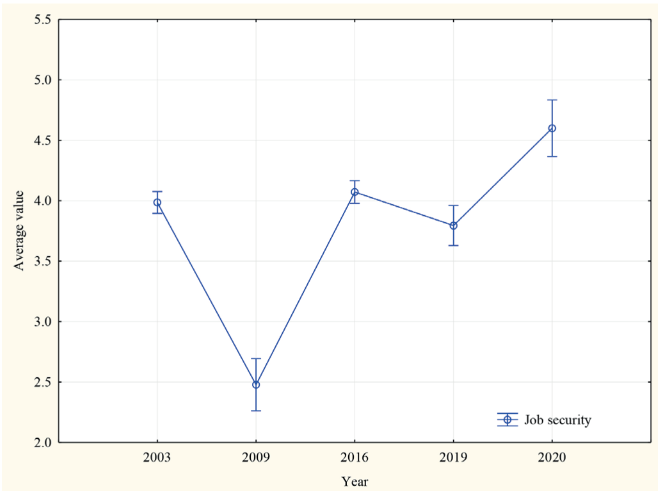


***Figure 5*** *Arithmetic means and confidence interval for the motivation factor Job security*

team, self-actualization, job security) changed. The order was determined following the order of importance in the year 2020. The results of the research, carried out by the questionnaire in the years 2003, 2009, 2019, 2019 and 2020, showed the parts of employee motivation in which new measures resulting in their improvement must be taken. Following the findings, the hypotheses: the workers' motivation in repair and maintenance service enterprise in the rail transport will be different in structure and the workers' motivation in repair and maintenance service enterprise in the rail transport will be different in terms of importance, were confirmed.

## 5 Conclusions

Human resources are the essential factor determining the enterprise performance. Therefore, they must be in the centre of our attention. Employees can have abilities, skills, however if they are not willing to work, they do not achieve the required level of performance [56-57]. At this point, the employee motivation has to be taken into account as an important element affecting the employee performance. The main role of motivation is to ensure that the employees will be willing to work and achieve the greatest performance. Requirements for their performance are not as important as the needs to meet their personal requirements. General knowledge of theories associated with employee motivation is accepted in the research on motivation needs of employees and it is considered as the first step necessary for creating the motivation programme of an enterprise. Following the knowledge together with methods used in psychological and sociological research, the state-of-the-art of the human resources in an enterprise can be evaluated. Strength and weaknesses of the management and their impact on motivation can be defined this way as well.

The process of motivation is one of the most important elements of the human resource management [58]. Satisfaction of employees' needs affecting their behaviour and performance in positive way must be provided in order to have a required effect. Motivation programme covering the requirements of an enterprise and employees must be created. During the creating of a motivation programme, the most important motivation factors and their impacts on employees must be identified and modified to achieve the required effect.

The analysed enterprise can be recommended to carry out an analysis of the motivation factors in the course of twelve months. It should be aimed at defining the changes in the structure of motivation factors after implementing the measures to improve the motivation climate in the enterprise. In the case of further significant changes, the motivation programme must be modified to reflect the changes in employees' needs.

Employee motivation provided by supervisors - managers should ensure that the work covers not only existential needs of employees but also makes the employees happy and satisfied. Managers must be aware of the fact that employees are human beings with their personal demands, wishes and goals. Therefore, each company should implement employees' needs, wishes and goals in the motivation factors and motivation programme. In this way, the motivation can result in satisfied and especially high performing staff that meet their personal needs in the workplace and at the same time they will fulfil the business goals. The main role of motivation is to ensure that employees are identified with their tasks at work and their personal goals are identical with those of the enterprise. Each enterprise should be aware of this fact and therefore turn more attention to employee motivation.

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Tamas Kozak - Radovan Madlenak - Gyorgy Ivan Neszmelyi

# HOW THE LEAN MANAGEMENT DECISION INFLUENCES THE TRANSPORTATION COST IN THE SUPPLY CHAIN?

*The purchase decisions require information on where each phase in aretail supply chain should be placed. The presented method is an integrated tool for retail supply chain totransaction cost optimization. The model does not only present a company-level lean management's decisions within a supply chain, but it also shows the exact methodto optimize the supply chain competitiveness. The allocation model also illustrates how the purchase decisions are allocated for producer, distributor and retail companies. The complexity of the allocation model may be affected by the size of the logistic costs, the algorithm used to calculate the supply chain purchase decisions and the final needs of the customers. The lean management approach could be a redemption to a company, but the results do not help to enhance competitiveness for the whole supply chain in every case. In this paper, a model method is demonstrated that helps to gain benefit of the lowest cost of integrated inventory management decisions. One of the essential parts ofthis research is that not onlythe lean management' result is considered, but effects of purchase decisions are integrated into the whole retail supply chain, as well. This type ofintegrated approachcan have an exponential impact on profitability on supply chain level effectiveness. In the paper are discussed issues that are important from the perspective of carriers, truck owners and operators, transportation policy makers and shippers. Different capacities of transportation and their costs and performance characteristics from lean aspect are discussed as well.*

***Keywords:*** *lean management, category management, inventory management, gross margin, supply chain, transportation*

## 1 Keyconcepts for the research approaches

Traditional standard approach where the transportation cost optimised itself is in many ways inadequate and has been overcome nowadays. Therefore, a new, progressive approach based on the latest lean knowledge and supply chain technologies need to be sought. This paper describes a progressive method of lean supply chain metrology in more detail, applied to assessing the impact of transportation cost in supply chain.

The methodological research approach is affected mainly by three areas, which are discussed in the paper. The selected and discussed business themes are:

- Supply Chain Management
- Inventory Management
- Transportation Management
- Lean Management.

Other business issues could be identified which influence the research topic, in spite of all these the direct strategic drivers are examined in this paper. In several case these issues are in contract with each other from the effectiveness point of view, in the paper the method is presented to solve the conflicts.

### 1.1 Introduction

Transportation refers to the movement of goods from location 'A' to location 'B' as it makes its way from the beginning of a supply chain to the customer. Transportation is one of the most important supply chain drivers because products are rarely produced and consumed in the same area mainly in retail business [1]. The supply chain strategy explores the issues and provides answers to problem of optimizing operations in any business system, whether it be manufacturing, mortgage loan processing, or supply chain management [2]. In this definition, throughput refers to the rate at which sales to the end customer occur. Depending on the market being served, sales or throughput occur for different reasons. In some markets, customers value and will pay for high levels of service. In other markets customers seek simply the lowest price for an item. There are five areas where companies can make decisions that will define their supply chain capabilities: production, inventory, location, transportation, and information [3].

Traditionally, manufacturers were the dominant forces in the supply chain in the consumer goods industry, but with the trend towards the retail consolidation and

**Tamas Kozak**[1]**, Radovan Madlenak**[2,*]**, Gyorgy Ivan Neszmelyi**[1]
[1]Department of Commerce, Faculty of Commerce, Hospitality and Tourism, Budapest Business School, University of Applied Sciences, Hungary
[2]University of Zilina, Slovakia
*E-mail of corresponding author: radovan.madlenak@fpedas.uniza.sk

concentration of large retailers, power in the supply chain has been shifting towards the retail level [4]. Whereas manufacturers previously designed, produced, promoted and distributed their goods, retailers have been able to exert pressure back into the supply chain. Retailers convinced manufacturers to change their supply chain strategies and, for example, include tailored pallet packs, scheduled deliveries, continuous replenishment systems, etc. [5].

The supply chain in the consumer goods industry includes all the parties directly or indirectly involved in receiving and fulfilling customer requests, e.g. manufacturers, suppliers, wholesalers, retailers, third party service providers (transporters, warehouses) and customers [1]. Supply chains are dynamic and involve the constant flow of products, information and finance between the different stages. The first flow (products and related services) is one of the main elements in supply chain management. Traditionally, it is the major topic in logistics, because customers expect their orders to be delivered on time, reliably and damage-free. Information flows comprise, for example, orders, inventory, demand or sales data. These flows are important for replenishment and (demand) forecasting at all the stages of the supply chain. Financial flows include the transfer of funds or cash between the supply chain partners [5].

### 1.2 Key concepts of inventory management

One of the most important merchandise management tasks of the planning process is to develop an optimal purchase plan. An assortment is a set of stock keeping units (SKUs) that a retailer offers in a merchandise category in each of their stores. The variety, or breadth of a retailer's merchandise is the number of different merchandise categories offered, and the assortment, or depth of merchandise is the number of SKUs within each category. In the context of merchandise planning, the concepts of variety and assortment are applied to one merchandise category in the given retail department or store. On the category level, variety reflects the number of different types of merchandise and assortment is number of SKUs per type. The process of determining the variety and assortment within a category is called editing the assortment. When editing the assortment for a given category, the effect of assortments on gross margin return on investment (GMROI), the complementarities and possible substitutes between categories and the effects of assortments on the buying behavior should be considered, as well as the physical characteristics of the store and the shelves [6]. In developing the assortment plan, the retailer needs to seek an increase in sales by offering greater breadth and depth, but at the same time inventory turnover and GMROI will potentially decrease because of the increased inventory investment. Increasing assortment breadth and depth may also decrease gross margin. For example, the more SKUs offered, the greater the chance of breaking sizes- that is, stocking out of a specific size or color of SKU. If stockout occurs of a popular SKU in a fashion merchandise category and the retailer cannot reorder it during the season, they would typically discount the entire merchandise type, thus reducing the gross margin. The retailer's objective is to entirely remove the merchandise type from the assortment, so customers would not be disappointed when they do not find the size and color they want [7]. When the retailer develops an assortment plan, they should consider the degree to which the categories complement each other in the given department. If the retailer maintains a wider assortment of goods, this leads to an increase in the more profitable accessory sales. Retailers typically make model-stock plans for the different product types in a portfolio. For example, they mostly classify their merchandise as A, B, and C products, based on the sales volume or the gross margin. The basic assortment of a category is stocked in the given shop [8]. A larger shelf means more available space, so more SKUs can be placed on it, which increases the GMROI, but the final goal is to maximize the portfolio level yield. In the next part it is examined how the portfolio level yield can be optimized by changing the size of space that each product category occupies on a shelf - taking their sales and gross margin increasing potency into account [9].

### 1.3 Key concepts of the lean management

Transportation refers to movement of product from one location to another as it makes its way from thebeginning of a supply chain to the customer. Transportation is an important supply chain driver because in retail products are often carried and consumed in the trade location. Transportation is a significant component of the costs incurred by most supply chains.

To understand transportation in a supply chain, it is important to consider the perspectives of all retailer's parties. A carrier makes investment decisions regarding the transportation equipment (locomotives, trucks, airplanes, etc.) and in some cases infrastructure (rail) and then makes operating decisions to try to maximize the return from these assets. A shipper, in contrast, uses transportation to minimize the total cost (transportation, inventory, information-sourcing and facility) while providing an appropriate level of responsiveness to the customer. The effectiveness of carriers is influenced by infrastructure such as ports, roads, waterways and airports and the asset capacity in transportation. Most transportation infrastructure throughout the world is owned and managed mainly by distributor and producer.

The design of a transportation network affects the performance of a supply chain by establishing theinfrastructure within which operational transportation decisions regarding scheduling and routing are made. A well-designed transportation network allows a supply chain to achieve the desired degree of responsiveness at a low cost. Three basic questions need to be considered when designing a transportation network between two stages of a supply chain:

1. Should transportation be direct or through an intermediate site?
2. Should the intermediate site stock product or only serve as a cross-docking location?
3. Should each delivery route supply a single destination or multiple destinations (milk run)?

Based on the answers to these questions, the supply chain ends up with a variety of transportation networks. In this paper we discuss these options in the context of a seller with partners [1].

### 1.4 Key concepts of transportation management

Mass production is based on producing the large lots of identical items to meet anticipated demand. This makes great efficiencies possible because the costs of setups, tooling, etc. are amortized over a very large number of units, making the per-unit costs very low. That also means inventory (queues for parts and materials), and longer cycle times due to the queue are also crucial to retail businesses [10]. Production is to schedule to demand, product flow focuses on the object of customer value. The product, design, service, order, etc., that is being created for the customer. All the work practices in supply chain are carefully evaluated and rethought to eliminate stoppages of any kind so the object of value proceeds smoothly and continuously to the customer [11].

Tools, such 5S is the starting point for lean deployment. 5S stands for Sort, Set in order, Shine, Standardize, and Sustain. These terms are defined as follows: Sort-Clearly distinguish what is necessary to do the job from what is not. Eliminate the unnecessary. Set in order-Put needed items in their correct place to allow for easy accessibility and retrieval. Shine-Keep the workplace clean and clear of clutter. This promotes safety as well as efficiency. Standardizedclean-up: develop an approach to maintaining orderly work environment that works. Clean and Sustain-Make a habitof maintaining your workplace [12].

Constraints, or bottlenecks, require special attention. Aprocess constraint is that step or part of the process that limits the throughput of the entire process considering that the producer does not hold inventory, "suddenly" carry the goods for distributor. When a constraint isn't producing, the stocking capacity needs to be considered Every effort needs to be focused on assuring that the companies have sufficient transportation and stocking resources to keep running. Every unit produced by the constraint is of acceptable quality in order to match with customer needs. The constraint is operated in as efficient a manner as possible [13].

Level loading is the process of generating a schedule that is level, stable, smooth and responsive to the market. The goal of level loading is to make the same quantity of an item every day. It is driven by Takt time. A level loaded schedule can be obtained as follows: N daily work time daily quantity needed Calculate = Take time. For each part, list part name, part number, daily quantity needed, Takt time. Sort the list by quantity needed and Takt time. This is the level loaded schedule [14].

The Pull systems are opposite to the traditional mass production push system. The Push systems can be summarized as "Make a lot of stuff as cheaply as possible and hope people will buy it." Push systems minimize the number of setups and changeovers and use dedicated, specially designed equipment to produce identical units. The pull systems can be summarized as "Do not make anything until it is needed, then make it fast". The pull system controls the flow and quantity produced by replacing items when they are consumed. The storage area of a modern super- market is very small compared to the retail floor area. In fact, supermarkets were the inspiration behind Taiichi Ohno's creating Lean at Toyota. The pull systems require level loading and flexible processes Flexible process [15].

Flexible processes are lightweight and manoeuvrable tools, and fixtures and equipment located and positioned to improve safety, ergonomics, quality, and productivity. They are the opposite of the big, heavy, permanently positioned counterparts traditionally used for mass production. A flexible shop can be quickly reconfigured to produce different items to meet changing customer demands. Flexible processes are related to level loading and pull. A completely flexible process would be reconfigured to produce an item as soon as an order for it arrived. This ideal cannot be met, but it can be approximated over some small-time interval, such as the factory is able to change the lot size in short time.

Lot size refers to amount of an item that is ordered from the plant or supplier or issued as a standard quantity to the production process. The ideal lot size for flow is one. Larger lot sizes lead to larger quality problems due to delayed feedback, excessive inventory, obsolete inventory, etc. Of course, there are offsetting benefits such as quantity discounts, fewer setups, lower transportation costs, etc. In practice, the costs and benefits must be balanced to achieve an optimum.

## 2 Development of cost optimization in a supply chain

Production scheduling allocates available capacity (equipment, labor and facilities) to the work that needs to be done. The goal is to use available capacity in the most efficient and profitable manner [16]. The productionscheduling operation is a process of finding the right balance between several competing objectives: High utilization rates- this often means long production runs and centralized manufacturing and distribution centers [17]. The idea is to generate and benefit from economies of scale, - this usually means short production runs and just-in-time delivery of raw materials. The idea is to minimize the assets and cash tied up in inventory High levels of customer service- this often requires high levels of inventory or many short production runs. The aim is to provide the customer with quick delivery of products and not to run out of stock

***Table 1*** *Variable costs*

| variable costs | fixed producing capacity | retail lean management approach | fixed production capacity with EOQ approach |
|---|---|---|---|
| production set up costs | 0.00 | 3.20 | 0.00 |
| transportation and ordering costs | 38.40 | 38.40 | 34.40 |
| holding costs | 50.00 | 39.00 | 20.00 |
| total costs | 88.40 | 80.60 | 54.40 |

of any product. The base model (Appendix 1), developed for supply chain variable cost optimization, is built on these assumptions:

- The basic data show products placed on an expected sales of retailer and the fixed volume purchase plan,
- Producer plans fixed volume production schedule considering the expected customer needs for the period,
- Distributor purchases end sells goods in terms of producer and retailer inventory plans.
- Considering the high-level service performance retailer and distributor keep minimum 1unit safety stock, which influences the stock opening balances.
- The ordering stock USD 1 and USD 0.8 for retailer (per order), the retailer does not transport the goods towards.
- The transportation cost per delivery USD 0.4 for producer and USD 0.2 for distributor assuming 1unit truck capacity for producer and 0.8 for distributor.
- The carrying (holding) stock USD 2 and USD 1 for retailer and distributor respectively (per stock value).

The runout time calculation for a product is expressed as R = P/D where: R = runout time on hand P = number of units of product Dproduct demand in units for a day or week, in this case the planed customer demand 24 unit for 6 periods, so the producing lot size in a period 4units. Taking into account the basic assumptions of the basic model (Appendix 1) with fixed production, the **total variable cost in the supply chain USD 88.4 of which the retailer bears USD 48.8** (Table 1).When a single product is to be made in a dedicated facility, scheduling means organizing operations as efficiently as possible and running the facility at the level required to meet demand for the product.

The second step in scheduling the purchase, when retailer would like to decrease the average inventory level using the lean approach expecting the decrease of total logistic variable cost (Appendix 2). The task is to determine the economic lot size for the production runs of each product. If production costs are minimized by doing long production runs, then inventory levels will be higher and product inventory carrying costs will be higher. Once production quantities have been determined, the second step is to set the right sequence of production runs for each product. The basic rule is that if inventory for a certain product is low relative to its expected demand, then production of this product should be scheduled ahead of other products that have higher levels of inventory relative to their expected demand. The main difference from the fixed production schedule is the set-up cost for manufacturer because of the need of flexible capacity. In the model it is assumed USD 0.8 if production volumes change between the two periods, calculating with the same ordering and carrying costs which are used for basic model, **thetotal variable cost in the supply chain USD 80.6 of which the retailer bears USD 16.8.** Notice the decreased total cost in spite of the increased cost level for the whole supply chain and the retailer does not carry the goods toward. The retailer could decrease its average inventory at the expense of distributor and besides the producer bears the fluctuating production schedule.

The third step in scheduling a single production facility is to determine the economic lot size for the production runs of each product with less ordering transaction and avoiding the cost due to the cost of production capacity change. This is a calculation much like the economic order quantity (EOQ) calculation used in the inventory control process. The calculation of economic lot size involves balancing the production setup costs for a product with the cost of carrying that product in inventory. If setups are not done and production runs are done in bigger batches, the result will be higher levels of inventory, but the production costs will be lower due to eliminated or decreased setup activity (Appendix 3). Finally, the integrated supply change management could push down the total costs below the original level using the fixed production schedule and more flexible purchase plan, the total cost: **USD54.4**. Notice the distributor purchase the goods in term of fixed production schedule and flexible retailer buying strategy focusing on economic order quantities. The retailer focuses on the minimum closing stock which enough to keep the safety level.

Inventory aggregation decisions must account for inventory and transportation costs. Inventory aggregation decreases the supply chain costs if the product ordered in terms of economic quantity, resulting low transportation costs, and customer orders are large. If a product was produced with fixed capacity, low demand uncertainty, large transportation cost, or small customer orders, inventory aggregation may increase supply chain costs. If a product was produced in a flexible way, high demand uncertainty, large transportation costs, or small customer orders, inventory aggregation may increase supply chain costs, including the production set up cost.

***Table 2*** *Summary of supply chain cost*

| variable costs | fixed producing capacity | retail lean management approach | fixed production capacity with EOQ approach |
|---|---|---|---|
| production set up costs | 0.00 | 3.20 | 0.00 |
| transportation and ordering costs | 38.40 | 38.40 | 34.40 |
| holding costs | 5.00 | 3.90 | 2.00 |
| total costs | 43.40 | 45.50 | 36.40 |

## 3 Conclusion

Order management is the process of passing order information from customers back through the supply chain from retailers to distributors to service providers and producers. This process also includes passing information about order delivery dates, product substitutions and back orders forward through the supply chain to customers. In the examined model this process has long relied on used information such as purchase orders, sales orders, change orders. Retailer company generates a purchase order and calls a supplier to fill the order. The delivery scheduling operation is of course strongly affected by the decision made concerning the modes of transportation that will be solved and the delivery-scheduling process works within the constraints set by transportation decisions. For the verified method the direct deliveries are assumed. Direct deliveries are made from one originating location to one receiving location. With this method of delivery, the routing is simply a matter of selecting the shortest path between the two locations Scheduling this type of delivery involves decisions about the quantity to deliver and the frequency of deliveries to each location. The advantages of this delivery method are found in the simplicity of operations and delivery coordination. With respect to suppliers, retailers, buyers have to negotiate continually lower prices. Due to its volume power, buyer can often force the integration of suppliers' operations into its supply chain. **This might imply the implementation of a joint business plan with contracts specifying price, volume, delivery - schedule, packaging and quality**. It might also involve a subsequent close monitoring of their suppliers' production and gaining access to their books and accounts. In this paper an integrated model is demonstrated, where the popular lean approach is developed towards an Economic Lean Method on supply chain level. It is not enough to optimize the inventory level through less stocking, more important to optimize the cost on supply chain level in spite of the higher asset requirements. The one-sided lean approach does not take into account external costs either because of increase or more frequent product movement. The stock itself is not an enemy, the real friend of business the asset efficiency.

As the costs presented in Table 2, the transportation and ordering costs are higher than the economic order of quantity is the primary determinant in supply chain management. Although the lean approach helps to reduce the inventory level, at the same time in retail sector the intensive volume of movement of goods increase the transportation and ordering costs not to mention the external costs, but this last issue could be a topic of a new research.

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**Appendix 1 Fixed producing schedule**

| Retail | Period 1 | Period 2 | Period 3 | Period 4 | Period 5 | Period 6 |
|---|---|---|---|---|---|---|
| opening stock | 5.0 | 6.0 | 5.0 | 2.0 | 1.0 | 3.0 |
| purchase | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |
| sales | 3.0 | 5.0 | 7.0 | 5.0 | 2.0 | 2.0 |
| closing stock | 6.0 | 5.0 | 2.0 | 1.0 | 3.0 | 5.0 |

| Distributor | Period 1 | Period 2 | Period 3 | Period 4 | Period 5 | Period 6 |
|---|---|---|---|---|---|---|
| opening stock | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| purchase | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |
| sales | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |
| closing stock | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

| Producer | Period 1 | Period 2 | Period 3 | Period 4 | Period 5 | Period 6 |
|---|---|---|---|---|---|---|
| manufacturing | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |
| cumulated selling | 4.0 | 8.0 | 12.0 | 16.0 | 20.0 | 24.0 |

*Source: The authors' own edition*

**Appendix 2 Flexible producing schedule with retailer lean approach**

| Retail | Period 1 | Period 2 | Period 3 | Period 4 | Period 5 | Period 6 |
|---|---|---|---|---|---|---|
| opening stock | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| purchase | 3.0 | 5.0 | 7.0 | 5.0 | 2.0 | 2.0 |
| sales | 3.0 | 5.0 | 7.0 | 5.0 | 2.0 | 2.0 |
| closing stock | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

| Distributor | Period 1 | Period 2 | Period 3 | Period 4 | Period 5 | Period 6 |
|---|---|---|---|---|---|---|
| opening stock | 1.0 | 1.0 | 1.0 | 8.0 | 8.0 | 8.0 |
| purchase | 3.0 | 5.0 | 7.0 | 5.0 | 2.0 | 2.0 |
| sales | 3.0 | 5.0 | 7.0 | 5.0 | 2.0 | 2.0 |
| closing stock | 1.0 | 1.0 | 1.0 | 8.0 | 8.0 | 8.0 |

| Producer | Period 1 | Period 2 | Period 3 | Period 4 | Period 5 | Period 6 |
|---|---|---|---|---|---|---|
| fix capacity | | | | | | |
| manufacturing | 3.0 | 5.0 | 7.0 | 5.0 | 2.0 | 2.0 |
| cumulated selling | 3.0 | 8.0 | 15.0 | 20.0 | 22.0 | 24.0 |

*Source: The authors' own edition*

**Appendix 3 Fixed production capacity with EOQ approach**

| Retail | Period 1 | Period 2 | Period 3 | Period 4 | Period 5 | Period 6 |
|---|---|---|---|---|---|---|
| opening stock | 4.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| purchase | | 5.0 | 7.0 | 5.0 | 2.0 | 2.0 |
| sales | 3.0 | 5.0 | 7.0 | 5.0 | 2.0 | 2.0 |
| closing stock | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

| Distributor | Period 1 | Period 2 | Period 3 | Period 4 | Period 5 | Period 6 |
|---|---|---|---|---|---|---|
| opening stock | 2.0 | 6.0 | 5.0 | 2.0 | 1.0 | 3.0 |
| purchase | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |
| sales | | 5.0 | 7.0 | 5.0 | 2.0 | 2.0 |
| closing stock | 6.0 | 5.0 | 2.0 | 1.0 | 3.0 | 5.0 |

| Producer | Period 1 | Period 2 | Period 3 | Period 4 | Period 5 | Period 6 |
|---|---|---|---|---|---|---|
| fix capacity | | | | | | |
| manufacturing | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |
| cumulated selling | 4.0 | 8.0 | 12.0 | 16.0 | 20.0 | 24.0 |

*Source: The authors' own edition*

Kveta Papouskova - Martin Telecky - Jiri Cejka

# PROCESS EFFICIENCY ANALYSIS OF SELECTED AUTOMOTIVE COMPANIES IN EUROPE

*The automotive industry has lately been undergoing major changes having a considerable impact on the whole vehicle sector. This does not only refer to what is technologically new on vehicles themselves, but also to the new modern management methods, frequently associated with the Industry 4.0 concept. As well as other companies, car factories are pushing their costs downwards to increase their production efficiency. This paper analyses the economic situation of 5 car manufacturers, two of which having their factories in the Czech Republic and three in Germany. The task was to ascertain efficiency of individual companies in order to propose possible improvements. To do this, the Data Envelopment Analysis (DEA) for two models (CCR - model based on Charnes, Cooper & Rhodes and BCC - model based on Banker, Charnes & Cooper) was used. The BCC model was found to be more applicable to the established efficiencies, than the CCR one.*

***Keywords:*** *automotive sector, business processes, efficiency, correlation analysis, DEA method*

## 1 Introduction

The automotive industry brings a number of innovation processes and methods - from the manufacturing process and selection of supplier companies to management systems and the customer orientation. From the quality assurance aspect, these processes are at the top of efficiency of individual processes as the safety of motorised vehicles is strongly emphasized.

Most of these activities are related to the Industry 4.0 strategy within the innovation processes. Industry 4.0, also known as the fourth industrial revolution, is the digitalization-based concept. Individual activities, demonstrating a certain degree of repetition and simplicity, are computerized based on the control processes. This way, the human factor is being replaced by the robotic work. This concept considerably changes the powers on the market, giving a huge market advantage to those undertakings, which are able to put the Industry 4.0 concept in place. These companies save their time and money, while increasing their efficiency.

In line with the EU´s long-term sustainable development plan, large companies are obliged to incorporate this concept in their long-term strategies. This concept has become a trend which has to be included by all the major enterprises in their plans. The annual reports from where the research data are taken clearly show that the automotive industry already deems the sustainability to be one of the pillars of their activities.

The sustainable development was established and for the first time defined in Our Common Future report [1] in 1987 as "*the development which meets the needs of today´s generations, without compromising the ability of future generations to meet theirs.*"

As defined by the Czech Act No. 17/1992 Sb. on environment, the sustainable development is a process, which fulfils the existing needs of the human society, without affecting the ability of future generations to meet their own needs. It is aimed to increase the length of the human life within the limits of the ecosystem of our planet. Some researchers have already been carried out in this area, including [2-4].

The packaging data method (DEA) has been shown in many types of research to determine the effectiveness of automotive companies [5-8]. Our research was beneficial in studies where the DEA method was combined with Correlation Analysis directly from the Automotive field [9-10].

## 2 Theoretical rationale

### 2.1 Process approach

The set of activities, which can be called basic processes, can be found in every company. These processes are the very essence of its existence. The process outputs include the product, service, etc. Processes are performed by employees, each of them being responsible for the operation they perform in sense of their qualification and for contributing to the quality of a final product. Processes are managed and organized by means of managers in a certain hierarchy and streamlined with the company´s strategy [11].

**Kveta Papouskova*, Martin Telecky, Jiri Cejka**
The Institute of Business and Technology in Ceske Budejovice, Czech Republic
*E-mail of corresponding author: kvetapapouskova@gmail.com

One of the publications [12] defines the process approach as the basis of the labour organization in the undertaking-as the basis of all business activities. Strategic, tactical or operational management - all of that may be carried out either in accordance with the division (specialization) of labour principle, which, however, currently fails to meet the companies´ needs reflecting the change in the environment, or in line with the process principle.

The prerequisite for effective and efficient functioning of the company is to define and manage many interrelated activities. Any activity, which uses the resources and is also managed to convert inputs into outputs, is considered a process. Application of the system of processes within a company, along with identifying these processes, their interactions and management can be called the process approach. The benefit of such a process is continuous management of relations among individual processes within the process system, as well as their combination and interactions [13].

## 2.2 Essential insight into process environment and definition of terms

The process is a series of logically related activities and tasks through which, if performed gradually, the pre-defined set of outcomes is to be created. This definition describes the process as to its purpose, i.e. making a product or providing/ensuring a service [14].

The process is defined as a set of activities through which the set of inputs is transformed into the set of outputs (goods or services) for other people or processes, which uses the labour and tools to do so [13].

Based on another definition, the process may be described as a set of consecutive activities, which transform the defined inputs into a desired output, bind resources to themselves and deliver measurable characteristics. The key element in the definition above is the activity. In principle, it can be assumed that every activity might be described as a process. The process approach to the activity description and definition, therefore, depends on the clarity of the model, tools used, as well as the invention and the style of who describes the model [15].

Very interesting and recently often discussed strategies are represented by Balanced Scorecard and Blue Ocean strategies.

### 2.2.1 The balanced scorecard

The Balanced Scorecard (BSC) transforms the mission and strategy of the company into a clear set of individual benchmarks of the company's performance. This method combines financial and non-financial benchmarks. In the BSC, the company is considered as a participant in coalition relations with a wide range of stakeholders. The performance measurement is focused on future development, in particular. The BSC benefit is that it creates a room for self-reflection. The BSC monitors performance in four perspectives: financial, customer, internal business processes and learning and growth, which allows to make overall and balanced evaluation of a company, as stated in [16] or also [17].

Very interesting publications dealing with this strategy can be found in the scientific literature. Works by other authors [18-22] are also of interest.

### 2.2.2 The Blue ocean strategy

The Blue ocean strategy (BOS) is an alternative approach to the strategy management in the company. It puts into question fundamental prerequisites for the strategic success and changes the traditional approach to the strategy, as a whole. Nowadays, companies, as a rule, venture into direct confrontation with their competitors, striving to find something, which would differentiate them from the latter. Unlike other strategies, the Blue Ocean Strategy is different in its goals and the employed resources, which require unconventional thinking. Whilst the most common company strategy is competition-oriented, the Blue Ocean one strives to wipe out the competitors. The BOS´ goal is to create a sovereign market space without competitors and to ensure the future profit growth of the company by means of the value innovation. The Blue Ocean Strategy entails a systematic approach how to create system frameworks and to apply analytical tools and principles [23].

*«The only way how to beat competition is to stop trying to beat it*"[24]. This issue is also discussed in [23] or [25-26]. Based on monitoring the long-term development of individual industries, the results achieved by means of creating the blue ocean were found to be sustainable [27].

The Blue Ocean strategy is not, however, only applicable to companies, but also to public services. As an example of the BOS implementation in the political practice, one can mention Malaysia where the local government adopted the Blue Ocean strategy in providing programmes and services to the public [28]. In 2010, the operation of the Blue Ocean strategy research centre was commenced in India, too [29].

## 3 Methodology

## 3.1 Correlation analysis

The correlation analysis examines the mutual (mostly linear) dependencies where the intensity (strength) of the interrelation is emphasized more than investigation of variables from the cause and effect viewpoint.

Imagine that there is a random sample $(X_1, Y_1)$, $(X_2, Y_2)$, ..., $(X_n, Y_n)$ from any two-dimensional distribution according to [30].

The strength of dependence between a pair of variables can be quantified using the Pearson correlation coefficient [31]:

$$r_{yx} = r_{xy} = \frac{n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{\sqrt{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}\sqrt{n\sum_{i=1}^{n} y_i^2 - \left(\sum_{i=1}^{n} y_i\right)^2}}, \quad (1)$$

where:
$n$ ... number of values,
$x_i$ , $y_i$ ... real values of various statistical signs (random variables X and Y) expressing the sample variance.

This coefficient obtains values in the interval from -1 to 1. Negative values account for indirect linear dependence, positive values for direct linear dependence and zero means the linear independence.

### 3.2 Spearman's rank correlation coefficient

If there are a few identical values, one will allocate the average rank to them. It is clear that if $Y_i$ tends to increase when $X_i$ increases, the same relationship will apply to their rank, too. If $Y_i$ tends to decrease when $X_i$ decreases, the identical relationship will apply to their rank, too. Assume that $R_1, R_2, ... R_n$ denote the rank $X_1, X_2, ... X_n$ and $Q_1, Q_2, ... Q_n$ denote the rank $Y_1, Y_2, ... Y_n$. If variables $X$ and $Y$ are independent, he values of their ranks will be randomly scrambled, as well [30].

According to [30], the Spearman´s rank correlation coefficient $r_s$ will be defined by the relationship:

$$r_s = 1 - \frac{6}{n(n^2-1)}\sum_{i=1}^{n}(R_i - Q_i)^2, \quad (2)$$

where:
$n$ … number of values,
$R_1, R_2, ... R_n$ indicate the order $X_1, X_2, ... X_n$,
$Q_1, Q_2, ... Q_n$ indicate the order $Y_1, Y_2, ... Y_n$.

If X and Y are independent, then their order values will be randomly shuffled [30].

The Spearman´s rank correlation coefficient obtains the values within the interval $\langle -1;1 \rangle$, as well. In the case of the identical rank, the value of the Spearman´s rank correlation coefficient is 1. In the case of the opposite rank, its value is -1. In the case of independence of both variables (X and Y), its value is 0.

### 3.3 The DEA method

The DEA (Data Envelopment Analysis) method is an optimization method which belongs to the field of multi-criteria evaluation. It is used to evaluate performance and efficiency, as well as to optimize the units in private and public sectors [32-35].

The set of units, engaging in production of identical or equivalent effects is called a homogeneous production unit. Those effects are referred to as outputs which are represented, in particular, by the so-called desired (positive) effects. It means that if the value of these effects increases under otherwise unchanged conditions, the productivity of the given unit will rise. The production unit consumes inputs to create effects. Those inputs are of a minimising nature, which means that reduction of values of these inputs will lead to higher efficiency of the unit being monitored. The input and the output may be represented by, for example, company´s staff headcount and sales, respectively [34-35].

The input/output ratio is called the production unit efficiency. This ratio can be described using the relationship [36]:

$$efficiency = \frac{output}{input}. \quad (3)$$

It must be borne in mind that a situation may happen in the case of the overall efficiency of production units when the whole set of inputs and outputs is determined. The relationship for a relative measure of efficiency is used in this situation. It is expressed as follows [36]:

$$relative\ measure\ of\ efficiency = \frac{weighted\ sum\ of\ outputs}{weighted\ sum\ of\ inputs}. \quad (4)$$

Assume that the sample under examination includes $p$ units. Each of them consumes $m$ inputs to produce $n$ outputs. Assume that $x_{ik}$ is the amount of input consumed by the unit $k$ and $y_{jk}$ is the amount of the output $j$ produced by the $k^{th}$ unit [36].

Mathematically, the relationship can be expressed as follows:

$$\Phi_k = \frac{\sum_{j=1}^{n} u_j y_{jk}}{\sum_{i=1}^{m} v_i x_{ik}}, k = 1,...,p, \quad (5)$$

where:
$k$… unit of the sample under investigation,
$p$… number of units of the sample examined,
$m$ … input,
$n$ … output,
$x_{ik}$ … the amount of input $i$ consumed by the unit $k$,
$y_{jk}$ … the amount of input $j$ produce $k$-th unit,
$u_i$ and $v_j$ are uniform weights of individual inputs and outputs for all the units being evaluated [36].

#### 3.3.1 CCR model

The CCR model (based on Charnes, Cooper & Rhodes, 1978) maximizes the measure of efficiency of the evaluated unit as a quotient of weighted outputs and weighted inputs on condition that the measures of efficiency of all other units are less than or equal to one. The input-oriented CCR model focuses on such an amount of inputs which are consequently evaluated by this model. The model recommends such changes so that the inefficient unit becomes the efficient one. At the same time, the model foresees the **constant returns to scale**; i.e. the change

***Table 1** Input data for analysis*

| Company | Total costs* | Total sales* | Fixed assets* | Number of manufactured vehicles | Staff headcount | Equity* | Earnings after taxes* |
|---|---|---|---|---|---|---|---|
| SKODA AUTO BMW | 14.04 | 16.28 | 4.64 | 1254000 | 33696 | 4.36 | 1.13 |
| HYUNDAI | 4.43 | 5.05 | 3.62 | 340300 | 3312 | 1.66 | 0.28 |
| VW | 72.70 | 78.00 | 119.71 | 10834000 | 119400 | 24.00 | 0.01 |
| BMW | 78.92 | 97.48 | 13.05 | 2490664 | 131565 | 58.09 | 7.21 |
| PSA | 59.18 | 73.97 | 6.71 | 3878000 | 17200 | 19.59 | 4.42 |

*The above figures are in EUR billion.

***Table 2** Application of the correlation analysis*

| | Total costs | Total sales | Fixed assets | Number of manufactured vehicles | Staff headcount | Equity | Earnings after taxes |
|---|---|---|---|---|---|---|---|
| Total costs | 1.0 | 1.0 | 0.9 | 0.7 | 0.9 | 1.0 | 0.4 |
| Total sales | 1.0 | 1.0 | 0.9 | 0.7 | 0.9 | 1.0 | 0.4 |
| Fixed assets | 0.9 | 0.9 | 1.0 | 0.9 | 0.8 | 0.9 | 0.0 |
| Number of manufactured vehicles | 0.7 | 0.7 | 0.9 | 1.0 | 0.5 | 0.7 | -0.1 |
| Staff headcount | 0.9 | 0.9 | 0.8 | 0.5 | 1.0 | 0.9 | 0.3 |
| Equity | 1.0 | 1.0 | 0.9 | 0.7 | 0.9 | 1.0 | 0.4 |
| Earnings after taxes | 0.4 | 0.4 | 0.0 | -0.1 | 0.3 | 0.4 | 1.0 |

in the amount of inputs will be directly proportional to the change in the output amount. This model will set individual weights of inputs and outputs for each unit to maximize the technical efficiency coefficient. Certain conditions pursuant to [37], however, must be met, namely:

- Weights cannot be negative,
- When using this set of weights for all entities, no coefficient of the technical efficiency must be greater than one.

#### 3.3.2 The BCC model

The input-oriented BCC model (based on Banker, Charnes & Cooper, 1984) is a modification of the previous model CCR. This model already takes into consideration the **variable returns to scale**, i.e. increasing, decreasing or constant returns. It foresees the variable, in certain parts, linear returns to scale and can evaluate efficiency of entities for the generally non-constant returns to scale [37].

### 3.4 Input data for analysis

The analysed data are clearly listed in Table 1.

It is the secondary data from annual reports [38-42] of individual companies. The values in CZK have been converted to EUR using the current exchange rate of CZK 25.60 per 1 EUR (Czech National Bank, 25.06.2019).

## 4 Results of investigation

### 4.1 Results of the correlation analysis

The correlation analysis application was carried out using the statistic software *R* [43]. The Spearman´s function of the correlation analysis was applied to a minor sample of accounting units.

The results in Table 2 make it clear that the earnings after taxes (EAT) represent the lowest statistical dependence between selected variables. The relationship between EAT and fixed assets is the absolute statistical independence. This means that EAT do not initiate any change in fixed assets and vice versa.

In the accounting and financial perspective, however, this economic principle is meaningless. The aim of fixed assets, reported in the balance sheet or the off-balance sheet, is to provide the accounting entity with economic benefits. Production factors seen as inputs make up the capital for the stocks and fixed assets and are aimed to generate the returns and the profit, while spending minimum costs.

The goal of the accounting unit is to provide such a product, which would meet requirements and maximize benefits of consumers, while respecting the optimal operating costs.

***Table 3** Evaluation using the DEA method*

| Company | BCC<br>[%] | CCR<br>[%] |
|---|---|---|
| BMW | 100.0 | 100.0 |
| HYUNDAI | 100.0 | 96.5 |
| PSA | 100.0 | 100.0 |
| VW | 100.0 | 100.0 |
| SKODA AUTO | 100.0 | 100.0 |

***Table 4** Recommended changes in variables when minimizing inputs*

| Variables | Real values | Goal | Potential improvement [%] |
|---|---|---|---|
| Total costs [in EUR billion] | 4.43 | 4.28 | -3.45 |
| Total sales [in EUR billion] | 5.05 | 5.20 | 3.01 |
| Fixed assets [in EUR billion] | 3.62 | 3.62 | -59.68 |
| Number of manufactured vehicles | 340300 | 340300 | 0.00 |
| Staff headcount | 3312.00 | 3197.65 | -3.45 |
| Equity [in EUR billion] | 1.66 | 1.41 | -15.30 |
| Earnings after taxes [in EUR billion] | 0.28 | 0.28 | 0.00 |

***Table 5** Recommended changes in variables when maximizing outputs*

| Variables | Real values | Goal | Potential improvement [%] |
|---|---|---|---|
| Total costs [in billion EUR] | 4.43 | 4.43 | 0.00 |
| Total sales [in billion EUR] | 5.05 | 5.39 | 6.70 |
| Fixed assets [in billion EUR] | 3.62 | 3.62 | -58.24 |
| Number of manufactured vehicles | 340300.00 | 352469.76 | 3.58 |
| Staff headcount | 3312.00 | 3312.00 | 0.00 |
| Equity [in billion EUR] | 1.66 | 1.46 | -12.27 |
| Earnings after taxes [in billion EUR] | 0.28 | 0.29 | 3.58 |

### 4.2 Results of the DEA method application

The DEA method (i.e. a method of applied mathematics) was applied to verify efficiency of selected accounting units focusing on the production activity, or more precisely, the undertakings in automotive industry. Efficiency was measured using the Frontier Analyst software [44].

The input variables for the DEA method included the staff headcount, total costs, equity and fixed assets. Total sales, earnings after taxes and the number of vehicles made are the output variables.

Minimization of inputs and maximization of outputs are analysed for both models (BCC and CCR). Table 3 shows the DEA method results in Frontier Analyst.

#### 4.2.1 Variable returns to scale (BCC)

The data needed for purposes of minimization of inputs and maximization of outputs with variable returns to scale can be found in the first column.

The result makes it clear that all the companies report full efficiency. This means that the selected variables are in line with the expected (optimal) condition where the minimum inputs are used and, at the same time, the condition of output maximization is met.

#### 4.2.2 Constant returns to scale (CCR)

For purposes of minimization of inputs and maximization of outputs with constant returns to scale, the data in the second column of Table 3 were used.

Application of the CCR method, with minimisation of inputs, analysed the status quo of the manufacturing process involving the selected inputs. The result shows that Hyundai fails to meet the production process efficiency assumption by 3.5%, as compared to other efficient companies.

Table 4 lists the recommended changes in variables that are based on the Peers units (sample efficient companies). In this case, PSA, VW and SKODA are efficient units. They propose reduction in total costs and staff headcount by 3.45% and a significant decrease in fixed assets by 59.68% and in equity by 15.30%. Changes proposed by the CCR method would encourage Hyundai´s efficiency.

Application of the CCR method while maximizing outputs analysed the status quo of the manufacturing process involving the selected inputs. The result shows that Hyundai meets the assumption of the production process efficiency again up to 96.5% as compared to other efficient companies.

For Hyundai´s efficiency, the following measures were proposed in Table 5, by efficient units, again represented by PSA, SKODA and VW. Total costs are spent effectively. When maximizing the outputs, the CCR method recommends the following changes to be made in variables, which do not report 100% efficiency. It is necessary to increase total sales by 6.7 %. It is recommended to increase the number of vehicles made by 3.58%, which will lead to generating a profit increased by the same value. Another recommendation is to reduce the equity by 12.27%.

## 5 Conclusions

As to the CCR method application, it is important to note that constant returns to scale practically do not occur. It is just a theoretical framework designed to check potential deviations which may occur. The proposed changes would not be feasible as this is the case of strong reduction of fixed assets which brings the economic benefit.

This implies that the BCC method assumes variable returns to scale and it can be aptly applied for a number of reasons. The production structure of companies is a relevant reason. It means that it takes into consideration the large-lot production - economies of scale, constant, rising and decreasing prices of inputs, a type of the market structure (perfect/imperfect competition), differentiated but similar products, know-how affecting efficiency, product innovation, exchange rates, bargaining power and many more.

Another factor of the production structure change stems from the non-systematic risk component that is represented by a potential change of the production process in the political and economic area. Wrong decision-making processes may result in other additional costs, such as increasing costs of vehicle storage before their sale or as a result of modifications of the zero kilometre or an increase in overhead (administrative) expenses.

New technical aspects of manufactured vehicles are one of decisive factors for both the customer and the sustainable development. The transition from the today´s use of fossil fuels to renewables is a frequently discussed topic. This need does not depend on the environmental improvement issues only, but also on the situation of the country. The Czech Republic is currently one of many countries, which depend on oil supplies. In respect of the worldwide efforts to increase the use of renewables and to free a country from dependency on the global power of oil-exporting countries, it is possible to establish relations with other countries having a similar environmental policy in the future [45]. It is also safe to predict that countries, which are striving to transform the use of fossil fuels to a large extent already today, will gain a great advantage in the form of decentralised power since in most countries the level of availability of renewables is different. The renewable energy, thus, may be easily generated and consumed in a decentralized way.

The next factor is an undoubtedly adverse effect of carbon dioxide emissions. This is a frequently discussed issue all over the world. A number of countries, including the European Union, strive to enact legislation to regulate the amount of pollutants emitted to atmosphere. The fact that this issue is increasingly addressed by countries with a rapid population growth and the developed industry, such as India or China, means substantial improvement.

Automotive manufacturing is essential for the economy of a majority of European countries. The automotive sector plays a very substantial role in the industrial production and exports. Even this field, however, shows minor, yet noticeable, symptoms of the potential forthcoming recession. How influential it will be and whether it will meet or surpass expectations is a question for the world´s leading analysts to answer. The 2008 recession might help to better grasp the situation and the follow-up utilisation of reserves in the period after the end of the crisis, when the interest rates tend to decrease and the economic situation tends to improve.

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Milos Poliak - Jana Tomicova - Marek Jaskiewicz - Pawel Drozdziel - Natalia Lakhmetkina

# IDENTIFICATION OF NEUTRALIZATION OF THE CMR DOCUMENTS IN EUROPEAN UNION CONDITIONS

*Year 1956 was an important year for international road and freight transport. By this year Convention on the Contract for the International Carriage of Goods by Road (CMR) was made. The basic purpose of the Convention was to unify the rules in the international carriage of goods and thereby promote development of international trade. From the practical point of view, this was very important for both carriers and transporters. This Convention also describes the most important document in the international carriage of goods, which includes the consignment note of CMR as well. Recently this document is often associated with the term neutralization. Objective of this article was to clarify the meaning of this phrase in transport. In addition, the aim was to find out in what range carriers have real experience with neutralization of the consignment note of the CMR during the transport, for what types of goods and on what types of routes is the neutralization being used the most.*

***Keywords:*** *document, CMR, convention, agreement, transportation*

## 1 Introduction

Transport is an important need for humanity and is also a necessary requirement for the functionality of international trade. Within the EU, the road transport has gradually gained a dominant position, mainly due to reasons such as quality and variety of road network within the EU, flexibility, speed, convenience, adaptability and many others [1-2]. Within international trade it is possible to transport goods only based on the conclusion of the transport contract. Concluding a transport contract for international transport is much easier thanks to the CMR [3]. Fortunately for carriers, in 1956 the CMR was concluded in Geneva. The purpose is to set the standards of conditions, which are being used in an agreement about transport of goods within the cross-border transportation of goods. An important role during the international transportation of goods is being held by a consignment note of the CMR [4-5]. It is a document about conclusion of an agreement on transport and at the same time it is a document about acceptance of a package by a carrier.

Recently, in the transportation segment, a new term is being used very often. This new term is called “neutralization of consignment note of the CMR”. There is no any legal prescription or standard, which would define this term. The aim of this article is to explain what the term “neutralization of consignment note of the CMR” means. The intention is also to verify if the neutralization of consignment note of the CMR is being really used in international road transport and if it is being used only for transport of certain goods, like for example food. Next, it is also needed to know if transport documents are being traded during the transportation from or into Slovakia, so by that one would know if it is being used only for international transports. For verification of these hypotheses a survey among carriers was conducted.

## 2 Analysis of the current state

Concluding a contract of carriage during the international transport would be significantly more complicated for the carrier with the absence of the CMR. In the absence thereof, the carrier would have to know all the national transport regulations of the countries through, which he would transport the goods. Due to the differences in legislation and their inconsistent interpretation, many misunderstandings could be made for example during the contracts conclusion and demands for a carrier. This was the main reason for concluding a CMR in 1956 in Geneva [6]. In addition, this is an agreement on transport in an international road and freight transport. Its main purpose is to merge rules inside an international road group of transporters and at the same time support expansion of an international market. In real practice, this has a huge impact for carriers and transporters. If this convention would not exist everything would be managed by national regulations of a current country [7]. In 1978 protocol for convention was signed in Geneva. It included only regulation of an article 23 that consists of information about replacement of damage. Later in 2008 this convention was completed by an extra protocol, while this addition was focused on possibility of using electronic freight note [8]. International

**Milos Poliak[1,*], Jana Tomicova[1], Marek Jaskiewicz[2], Pawel Drozdziel[3], Natalia Lakhmetkina[4]**
[1]Department of Road and Urban Transport, University of Zilina, Slovakia
[2]Department of Motor Vehicles and Transport, Kielce University of Technology, Poland
[3]Politechnika Lubelska, Lublin, Poland
[4]Logistics Transport Systems and Technologies, Russian University of Transport (RUT - MIIT), Moscow, Russia
*E-mail of corresponding author: milos.poliak@fpedas.uniza.sk

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***Figure 1*** *Contracting parties of the CMR, [11]*

transport is transport where loading of goods is happening in one state and unloading of goods is done in another state or country. In order to be able to apply the CMR during the international transport of goods, either a place of loading or a place of unloading must be in a country that has signed the CMR [9]. There are three exceptions when it is not possible to make a transport under the CMR, even though it is an international carriage. It does not apply to the carriage of postal items, dead bodies and migratory uppers. The main reason why these consignments cannot be transported under the terms of the CMR is the fact that the value of these packages cannot be determined objectively. Because of that, it is not possible to set the level of responsibility of a carrier during the transport. The Convention has been gradually ratified by individual European countries, but the non-European countries are the contracting parties as well. Currently there is 56 countries who signed the CMR while 45 of them ratified the protocol as well [10]. Figure 1 shows the member countries of the CMR Convention.

The CMR sets the rules, rights, obligations and responsibilities of the carrier and the transporter. It also regulates the conclusion and realization of transport contracts, as well as the procedures for claiming damages. It specifies what the accompanying documents for transport should contain. It describes the most important document in the international transport of goods - consignment note of the CMR [12]. It is an official document that has a standardized form and is usually written in two languages. It is prepared in three original copies, signed by the sender and the carrier. If permitted by the law of the current country where the consignment note is drawn up, these signatures may be printed or replaced by the stamps of the sender and the carrier. The first (red) letter is addressed to the sender and constitutes proof that the goods have been handed over to the carrier by the sender for transport. The second (blue) letter is intended for the receiver of the goods to know how many goods to take over from the carrier. The third (green) letter is addressed to the transporter and confirms that the goods have been handed over to the receiver. The transport note is a trustable note about conclusion of transport contract, as well as a note about accepting the package if opposite is not claimed [13]. If the transport note does not contain reservations from the carrier, the legal presumption is that the package and its cover was in a perfect state during the process of accepting it and that number of pieces and its marks were matching data from the transport note [14-15].

The carrier's liability shall commence at the moment of acceptance of the goods for transport and ends at the moment of delivery of the goods to the receiver. The carrier is responsible for damage or loss of the package during the transport. He is also responsible for exceeding the delivery time. The Carrier shall, under the provisions of the CMR, be reliable for damages for the total or partial loss of the package incurred during the transport. Compensation for damages is calculated from the value of package at the place and time of its acceptance for transport [16]. Value of package is determined by the stock exchange price; if there is no stock exchange price, then according to the current market price. If there is neither stock exchange nor market price, then according to the general value of goods of the same kind and quality. The CMR provides that damages may not exceed a fixed amount per kilogram of missing gross weight of package. In the original version of the CMR, damages may not exceed 25 francs per kilogram of missing gross weight. Franc means a golden franc weighing 10/31 grams and a purity of 0.900. This limitation of responsibility applies only in eleven countries that have not yet ratified the CMR Protocol. The remaining countries have significantly reduced the responsibility of carriers by ratifying the Protocol. This is because the gold franc is replaced by a Special Drawing Rights Unit (SDR). The

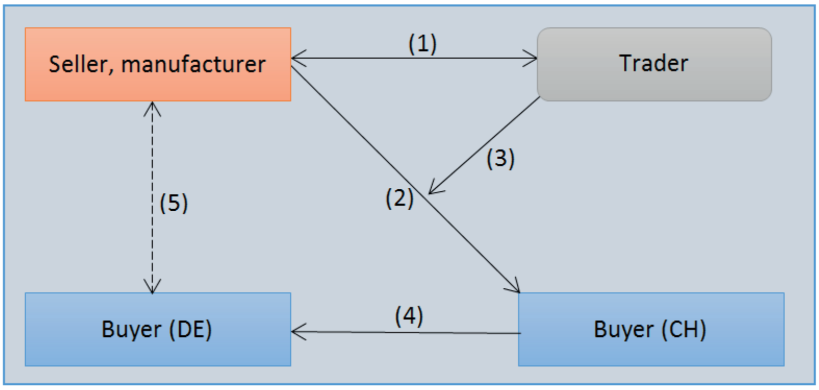


***Figure 2*** *Scheme of neutralization of transport document in parallel trade*

Carrier is obliged under the Protocol to pay the owner of the transported goods in the amount of 8.33 SDR per each kilogram of damaged, destroyed or lost goods. The specific value of the SDR depends on the exchange rate of the SDR and the EUR. In addition, the carrier must pay the transport, customs and other expenses associated with the transport of a package. This responsibility value is also covered by the liability insurance of the carrier. However, if the consignment note of CMR states the value of the package or a particular interest in delivery, the carrier is reliable for the full value of the damaged goods. In such a case, in the event of total loss of package, the carrier must pay the full value of the goods, as well as import, customs, VAT, excise duties, etc. If this value is higher than the amount of the insurance coverage of the carrier's liability resulting from the CMR, it is recommended that these goods are insured by the carrier. This applies in particular to light and expensive goods. If the delivery time is exceeded and receiver proves that because of this he received damage, the carrier is obliged to pay the damages only up to the amount of the transport charge [17-18]. This analysis confirms that the CMR is an important legal standard for international road freight transport. It is important for carrier and transporter, as well. The consignment note of the CMR constitutes a credible document for both parties. Consignment note of CMR is also a credible document for third parties, e.g. customs offices, insurance companies, etc. It is therefore necessary to consider further whether the consignment note of the CMR can be neutralized under the rules currently in force and whether the neutralization of the consignment note of the CMR does not jeopardize the functioning of the existing system.

## 3 Neutralization of the CMR consignment note and its reasons

Document neutralization is a procedure known only for the transport sector. Unfortunately, the authors of this paper have not been able to determine the definition of this phrase in any legislation or standards. Nevertheless, this connection has been known and used in road freight transport for several years. The word neutralization has several meanings. In general, it means cancellation of the effect. In transport, neutralization means an exchange of original transport notes or transport documents with other transport notes or transport documents. In general, one is speaking about cancellation of the first transport note [2]. Neutralization of transport documents is in most cases associated with illegal logistics activities called „parallel trade ". Parallel trade is defined as a trade with products that takes place outside the official distribution [19]. Through the self-distribution of the system, companies can cause price differences across countries, taking advantage of national differences in consumer behavior. At the same time, merchants buy products in countries where they are being sold at lower prices and sell them in higher priced countries. There is no falsification of the product, but the product is imported from the country without the permission of the intellectual property owner [20].

Neutralization of transport note in "parallel trade" can be explained in Figure 2.

(1) The trader agrees with the seller (manufacturer) that he will distribute his product to a country where his product is not sold yet (e.g. Switzerland) if he provides a price lower than his original selling price. Lower sales price due to the entrance to new market. (2) The consignment note of the CMR is listed, showing the sender as manufacturer and the buyer is a company in Switzerland. (3) After the goods have been transported, the driver will be given a duty to neutralize, he will stop a vehicle for example at gas station and then he will neutralize the consignment note of the CMR (exchange it for another one). (4) Sender is a company in Switzerland and receiver will be a company in Germany. Trader will sell these goods in Germany for way higher price compared to price for which he bought the goods. (5) While the manufacturer has no idea that his goods are sold in Germany, where he already sells those goods [21]. The purpose of neutralizing the transport notes in "parallel trade" is to ensure a trade secret where the seller wants to prevent the recipient from knowing the manufacturer and its purchasing conditions [22]. Based on theoretical research, the following reasons for neutralizing consignment notes can be identified by:

- *Reason A - when the seller does not want the manufacturer to find out to whom his product is sold*
  In that case, driver loads the goods in the vehicle and writes out consignment note of the CMR including

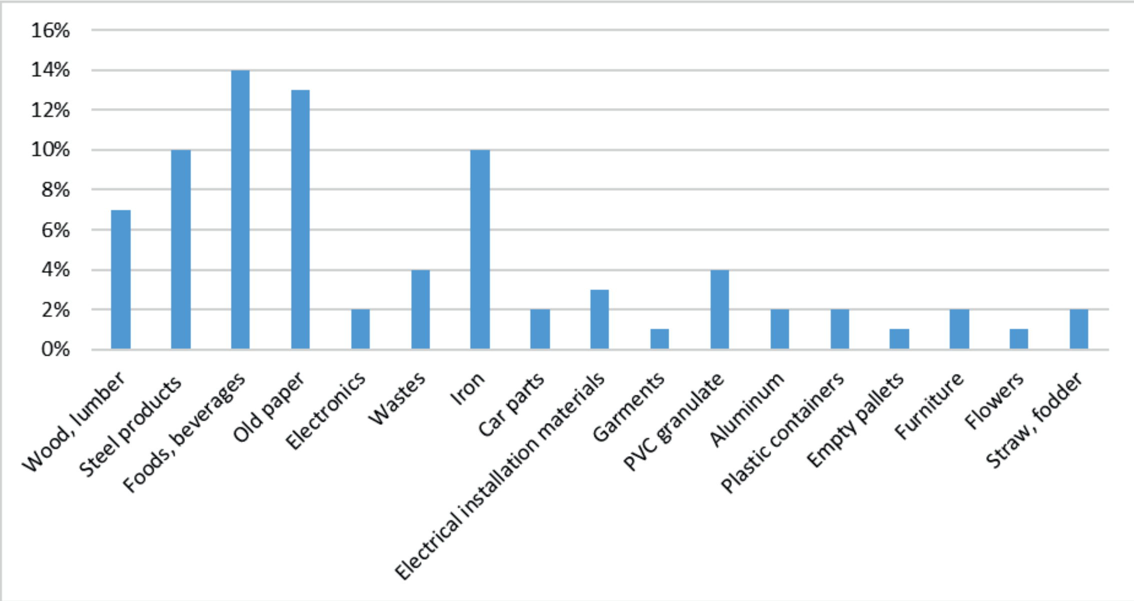


***Figure 3*** *Carried goods at neutralization*

the sender and the original receiver. After a while, the driver will be instructed to neutralize and he will write out new documents, which include a different receiver already.

- *Reason B - when the seller does not want the customer to find out where the goods are produced*
  The driver loads the goods into the vehicle and the bill of loading is sent to the receiver's warehouse indicating the place of loading other than the actual one. In case of some random control on the road, driver will write out transport note in which the real final place of the load and unload is written correctly. However, the final customer will get documents including different place of loading compared to the real one, due to that he will never know who the real producer of goods is [23-24].
- *Reason C - nobody does not know anything, means that producer has no idea where the final goods will be delivered and final customer has no idea from where the product came*
  This case occurs mainly when transported loads goods into a transport vehicle, write out the transport note which is stored in the warehouse of loading goods. Later, the transporter gets an order to neutralize and he will write out the new transport letter including the real sender of goods but a new receiver. Following this step, when he will get close to the new receiver, he will write out another document including the new sender and the new receiver who was already included in the second note. Based on this statement, one can easily say that in practice there are three ways of neutralizations of transport documents. Based on the theoretical identification of this issue with neutralizing transport documents, the research is conducted, which is described in next section. Thanks to that research, the objective was to confirm or refuse hypotheses, which were set at the beginning of this work.

## 4 The conducted survey

For acquiring information about neutralization of consignment note of CMR, a survey was conducted electronically, in a software called "Google Forms". After creation of a survey, the pre-test was done to confirm that questions are understandable enough. Later, this survey was sent to public on discussion forums, then it was resend through the social sites and added into groups including members of the road freight transport (transporters). There were 190 respondents who filled the survey. It consists of 3 questions. Objective of the first question was to know if asked transporters have any experience with neutralization of the CMR consignment note. The second question was aimed to obtain information about kinds of goods where the neutralization is used the most. The last question was meant to gather information about roads on which the neutralization is being done the most, as well as what is the country of loading goods and what is the country of unloading goods. The survey was realized with the main goal to get information from transporters and to know what is their experience with neutralization of documents and to find out what countries suffer from this issue the most. Majority of people who completed the survey were transporters who conduct transports through 18 countries, for example Germany, Spain, France…

Based on this survey the information was gathered that confirmed that transporters have real experience with neutralization of the CMR consignment note. It is known that 66% from asked respondents (transporters) have experience with neutralization and 34% do not have experience with neutralization and they never heard about this term. Even due to the fact that none of professional books does not describe neutralization of the CMR consignment note, it is necessary to state that transporters are doing these practices on a regular basis.

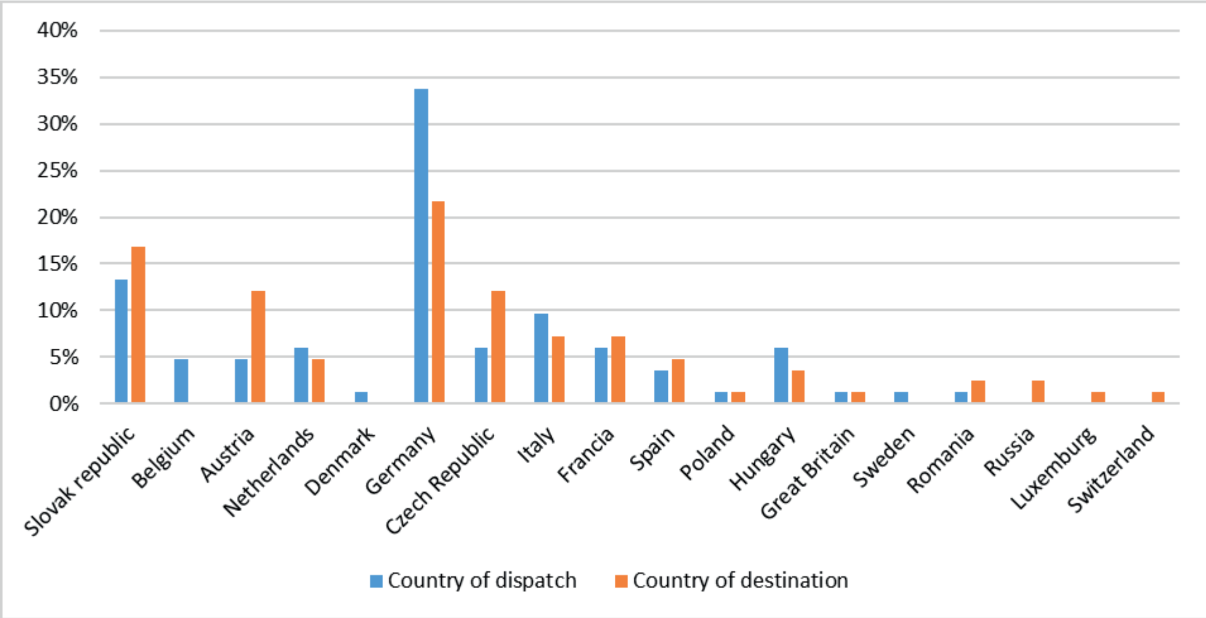


***Figure 4** Country of dispatch and destination at neutralizing transport documents*

The second part of this research was about question: For what kinds of goods the neutralization is the most requested? Results of this research are being shown in Figure 3. This picture describes certain categories of goods which transporters set as a “transported goods” which was written in the CMR consignment note in row number 9 (marking of goods). It is easy to see that neutralization is being done with different kinds of goods. Thus, neutralization is not linked to only one certain kind of goods. From this research one can see that neutralization is being done mostly during the transport of food and drinks, which represent 18% from overall transported materials and on the second place one can see old paper with 16%. The third place is being represented by iron with 13%. Less neutralized goods are textile materials and empty wooden pallets and flowers.

The last part of this research was focused on gathering information about roads of transport on which the neutralization was done the most. From carriers the information was sought on what kinds of roads they got the request to edit and neutralize the transport note. Considering the fact that multiple different roads were listed, they were at least divided into countries of sending and receiving goods. Results are shown in Figure 4, which shows that Germany is the country where neutralization is happening the most. Almost 35% answers are targeting Germany as a country of sending goods and in 22% of cases it is a country of receiving goods. Neutralization is also happening in Slovak Republic. Other countries listed on graph were not represented by the huge amount like Germany and Slovak Republic.

From this survey one can also say that neutralization is not being used just during the international transports but also during the transportations inside a country (cabotage) transports. 87% of carriers who entered this survey were ordered to neutralize the transport note during the international transport. Remaining 13% were ordered during the internal transport.

## 5 Conclusion

The CMR, which sets the transport contracts during the international road freight transport is today the most important tool of dividing responsibility among carrier and customers of a transport. It also defines the trustworthy documents, which are necessary for realization of transport and which represent documents about realization of a transport, not only for parties but for the third party people as well. Considering the fact that there is not a trustworthy research about the fact that neutralization of transport notes happens in reality, main goal of this article was to apply the hypothesis that the neutralization is really happening around us. Research of authors confirmed that during the practical transport many carriers do neutralize the transport notes and documents. 66% of carriers who participated in the survey confirmed that on the request from side of the order of transport they had to realize the neutralization of transport notes. From the further research one can discuss that neutralization is not only linked to transport of certain goods but it affects many different categories and kinds of transported goods, as well. From this research follows that goods that being the most neutralized are food, drinks, paper, iron. The conclusion is also drawn that neutralization happens on different roads, while being the most frequent on roads between Germany and Slovakia. Neutralization is not used only during the international freight transport, but even during the internal transport, where many threats can occur while not following these requirements for sabotage. Neutralization of transport document is not a professional term and it is not defined in any law or order and not even in the CMR; one cannot say how the neutralization would affect sender, transporter and receiver. It will be suitable to focus on consequences of neutralization of the transport document. Considering the fact that it is a process of replacing original transport note by a new one, then the note loses its trustworthiness and it can make many different risks in practice, which can be a threat for all the named parties before or during the transport. It is also recommended to monitor the impact of using neutralization of the transport note, including the GDP or if there are not any scams done with the GDP. Next, it is recommended to research impact on insurance of responsibility of a carrier, claiming of goods, insurance of package and similar affairs linked to transport of goods.

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Ewelina Sendek-Matysiak - Hubert Rzedowski - Tomas Skrucany

# ELECTROMOBILITY IN POLAND AND SLOVAKIA. BENCHMARKING OF ELECTRIC VEHICLES FOR 2019

*Since the entry into force of the Paris Agreement in 2015, and with the publication of the Intergovernmental Panel on Climate Change report on the consequences of 1.5 degrees of global warming, the issue of reducing greenhouse gas emissions in a cost-effective manner and within the timeframe outlined has become a matter of urgency. The transport sector, which accounts for a quarter of total GHG (Greenhouse Gas) emissions in the 28 EU Member States, is no exception. Due to the serious environmental impacts of transport, new mobility concepts are being implemented at both national and international levels. One of these is the large-scale deployment of electric vehicles, including those powered exclusively by Battery Electric Vehicle (BEV) batteries. They are quiet and virtually emission-free and, in terms of safety, have the feature that, in the event of an accident, they reduce the risk of detonating the vehicle and of burning or burning out the passengers. This article presents the current state of electromobility in Poland and Slovakia with an indication of light electric cars BEV and the most important factors stimulating its development.*

***Keywords:*** *electromobility, electric car, charging station, noise*

## 1 Introduction

The framework established by the European Union in the field of climate and energy for 2030 sets targets for reducing greenhouse gas emissions (carbon dioxide emissions by 20%), increasing the share of renewable energy by 20% and increasing energy efficiency by 20%. It is assumed that by 2030 the emission of greenhouse gases should be reduced by 40% compared to 1990 and at least 32% of energy should come from renewable sources [1-2]. In order to achieve these assumptions, the European Parliament noted that efforts will have to be made in all the sectors, as well as the introduction of many different solutions with a converging target [3-4]. Currently, among the sectors of the economy, the largest source of emissions is transport, which accounts for a quarter of the greenhouse gases emitted in the EU, and its share has been still growing in recent years. As a result, significant progress has been made in recent years in reducing the environmental impact of vehicles. This progress mainly concerns the reduction of pollutant emissions through development of the power trains and use of alternative fuels, reduction of consumption of natural resources and reduction of waste through recycling of the end-of-life vehicles or reduction of the noise emissions. However, on a sectoral basis, this impact still remains significant, due, inter alia, to the steadily increasing number of vehicles on the road and increasing mileage. The European Environment Agency forecasts that demand for mobility in the EU will increase by around 60% in 2050. The continuous increase in demand for transport therefore requires further steps to reduce its negative effects so that carbon dioxide emissions are reduced by 80 to 90% by 2025 [5-8]. One of them is the intensively implemented strategy of using alternative vehicles, including those powered exclusively by Battery Electric Vehicle (BEV), in the European Union transport sector. The scale of changes to be made in this respect in the coming years is best illustrated by one of the assumptions of the White Paper entitled “The European Union’s transport policy for alternative vehicles”. “A Roadmap to a Single European Transport Area - Towards a Single European Transport Area a competitive and resource-efficient transport system” - halving the number of conventionally propelled cars in urban transport by 2030 and eliminating them from cities by 2050, and according to the EU, all the new passenger cars sold at that time are to be fully electric by 2035 [9]. The goal, which from today’s point of view seems unrealistic to meet due to many economic, technological and social barriers, may be achieved within the next few decades, taking into account the continuous development and technical progress [10]. Electromobility, is currently considered to be the best possible solution to solve the problems discussed above [11]. The manufacturers point out that with limited possibilities of modification of internal combustion engines, electric cars may be not only one of the ways to improve the local air quality but also affect development of the dispersed renewable sources, lower dependence on the import of fossil fuels and, thus, a higher level of energy security. These favorable features make battery-powered cars a serious candidate for the mitigation of greenhouse gas emissions and air pollution from transport [12-14]. This publication discusses the current state of electromobility

**Ewelina Sendek-Matysiak[1], Hubert Rzedowski[1,*],Tomas Skrucany[2]**
[1]Departament Machatronics and Machine Building, Politechnika Swietokrzyska, Kielce, Poland
[2]Department of Road and Urban Transport, University of Zilina, Slovakia
*E-mail of corresponding author:hubertrz95@interia.pl

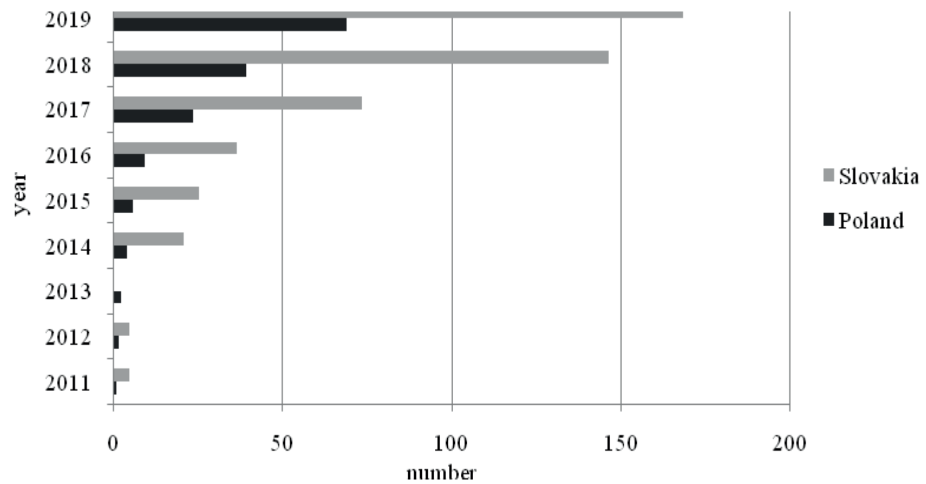


*Figure 1* Number of BEVs in Poland and Slovakia per 1 million inhabitants [15]

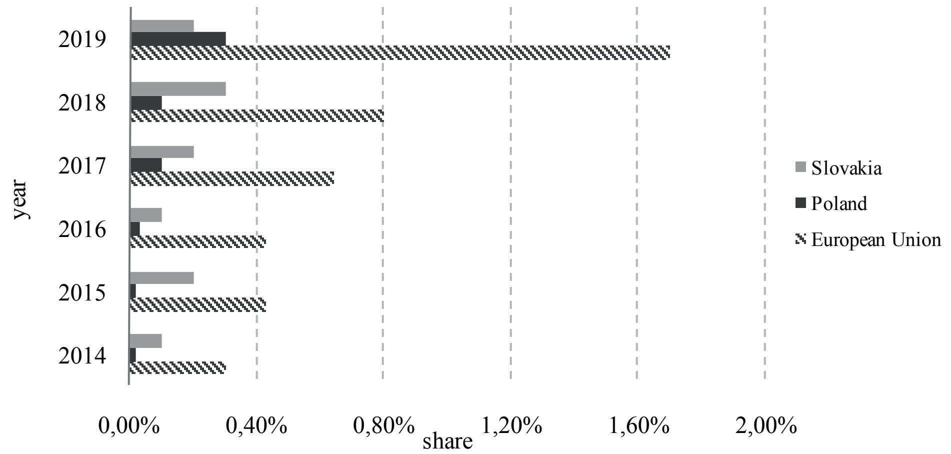


*Figure 2* Share of BEV electric cars in the automotive market in 2014-2019 [15]

in Poland and Slovakia, paying special attention to M1 passenger cars of the BEV type.

## 2 Current electric car market in Poland and Slovakia

Analyzing the global statistics on the rate of growth of electric cars and realizing EU requirements concerning, among others, the improvement of air quality, also Poland and Slovakia are facing the electricity age. In 2019, 68 such vehicles were registered in Poland per 1 million inhabitants, while 169 in Slovakia (Figure 1), which represents 0.3% (Poland) and 0.2% (Slovakia) of the automotive market in the analyzed countries (Figure 2).

In the years 2011-2019, the number of registrations of the new BEVs in Poland grew on average by 56% year on year, while in Slovakia by 24% (Figure 3, Table 1). The greatest increase in the number of newly registered BEVs, as compared to the previous year, was recorded in Poland in 2017. The number of new registrations increased there by 244%. In Slovakia, the biggest growth year by year was in 2013 - 433%. In 2019 the number of the new BEV registrations, compared to 2018, increased by 91% in Poland and decreased by 55% in Slovakia. In 2019, the number of electric cars has increased since 2011 - by 3560% in Slovakia and twice as many in Poland - by 7349%.

Number of the new BEVs registered in 2019 per 1 million inhabitants in Poland was 69 and 168 in Slovakia, which makes them ranked 22 and 26 among the European Union countries (Figure 4).

In January 2018 the Parliament (Sejm) of the Republic of Poland passed the Act on Electromobility and alternative fuels, in which it obliged municipalities and districts of over 50000 inhabitants to assure a minimum 10% share of electric vehicles in their fleet by 1 January 2022. The sanction for failure to implement the regulations will be the expiration on 31 December 2021 of contracts for the performance of public tasks with entities that do not comply with the requirements (except for public mass transport). The provision is to apply not only to local government offices themselves, but also to all companies performing public tasks commissioned by the local government. Such units deal, inter alia, with public transport, waste management or fire protection. Additionally, from 2028, local governments will be able to outsource the performance of services only to such entities, which will be able to provide a fleet with a 30% share of low-emission vehicles in a given area. A challenge may be to ensure that an appropriate percentage of the fleet of electric refuse collectors, snow

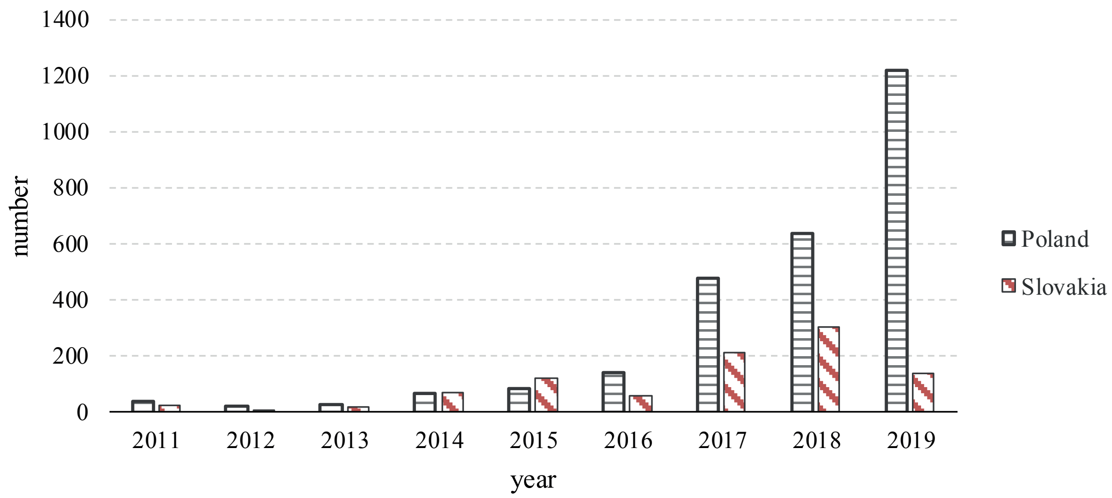


***Figure 3*** *Number of new registrations of the BEV electric cars in Poland and Slovakia in the years 2011-2019 [15]*

***Table 1*** *Number of new BEV registrations in 2011-2019 (growth, dynamics)*

| Year | Number of BEV registrations | | Absolute growth (compared to the previous year) | | Increase Relative (compared to the previous year) | | Growth rate in % | | Individual Chain Indices | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Poland | Slovakia | Poland | Slovakia | Poland | Slovakia | Poland | Slovakia | Poland | Slovakia |
| 2011 | 35 | 25 | | | | | | | | |
| 2012 | 19 | 3 | -16 | -22 | -0.46 | -0.88 | -46% | -88% | 0.54 | 0.12 |
| 2013 | 27 | 16 | 8 | 13 | 0.42 | 4.33 | 42% | 433% | 1.42 | 5.33 |
| 2014 | 68 | 69 | 41 | 53 | 1.52 | 3.31 | 152% | 331% | 2.52 | 4.31 |
| 2015 | 86 | 123 | 18 | 54 | 0.26 | 0.78 | 26% | 78% | 1.26 | 1.78 |
| 2016 | 138 | 55 | 52 | -68 | 0.60 | -0.55 | 60% | -55% | 1.60 | 0.45 |
| 2017 | 475 | 209 | 337 | 154 | 2,44 | 2.80 | 244% | 280% | 3.44 | 3.80 |
| 2018 | 639 | 302 | 164 | 93 | 0.35 | 0.44 | 35% | 44% | 1.35 | 1.44 |
| 2019 | 1221 | 136 | 582 | -166 | 0.91 | -0.55 | 91% | -55% | 1.91 | 0.45 |
| | | | average rate of change | | | | | | 1.56 | 1.24 |
| | | | medium-term pace of change | | | | | | 56% | 24% |

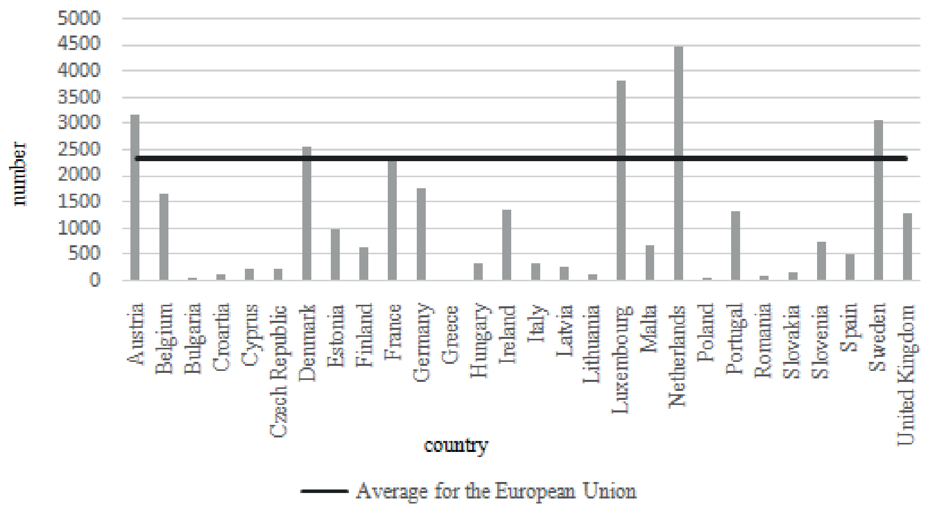


***Figure 4*** *Number of the new BEVs registered in the European Union in 2019 per 1 million inhabitants [15]*

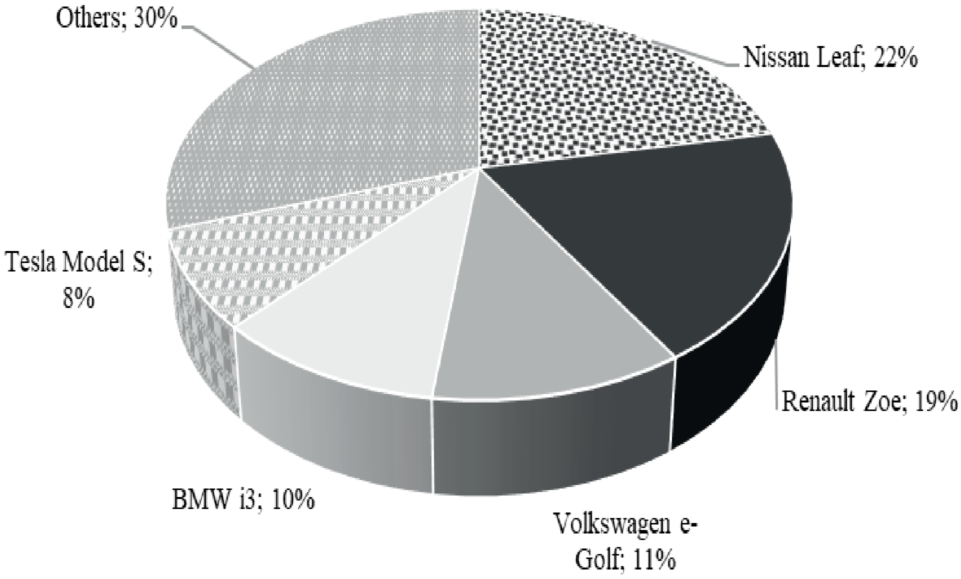


***Figure 5*** *The five most frequently purchased electric cars in the European Union in 2018 [15]*

***Table 2*** *BEV car prices [20-27]*

| Mark | Model | Price (euro) | | Difference in value (%) |
|---|---|---|---|---|
| | | Poland | Slovakia | |
| 1 | 2 | 3 | 4 | 5 |
| Renault | Zoe R110 | 29251.64 | 31900 | -8% |
| Volkswagen | e-UP! | 22532.34 | 19900 | 13% |
| Volkswagen | e-Golf | 33202.97 | 37270 | -11% |
| Nissan | Leaf | 36387.78 | 34250 | 6% |
| Kia | e-Soul | 36972.79 | 31790 | 16% |
| Hyundai | Kona Electric | 38836.69 | 38490 | 1% |
| Hyundai | Ioniq | 38508.95 | 37290 | 3% |
| BMW | i3 | 39538.98 | 55258 | -28% |
| BMW | i3s | 42933.38 | 55258 | -22% |
| Audi | e-Tron 50 Quatro | 70207.50 | 79900 | -12% |
| Tesla | M Model 3 Long Range RWD | 60968.43 | 56700 | 8% |

shovels or sweepers is available. Such vehicles are difficult to access on the market - it was only in 2018 that the first electric garbage truck in Europe took to the streets of Amsterdam. In addition, the cost of such equipment can be high for a long time, which will translate into the price of services that residents will have to pay. In turn, the central and central governments have been obliged to increase the share of the BEVs in their fleet to a minimum of 10% by the end of 2021, to min. 20% by the end of 2022 and until min. Exemption from this obligation is provided for vehicles used by the Ministry of Foreign Affairs, SW (Prison Service), KGP (Chief of Police), ITD (Road Transport Inspection), ABW (Internal Security Agency), KGPSP (State Fire Service Headquarters), AW (Intelligence Agency), KAS (National Revenue Administration), KGSG (Border Guard Headquarters), CBA (Central Anti-Corruption Bureau), SWW (Military Intelligence Service), GDDKiA (General Directorate for National Roads and Motorways) and State Protection Services. The sanction for non-compliance is the same as in the case of local government units - termination of the contract with the entity providing business services in the field of transport.

## 3 Barriers to electromobility development in Poland and Slovakia

The marginal number of the BEVs in use today proves that the market for electric mobility in both Poland and Slovakia is still in its infancy. Today, having an electric car - although it has many advantages - is still quite burdensome for the owner. The first difficulty, already when buying such a car is limited choice and then their price. In 2018 (as of 06/2018), consumers had only fifty-two BEV models

***Table 3** Price of selected new passenger cars with different engines in Poland [euro]*

| Mark | Model EV | Price | Model whit ZS | Price | Model whit ZI | Price |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Nissan | Leaf | 30 184.64-38 909.89 | Juke | 16 980.73-19 808.67 | Juke | 16 980.73-20 990.07 |
| Renault | Zoe | 28 746.15-33 725.62 | Clio | 13 323.69-14 856.50 | Twingo | 10 848.80-14 620.68 |
| Volkswagen | e-golf | 33 202.97 | golf | 20 280.30-27 826.46 | golf | 18 865.40-22 166.84 |
| Volkswagen | e-Up! | 22 532.34 | - | - | Up! | 9 432.70 |

***Table 4** Price of selected new passenger cars with different engines in Slovakia [euro]*

| Mark | Model EV | Price | Model whit ZS | Price | Model whit ZI | Price |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Nissan | Leaf | 34 250 | Juke | - | Juke | 16590 |
| Renault | Zoe | 31 900 | Clio | 15 400 | Clio | 9850 |
| Volkswagen | e-golf | 37 270 | golf | 16990 | golf | 21050 |
| Volkswagen | e-Up! | 19 900 | - | - | Up! | 22 170 |

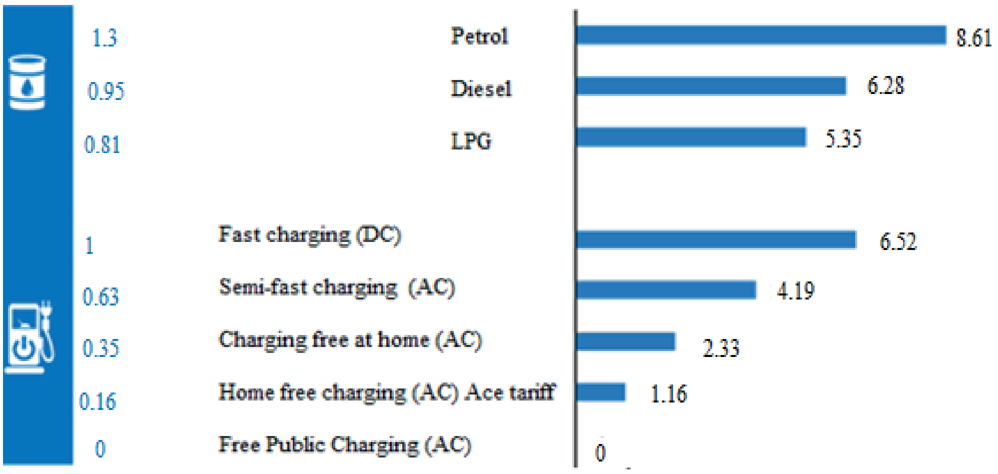


***Figure 6** Costs of refueling combustion cars and charging electric cars in Poland [euro] [32]*

to choose from with over four hundred of the Internal Combustions Engines (ICE) models. The lion's share at that time belonged to five models, as shown in Figure 5.

Often, both in Poland and Slovakia, the BEV models cannot be seen in the dealership and after one buys it, he/she has to wait long to collect it. Almost all the consumer studies have shown that one of the main obstacles to the implementation of e-mobility is the higher price of battery-powered electric cars compared to similar models with conventional internal combustion engines [16- 19]. In Table 2, the ratings of new the BEVs in Poland and Slovakia are presented and for the selected ones, in Tables 3 and 4, they are compared to prices of cars with conventional drive of similar power and equipment.

Meanwhile, already today, from the economic point of view, the total costs of ownership (TCO = costs of purchasing a car (CAPEX) + costs of its use in a specific time (OPEX) of an electric car are lower than that of a vehicle with a conventional engine [28]. This is primarily due to significant differences in electricity prices vs. other fuel, lower maintenance, service and repair costs due to their simpler construction. Compared to the ICE vehicles prices, they may be even for 30% lower [29]. According to the research, consumers rarely make a purchase decision based on a rational financial analysis [30]. Most of them even think so that the costs related to the operation of an electric car are much higher than in the case of vehicles with conventional drive [31]. Taking into account the current prices of energy (antismog tariff) and fuel, the costs of driving 100 km through the BEV in Poland is at least five times lower than in the case of vehicles with classic propulsion. The costs of fueling combustion cars and charging electric cars, presented in Figures 6 and 7, were developed for a B-segment car, normal driving (15000 km/year) in a mixed cycle, according to fuel prices, of a network of chargers and average energy prices for individual consumers. The consumption per 100 km is assumed: 15 kWh, 61 diesel, 81 unleaded petrol (95), 111 LPG. Table 5 shows the costs of driving 100 km by electric vehicle in Poland and Slovakia in 2018.

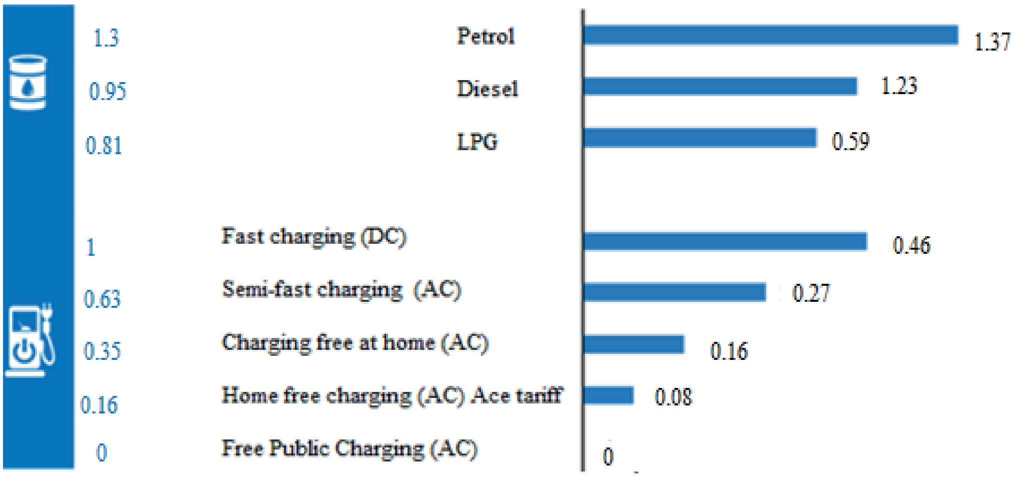


***Figure 7*** *Costs of refueling combustion cars and charging electric cars in Slovakia [euro] [32]*

***Table 5*** *Costs of driving 100 km by electric car in Poland and Slovakia in 2018 [33]*

| Mark | Model | Cost of Driving 100 km (euro) | |
|---|---|---|---|
| | | Poland* | Slovakia** |
| 1 | 2 | 3 | 4 |
| Hyundai | Ioniqelectric | 1.98 | 2.32 |
| Nissan | Leaf | 2.75 | 3.23 |
| BMW | I3 | 2.34 | 2.74 |
| Tesla | Model S P90D | 3.22 | 3.78 |
| TeTesla | X 100D | 3.22 | 3.79 |
| Renault | Zoe | 2.73 | 3.20 |
| Volkswagen | e-golf | 2.32 | 2.73 |
| Volkswagen | e-up! | 1.96 | 2.30 |

**0.13 euro/kWh*
***0.16 euro/kWh*

Problems related to the spread of battery cars in Poland and Slovakia should be considered not only in financial terms, but in terms of their efficiency, long charging time and infrastructure barriers, as well. The infrastructure in this market relates mainly to the network of charging stations, on which the mobility of electric vehicles depends and appears to be a key barrier to market diffusion, as well as a major source of consumer concern about changing their preferences. In the case of early stage markets, which is undoubtedly the market for electric cars BEV in Poland and Slovakia, it is important to adapt the pace of infrastructure development to increase in the number of its users. Too many vehicles with a shortage of charging stations may discourage future users. On the other hand, building a large number of stations in the absence of charging demand will make investments in stations scarce. It can be expected that barriers related to charging infrastructure will gradually disappear in Poland and Slovakia.

Development of infrastructure is driven by government regulations and subsidies, but also by the strategies of energy companies and companies from the automotive sector. Directive 2014/94/EU of the European Parliament and of the Council, "Clean energy for transport", recommends that by 2020 there should be one public charging point for every 10 registered plug-in electric and plug-in hybrid cars [34]. Figure 8 shows the number of the PEV (electric and plug-in hybrid cars) per charging point in the European Union in 2019.

At present (as of 12/2019), there are 247 public charging stations in Poland, located mainly in large cities (the largest number of stations is in Warsaw, followed by the most important examples of the type of chargers (for example in Krakow, Wroclaw, Katowice and Poznan), which provide a total of 582 plugs, of which only 64% allow for charging to 22 kW, 38% belong to the category of fast chargers (> 22 kW) (Figure 9). In Slovakia, 65% are slow chargers and 35% are fast chargers (Figure 9) [15].

In order to increase the number of public chargers for electric vehicles, the Polish legislator imposed an obligation on municipalities to put the relevant technical infrastructure into operation by 31 December 2020. The minimum number of charging points in publicly available charging stations was determined based on the number of inhabitants and registered vehicles in a given municipality. In the first years, the infrastructure is to be developed on a commercial basis. This means that the possibility of

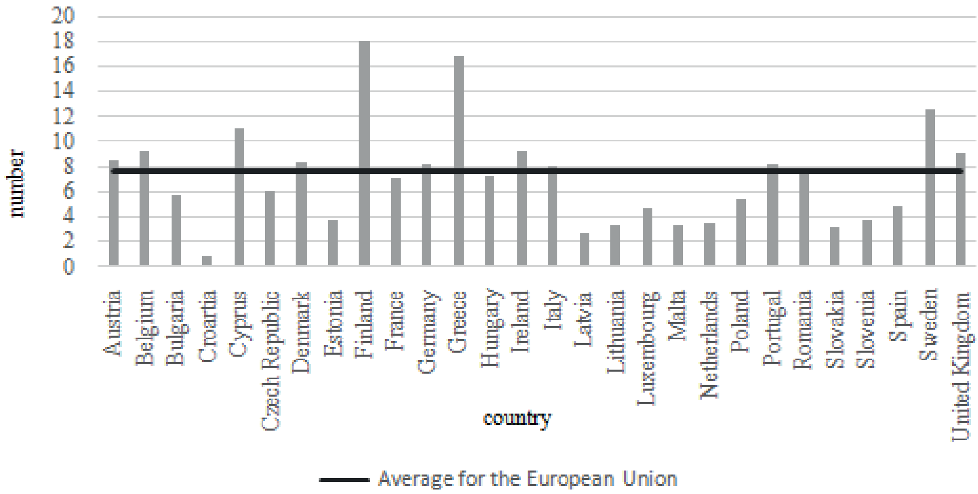


***Figure 8*** *The number of PEV (BEV + PHEV) per one charging point in 2019 in EU countries [15]*

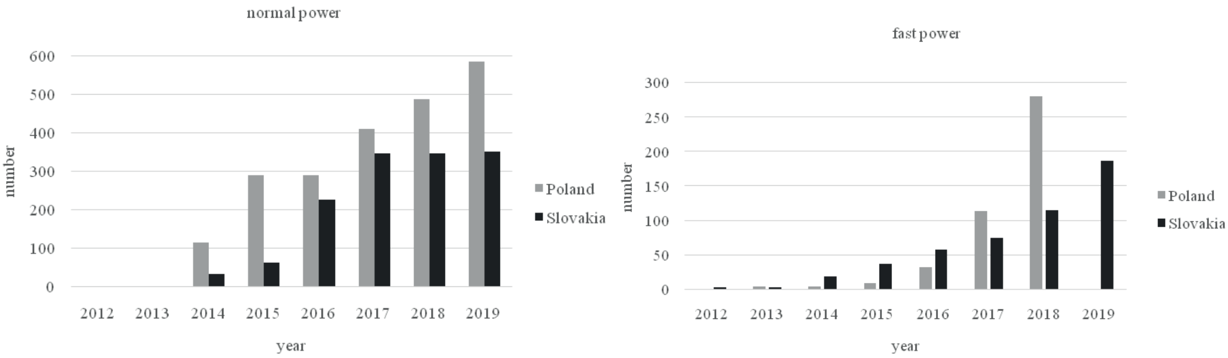


***Figure 9*** *Number of publicly available electric vehicle charging points in Poland and Slovakia [15]*

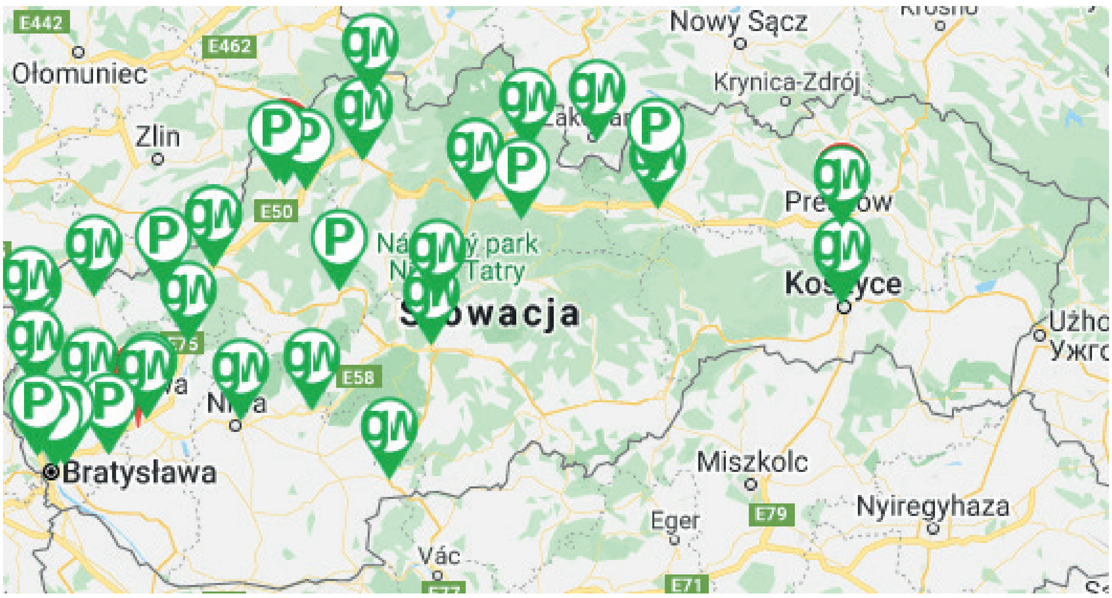


***Figure 10*** *Charging stations in Slovakia Greenway [37]*

building publicly available stations will be open to all the entrepreneurs through the public tenders. If the minimum number indicated in the Act is not reached by 15 January 2020, the burden of network development will lie with the distribution network operators (DSOs). In such a case, the executive bodies of local governments will be obliged to draw up a schedule for station construction, consulted with the DSO. However, no discounts are foreseen for the construction of the charging infrastructure or its financing from the central budget. Moreover, the legal procedures for obtaining a station construction permit may take up to 18 months. According to the concept of the Ministry of Energy of the Republic of Poland, 6000 publicly available charging points of normal power and 400 of high power will be built in Poland by 2020. Electric vehicle charging stations in Slovakia are located in every region (Figure 10).

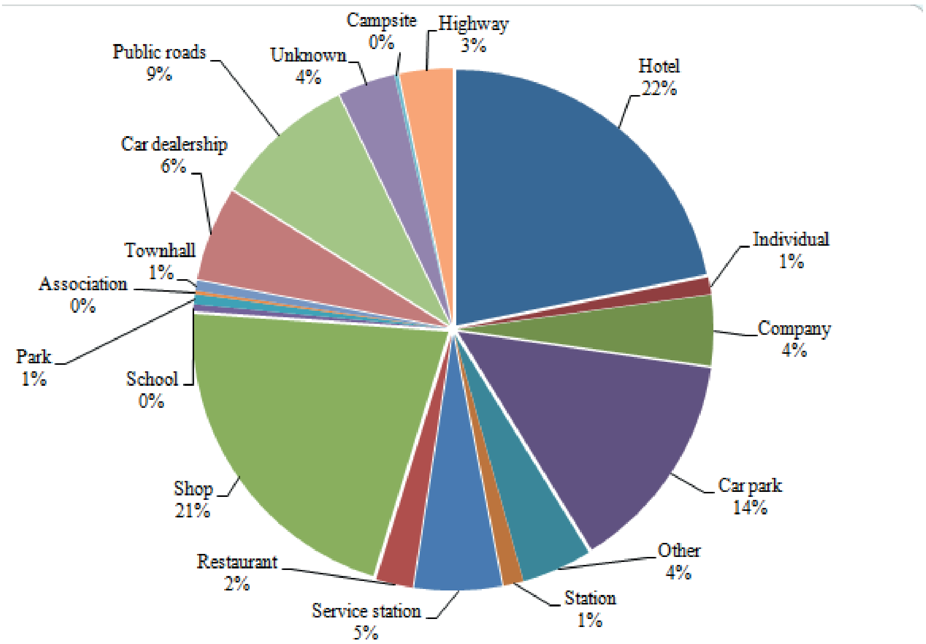


**Figure 11** *Location of charging points in Poland [38]*

Additionally, another 80 new stations are planned to be built near motorways, first class roads and cities [35]. In Budca, the first 350 kW ultra-fast station was built in 2018 and two 175 kW stations in the Next-E project. The location of the charging point is near the R1 motorway and it is equipped with all the typical connections [36]. It belongs to the WEEE (*Waste of Electrical and Electronic Equipment)*, which built another 9 Budca stations this time at McDonald's car park. They are planning 13 new stations in Bratislava, Trnava, Nitra, Trencin, Zilina, Zvolen, Banska Bystrica, Prievidza, Liptovsky Mikulas, Martin, Kosice and Presov. The Next-E project, which is financed by a fund from the CEF of the European Union and in the Slovakian training area, provides for the construction of 25 stations 18 fast and 7 ultra-fast chargers [20].

However, the problem of the number of charging points is not the only problem related to the infrastructure of electric cars in Poland. It is very often difficult to access them (Figure 11).

One often needs to call and make an appointment in advance to benefit from charging. One may also find that he/she cannot use the charger as there is no suitably qualified person to start the charger. It happens that the free charging at the car wash can be used only after buying the most expensive package [39].

## 4 Proposed incentives in Poland and Slovakia

In order to encourage the potential car buyers to buy the BEV electric cars, several incentives have been introduced in Poland and Slovakia to encourage them to buy this type of vehicle. In Poland, the Ministry of Energy has in recent months presented plans to introduce subsidies of up to 30% of the cost of purchasing an electric vehicle. In the latest version of the draft, this amount is expected to be a maximum of EUR 8 658.56 for passenger cars, whose purchase price must not exceed EUR 29 237.68. This means that only a few models available on the Polish market will be able to count on surcharges (Skoda CITIGOeiV- 20 265.36 euro, Volkswagen E-UP! - 22 532.34 euro, Seat MII electric - 18 720.40 euro, Peugeot E-208 - 29 222.47 euro, Renault ZOE - 29 237.68 euro, Opel E-Corsa - 29 231.62 euro and Smart EV For two - 22 116.80, EV For four - 22 467.86 euro), none of which belongs to the bestselling vehicles on the European market. Support for commercial vehicles, for which subsidies may amount to as much as EUR 47 163.50 regardless of the price of the vehicle, may prove much more beneficial. An important stimulation of development and at the same time benefit for users of electric cars is to be the application of the so-called soft support instruments. In Poland, drivers of the BEV electric vehicles, thanks to the Act on Electromobility, were given the opportunity to drive from February 2018 to 2026 on bus pass. In addition, the road manager may make the driving of such vehicles on the designated lanes dependent on the number of people travelling together in such vehicles [40]. In 2018, there were 276.9 km of bus lanes in Poland as a whole (an increase of 7.2% y/y), more than half of which were designated in only four cities: Warsaw, Krakow, Wroclaw and Lodz [41]. Over the last six years in some cities, the length of bus lanes has been reduced, for example in Torun as much as 13 times (from 17 km in 2013 to 1.3 km in 2018). Electric car drivers will therefore be able to use from the privilege, as long as they move in the four largest cities. In order to help identify vehicles entitled to use the BEV's bus ports for electric vehicle users, blue stickers with the indication "EE" are issued in Poland and from 2020 they can apply for green license plates. Another privilege granted to BEV electric vehicle users is the possibility of free parking in the paid parking zone in cities. Additionally, as is apparent from the above law, in addition to hydrogen and natural gas cars, electric cars will be able to drive in the low-emission zones, which can be designated by the municipality.

The Ministry of Economy of the Slovak Republic, on the other hand, introduced Act No. 71/2013 in accordance with § 11 Section 6, introduced electronic registration for granting of subsidies for the purchase of an electric vehicle for 2019. The Ministry of Economy of the Slovak Republic will co-finance the purchase of an electric vehicle in the amount of EUR 8000. This is the second version of the grant. The first one from the middle of 2016 provided for the co-financing in the amount of 5000 euro and it covered 800 BEVs, which was 70% of the e-vehicles. The Act aims to encourage Slovak drivers to purchase alternative powered vehicles including the BEVs. Private persons are entitled to receive such a subsidy, as well as The Legal entities: entrepreneurs and business entities without public participation. It is also available to the public administration of the commune and higher units, budget organizations supported by the commune and economic entities, which are partially owned by the commune. Private persons are persons who are not entrepreneurs and are the registered as tax-payers. Only the new cars not previously registered without the first owner are subsidized [36, 42]. In 2017, the Slovak government encouraged the purchase of electric cars by granting benefits from the registration tax, and other financial benefits [43]. In 2019, the Slovak government is considering an electromobility development plan. This plan consists of 16 measures to encourage drivers to buy electric vehicles. The measures are to be: financial assistance for the purchase of zero-emission vehicle, investments in charging stations, green procurement, license plates for electric vehicles not used in Slovakia, use of the zero-emission zone and lanes, simplification of administrative procedures for the construction of infrastructure [20, 44].

## 5 Discussion and conclusions

Currently, the BEV electric car market both in Poland and Slovakia is in the early stages of development, as evidenced by the small share of such vehicles in the automotive market and the lack of a sufficiently developed network of public charging points. Undoubtedly, an important factor in the intensification of e-mobility in Poland and Slovakia will be the proposed financial incentives, so that the purchase of an electric car will not deviate significantly from prices of similar models equipped by the conventional internal combustion engines. It is because that is currently the biggest barrier to the development of electric cars. For example, the electric version of the popular VW Golf costs at least 40 088.97 euro and its petrol-fueled equivalent 24 053.38 euro (with similar engine power and equipment) while with a diesel engine 25 235.25 euro [45].

It is also important on the part of the principals, to launch a set of non-financial incentives, as well as financial support for expansion of the charging infrastructure. This is all the more important since nowadays a mid-range fully charged electric car can cover a distance of 100-200 km, depending on the year of production, which, with a daily mileage of 25 km in the city, requires recharging every few days [46]. If the vehicle is used for commuting to work and shopping, in most cases it will need free charging points at owner's home or workplace. A challenge arises when it is necessary to go out of town or move between distant towns [47]. The car will travel exactly as much as the capacity of the battery, whose charging cycle is up to several hours. In practice, it makes it impossible to travel more than 200 km, which is a significant concern for drivers. When travelling in such a car, drivers are afraid that the battery in their car will run out in a place far away from the charging station. In conclusion, if the legislators of the analyzed countries implement the announced BEV measures, this will undoubtedly affect development of the electromobility market. One of the attributes of electromobility is its quiet vehicle operation. The low level of noise emitted by the vehicle has less impact on the environment - other road users - and also on the vehicle crew [48]. Often, this aspect is in the assessment and comparison of an electric vehicle as an alternative to its other advantages, such as emission production. Governments and municipalities should also take into consideration the fact - how the environmental friendly electricity is available for charging the vehicle in a specific country. The mix of energy sources used for electricity production influences the GHG emissions from electromobilty. Each country reaches different values of the GHG production during the electricity production [49], thus the specific country needs specific sensible solutions in the problem of the future of mobility. Not everywhere is supporting electromobility really eco-friendly and brings decreasing of the GHG production of the country or region. This fact is also noticeable in the comparison of Poland and Slovakia.

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Svetla Stoilova

# STUDY OF A RELATIONSHIP BETWEEN THE CRITERIA FOR SELECTION OF THE TRANSPORT TECHNOLOGY FOR THE PASSENGERS CARRIAGE USING THE DEMATEL METHOD

*This study defines criteria and sub-criteria for evaluation of the transport technology for carriage of passengers by railway and road transport. The main criteria are divided into four groups: business, environmental, social and technological, named BEST analysis. Twenty-four sub-criteria have been examined. The method of multi-criteria analysis Decision Making Trial and Evaluation Laboratory (DEMATEL) has been applied to analyse importance and the relations between the criteria. Results show that e criteria of the great importance are business group (29.47%) and technological group (27.49%). The sub-criteria: transport costs for fuel (7.83%); ticket price (8.29%); time travel (6.99%); directness (6.47%) and direct operating costs (6.30%) are the most important. The defined criteria and sub-criteria can be applied for evaluation, comparison and selection the transportation variant.*

***Keywords:*** *DEMATEL method, transport technology, passenger, multi-criteria analysis*

## 1 Introduction

The choice of criteria for assessing the technology for carriage of passengers is an important task in organization of transport. The transport plan of passengers depends on various criteria that on the one hand, are important for transport operators, and on the other hand are significant for passengers. The main factors for the quality of the transport service are speed, direct journey, frequency, security and ticket price. The fuel consumption, operating costs, taxes are major factors for the transport operator.

Carriage of passengers by the bus transport is performed mostly by private companies that have a different position in the transport services market. The railway transport is in the most cases carried out by public operators or public and private transport companies.

The different criteria have different weights when choosing a transport plan, as well as different interactions. It is therefore necessary to examine the problem of assessing the mutual influence between the criteria.

The problem of choosing criteria for evaluation and selection of transport has been a subject of research by various authors.

In [1] authors determined convenience and comfort as the main criteria for measurement of the bus transit services quality. The main group convenience contains the sub-criteria: span of service, frequency, capacity, accessibility, network coverage. The sub-criteria comfort contains the sub-criteria for the main group criteria: vehicle occupancy rate, speed, air-conditioned vehicle rate, route directness. The Analytic hierarchy process (AHP) method has been applied to determine weights of the main criteria and sub-criteria. It was found that the frequency, capacity and route directness are the most important criteria from the passengers' point of view.

In [2] the Principal Component Analysis method, Quality Function Deployment and an interval-valued intuitionistic fuzzy approach have been used to analyse the customer satisfaction criteria of public transport. The criteria that were studied are frequency, convenience, information, travel time, driver behaviour, cleanliness and ergonomics, safety and security, emission reduction. The methodology is applied for Istanbul. It was found that the most important areas for the bus users according to the questionnaire research are frequency and time; the safety and security, and emission reduction are the most important factors according to the decision maker's weights.

The following travel purposes are examined in [3] business trips, holiday and leisure trips. The distance and seventeen criteria including price, travel time, reliability, flexibility, simplicity, safety, safety (crime), sustainability, infrastructure, comfort, staff, pastime, image, luggage, pet policy, social contacts, accessibility, have been studied as the key factors of a modal choice, as well. It was found that the most significant determinants for all the trip categories are price, travel time/speed, convenience/comfort, reliability and carriage of luggage.

The goal programming methodology integrated with the AHP method is applied in [4] for performance optimization of public transport undertakings. Twelve decision variables are identified, taking into account both user and operator perceptions: controllable costs, no controllable costs, taxes,

**Svetla Stoilova**
Faculty of Transport, Technical University, Sofia, Bulgaria
E-mail of corresponding author: stoilova@tu-sofia.bg

staff per bus ratio (fleet operated), safety, accessibility, regularity, load factor, fleet utilization, percentage of effective kilometers, journey speed and percentage of cancelled kilometers to scheduled kilometers. It was found that the operator costs and staff per schedule are the most important variables for the operator, whereas among the user perceptions, safety of travel has the highest weighting.

Passenger satisfaction, as the quality criteria of public transport has been analysed in [5]. The time accessibility criteria, which include accessibility of stops, waiting for a connection and transferability in the public transport network, are considered as the most significant criteria that influence a passenger's decision to utilize public transport options. In [6] the authors studied the bus passenger comfort perception based on passenger load factor and in-vehicle time. The quality of intercity road transportation of passengers, according to the customers' perspective, is studied in [7]. The main factors that have influence on quality of service are attendance (degree of courtesy of staff, fast and organized queues, staff appearance and ease of purchasing tickets), vehicle (vehicle condition, bathroom existence, air conditioning existence, vehicle cleanliness and accessibility to disabled people), route (departure time as scheduled, variety of departure times, appropriate travel time, quantity of stops along the route), passengers security, differential services, ticket fare.

In [8] are considered the seventeen criteria in 4-dimensions (economical; environmental; social; risk and security) are considered to assess five simulation scenarios of the Bus Rapid System service. The grey SWARA method is applied to determine the weights of criteria. The alternatives were assessed by using the grey COPRAS method. In [9] the following criteria for evaluation of the $CO_2$ emission strategies have been determined: air pollution, traffic congestion, investment costs and natural environment. The authors examined three strategies: reduce the $CO_2$ emissions per kilometer, avoid using personal car, replace Fossil Fuel. The AHP method has been used to assess the weights of criteria and to prioritize the strategies.

The different transportation solution has been assessed by criteria average travel time, traffic safety, investment costs, investment profitability, environmental friendliness [10]. Computational experiments have been carried out with use of ELECTRE III and AHP methods.

In [11] the authors defined the criteria that allow evaluating the transportation activity in an agribusiness industry: transportation costs, delivery time, fleet modernity, transportation reliability, transportation quality, safety, environmental friendliness, fleet utilization. It was found that the most important criterion with the highest value of weights is the transportation costs criterion. The next places are held by criterion delivery time and transportation quality. In [12] the speed, reliability, capacity, costs and safety factors are used to assess three timetables for the train services on the Iran rail network. In [13] the indicators safety, rapidity, time and comfort are applied to analyse the qualitative factors, which influences the operation efficiency of the transport enterprises in the highway passenger. In [14-15] the criteria direct operating costs, average speed, availability of service with direct transport, reliability, transport satisfaction, average number of train stops, average distance travelled and the transport capacity have been defined to evaluate the scheme of transportation of intercity trains.

The cluster analysis is used in [16] to identify advantages and disadvantages of five modes of transport. The following criteria have been investigated: comfort, time, costs, accessibility and safety. It was found that the comfort is the most important one.

It can be summed up that the most important criteria, which affect the transport process are the economical; environmental; ticket fare, travel time, speed, frequency, capacity, route directness, security, reliability.

The multi-criteria analysis is an appropriate method for assessment of criteria and determination of their weights. Most methods only define the weights without investigation of the mutual influence between the criteria. Some of multi-criteria methods as Decision Making Trial and Evaluation Laboratory (DEMATEL) method and Analytic Network Process (ANP) allow conducting an analysis of criteria. The DEMATEL method permits to draw up the cause-effect model, which represents the relationships between criteria.

This paper aims to propose an approach for examining the criteria for choice of the transport technology for the passengers carriage, their impact and relationship by taking into account the transportation process. This study applies the method of multi-criteria analysis Decision Making Trial and Evaluation Laboratory (DEMATEL) method to study the criteria and their interdependencies to establish the relationship between the causes and effects of criteria into a structural model.

## 2 Methodology

The methodology of research includes the following steps:

Step 1: Defining the criteria for choice of transport technology for the carriage of passengers.

Step 2: Application of the DEMATEL method for assessment of a relationship between the criteria

### 2.1 Defining the criteria for assessment of the transport technology for passenger transportation

This study includes BEST multi-criteria analysis (Business, Environmental, Social, and Technological) by determining the main criteria and sub-criteria for assessment of the transport technologies for the carriage of passengers. The main criteria are as follows:

- B - Business criteria. These include economic criteria for realisation of the transport process.
- E - Environmental criteria. These criteria include assessment of environmental pollutants from transport.

- S - Social criteria. They are related to the passengers' requirements.
- T - Technological criteria. They are related to realization of the transportation.

The sub-criteria for the main group Business criteria (B) are B1 - Transport costs for fuel (electric energy); B2 - Ticket price.; B3 - Direct operating costs; B4 - Infrastructure charges; B5 - Company position in the market.

The sub-criteria for the main group Environmental criteria (E) are E1 - Carbon dioxide ($CO_2$), g/(pass.km); E2 - Carbon monoxide (CO), g/(pass.km); E3 - Nitrogen oxides (NOx), g/(pass.km); E4 - Non-methane hydrocarbons (NC), g/(pass.km); E5 - Particulate matter (PM), g/(pass.km).

The sub-criteria for the main group Social criteria (S) are S1 - Comfort; S2 - Security; S3 - Reliability; S4 - Stability; S5 - Punctuality; S6 - Cleanliness, ergonomics; S7 - Security and comfort in the place of time-off.

The sub-criteria for the main group Technological criteria (T) are T1 - Time travel; T2 - Frequency of shipments; T3 - Directness; T4 - Number of stops; T5 - Service period; T6 - Vehicle occupancy rate; T7 - State of infrastructure.

The sub-criteria Company position in the market (B5), Social group sub-criteria: S1-S7, Directness (T3) and State of infrastructure (T7) are qualitative and others sub-criteria are quantitative. The qualitative sub-criteria can have values for example 0 or 1; 1 - if the answer is yes; 0 otherwise. The criterion Company position in the market (B5) could be determined for example as a good (value 1) or bad (value 0) according to the demand for transportation from the passenger.

## 2.2 DEMATEL Method

This study applies the DEMATEL method to evaluate the criteria and their interdependencies. The procedure of DEMATEL method is summarized as follows [17]:

- Step 1: Formation of experts 'perception matrixes. Each expert evaluates the direct influence between any two criteria by using an integer score as follows: 0 - no influence; 1 - low influence; 2 - medium influence; 3 - high influence; 4 - very high influence. For each established a matrix $X^k = [x_{ij}^k]_{nxn}$ was established, where $k = 1, \ldots, H$ is the number of experts; $n$ is the number of criteria; $x_{ij}^k$ indicates the degree to which the expert assesses factor $\boldsymbol{i}$ affects factor $j$. For $i = j$, the diagonal elements of each expert answer matrix are set to zero.
- Step 2: Determination of the average answer matrix $A = [a_{ij}]_{nxn}$. The elements of the average perception matrix $A$ are calculated as follows:

$$a_{ij} = \frac{1}{H}\sum_{k=1}^{H} x_{ij}^k . \tag{1}$$

- Step 3: Determination of the average normalized perception matrix $D = [d_{ij}]nxn$

$$D = A/S , \tag{2}$$

where: $A$ is the average answer matrix; $S$ is the major value of the sum of each column $j$ of the matrix $A$ and the major value of the sum of each row $i$ of the matrix $A$.

The values of each element in matrix $D$ are between 0 and 1.

- Step 4: Determination of the total relation matrix $T = [t_{ij}]_{nxn}$

$$T = D(I - D)^{-1} , \tag{3}$$

where: $I$ is an $nxn$ identity matrix.

- Step 5: Determination of the both direct and indirect effects between criteria.

The sum of the columns and the sum of the rows of the matrix $T$ are determined.

The vector R represents the sums of rows of the $T$ matrix. The vector C represents the sum of columns of the $T$ matrix.

$$R = [r_i]_{nx1} = \left[\sum_{j=1}^{n} t_{ij}\right]_{nx1} , \tag{4}$$

$$C = [c_i]'_{1xn} = \left[\sum_{i=1}^{n} t_{ij}\right]_{1xn} , \tag{5}$$

where: $r_i$ is the sum of the $i$-th row in matrix $T$; $c_j$ is the sum of the $j$-th column in matrix $T$;' is the symbol that denotes the transposed matrix.

Both the direct and indirect effects by the $i$-th criterion on the other criteria are presented by the elements of vector; the both direct and indirect effects by criterion $j$ from the other criteria are shown by the elements of vector $C$.

The sum of columns and rows (R+C) called "Prominence" means that all the criteria are relatively important. According to the difference (R-C) named "Relation" the criteria are divided into a cause and effect group depending upon the positive and negative values of all the elements in the (R - C) column.

Step 6: For each criterion the normalized degree of influence is determined as follows:

$$e_i = \frac{r_i + c_i}{\sum_{i=1}^{n}(r_i + c_i)} \cdot 100\% , \tag{6}$$

where: $r_i$, $c_i$ are the elements of vector R and vector C.

The degree of influence presents also the weights of criteria.

- Step 7: Determination of the threshold value. It serves to calculate the relationships between criteria in the considered system. Elements that are smaller or equal to the threshold value $v$, are set to zero. Elements that are larger than the threshold value $v$, retain their value.

The threshold value $\boldsymbol{v}$ is determined as an average value of elements of matrix $T$ [18]:

$$v = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}[t_{ij}]}{N} , \tag{7}$$

where: $N$ - the total number of elements in the matrix $T$.

- Step 8. Drawing a relationship diagram.

The relationship diagram is drawn by coordinate sets by $(r_i + c_i)$, $(r_i - c_i)$ to visualize the complex interrelationship. It gives an information on which are the most important factors and how they influence the affected factors. The diagram includes the factors $t_{ij}$ that are greater than threshold

**Table 1** *Average Matrix A for the Main group criteria*

| Criteria | B | E | S | T | Total |
|---|---|---|---|---|---|
| B | 0.0 | 1.2 | 1.5 | 2.0 | 4.7 |
| E | 1.1 | 0.0 | 0.8 | 0.4 | 2.3 |
| S | 1.3 | 1.0 | 0.0 | 1.1 | 3.4 |
| T | 2.2 | 0.8 | 1.7 | 0.0 | 4.7 |
| Total | 4.6 | 3.0 | 4.0 | 3.5 | - |

**Table 2** *Average normalized perception matrix D for the Main group criteria*

| Criteria | B | E | S | T |
|---|---|---|---|---|
| B | 0.00 | 0.26 | 0.32 | 0.43 |
| E | 0.23 | 0.00 | 0.17 | 0.09 |
| S | 0.28 | 0.21 | 0.00 | 0.23 |
| T | 0.47 | 0.17 | 0.36 | 0.00 |

**Table 3** *Total Relation Matrix T. Direct and indirect influence for the Main group criteria*

| Criteria | B | E | S | T | R | C | R+C | R-C | e (%) | Rank | Impact |
|---|---|---|---|---|---|---|---|---|---|---|---|
| B | 1.356* | 1.161* | 1.472* | 1.446* | 5.435 | 5.216 | 10.651 | 0.219 | 29.47 | 1 | Cause |
| E | 0.908 | 0.523 | 0.804 | 0.704 | 2.940 | 3.725 | 6.665 | -0.786 | 18.44 | 4 | Effect |
| S | 1.244* | 0.910 | 0.935 | 1.060 | 4.150 | 4.738 | 8.888 | -0.588 | 24.59 | 3 | Effect |
| T | 1.707* | 1.132* | 1.526* | 1.180* | 5.545 | 4.390 | 9.935 | 1.155 | 27.49 | 2 | Cause |

Threshold value is 1.129. With * are shown the elements greater than or equal to the threshold value.

value $v$. The coordinate is speared into four parts [19]: $(r_i - c_i)$ is positive and $(r_i + c_i)$ is large. This indicates that the criteria are causes, which are also key factors for solving problems; $(r_i - c_i)$ is positive and $(r_i + c_i)$ is small. This indicates that the criteria are independent and can influence only a few other factors; $(r_i - c_i)$ is negative and $(r_i + c_i)$ is large. This indicates that the criteria are the core problems that must be solved; however these are the effect-type criteria, which are of indirect impact; $(r_i - c_i)$ is negative and $(r_i + c_i)$ is small. This indicates that the factors are independent and can be influenced only by a few others attributes.

Therefore, the decision makers can visually study the complex causal relationships between criteria and also take decision about investigated system.

## 3 Results and discussion

The main group criteria and all 24 sub-criteria were evaluated by 7 experts, who are specialists with long experience in transport by academia (3 experts) and specialists by railway and automotive administration (4 experts). Each expert has given assessment according to scale 0-4 of the pair-wise comparisons between criteria.

Table 1 presents the average answer matrix for the main group criteria. The end row represents the sum of the columns; the end column represents the sum of the rows of the average answer matrix. Table 2 shows the average normalized perception matrix. Values of elements of this matrix are determined according to Equation (2); the value S = 4.7.

Table 3 presents the total relation matrix *T* and values of direct and indirect influence for main group criteria. The threshold value determined by Equation (7) is 1.129. The elements that are larger than the threshold value are marked. The end column of the table indicates the weights of criteria, rank of the criteria and their impact.

The column (R+C) indicates the importance of the criteria. The column (R-C) serves to separate the criteria into cause group and effect group. The cause group factors have a direct impact on the overall system. The effect group factors are influenced by other factors.

Results in Table 3 show:

- The Business criteria (B) have the highest degree of importance (weight 29.47%).
- The prioritization is B>T>S>E.
- The Business criteria (B) and Technological criteria (T) have close weights.
- The Business criteria (B) and Technological criteria (T) have positive values of the (R-C) named "Relation". Therefore, they are in the cause group.
- The Environmental criteria (E) and Social criteria (S) have negative values of the (R-C). Therefore, they are in the effect group.

Figure 1 presents the cause and effect diagram of the main group criteria. The parts of the diagram are formed according to the main of (R+C); it is 5.325 (by Table 3, value 10.65). The dashed line in the figure shows the division of the four parts. The arrows in the figure present the relationships between criteria according to the threshold value and the marked elements in the total relation matrix presented in Table 3.

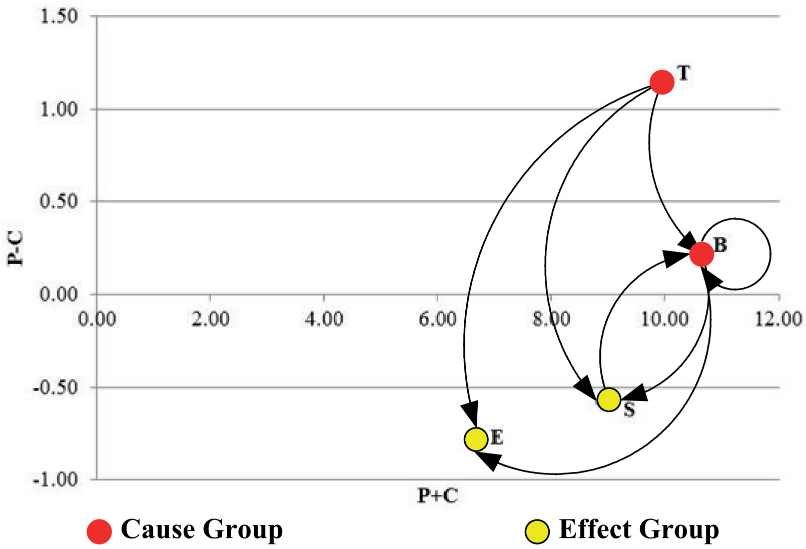


***Figure 1*** *The cause and effect diagram of main criteria. Threshold value v =1.129*

**Table 4** *Sub-criteria. The Average Matrix A*

| | B1 | B2 | B3 | B4 | B5 | E1 | E2 | E3 | E4 | E5 | S1 | S2 | S3 | S4 | S5 | S6 | S7 | T1 | T2 | T3 | T4 | T5 | T6 | T7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B1 | 0.0 | 1.5 | 1.7 | 0.7 | 1.0 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 1.0 | 0.5 | 0.5 | 0.5 | 0.8 | 0.5 | 1.0 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 1.0 | 0.5 |
| B2 | 1.3 | 0.0 | 1.0 | 1.4 | 0.5 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 1.4 | 0.5 | 0.5 | 0.5 | 0.5 | 0.8 | 0.0 | 1.5 | 1.0 | 1.5 | 0.4 | 0.3 | 1.0 | 0.1 |
| B3 | 1.0 | 2.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.5 | 0.2 | 0.2 | 0.0 | 0.0 | 0.3 | 0.0 | 1.5 | 0.2 | 1.0 | 0.6 | 0.2 | 0.3 | 0.1 |
| B4 | 0.1 | 1.0 | 1.0 | 0.0 | 0.0 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 | 0.2 |
| B5 | 0.5 | 0.5 | 0.4 | 0.4 | 0.0 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.7 | 0.5 | 0.5 | 0.7 | 0.4 | 0.4 | 0.3 | 0.3 | 0.5 | 0.5 | 0.8 | 0.5 | 0.5 | 0.0 |
| E1 | 0.8 | 0.3 | 0.3 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.1 | 0.3 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 |
| E2 | 0.8 | 0.3 | 0.3 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.1 | 0.3 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 |
| E3 | 0.8 | 0.3 | 0.3 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.1 | 0.3 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 |
| E4 | 0.8 | 0.3 | 0.3 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.1 | 0.3 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 |
| E5 | 0.8 | 0.3 | 0.3 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.1 | 0.3 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 |
| S1 | 0.5 | 0.6 | 0.6 | 0.0 | 0.6 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.0 | 0.5 | 0.8 | 0.8 | 0.5 | 0.8 | 0.8 | 0.1 | 0.4 | 0.5 | 0.8 | 0.2 | 0.6 | 0.2 |
| S2 | 1.0 | 1.0 | 1.0 | 0.5 | 0.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 0.0 | 1.0 | 1.0 | 0.8 | 0.3 | 0.0 | 0.6 | 0.1 | 0.5 | 0.8 | 0.2 | 0.8 | 0.2 |
| S3 | 0.8 | 0.5 | 0.3 | 0.2 | 1.0 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.4 | 0.5 | 0.0 | 0.5 | 0.8 | 0.2 | 0.5 | 0.2 | 0.2 | 0.2 | 0.9 | 0.1 | 0.1 | 0.3 |
| S4 | 1.0 | 1.0 | 1.0 | 0.0 | 1.0 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.5 | 0.8 | 0.8 | 0.0 | 1.0 | 0.0 | 0.2 | 0.8 | 0.0 | 1.0 | 0.5 | 0.3 | 0.5 | 0.2 |
| S5 | 0.5 | 0.1 | 0.0 | 0.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.5 | 1.0 | 0.0 | 0.0 | 1.0 | 1.0 | 0.0 | 0.0 | 0.5 | 0.2 | 0.1 | 0.2 |
| S6 | 0.0 | 0.8 | 0.0 | 0.0 | 0.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 0.5 | 0.5 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 0.3 | 0.8 | 0.0 |
| S7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.5 | 0.3 | 0.3 | 0.1 | 0.0 | 0.0 | 0.2 | 0.5 | 0.5 | 0.5 | 0.2 | 0.0 | 0.0 |
| T1 | 1.4 | 2.0 | 2.0 | 0.5 | 1.2 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.0 | 0.8 | 0.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.0 | 1.0 | 0.5 | 0.8 | 0.3 |
| T2 | 1.0 | 1.0 | 1.2 | 0.0 | 1.0 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.8 | 0.4 | 0.5 | 0.3 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.8 | 0.2 |
| T3 | 1.5 | 2.0 | 1.5 | 0.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.3 | 0.3 | 0.1 | 0.0 | 0.0 | 0.2 | 2.0 | 0.3 | 0.0 | 1.0 | 0.5 | 1.0 | 0.4 |
| T4 | 0.5 | 0.9 | 0.9 | 0.0 | 0.9 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.8 | 0.5 | 0.5 | 0.8 | 0.5 | 0.2 | 0.4 | 1.0 | 0.0 | 1.0 | 0.0 | 0.3 | 0.6 | 0.3 |
| T5 | 0.2 | 0.5 | 0.4 | 0.0 | 0.5 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.5 | 0.1 | 0.2 | 0.4 | 0.2 | 0.0 | 0.0 | 0.2 | 0.0 | 0.6 | 0.5 | 0.0 | 0.5 | 0.1 |
| T6 | 0.1 | 0.5 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.2 | 0.1 | 0.1 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 |
| T7 | 0.5 | 0.2 | 0.3 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.4 | 0.4 | 0.4 | 0.5 | 0.4 | 0.0 | 0.1 | 0.8 | 0.6 | 0.6 | 0.5 | 0.2 | 0.3 | 0.0 |

It can be seen that for Business criteria (B) and Technological criteria (T) "Relation" (R-C) is positive and "Prominence" (R+C) is large. This indicates that these criteria are the key factor for the choice of the transport technology for the carriage of passengers. The Environmental criteria (E) and Social criteria (S) have negative (R-C) and large (R+C). This shows that they have indirect impact on the studied system.

The DEMATEL method has been applied also for all 24 sub-criteria to investigate their relationships. The study was conducted together for all the sub-criteria. Table 4 shows the average answer matrix for sub-criteria.

**Table 5** *Sub- criteria. Total Relation Matrix T and the direct and indirect influence*

| | B1 | B2 | B3 | B4 | B5 | E1 | E2 | E3 | E4 | E5 | S1 | S2 | S3 | S4 | S5 | S6 | S7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B1 | 0.08* | 0.17* | 0.17* | 0.07* | 0.12* | 0.06* | 0.06* | 0.06* | 0.06* | 0.06* | 0.12* | 0.07* | 0.08* | 0.07* | 0.07* | 0.06* | 0.08* |
| B2 | 0.15* | 0.10* | 0.14* | 0.10* | 0.10* | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.14* | 0.07* | 0.08* | 0.07* | 0.06* | 0.07* | 0.03 |
| B3 | 0.11* | 0.18* | 0.06* | 0.03 | 0.05* | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.07* | 0.04* | 0.04* | 0.03 | 0.02 | 0.04* | 0.02 |
| B4 | 0.03 | 0.08* | 0.08* | 0.01 | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.02 | 0.03 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| B5 | 0.08* | 0.09* | 0.07* | 0.04* | 0.04* | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.08* | 0.05* | 0.06* | 0.07* | 0.04* | 0.04* | 0.03 |
| E1 | 0.06* | 0.04* | 0.04* | 0.01 | 0.04* | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.03 | 0.02 | 0.03 | 0.03 | 0.01 | 0.01 | 0.01 |
| E2 | 0.06* | 0.04* | 0.04* | 0.01 | 0.04* | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.03 | 0.02 | 0.03 | 0.03 | 0.01 | 0.01 | 0.01 |
| E3 | 0.06* | 0.04* | 0.04* | 0.01 | 0.04* | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.03 | 0.02 | 0.03 | 0.03 | 0.01 | 0.01 | 0.01 |
| E4 | 0.06* | 0.04* | 0.04* | 0.01 | 0.04* | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.03 | 0.02 | 0.03 | 0.03 | 0.01 | 0.01 | 0.01 |
| E5 | 0.06* | 0.04* | 0.04* | 0.01 | 0.04* | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.03 | 0.02 | 0.03 | 0.03 | 0.01 | 0.01 | 0.01 |
| S1 | 0.08* | 0.09* | 0.08* | 0.02 | 0.08* | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.04* | 0.06* | 0.08* | 0.07* | 0.05* | 0.06* | 0.06* |
| S2 | 0.12* | 0.13* | 0.12* | 0.05* | 0.10* | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.10* | 0.04* | 0.09* | 0.09* | 0.07* | 0.04* | 0.02 |
| S3 | 0.09* | 0.08* | 0.06* | 0.03 | 0.09* | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.06* | 0.05* | 0.03 | 0.06* | 0.07* | 0.03 | 0.05* |
| S4 | 0.12* | 0.13* | 0.12* | 0.02 | 0.11* | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.08* | 0.08* | 0.08* | 0.04* | 0.08* | 0.02 | 0.03 |
| S5 | 0.06* | 0.05* | 0.04* | 0.01 | 0.09* | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.03* | 0.05* | 0.05* | 0.08* | 0.02 | 0.01 | 0.07* |
| S6 | 0.03 | 0.08* | 0.03 | 0.01 | 0.07* | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.08* | 0.04* | 0.05* | 0.03 | 0.01 | 0.01 | 0.01 |
| S7 | 0.02 | 0.03 | 0.02 | 0.01 | 0.05* | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.05* | 0.04* | 0.03 | 0.03 | 0.02 | 0.01 | 0.01 |
| T1 | 0.17* | 0.22* | 0.20* | 0.06* | 0.13* | 0.05* | 0.05* | 0.05* | 0.05* | 0.05* | 0.07* | 0.09* | 0.09* | 0.04* | 0.03 | 0.03 | 0.03 |
| T2 | 0.10* | 0.11* | 0.11* | 0.02 | 0.09* | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.08* | 0.05* | 0.06* | 0.04* | 0.02 | 0.02 | 0.04 |
| T3 | 0.16* | 0.21* | 0.16* | 0.03 | 0.12* | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.09* | 0.06* | 0.06* | 0.04* | 0.03 | 0.03 | 0.03 |
| T4 | 0.09* | 0.12* | 0.11* | 0.02 | 0.10* | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.09* | 0.06* | 0.06* | 0.08* | 0.05* | 0.03 | 0.04* |
| T5 | 0.04* | 0.06* | 0.05* | 0.01 | 0.05* | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.05* | 0.02 | 0.03 | 0.04* | 0.02 | 0.01 | 0.01 |
| T6 | 0.02 | 0.04* | 0.02 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.04* | 0.02 | 0.02 | 0.01 | 0.01 | 0.03 | 0.01 |
| T7 | 0.07* | 0.06* | 0.06* | 0.03 | 0.03 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.05* | 0.04* | 0.05* | 0.05* | 0.04* | 0.01 | 0.02 |

Threshold value is 0.04. The elements greater than or equal to the threshold value are shown with *

**Table 6** *Sub - criteria. Total Relation Matrix T and the direct and indirect influence*

| | T1 | T2 | T3 | T4 | T5 | T6 | T7 | R+C | R-C | e (%) | Rank | Impact |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B1 | 0.09* | 0.05* | 0.09* | 0.09* | 0.05* | 0.11* | 0.04* | 3.91 | 0.09 | 7.83 | 2 | Cause |
| B2 | 0.14* | 0.08* | 0.15* | 0.08* | 0.05* | 0.11* | 0.03 | 4.13 | -0.32 | 8.29 | 1 | Effect |
| B3 | 0.13* | 0.03* | 0.11* | 0.07* | 0.03 | 0.06* | 0.02 | 3.14 | -0.64 | 6.30 | 5 | Effect |
| B4 | 0.02 | 0.01 | 0.02 | 0.02 | 0.01 | 0.03 | 0.02 | 1.22 | 0.00 | 2.44 | 18 | Cause |
| B5 | 0.06* | 0.04* | 0.07* | 0.08* | 0.04* | 0.06* | 0.01 | 2.90 | -0.44 | 5.81 | 6 | Effect |
| E1 | 0.02 | 0.01 | 0.02 | 0.03 | 0.01 | 0.01 | 0.01 | 0.94 | -0.03 | 1.89 | 20 | Effect |
| E2 | 0.02 | 0.01 | 0.02 | 0.03 | 0.01 | 0.01 | 0.01 | 0.94 | -0.03 | 1.89 | 21 | Effect |
| E3 | 0.02 | 0.01 | 0.02 | 0.03 | 0.01 | 0.01 | 0.01 | 0.94 | -0.03 | 1.89 | 22 | Effect |
| E4 | 0.02 | 0.01 | 0.02 | 0.03 | 0.01 | 0.01 | 0.01 | 0.94 | -0.03 | 1.89 | 23 | Effect |
| E5 | 0.02 | 0.01 | 0.02 | 0.03 | 0.01 | 0.01 | 0.01 | 0.94 | -0.03 | 1.89 | 24 | Effect |
| S1 | 0.05* | 0.04* | 0.07* | 0.08 | 0.03 | 0.07* | 0.02 | 2.72 | -0.26 | 5.46 | 8 | Effect |
| S2 | 0.09* | 0.03 | 0.08* | 0.09* | 0.03 | 0.09* | 0.03 | 2.55 | 0.46 | 5.11 | 10 | Cause |
| S3 | 0.05* | 0.03 | 0.05* | 0.08* | 0.02 | 0.04* | 0.03 | 2.27 | -0.10 | 4.54 | 11 | Effect |
| S4 | 0.10* | 0.02 | 0.11* | 0.08* | 0.04* | 0.07* | 0.03 | 2.56 | 0.38 | 5.13 | 9 | Cause |
| S5 | 0.08* | 0.01 | 0.03 | 0.06* | 0.03 | 0.03 | 0.02 | 1.66 | 0.08 | 3.33 | 13 | Cause |
| S6 | 0.02 | 0.01 | 0.05* | 0.02 | 0.03 | 0.07* | 0.01 | 1.30 | 0.10 | 2.60 | 17 | Cause |
| S7 | 0.03 | 0.04* | 0.05* | 0.05* | 0.02 | 0.02 | 0.01 | 1.19 | -0.10 | 2.38 | 19 | Effect |
| T1 | 0.08* | 0.03 | 0.18* | 0.12* | 0.06* | 0.11* | 0.04* | 3.49 | 0.55 | 6.99 | 3 | Cause |
| T2 | 0.04* | 0.02 | 0.04* | 0.04 | 0.04* | 0.08* | 0.02 | 1.77 | 0.56 | 3.55 | 12 | Cause |
| T3 | 0.18* | 0.04* | 0.07* | 0.11* | 0.06* | 0.11* | 0.04* | 3.23 | 0.28 | 6.47 | 4 | Cause |
| T4 | 0.11* | 0.02 | 0.11* | 0.05* | 0.04* | 0.08* | 0.03 | 2.83 | 0.02 | 5.67 | 7 | Cause |
| T5 | 0.04* | 0.01 | 0.06* | 0.05* | 0.01 | 0.05* | 0.01 | 1.35 | 0.03 | 2.71 | 15 | Cause |
| T6 | 0.01 | 0.01 | 0.01 | 0.04* | 0.01 | 0.01 | 0.00 | 1.65 | -0.96 | 3.31 | 14 | Effect |
| T7 | 0.08* | 0.04* | 0.06* | 0.06* | 0.03 | 0.04* | 0.01 | 1.30 | 0.44 | 2.61 | 16 | Cause |

Threshold value is 0.04. The elements greater than or equal to the threshold value are shown with *

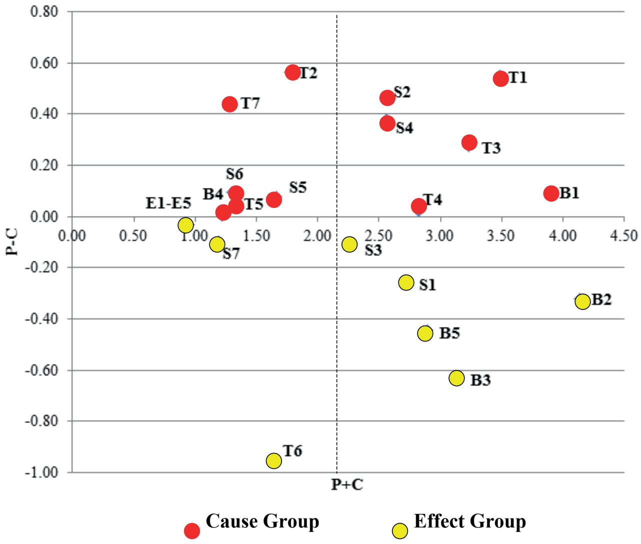


***Figure 2*** *The cause and effect diagram of all the sub-criteria*

Table 5 and Table 6 present Total Relation Matrix T and the direct and indirect influence. The threshold value determined by Equation (7) is 0.044. The elements that are larger than the threshold value are marked. The end column of the Table 6 indicates the weights of criteria. The results in Table 5 and Table 6 show:

- The Ticket price (B2) has the highest degree of importance (weight 8.29%).
- The prioritization is: B2>B1>T1>T3>B3>B5>T4>S1>S4>S2>S3> T2>S5>T6>T5>T7>S6>B4>S7>E1>E2>E4>E5>E3.
- The sub-criteria Ticket price (B2) and Costs for fuel (B1) have close weights.

The sub-criteria in cause group that have positive (P-C) are: Costs for fuel (B1), Security (S2), Stability (S4), Punctuality (S5), Cleanliness, ergonomics (S6), Time travel (T1), Frequency of shipments (T2); Directness (T3); Number of stops (T4), Service period (T5) and State of infrastructure (T7). Therefore, they are in the cause group. The sub-criteria Ticket price (B2), Direct operating costs (B3), Company position in the market (B5), Ecological sub-criteria E1-E5, Comfort (S1), - Reliability (S3), Security and comfort in the place of time-off (S7), Vehicle occupancy rate (T6) have negative values of the (R-C). Therefore, they are in the effect group.

Results in Table 6 also show ranking of the sub-criteria. The sub-criteria of the main group Business (B) and Technological (T) are ranked in the first seven positions B2>B1>T1>T3>B3>B5>T4. These results are similar to ranking of the main group criteria, where Business (B) and technological (T) criteria are ranked first and second.

Figure 2 presents the cause and effect diagram of all sub-criteria. The parts of the diagram are formed according to the main of (R+C); it is 2.065 (by Table 6, value is 4.13). The dashed line in the figure shows the division of the four parts.

The sub-criteria located above the abscissa are in the cause group; the sub-criteria located below the abscissa are in the effect group. The sub-criteria Transport costs for fuel (B1), Security (S2), Stability (S4), Time travel (T1), Directness (T3) and Number of stops (T4) are in the part of the diagram where the "Relation" (R-C) is positive and "Prominence" (R+C) is large. This indicates that these criteria are the key factor for the choice of transport technology for the carriage of passengers. The sub-criteria Comfort (S1), Reliability (S3), Ticket price (B2), Direct operating costs (B3) and Company position in the market (B5) have a negative (R-C) and large (R+C). This shows that they have indirect impact on the studied system.

The sub-criteria Infrastructure charges (B4), Punctuality (S5), Cleanliness, ergonomics (S6), Frequency (T2), Service period (T5) and State of infrastructure (T7) have positive (R-C) and small (R+C), which indicates that these criteria are independent and influenced only by a few other factors. The sub-criteria E1-E5, Security and comfort in the place of time-off (S7) and Vehicle occupancy rate (T6) negative (R-C) and small (R+C), which shows that they are independent and can be influenced by a few other factors.

Figure 3, Figure 4, Figure 5 and Figure 6 present examples of the cause and effect diagram for some of criteria. Figures are compiled according to results in marked values given in Table 5 and Table 6. Arrows in figures present the relationships between criteria according to the threshold value and the marked elements in the total relation matrix presented in Table 5 and Table 6. Figure 3 shows the relationship for the sub-criterion Ticket price (B2). This sub-criterion is in the Effect group.

The strongest relationships for the ticket price (B2) are with Costs for fuel (B1), Direct operating costs (B3), Comfort (S1), Time travel (T1) and Directness (T3) (values of Total Relation Matrix between 0.14-0.15). Figure 4 shows the relationship for sub-criterion Time travel (T1). This sub-criterion is in the cause group. The strongest relationships for Time travel (T1) are with Ticket price (B2), Direct operating costs (B3) and Directness (T3) (values of Total Relation Matrix between 0.20-0.22). Figure 5 presents relationship for the ecological sub-criteria E1-E5. These

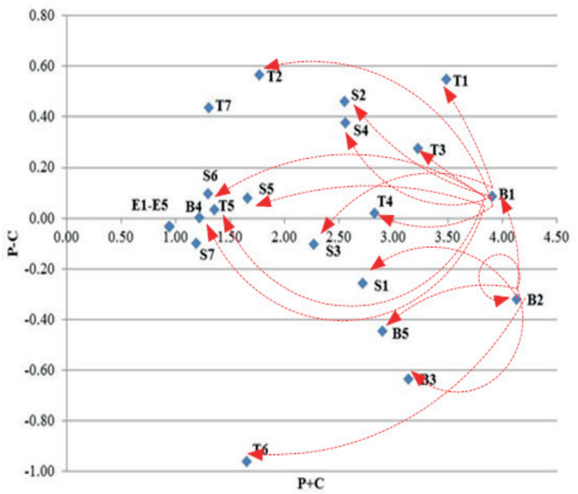


*Figure 3 The cause and effect diagram for the sub-criterion B2. Threshold value v =0.04*

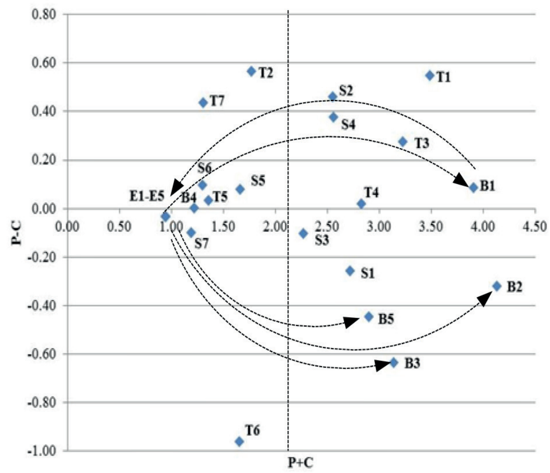


***Figure 5*** *The cause and effect diagram for the sub-criteria E1-E5. Threshold value v =0.04*

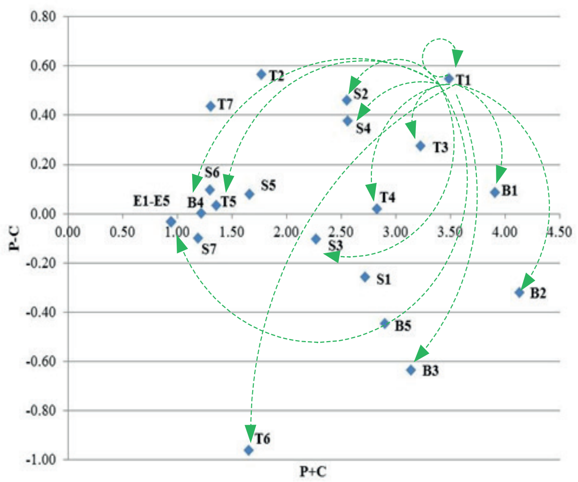


***Figure 4*** *The cause and effect diagram for the sub-criterion T1. Threshold value v = 0.04*

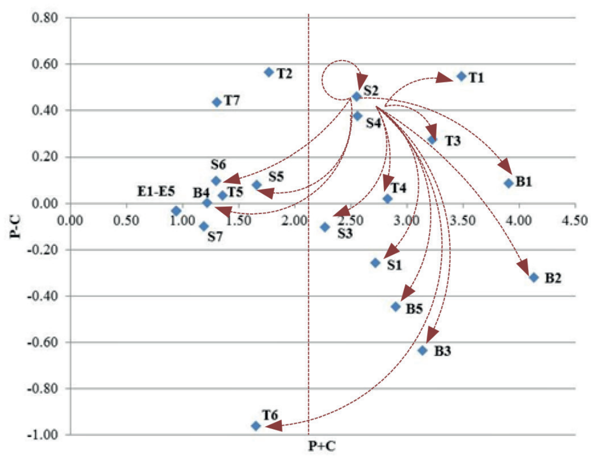


**Figure 6** *The cause and effect diagram for the sub-criterion S2. Threshold value v = 0.04*

sub-criteria are in effect group. The strongest relationships these sub-criteria have with costs for fuel (B1), (values of Total Relation Matrix between 0.20-0.22). Figure 6 shows the relationship for sub-criterion Security (S2). This sub-criterion is in cause group. The strongest relationships for Security (S2) are with Costs for fuel (B1), Ticket price (B2), Direct operating costs (B3) (values of Total Relation Matrix between 0.12-0.13).

## 4 Conclusions

This research defined the criteria for the choice of transport technology for the carriage of passengers. The DEMATEL multi-criteria method has been applied to study the impact and the influence of the criteria on one another. Four main criteria and 24 sub-criteria have been defined. It was found that the Business criteria have the highest degree of importance (29.47%). The Business criteria and Technological criteria are in the cause group. The Environmental criteria and Social criteria have indirect impact on the studied system. The criteria of great importance are the transport costs for fuel (7.83%); ticket price (8.29%); time travel (6.99%); directness (6.47%) and direct operating costs (6.30%).

The sub-criteria Transport costs for fuel (B1), Security (S2), Stability (S4), Time travel (T1), Directness (T3) and Number of stops (T4) are the key factor for the choice of transport technology for the carriage of passengers. The sub-criteria Comfort (S1), Reliability (S3), Ticket price (B2), Direct operating costs (B3) and Company position in the market (B5) have indirect impact on the studied system. The sub-criteria of the main group Business (B) and Technological (T) are ranked at the first seven positions. These results are similar to the ranking of the main group criteria, where Business (B) and technological (T) criteria are ranked as the first and second.

The defined criteria and the received results can be applied for evaluation, comparison and selection of variants of carriage with different modes of transport. Results for the criteria weights can be used as input data when applying another method of ranking the transportation alternative.

**Acknowledgments**

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Sayabek Ziyadin - Dimash Yergobek - Aigerim Kazhmuratova - Aigerim Kuralova

# KAZAKHSTAN'S TRANSIT POTENTIAL DEVELOPMENT THROUGH TRANSFORMATION OF LOGISTICS PROCESSES AS A PART OF ECONOMIC GROWTH

*The rapid development of transport, the widespread introduction of modern transport technologies, close cooperation with Russia, China and other neighboring countries, will allow Kazakhstan to become a serious player in the transportation market between Europe and Asia in the coming years. Such existing transport potential directly affects the economic growth of the country which will lead to high living standard. The global movement towards digitalization is transforming the logistics industry, as well. The "digit" changes the channels of movement of goods, delivery formats and management processes. Development of e - commerce and the increasing supply requirements - multichannel, responsiveness, transparency, accuracy - stimulate retailers and logistics operators to increase efficiency of processes and introduce new technologies. Therefore, the ways of prosperity of Kazakhstani economy, through digitalization of logistics processes is considered in this article.*

***Keywords:*** *digitalization, transit potential, logistics operations, economic growth, e - commerce, innovations, new technologies*

## 1 Introduction

The demand for transit services is constantly growing, and accordingly, the market for these services is expanding. In the first approximation, the volume of transit traffic directly depends on the number of countries in the world, volume of the world trade, share of products with a high degree of processing in it and, conversely, on share of the transport costs in the cost of the transported goods.

For countries that provide transit services, like Austria, Hong Kong, Singapore, Ukraine, this is a kind of "invisible" export, which in some cases brings the state income. According to the World Trade Organization data for 2013, the share of transport services in the world trade in goods and services was 4.8% in exports and 5.2% in imports [1]. Of course, transit is only one of components of both export and import of transport services. Cargo and leasing vehicles, provision of repair and bunkering services, transportation on national vehicles between third countries, etc. occupy a significant share. However, transit countries can provide up to half of the revenue from international transport services.

The economic significance of transit is not limited to balance of income and expenditure of countries on transit operations. Its volumes reflect the level of transport development and its international competitiveness, which is important for the national economy. This is closely related to activities of related industries: insurance, logistics, energy, etc. Transit attractiveness of communications is an important factor in development of the neighboring regions. In this sense, the volume of international transit traffic is an indicator of the development level of transport and logistics, national rules governing the transit transport.

Countries seek to benefit from transit by offering new options for international transport through their territories or by improving the quality of transit services, primarily by speeding it up and improving the safety of goods in transit, as well as for passengers, which makes travel more comfortable. For this purpose, new transport routes are created and upgraded, new transport technologies are introduced, preferential tariffs are provided. The competition of transit routes largely regulates tariffs and simplifies transit rules.

Development of transit today is due not so much to peculiarities of the transport and geographical position of the world countries and the geography of their foreign trade, but to the pace of introduction of modern transport and logistics technologies. The second half of the last century and the beginning of the new century were marked by unprecedented technical progress in the main types of international transport, which significantly changed the overall picture of the world economy. The global economic space has become more accessible and convenient for development and profitable use.

Thus, at the same time, there is a desire in the countries of the world to reduce transit dependence, increase revenues from international transit, and use it

**Sayabek Ziyadin[1], Dimash Yergobek[2,*], Aigerim Kazhmuratova[2], Aigerim Kuralova[2]**
[1]Korkyt ata Kyzylorda State University, Kazakhstan
[2]Al-Farabi Kazakh National University, Kazakhstan
*E-mail of corresponding author: Yedk2017@mail.ru

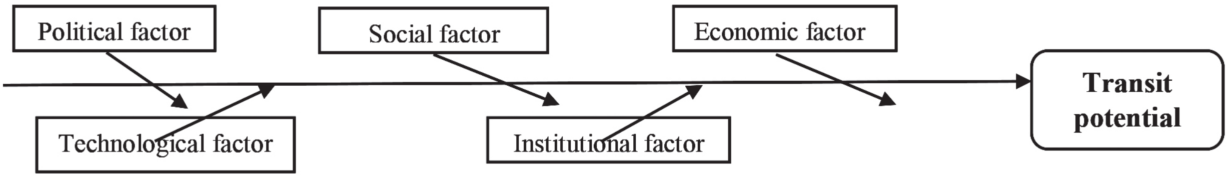


***Figure 1*** *Factors that affect country's transit potential*

***Table 1*** *Logistics 4.0 technologies and systems*

| Title of the technology/system | Main function |
|---|---|
| RFID: Radio - Frequency Identification Systems | Identification |
| Real time locating systems | Locating |
| CPS: Cyber Physical Systems | Sensing |
| IoT: Internet of Things | Networking |
| Big Data and Data Mining | Data Collecting and Analyses |
| IoS: Internet of Services | Business Service etc. |
| AGV: Automated Guided Vehicles | Material handling |
| WMS: Warehouse Management Systems | Support and optimization of warehouse functionality and distribution center management |
| TMS: Transportation Management Systems | Optimization of freight shipping process |
| Blockchain Technology | Record transactions |
| E - Marketplace (Freight Exchange) Platforms | Access to interact and exchange business |
| Autonomous Vehicles and Routes | Transportation |
| Active Communication and Agility | Effective interaction |
| Ambient Intelligence | Sensor networking |
| Innovative Horizontal Loading Technologies | Co - loading shipment |

widely to speed up the international transport and increase their reliability, while increasing competitive delivery route options. These trends make up a rather ambiguous picture of the transit development in the countries of the world, including Kazakhstan.

In the World Bank's logistics efficiency Index (LPI), Kazakhstan is taking the 71st place among 160 countries in 2018, which is 6 positions higher than in 2016, ahead of the member countries of the Eurasian economic Union. Significant improvements were made in two LPI indicators - "efficiency of the customs clearance process" and "Timely delivery of goods". At the same time, it should be noted that Kazakhstan has not yet fully used the potential, including international, of the country in the field of transport and logistics.

The transport industry is one of the most important sectors of Kazakhstan's economy: its share in the GDP structure in 2018 was 8.4%. The volume of cargo transported by all the modes of transport has doubled - from 1.9 billion tons in 2007 to 4.1 billion tons in 2018. The cargo turnover increased 2.2 times - from 263.6 billion to 596.0 billion tons/kilometers, an average of 5.3% annually. The observed trend indicates the most important socio - economic role of the transport industry in the development of the Republic. Moreover, today the salary of an employee in the field of transport and storage is higher than the national average by 40 thousand tenge and more.

The economic condition of Kazakhstan can be significantly improved by means of transport operations through the country. Currently, Kazakhstan can offer all the types of transport (rail, road, water, air and pipeline transport) for international transit, but many factors affect the transit potential. These are the main factors: political, social, economic, technological, and institutional (Figure 1).

Digitalization is the most relevant tool for technological development. The logistics industry is becoming one of the drivers of digitalization. One needs to master current delivery channels and formats, analyze big data, automate processes and implement block chain and robots.

All of the ideas, related to the technological development in major spheres, came with introduction of Industry 4.0. Industry 4.0 is a philosophy that integrates of all the value - added functions through the supply chain by using digitalization. Its key components are: Cyber Physical System (CPS), Internet of Things (IoT), Internet of Services (IoS) and Smart Factory. Therefore, logistics, as a part of supply chain, has its own similar system logistics 4.0, which shares same aims as Industry 4.0. Logistics 4.0, sometimes called Smart Logistics, is a system conversion from hardware - based operations to software - based operations. Its technical components and key elements include: Automatic Identification, Real Time Locating, Smart Sensing, Networking, Data Analyzing,

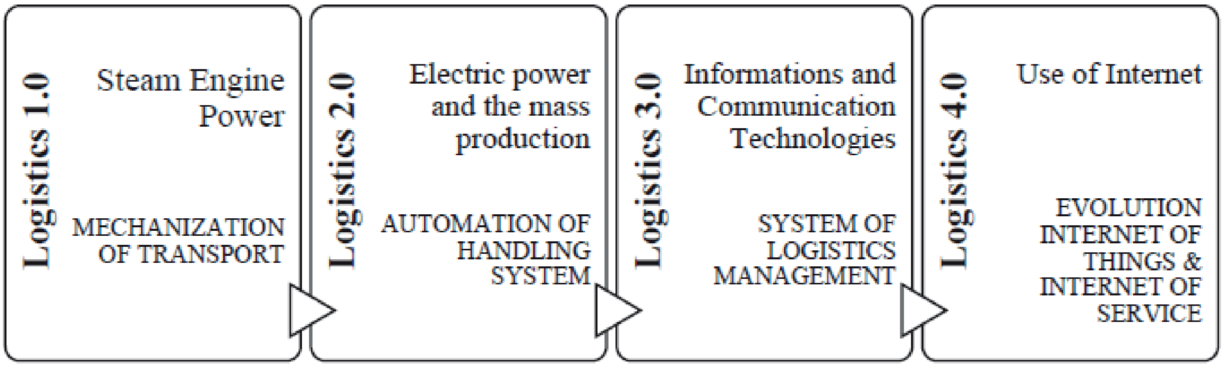


***Figure 2*** *Evolution of logistics [5]*

Internet for Business Services, Digitalization, Transparency, Automation, Modularization and Transportation and Distribution. All of the activities, done by the virtue of Logistics 4.0, are implemented in the area of Logistics Center 4.0. The main technologies and systems included in Logistics 4.0, which help to optimize logistics operations and minimize utilized time and expenditures, can be seen in Table 1.

## 2 Literature review

The transformations due to Industry 4.0, including operational, technological and social dimensions, not only affect manufacturing industries but also elements of the entire supply chain [2]. As one of the foremost critical components of supply chains, logistics operations are too anticipated to be influenced by characteristics of Industry 4.0, e.g. IoT, Cyber Physical Systems (CPS), Big Data and smart sensors [3]. Smart logistics or, as in used in this study, Logistics 4.0 can be defined as networking the whole supply chain through information technologies (IT), where high technological sensors and advanced robotics are used in operations [4]. Several key elements of logistics, including warehousing, handling, transportation, distribution and information services, have been forced to change by technological developments to increase efficiency [3].

Industry 4.0 affects logistics at both operational level and through broader concepts like Logistics Centers (LCs). Freight villages, distribution centers, dry ports, inland and intermodal terminals and logistics parks or nodes are several terms at different operation levels that are used in different countries and regions to describe Logistics Centers [5].

Logistics operations, such as transportation, warehousing and distribution, have confronted several changes in world trade history. All subsystems are affected by developments like industrial revolutions, new technologies, transitional concepts and business services. As shown in Figure 2, Logistics 4.0 is one of the fields influenced by the Industry 4.0 paradigm [6].

Multimodal transportation is generalized and intermingling concept that incorporate combining to utilize several transportation modes (air, rail, truck etc.) to transport of people or cargo [7]. In addition, since multimodal transport has some disadvantages and it is necessary to solve these problems, there is a need for new concepts of synchromodality, where a new solution towards more flexible and integrated freight transport has been implemented [8]. Vural [9] defined synchro - modality ensures efficient operations, so in short, LCs creates an integrated transportation infrastructure. In other words, from carriers to operators, all different stakeholders can easily evaluate the pros and cons of supply chain process by using the synchro - modality [10]. Moreover, the synchro - modality system facilitates supply chain optimization by considering all the transportation modes and relevant activities to access environmental, low risk and low cost - oriented approach and helps to stakeholders to organize best multimodal options and schedules strategically and to manage dynamic solutions for a quick fix demands operationally [11]. The new technological developments of logistics through Industry 4.0 are expected to alter LCs' operations including handling, warehousing, distribution and transportation, where smarter systems are needed [12].

From their compilation of relevant studies, Szymanska et al. [13] defined Logistics 4.0 within two approaches: (1) processual, meaning to increase supply chain members' efficiency and performance; (2) technical, which includes elements of Industry 4.0, such as digitalization, automation, mobility and IoT. Domingo Galindo [6] identified that, in general, Logistics 4.0 or Smart Logistics is a system that uses technological changes to improve flexibility and customer satisfaction, optimize logistics activities and adapt to global changes under the umbrella of Industry 4.0. One of logistics' primary objective is increasing capacity usage and using autonomous processes like high level of mobility, modularity, compatibility, communication and information in logistics facilities [14].

Tang and Veelenturf [15] summarized advantages of advanced technologies of Industry 4.0 on the logistics functions as: (1) faster speed by delivery services conducted by drones and delivery robots, (2) higher reliability by storage and retrieval systems using robots, (3) lower operating cost by inventory monitor and replenishment systems using smart sensors, (4) improved efficiency by container shipping enabled by block chain technology.

***Table 2** Multiple regression model*

| Regression statistics | | | | | |
|---|---|---|---|---|---|
| Multiple R | 0.870328 | | | | |
| R - squared | 0.757471 | | | | |
| Normalized R - squared | 0.65353 | | | | |
| Standard error | 0.013516 | | | | |
| Observations | 11 | | | | |
| Analysis of variance | df | SS | MS | F | Significance F |
| Regression | 3 | 0.003994 | 0.001331 | 7.287518 | 0.014728 |
| The remainder | 7 | 0.001279 | 0.000183 | | |
| Total | 10 | 0.005273 | | | |
| | Coefficients | Standard error | t - statistic | P - value | |
| Y intersection | 0.060792 | 0.021513 | 2.825818 | 0.025559 | |
| Variable $X_1$ | 1.11E-08 | 2.49E-09 | 4.451192 | 0.002967 | |
| Variable $X_2$ | -4.3E-08 | 3.1E-08 | -1.38641 | 0.208174 | |
| Variable $X_3$ | -8.7E-08 | 1.9E-08 | -4.58774 | 0.002521 | |
| Display residue | | | | Conclusion of probability | |
| Observation | Predicted Y | Remains | Standard remains | Percentile | Y |
| 1 | 22754491.47 | 13244533.63 | 0.847254674 | 8.333333333 | 4697115 |
| 2 | 36923807.69 | 2752025.208 | 0.176047439 | 25 | 35999025.1 |
| 3 | 35981100.54 | 4903033.061 | 0.313647713 | 41.66666667 | 39675832.9 |
| 4 | 35713580.29 | -31016465.29 | -1.984127636 | 58.33333333 | 40884133.6 |
| 5 | 48421741.43 | 5957116.371 | 0.38107757 | 75 | 54378857.8 |
| 6 | 57659779.38 | 4159757.022 | 0.26610024 | 91.66666667 | 61819536.4 |

***Table 3** Values of indicators, 2008 – 2018*

| Year | GDP growth (real), % | Annual GDP, mln tenge | Investments in transport and storage, mln tenge | Gross output of transport services, mln tenge |
|---|---|---|---|---|
| 2008 | 0.033 | 16052919.2 | 754359 | 2052517 |
| 2009 | 0.012 | 17007647 | 967724 | 2123850 |
| 2010 | 0.073 | 21815517 | 734505 | 2531615 |
| 2011 | 0.075 | 28243052.7 | 896323 | 2903264 |
| 2012 | 0.05 | 31015186.6 | 1038745 | 3439516 |
| 2013 | 0.06 | 35999025.1 | 1453656 | 4004633 |
| 2014 | 0.043 | 39675832.9 | 1192640 | 4600380 |
| 2015 | 0.012 | 40884133.6 | 1138572 | 5100619 |
| 2016 | 0.011 | 46 971 150.00 | 1176239 | 5898485 |
| 2017 | 0.04 | 54 378 857.80 | 1262907 | 6474355.567 |
| 2018 | 0.041 | 61819536.4 | 1453136 | 7522986.872 |

Faced with a challenge of Industry 4.0, logistics must adapt to new developments or needs, such as IT communication, production technologies, digitalization, big data usage, IoT, robotics and automation and RFID technologies. These would have both positive effects, such as high standardization, reduced labor force, more intelligent and transparent processes and negative effects, such as higher investment and infrastructure costs [13]. If an efficient, robust Logistics 4.0 system is desired, resource planning, warehouse and transportation management systems, intelligent transportation systems, and information security should also be considered [16].

In parallel with Industry 4.0's developments or changes, as in the logistics sector in general, LCs ought to adjust

***Table 4** The SWOT analysis of introduction of logistics processes digitalization to improve the economic growth*

| Strengths | Weaknesses |
|---|---|
| - Contributes to GDP growth in all the existing Kazakhstan regions;<br>- Significant replenishment of Kazakhstan's budget;<br>- Increase of strategically important partner countries;<br>- Fast and cheap delivery of oil and gas to processing points is possible by choosing the optimal transportation route;<br>- Better order tracking and payment services;<br>- High profit and service quality;<br>- High volume of freight forwarding;<br>- Customer satisfaction through brand new services. | - Requires significant time - period and high expenditures of maintenance;<br>- Technological and innovation factors are poorly developed in Kazakhstan;<br>- Sharp lack of local specialists in digitalization sphere;<br>- Lower customer service costs;<br>-Failure of critical IT systems. |
| Opportunities | Threats |
| - Simplification of internal processes with wider application of digital solutions;<br>- With further development of the transport and logistics infrastructure, the country's GDP, due to cargo transportation in the Republic of Kazakhstan, will grow at least annually by 4.5 -5% over the next 5 years;<br>- The process of increasing the efficiency of transport infrastructure facilities by 2-3 times can be facilitated by the introduction of innovations in automobile and railway communication in such large cities as Nur - Sultan, Almaty and Shymkent;<br>- Reducing the negative effect of the lack of qualified specialists;<br>- Quicker coordination with importer or exporter countries (clients);<br>- Attracts investments, while financial markets encourage pioneer innovators with unprecedented high value for their business. | - Difficult task of involvement of specialists with knowledge in the field of digital technology;<br>- Lose of competitive advantage due to alternative transit countries as Russia, Kyrgyzstan, Uzbekistan, Tajikistan, etc.;<br>- Threat of the unemployment increase on the labor market;<br>- Risk of brain drain to more technologically advanced countries;<br>- Inability to keep up with pace of change and technological advancement;<br>- New technologies obsolescing existing transport infrastructure. |

themselves to survive since they are significant logistics sector components in terms of their key role in local and global operations. To succeed, they must keep abreast of Industry 4.0 elements and brace themselves to adapt the new paradigm [17].

## 3 Methodology

The methodological approach of this article includes both statistics research and regression analysis to identify the role of logistics in economic growth and how digitization of logistics operations affects the whole logistics sphere in the country. Based on 2008 - 2018 data of dynamics of the logistics operations investment and Kazakhstan's economy, their relationship is the regression analysis, reflecting the internal relationship between the growth of logistics and economic growth. Calculation of values of the regression equation coefficients (Table 2) was carried out using the tools of the "Data Analysis" task in Microsoft Excel in two stages with neglecting the insignificant variables from the equation.

Regression analysis is a statistical analytical method that allows to calculate the estimated relationship between a dependent variable of one or more independent variables. Regression analysis uses the chosen estimation method, the dependent variable and one or more independent variables to create an equation that estimates the values of the dependent variable. The regression model includes output, such as $R^2$ and p - values, from which one can understand how well the model estimates the dependent variable.

Regression analysis is modeled based on the Least Squares Method (OLS), a form of multiple linear regression, assuming that the relationship between dependent and independent variables should be modeled by fitting the linear equation to the observational data. The OLS uses the following equation:

$$y_i=\beta_0+\beta_1x_1+\beta_2x_2+...+\beta nx_n+\varepsilon, \quad (1)$$

where: $y_i$ - observed value of the independent variable at point i, in this case, GDP growth,
$\beta_0$ - y - intercept (segment on the coordinate axis, constant value),
$\beta_n$ - regression coefficient or slope of the independent variable N at point I,
$x_n$ - value of variable N at point i, in this case:
$x_1$ - Annual GDP (at the rate 1KZT = 376.16USD for 21.02.2020) [18],
$x_2$ - Investments in foxed capital: transport and storage,
$x_3$ - Gross output of transport services,
$\varepsilon$ - regression equation error.

To create the regression model, the GDP growth indicator from 2008 to 2018 years was taken as an independent variable and indexes of annual GDP, investments in fixed capital: transport and storage, gross output of transport services of same years were taken as explanatory variables (Table 3). The statistic numbers were taken from the national statistics website stat.gov.kz [19].

Using the data from the above table to perform the multiple regression analysis, all the selected variables are forced into the regression, the economic growth rate as independent variable, annual GDP, investments in fixed capital: transport and storage, gross output of transport services as explanatory variables, sample period of 2008 - 2018, then the regression equation is:

$$y = 0.060792 + 1.11E\text{-}08\ x_1 - 4.3E\text{-}08\ x_2 - 8.7E - 0.8\ x_3 + 0.013516. \quad (2)$$

Calculation of indicators for assessing the significance of the obtained model and its parameters was carried out using the “Regression” tool of the “Data Analysis” task of MS Excel.

The statistical significance of the regression equation was estimated using the Fisher F - test. Actual value of F - Fisher test: F = 7.287. The table value of the criterion at a five percent level of significance and degrees of freedom = 3 and = 11-3 - 1 = 7 is Ftable = 4.35. Since F = 7.287 > Ftable = 4.35, the regression equation is recognized as statistically significant.

The statistical significance of the regression and correlation equations parameters was estimated using t - student statistics and by calculating the confidence interval of each of the parameters. The tabular value of the t criterion for the number of degrees of freedom 7 and significance level $\alpha = 0.05$ is t - table = 2.365.

Residual variance per degree of freedom is calculated by the formula:

$$s^2 \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}, \quad (3)$$

then: $S^2e = 0.000183$.

Square root of residual dispersion (standard error): S.e. = 0.013.

To identify measurements of significant and non - significant variable the following formula is used:

$$t = \frac{|\bar{x} - m|}{s/\sqrt{n}}. \quad (4)$$

In the regression equation, F (7.287) passes the test and the regression effect is significant, which shows that independent variable (the growth of logistics) has a higher interpretation to explanatory variable (economic growth rate), with general linear. In the interim, the determination coefficient $R^2 = 0.757471$ is quite high in the regression equation, indicating that Kazakhstan’s economic growth depends on logistics operations.

## 4 Discussion

In methodology we used multiple regression analysis model to identify the relationship between GDP growth and growth of logistics operations, which shows the important role of transit potential in overall economic growth of the country. The main idea of the article is to further enhance the logistics operations through digitalization in order to improve transit potential. Digitalization of the logistics industry is a matter of competitiveness of Kazakhstani global service. Therefore, the SWOT analysis is used in this section to discuss the holistic effect of logistics operations digitalization introduction (Table 4).

## 5 Conclusion

Digitalization is already transforming all the segments of transport and logistics, and according to forecasts, this will be the strongest trend in the coming years, which will radically change all the logistics activities. As technologies are developing dynamically, all economic and production processes are being digitalized. The Industry 4.0 is the major driver of majority digitalization operations, which include Logistics 4.0, as well. The main purpose of logistics 4.0 is digitalization of related logistics operations to increase effectiveness, profitability, productivity and optimization of costs and time. Such modern technologies have positive impact on transit potential of Kazakhstan since they directly influence the transportation activities.

The article considered relationship between digitalization of logistics operations and economic growth through use of the multiple regression analysis. The strong connection is identified during the calculation and analysis of existing strengths, weaknesses and possible opportunities and threats are discussed. Following the above - mentioned information, the following conclusions were drawn:

First, based on the growth rate, the digitalization of logistics is very important for the economic growth of Kazakhstan, which is one of the main factors and driving forces of Kazakhstan’s economic growth.

Second, Kazakhstan should continue to increase the introduction of investment and logistics supplies in order to protect national economic development.

Third, Kazakhstan should improve the quality of technologies and training of related specialists, promote optimization and modernization of the logistics structure and economic transition and promote economic development.

Fourth, Kazakhstan’s Statistics Committee should make reviews and statistics about modern areas as digitalization, sustainable development, etc., since most of the statistics are not available to conduct an analysis.

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Tomasz Lusiak - Andrej Novak - Martin Bugaj - Radovan Madlenak

# ASSESSMENT OF IMPACT OF AERODYNAMIC LOADS ON THE STABILITY AND CONTROL OF THE GYROCOPTER MODEL

*Aerodynamic modelling currently relates to development of mathematical models to describe the aerodynamic forces and moments acting on the aircraft. It is a challenging part of aerodynamics that defines a comprehensive approach to using traditional methods and modern techniques to obtain relevant data. The most complicated task for the aerodynamics and flight dynamics is definition, computation and quantification of the aerodynamic description of an object. This paper presents how to determine the aerodynamic load on a gyrocopter and defines the effect on its stability and control. The first step to solution is to develop simpler approximate aerodynamic model - a model that can be used in analysis of aerodynamic load and can represent the aerodynamic properties of the gyrocopter with an acceptable degree of accuracy. Control and stability are very important parts of aircraft characteristics and therefore those characteristics were analyzed in simulation. Finally, the aerodynamic data outputs are assessed in terms of impact of aerodynamic loads on stability and control of the gyrocopter model.*

***Keywords:*** *aerodynamics, stability, gyrocopter, propeller*

## 1 Introduction

An aircraft is a device that, using aerodynamic properties, can perform a flight in the atmosphere. Considering the principle of operation, based on which the flight is performed, aircrafts can be divided into aerostats and aerodynes. In the case of an aerostat, movement relative to the centre is not necessary. It is created in accordance with the Archimedes principle, thanks to which a load-bearing force that balances the weight is created. However, the aerodynamic movement is an indispensable element without which the flight cannot take place. Gyroplane - an aircraft heavier than air (aerodyne), from the rotorcraft family, equipped by a carrying rotor and a propeller (pushing or pulling). The impeller is not driven by the engine but rotates thanks to the autorotation of the rotorcraft relative to the air resulting from the progressive movement of the propeller.

## 2 State of the art

Aerodynamic characteristics enormously affects the aircraft performance, stability and control. The main concerns of aircraft aerodynamics are reducing drag, reducing noise and improving lift forces on aerodynamic objects. Simulation and model development are providing effective solutions in optimizing lift to drag ratios and impact of aerodynamic loads on the stability and control.

Computational Fluid Dynamics (CFD) is an analysis of the physical phenomena involved in fluid flow and heat conduction by computer numerical calculation and graphical display. The numerical method simulates the complexity of the physical problem and the precision of the numerical solution, which is directly related to the hardware speed of the computer and the hardware such as memory. With the continuous improvement of computer performance and the CFD technology, it has been widely applied to the field of water conservancy engineering, environmental engineering and industrial engineering. The CFD technology in the mechanical engineering related applications are summarized [1].

## 3 Methodology

The gyroplane model is a composite structure with a central steel lattice in which the drive unit will be placed inside. Rotorcraft cabin Aduster is a completely closed, two-seater structure. The system uses the so-called "Inverted V", which has a stationary part and a movable steering part. The four-point chassis system consists of a main shin hidden and mounted in the tail system of the rear legs of the chassis. The control system is divided according to the three axes of the aircraft (longitudinal axis, transverse axis and normal axis). The control of the rotor system, understood as inclination and tilting, is carried out using a control stick located at each of the two places in

**Tomasz Lusiak[1], Andrej Novak[2], Martin Bugaj[2], Radovan Madlenak[2,*]**
[1]Lublin University of Technology, Poland
[2]University of Zilina, Slovakia
*E-mail of corresponding author: radovan.madlenak@fpedas.uniza.sk

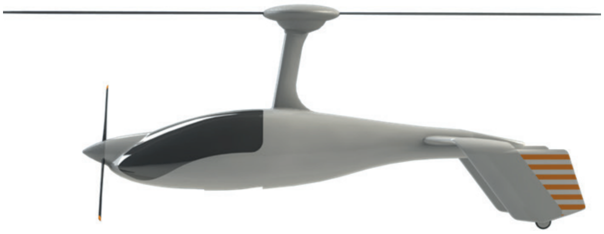

*Figure 1* Visualization of the gyroplane prototype

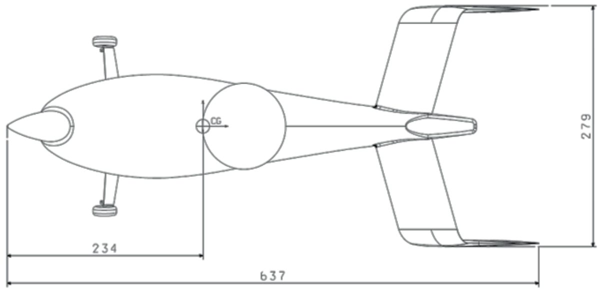


*Figure 3* Upper view of the gyroplane

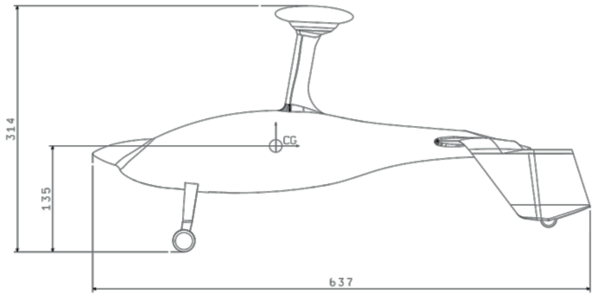


*Figure 2* Lateral view of the gyroplane

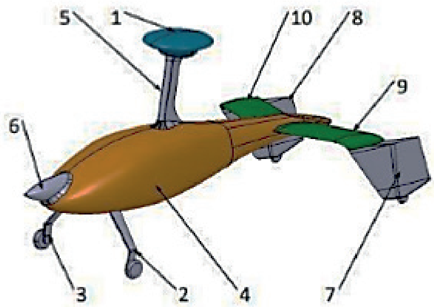


*Figure 4* Specification of a gyroplane: 1 - head, 2 - left shank, 3 - right shank, 4 - hull, 5 - pole, 6 - nose, 7 - left vertical stabilizer, 8 - right vertical stabilizer, 9 - left horizontal stabilizer, 10 - right horizontal stabilizer

the cabin [2]. The tilting of the rod to itself will increase the angles of attack, thus increasing the angle of attack of the aircraft and recruitment of heights. In order to make a turn, the control stick should be tilted to the side, which will cause the side of the rotor to tilt in the same direction. Application of the inverted V type enables the bend to be made without changing the rotor deflection, but only when the rudder is tilted [3].

### 3.1 The geometrical model

Gyroplane differs from the current designs of rotorcraft companies: CelierAviation, AutoGyro, MagniGyro, ELA Aviation, because of the engine's location and use of a pulling propulsor instead of a pusher. This project will be characterized by higher performance and less complexity of the engine-propeller system. Due to its highly aerodynamic design, the gyro Aduster is characterized by the low air resistance. The model used during the tests was provided by the ordering party. Figures 1-3 show a side view and a plan view of the gyrocopter concept [4].

The aerodyne model was made in the 1:8 scale, and the detailed height and length dimensions were given on two views of the technical drawing (Figure 4). The windmill during the tests in the wind tunnel is devoid of propellers and rotor blades. The extension consists of a double vertical stabilizer with rudders and a horizontal stabilizer with height controls. The mast is placed so that the gondola touches the center of gravity of the aircraft. During the experiments different geometric configurations were used, which will be discussed later in the work. The aircraft and model real dimensions included in the table below were used to size forces and moments to the appropriate coefficients.

## 4 Developing of the Aduster model

The aerodynamic tunnel is the basic research device for experimental aerodynamics. The most important part of each aerodynamic tunnel is the area (test chamber) in which the test object or its research model is placed. The tunnel, in addition to the chamber, consists of devices that generate a stream of air flowing around the object under test. The air acts in the same way on the object being examined, as if the object was moving and the air was still. This enables precise measurements of forces and moments, as well as flow visualizations. The tests were carried out in the wind tunnel of the Institute of Aviation in Warsaw [5]. The wind tunnel, test stand has a closed cycle with an open measuring space with a circular cross-section. Inside the open measuring space, a positioning system is installed that allows the model to be installed. The research was carried out using a multi-component sensor of forces and moments of the so-called aerodynamic weight 6-component. The center of the balance (reference point of the measured forces) is located in the middle of the rotation of the positioning system. The measuring system works in automatic mode, eating the model positions based on the prepared angle grid. The measurement performed is the effect of registering the value of the determined average with the test of the stationarity of the result [6-7].

***Table 1** Measurement of impact of weight of the "dynamic tare" model*

| Alfa | Beta | Fz | Fx | Cx | Cz | Cz/Cx |
|---|---|---|---|---|---|---|
| -20 | -10 | -9.4265 | 4.2926 | 0.0091 | -0.0199 | -2.1960 |
| -16 | -10 | -7.0512 | 3.4726 | 0.0073 | -0.0149 | -2.0306 |
| -12 | -10 | -4.1464 | 2.9072 | 0.0061 | -0.0087 | -1.4263 |
| -8 | -10 | -1.2058 | 2.6106 | 0.0055 | -0.0025 | -0.4619 |
| -4 | -10 | 1.9721 | 2.5099 | 0.0052 | 0.0041 | 0.7857 |
| -2 | -10 | 3.5317 | 2.5703 | 0.0054 | 0.0074 | 1.3741 |
| 0 | -10 | 5.3060 | 2.6047 | 0.0054 | 0.0110 | 2.0371 |
| 2 | -10 | 6.2942 | 2.8810 | 0.0060 | 0.0131 | 2.1847 |
| 4 | -10 | 7.4409 | 3.3982 | 0.0071 | 0.0155 | 2.1896 |
| 8 | -10 | 8.2456 | 4.4648 | 0.0093 | 0.0171 | 1.8468 |
| 12 | -10 | 9.1378 | 5.4436 | 0.0113 | 0.0189 | 1.6786 |
| 16 | -10 | 10.0007 | 6.4279 | 0.0133 | 0.0207 | 1.5558 |
| 20 | -10 | 11.0049 | 7.5269 | 0.0156 | 0.0229 | 1.4621 |
| -20 | 0 | -8.97146 | 3.685696 | 0.007641 | -0.0186 | -2.43413 |
| -16 | 0 | -6.66635 | 2.923756 | 0.006031 | -0.01375 | -2.28006 |
| -12 | 0 | -3.75749 | 2.48963 | 0.005135 | -0.00775 | -1.50926 |
| -8 | 0 | -0.44951 | 2.212088 | 0.004541 | -0.00092 | -0.20321 |
| -4 | 0 | 2.878314 | 2.097328 | 0.004307 | 0.005911 | 1.372372 |
| -2 | 0 | 4.554367 | 2.137357 | 0.004388 | 0.00935 | 2.130841 |
| 0 | 0 | 5.933 | 2.159 | 0.004426 | 0.012163 | 2.748031 |
| 2 | 0 | 7.096112 | 2.241016 | 0.004593 | 0.014543 | 3.166471 |
| 4 | 0 | 8.20449 | 2.687864 | 0.005511 | 0.016823 | 3.05242 |
| 8 | 0 | 9.112066 | 3.791049 | 0.007791 | 0.018726 | 2.403574 |
| 12 | 0 | 9.464429 | 4.595181 | 0.009441 | 0.019445 | 2.059642 |
| 16 | 0 | 9.97885 | 5.176055 | 0.010669 | 0.020568 | 1.927887 |
| 20 | 0 | 10.99508 | 6.061065 | 0.012465 | 0.022612 | 1.81405 |
| -20 | 10 | -9.28013 | 4.420572 | 0.009071 | -0.01904 | -2.0993 |
| -16 | 10 | -7.00537 | 3.527572 | 0.007226 | -0.01435 | -1.98589 |
| -12 | 10 | -3.87517 | 2.950275 | 0.006035 | -0.00793 | -1.31349 |
| -8 | 10 | -0.79507 | 2.631817 | 0.005379 | -0.00163 | -0.3021 |
| -4 | 10 | 2.349215 | 2.458541 | 0.005025 | 0.004802 | 0.955532 |
| -2 | 10 | 3.805268 | 2.491261 | 0.005107 | 0.007801 | 1.527447 |
| 0 | 10 | 5.824576 | 2.63908 | 0.005401 | 0.011317 | 2.095427 |
| 2 | 10 | 7.059668 | 2.852268 | 0.005837 | 0.014447 | 2.475107 |
| 4 | 10 | 8.532465 | 3.373581 | 0.006901 | 0.017453 | 2.529202 |
| 8 | 10 | 9.406529 | 4.544506 | 0.009319 | 0.019288 | 2.069868 |
| 12 | 10 | 10.01453 | 5.515316 | 0.011326 | 0.020565 | 1.815766 |
| 16 | 10 | 10.55115 | 6.463266 | 0.013335 | 0.02177 | 1.632479 |
| 20 | 10 | 11.67543 | 7.555151 | 0.015576 | 0.024071 | 1.54536 |

Measuring space dimensions: D = 1.2 m, L = 1.5 m.
Dimension from the PP inlet to the axle: l = 0.443 m
Air speed: up to 40 m / s
Angle ranges: $\alpha \in$ <-30; 25> and $\beta \in$ <-25; 25>

## 5 Stability and control of the aircraft

Behavior of the aircraft after the impact of the disturbing force on it characterizes these properties of undisturbed aircraft movement, which are known as stability and

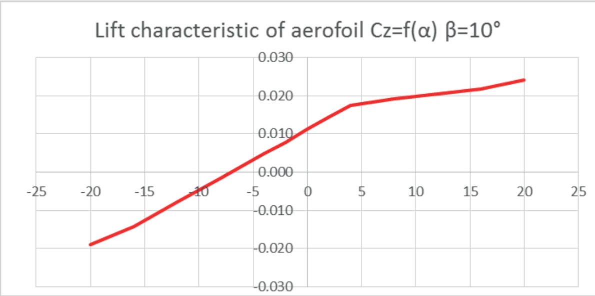


***Figure 5** Aerodynamic coefficients power of lift obtained during the measurements for the slip angle* $\beta = 10^{\circ}$

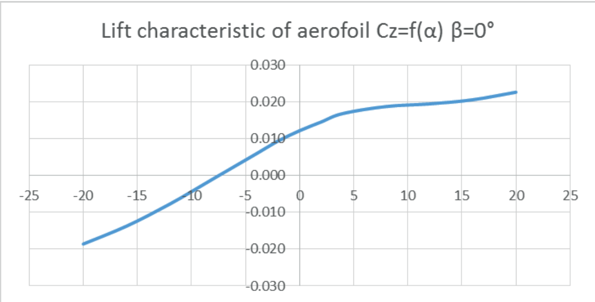


***Figure 6** Aerodynamic coefficients power of lift obtained during the measurements for the slip angle* $\beta = 0^{\circ}$

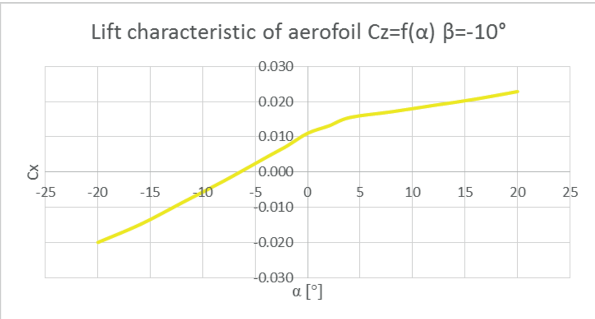


***Figure 7** Aerodynamic coefficients power of lift obtained during the measurements for the slip angle* $\beta = -10^{\circ}$

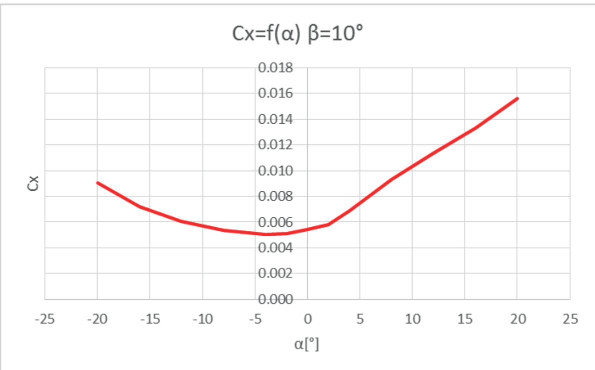


***Figure 8** Aerodynamic coefficients power of drag obtained during the measurements for the slip angle* $\beta = 10^{\circ}$

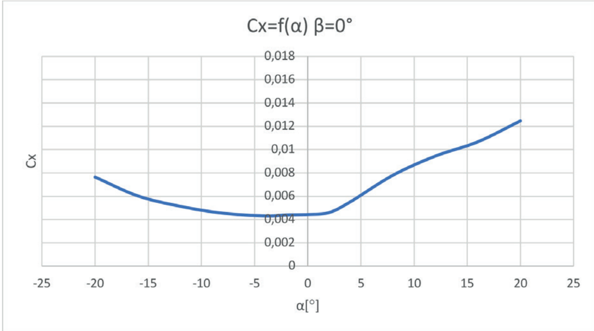


***Figure 9** Aerodynamic coefficients power of drag obtained during the measurements for the slip angle* $\beta = 0^{\circ}$

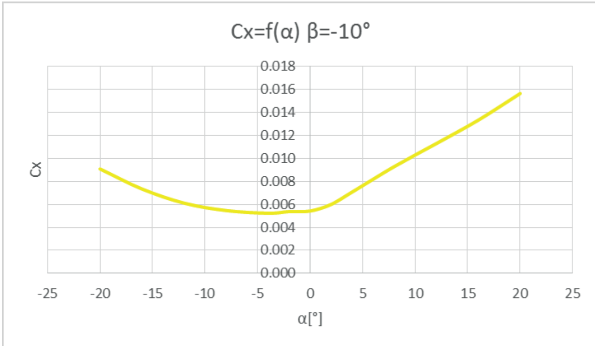


***Figure 10** Aerodynamic coefficients power of drag obtained during the measurements for the slip angle* $\beta = -10^{\circ}$

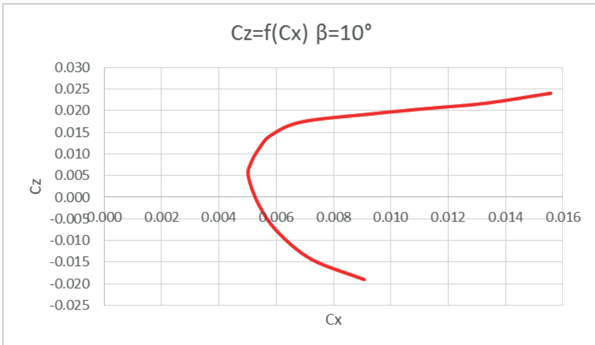


***Figure 11** Aerodynamic coefficients obtained during the measurements for the slip angle* $\beta = 10^{\circ}$

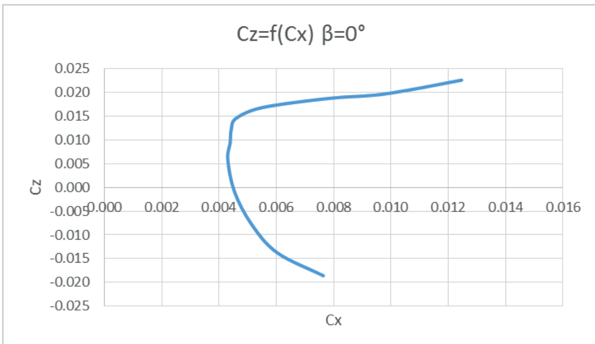


***Figure 12** Aerodynamic coefficients obtained during the measurements for the slip angle* $\beta = 0^{\circ}$

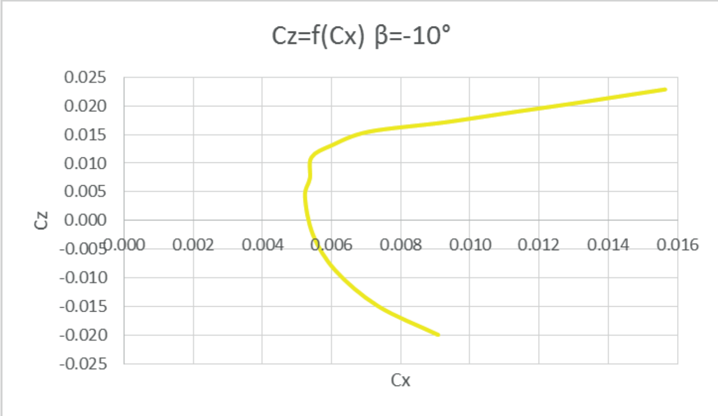


***Figure 13*** *Aerodynamic coefficients obtained during the measurements for the slip angle* $\beta = -10^{\circ}$

instability [8]. The necessary condition for the aircraft to move is not only the balance of all the forces acting on the plane, but also the balance of moments relative to the three coordinate axes (x, y, z) passing through its center of gravity. The plane's balance should be stable, that is, the plane derived from the equilibrium by some external factor, such as a blast, should return to the state of balance in a sufficiently short time without the intervention of the pilot (at least when the disturbance was not too high). The concepts of stability and balance are therefore closely related. When talking about stability, it is assumed that there is a balance, otherwise the notion of stability would not make sense. The static stability of an aircraft is called its ability to return independently (without the participation of the pilot) to the position of equilibrium, when the causes that break this balance cease to function. The dynamic stability, on the other hand, determines the type of movements that an airplane performs by returning to the equilibrium position (e.g. number, amplitude and time of deflections). The issues of static and dynamic stability are closely and inseparably connected, however, for the plane to be dynamically stable, it must be static [9]. The plane's stability with respect to the y axis is called longitudinal stability; it is secured by height. The stability with respect to the x and z axes, provided by the sash lift and the direction, is called the lateral and directional, respectively, but they are considered jointly as the lateral stability, since they are closely related to each other. These properties of undisturbed aircraft movement are known as stability and instability. The necessary condition for the aircraft to move is not only the balance of all the forces acting on the aircraft, but also the balance of moments relative to the three coordinate axes (x, y, z) passing through its center of gravity. The aircraft's balance should be stable, that is, the aircraft derived from the equilibrium by some external factor, such as a blast, should return to the state of balance in a sufficiently short time without the intervention of the pilot (at least when the disturbance was not too high). The concepts of stability and balance are therefore closely related [10].

## 6 The simulation assessment

Preparatory activities, related to assembly of the model were carried out in the following stages. The model was delivered in elements made of FDM 3D printing. The elements required matching, assembly and finishing. The activities were carried out: matching of elements and introduction of elements strengthening the internal structure and elements ensuring surface compatibility; assembly and gluing of the model; sanding and painting the external surface of the model to ensure smoothness [11].

The measurement series listed in Table 1 were implemented in the predefined positions of the model using the so-called grid of points in the space of angles. Measurement of individual measurement series was performed according to the procedure: measurement of the tare reference signal; before each measurement series, a reference signal was measured corresponding to signals in the unladen system; the measured signal is subtracted later in the measuring series from the measured signal.

Measurement of impact of the weight of the "dynamic tare" model. At each configuration, a signal measurement of forces acting on the measurement system was carried out at the changing setting of the model without aerodynamic interactions. In this measurement, impact of the weight of the model is determined at changing angles of the model's positioning. With the model placed in the measurement system in the horizontal position of the orientation of its symmetry plane, the gravity of the model mainly acts in the OY axis direction of the model, i.e. on the C measurement component. When the angle of the slide changes β gravity force affects the OX direction of the model, i.e. the X measurement component [12].

In this section, graphs of the Advent gyroplane characteristics are presented for selected angles of attack in relation to the slip angles. The research was carried out in several geometrical configurations. Values of selected aerodynamic coefficients, obtained during the measurements, are presented in the characteristics' graphs (see Figures 5-13). The characteristics in red are for the slip angle β =10°, the blue ones correspond to the zero-slip angle and the yellow ones are β = - 10°.

## 7 Conclusions

In this project the study about the aerodynamic characteristics of the aircraft - the Aduster gyroplane was dealt with. The purpose of the paper was to assess the impact of aerodynamic loads on the stability and control of the gyroplane model at various geometric configurations [13].

The graphs presenting Cz = ƒ (α) (see Figures 5-7) are similar in shape to the characteristics in literature. There are minimal changes in the graphs under the influence of different slip angle. Characteristics of the drag coefficient as a function of the angle of attack Cx = ƒ (α) is similar in shape to the characteristics in the literature - there is induced resistance. In the case of angle of attack equal zero, Cx is the smallest (Figure 9). For the slip angle -10° Cx is bigger (Figure 10), and for the slip angle 10° Cx is the largest (Figure 8), but the difference is not so big. The polar profile - Lilienthal's Curve Cz = ƒ (Cx) is similar in shape to characteristics in the literature. On the polar airfoil one can notice a small outline of the laminar profile, which has better properties for a range of small angles of attack (low value of the lift force). For the slip angle equal zero (Figure 12) the range of Cx values is the smallest, and in the case of slip angles different than zero there is a greater spread of graphs in relation to Cz, which indicates a higher coefficient of lift. Characteristics of airfoil attitude Cz/Cx in the case of a zero-slip angle as a function of the angle of attack is similar in shape to the characteristics in the literature. In the case of a slip angle of 10°, - 10°, the diagrams have a smaller spread. The characteristics of the moment coefficient as a function of the angle of attack Mz = ƒ (α) indicates the zero value of the moment coefficient as a function of the angle of attack for the graph showing the negative slip angle. The graph for the value of the slip angle equal zero assumes the smallest span of values. In the case of the slip angle 10° the moment coefficient takes positive values (Figure 13) and in the case of the slip angle -10° the moment coefficient takes negative values (Figure 11).

Comparing individual graphs for given slip angles, one can notice slight differences between the angle of attack equal zero and its limit values. Having that considered and with the use of appropriate mathematical formulas, one can calculate the drag forces or the lifting force for the entire structure. The obtained result also illustrates how much one would have to increase other parameters, e.g. flight speed, to maintain the horizontal flight conditions.

## Acknowledgements

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Adil Kadyrov - Akbope Karsakova - Bakytzhan Donenbayev - Kyrmyzy Balabekova

# ESTABLISHING THE STRENGTH CHARACTERISTICS OF THE LIFTING-LEVELING DEVICE STRUCTURES OF THE VPO-3-3000 MACHINES FOR THE TRACK STRAIGHTENING

*This article deals with replacement of the magnetic grippers on the VPO-3-3000 machines with roller grippers. The novelty lies in establishment of dependences characterizing stress and strain in elements of the lifting and straightening devices and in rails during the operation. Reliability of the program for calculating the structural parameters of the lifting and straightening device for the VPO-3-3000 track renewal machine is shown. The developed design of the lifting and straightening device makes it possible to select the rational parameters of technology and the operating mode of the device. This design is recommended for use when developing working bodies for the straightening machines. The article presents calculation of the lifting and straightening device structural elements' strength during operation, in the Ansys WB software package.*

***Keywords:*** *railway track, tamping, ballast, roller rail gripper, track repair*

## 1 Introduction

Railway ballast is the railway track foundation that is composed of graded stone ballast. The increasing flow of rail transport may inevitably deform or damage the railway line. In order to ensure the train safety, smoothness and fast running, as well as to extend the service life of various components of the railway track, the maintenance work of the line needs to be done timely to keep the line equipment in good condition [1-3].

At the moment, one of the main areas of resource-saving technologies used in repairing the railway track is the deep cleaning of the gravel ballast layer [4].

The quality of leveling is determined by requirements for the accuracy of positioning a railway track in terms of level, longitudinal section and plan. Quantitative values of these requirements are established and determined by applicable technical regulations [5].

The tamping operation is a continuous cycle process. The cycle itself has five phases: the first phase is that the tamping tines are inserted into the ballast around the sleepers, the second phase is that the tamping tines squeeze the ballast to fill the voids under the sleeper, the third phase is keeping the squeezing, the fourth phase is loosening the squeezing and the fifth phase is that the tamping tines are removed, as well as the tamping tines always maintain the vibration throughout the tamping operation process [6-10].

The dense train schedules, often with intermittent inter-train intervals, make it necessary to carry out track work within short periods of time. Despite this, in the areas of heavy freight or high-speed passenger train circulation, requirements for stability of the rail track parameters and strength characteristics of the track must be observed, which makes it necessary to introduce the latest track-and-field resource-saving technologies.

The degree of the ballast layer consolidation corresponds to its greatest bearing capacity and resistance to a shape change. Information about the degree of the ballast consolidation under sleepers is important because it gives the possibility to evaluate the quality of the repair works, as well as further deformation of the track geometry. As studies show [11-14], a well-consolidated ballast layer after the track repair enables to extend the lifecycle period of the ballasted track and track structures significantly.

In the course of the railway track operation, the ballast is clogged. The pores between the gravel particles are filled with weeds. The simultaneous moistening and contamination of the ballast leads to formation of a kind of grease between the gravels. As a result, the ballast layer loses its bearing capacity.

## 2 Machine park of the Akadyr mechanized distance

In the network of Kazakhstan railways, more than 55 track renewal trains VPO-3-3000, for track straightening and ballast compaction after deep cleaning, are used.

The track renewal machine VPO-3-3000 produced by the Tulazheldormash plant CJSC, is used for all the

**Adil Kadyrov[1], Akbope Karsakova[1], Bakytzhan Donenbayev[1], Kyrmyzy Balabekova[2,*]**
[1]Karaganda State Technical University, Karaganda city, Republic of Kazakhstan
[2]L.N. Gumilyov eurasian national university, Nur-Sultan city, Republic of Kazakhstan
*E-mail of corresponding author: 06_03_92@ mail.ru

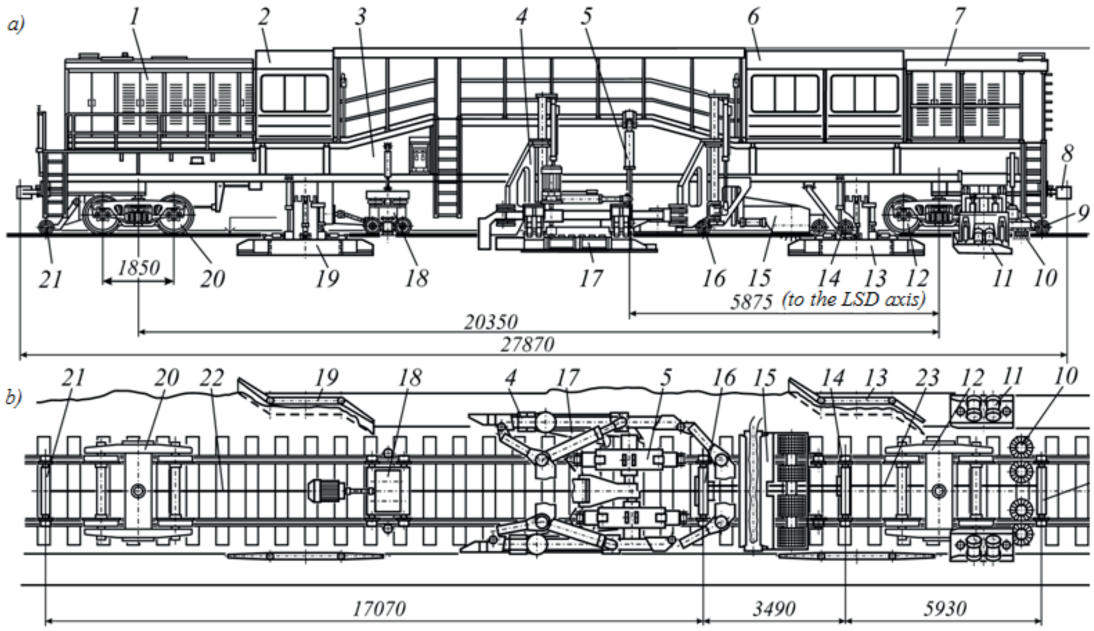



***Figure 1*** *The track renewal machine VPO-3-3000C: 1 - main and additional diesel-electric units of alternating current; 2 and 6 - front and rear control cabins, respectively; 3 - truss; 4 - mechanism for moving (suspension) of vibrating plates; 5 - LSD (lifting and straightening device); 7 - pumping station; 8 - automatic couplings; 9, 14, 16 and 21 - rear, intermediate and front carriages of the CTS, respectively; 10 - active rail brushes; 11 - seals of sloping shoulder and inter-track zones of the ballast; 14 and 20 - rear and front undercarriages (type 18-100) , respectively; 13 - planners; 15 - ballast picker; 17 - main vibro-plates; 18 - working body of the track dynamic stabilization; 19 - dispenser; 22 and 23 - cable chords of the working and control CTS, respectively.*

***Table 1*** *Availability of machines at the Akadyr mechanized distance*

| No. | Name | Amount, pcs. |
|---|---|---|
| 1 | Track renewal finishing machines VPO-3-3000 | 3 |
| 2 | Ballasting machines ELB-4S | 2 |
| 3 | Track renewal trains VPR-1200 | 4 |
| 4 | Straightening machines RB | 2 |
| 5 | Reclamation machines | 3 |
| 6 | Snow removal and snow cleaning machines | 5 |
| 7 | Motor platforms MPD | 12 |
| 8 | Track cranes UK | 7 |
| | Total | 38 machines |

types of track repair including formation, compaction and stabilization of the ballast after deep cleaning of the crushed gravel. The machine is designed to perform a set of final works of technological processes of repair and construction of the track (Figure 1) [15].

At present, a fairly large number of track machines are operated at the Akadyr mechanized distance: availability of the machines is shown in Table 1.

The main economic effect from the operation of the VPO-3-3000 machine is increasing the operating time of sections of the railway track, because the more time it takes to repair the track, the less time it is operated.

The operating time of the VPO-3-3000, as statistics have shown, is reduced due to the unplanned repairs, as well as to scheduled maintenance of machines. This indicates a significant loss of time for repairs within the “window”, disruption of the transportation process and economic losses in all the services (Figure 2).

Electromagnetic grippers used in the VPO-3-3000 machines are unreliable and lead to frequent failures (Figure 3). When the grate is discharged, additional time is required to recharge the working bodies and to eliminate distortions of the grate. As a result, the productivity and accuracy of the grating are reduced.

The discharge of the grating by electromagnetic grippers occurs for several reasons. On the way with the ballast metal inclusions adhere to the magnet. The electromagnetic field is dissipated; the lifting force of the gripper is reduced. It is necessary to clean the space from the ballast in the rail zone.

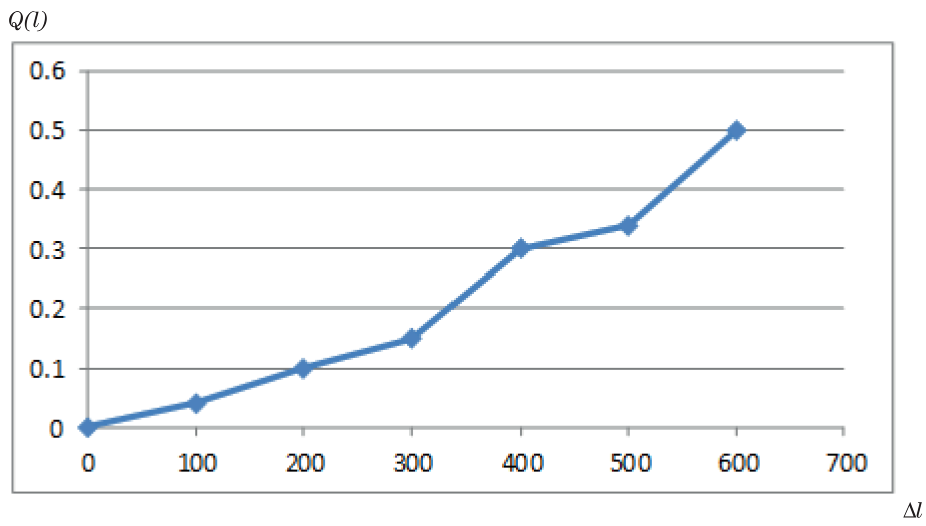



***Figure 2*** *Probability of the electromagnetic grippers failure Q(l) in terms of the operating time Δl, km*


***Figure 3*** *Electromagnetic grippers of the VPO-3-3000 machine*

Analysis of defects in work and technical failures due to track machines VPO-3-3000 shows that it is necessary to upgrade the weak components of the machine.

At the moment, the VPO-3-3000 machines with electromagnetic grippers are operating at the Akadyr machine-station.

To reduce unplanned failures and to increase reliability, in the VPO-3-3000 machines it is proposed to use the roller grippers instead of electromagnetic ones, which simplifies the operation of the machine (Figure 4).

## 3 Calculation and design of rail grips

The gripper design should permit the machine to pass the curved sections of the track and sections with changing gauge without jamming the rollers.

Important criteria for assessing design of the lifting machines are stock ratios for various parameters that determine their tension, deformability, bearing capacity and durability. Increasing the work resources leads to a sharp increase in both duration of the load and number of repetitions (cycles) of loading for some machines. Accumulation of the long-term static and low-cycle damage in the material can lead to premature destruction of mechanisms and machines in general. Strength calculation should be based on the accurate assessment of stresses and strains, taking into account stress concentration, knowledge of material properties under similar loading conditions and use of the modern concepts of damage accumulation.

Studying the spatial stress state became possible in connection with development of the finite element method (FEM) that allows implementing well-developed procedures for solving the elastoplastic problem and the introduction of the CAE systems of sufficiently high efficiency. For this purpose, refined methods of calculation on a computer have been developed.

When designing a lifting machine, the designer relies on his experience, developing a new or modifying the known structure and then carries out a verification calculation for strength. This leads to multiple repetitions of calculations and requires significant costs when selecting the best option. The development of a method for calculating the lifting-straightening device (hereinafter referred to as the LSD), taking into account the working conditions

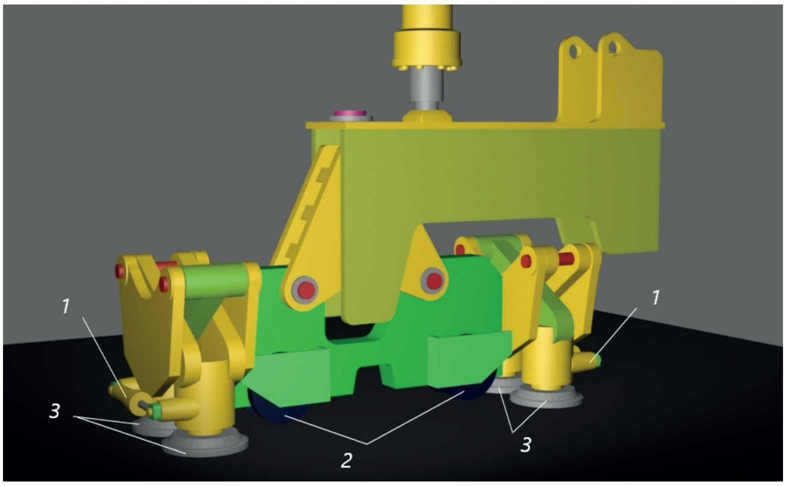



***Figure 4*** *Roller rail gripper: 1 - gripper drive hydraulic cylinder; 2 - straightening roller; 3 - pickup roller*

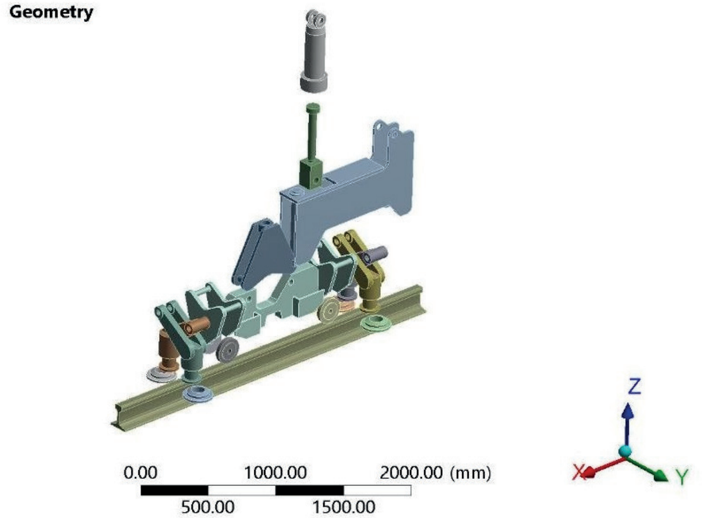



***Figure 5*** *Three-dimensional assembly model of the LLD (lifting-leveling device) design*

and strength requirements, implemented in the form of a computer-aided design system, is an urgent task. Solving this problem allows identifying the relationship of various requirements for strength, stiffness, working parameters of the structure and characteristics of the material with the optimal design. The design is to take into account not only static but also dynamic characteristics of machines, with detuning from critical loads in the operating range. In this regard, it is necessary to calculate initially the structure strength and rigidity.

In assessing strength of the structural elements of the lifting machines' experimental research methods are important. The main ones are testing structural elements at experimental stands. Systems for automatic control of stands allow developing cyclic loads, which makes it possible to study durability of structures. Such tests require additional calculations related to determining the type of loading cycle, the number of cycles, safety factors, etc.

The strength assessment methods, used in scientific and industrial practice, developed based on the numerical and analytical studies, cannot be reliable without any additional experimental studies.

Below there is a calculation of the structural elements strength of the LSD during its operation, in the AnsysWB software package

The AnsysWB analysis system consists of a lot of modules. The StaticStructural module was selected for implementation of this calculation. First, a three-dimensional assembly model of the switchgear design was built in the Component Systems Geometry (DesignModeler) (Figure 5).

The Static Structural project consists of six sections: geometry, materials, coordinate systems, connections, mesh, static structural.

In the geometry section, a three-dimensional (one-dimensional, two-dimensional) model is loaded, in which materials are assigned to each assembly node. In addition, where one can change the type of material, that is, to take a deformable or an absolutely rigid one.

In the materials section one can directly view and change the parameters of the materials.

The coordinate systems item allows setting and adjusting (moving, rotating) the coordinate system by switching the Cartesian and cylindrical coordinate systems.

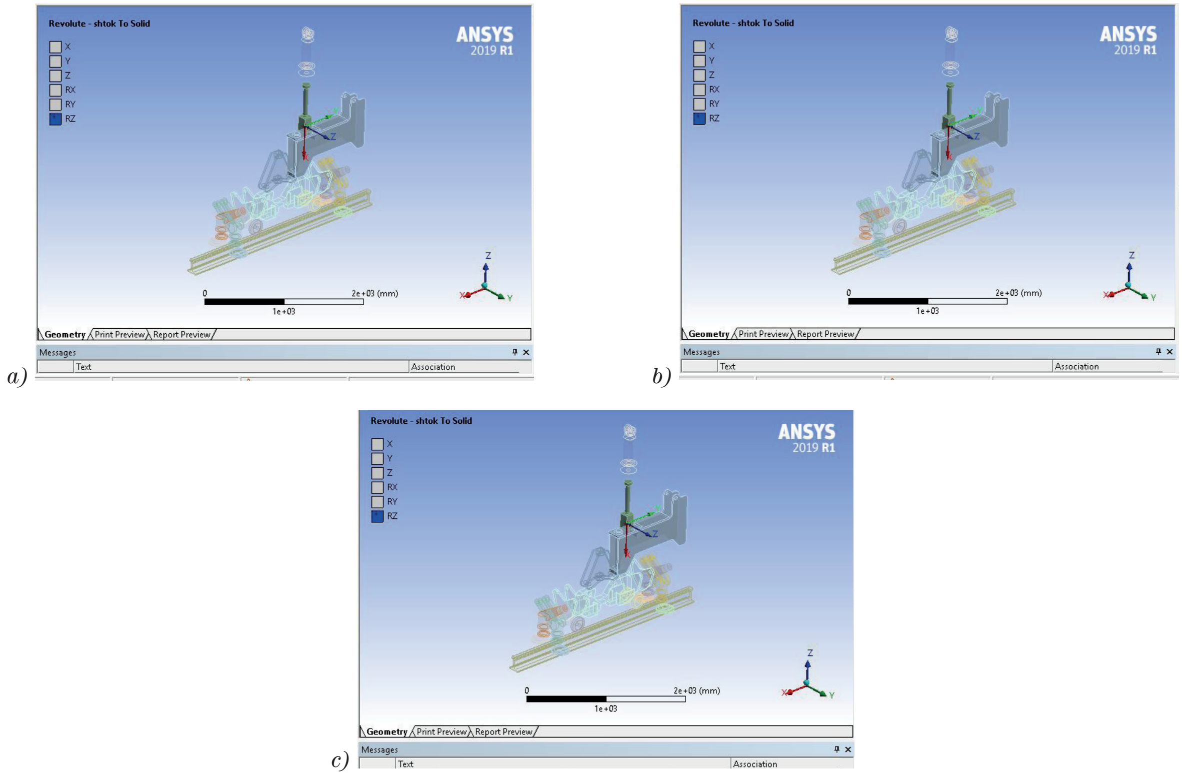



***Figure 6*** *Connections configuration*

The model has contact connections, which lead to solution of a nonlinear problem. All the nonlinear problems have no convergence of the solution. To improve the convergence of calculation, it is necessary to eliminate the motion of loose bodies, that is, before the calculation, it is necessary to ensure that there is a contact between all the parts that must be in contact. This is achieved by moving the bodies, adding a shift on the contact surfaces (contact offset) or using the damping mechanism (stabilization damping), as well as by setting friction on the contacting surfaces.

If there is also no convergence of calculation, then you should reduce the stiffness of the contact elements (smooth application of the load and decrease of the contact pairs stiffness provide solving to 90% of problems with the convergence of the calculation); seal the grid in the contact zone to reduce the proportion of elements in which the contact status changes during the calculation.

Building a three-dimensional model was carried out in the geometry section of this module. Methods of changing coordinates and Boolean operationswere used.

In the connections environment, joint (Figure 6) and contact pairs (contacts) are configured (Figure 7).

The vertical track displacement is a function of foundation system stiffness; therefore, if the displacement is known, then the system parameters (e.g., smeared values representing the entire system) can be back-calculated by using an appropriate foundation model [16].

The connections configuration is performed according to the degrees of freedom nature. Figure 8 w shows the graph of the nonlinear problem convergence.

A simple and widely accepted model for displacement of a railway track at low frequency is a beam on an elastic foundation [17].

The fourth theory of strength is the most often called the Mises criterion. It is based on the following hypothesis: strength of an element in the combination stress state is considered exhausted (i.e., the ultimate stress state occurs) if the specific potential energy of its shape change reaches the limit determined from simple tensile experiments [18]. Results of the strength calculation are given in Table 2.

According to Mises, stress is expressed as:

$$\sigma_{vonMises} = \sqrt{\frac{1}{2}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2]}, \tag{1}$$

where $\sigma_1$, $\sigma_2$, $\sigma_3$ are the principal stresses.

Strength with the n margin is provided under the condition:

$$\frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)}+(\sigma_2-\sigma_3)+\sqrt{(\sigma_3-\sigma_1)}= = \frac{\sigma_{\lim}}{n}=[\sigma]. \tag{2}$$

The condition of strength takes the final form:

$$\sigma_{vonMises} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2} \leq [\sigma], \tag{3}$$

where $[\sigma]=\frac{\sigma_{\lim}}{n}$ is admissible stress.

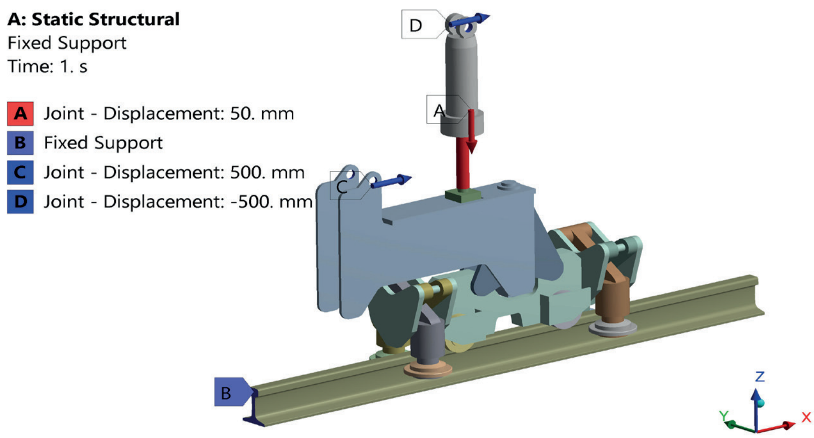



***Figure 7** Boundary conditions of the design*

***Table 2** Results of the strength calculation*

| Parts | Material | Mises stress $\sigma_{vonMises}$, MPa | Admissible stress $\sigma_{adm}$, MPa |
|---|---|---|---|
| R75 rail | M76 | 124 | 900/1.5=600 |
| Bracket arm | 30HGSA | 378 | 400 |
| Right gripper | Steel 45 | 80 | 240 |
| Left gripper | Steel 45 | 117 | 240 |
| Stock | 30HGSA | 252 | 400 |
| Cylinder | 30HGSA | 162 | 400 |
| Support rollers | Steel 45 | 210 | 240 |


***Figure 8** Graph of the nonlinear problem convergence*

The fourth theory of strength, as well as the third one, is well confirmed experimentally, as the theory of the material transition to the plastic state and alongside with the third theory of strength, it is widely used to calculate strength of parts made of plastic materials.

The following boundary conditions were adopted (Figure 7): A is the connection of the rod to the cylinder, in which all the degrees of freedom are limited except for the translational movement along the X axis (red down arrow); B is one end of the rail that is pinched (limited movement in all directions); C and D is a movable cylindrical hinge (there is a single movement and rotation).

Equivalent stresses, arising from operational loads, do not exceed the admissible stress.

Neglecting inertial effects and track roughness, this can be used to model the deflection due to a single static load (Figure 9(a)), a moving load or a train of moving loads (Figure 9(b)) [19].

The static displacement $w$, at a distance $x$ along a beam, with bending stiffness $EI$ on an elastic foundation with a system support modulus (stiffness per unit length) $k$, has the governing equation:

$$EI\frac{d^4 w(x)}{dx^4} + kw(x) = 0\,. \tag{4}$$

The deflection due to a single load $F$ acting at $x = 0$ (Figure 9(a)) has the solution:

$$w(x) = \frac{F}{2kL}e^{-\frac{|x|}{L}} \cdot \left(\cos\left(-\frac{|x|}{L}\right) + \sin\left(-\frac{|x|}{L}\right)\right), \tag{5}$$

where $L$ is a characteristic length:

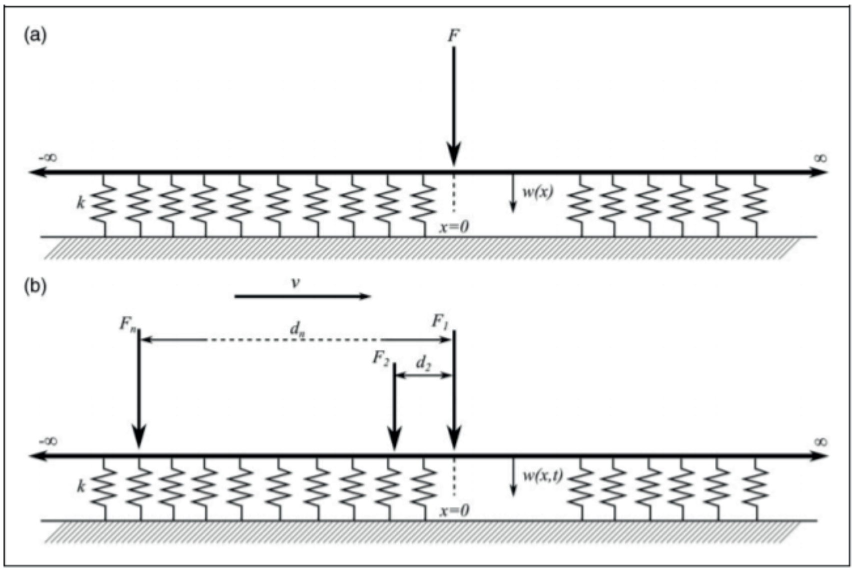



***Figure 9*** *Beam on an elastic foundation subjected to (a) a static point load and (b) a train of moving loads*

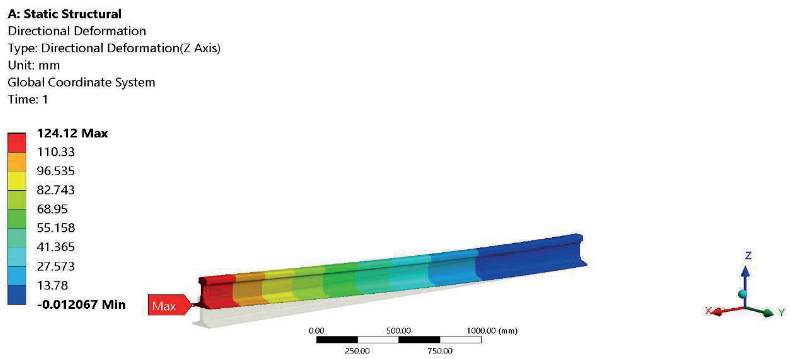



***Figure 10*** *Vertical strain of the R75 rail*

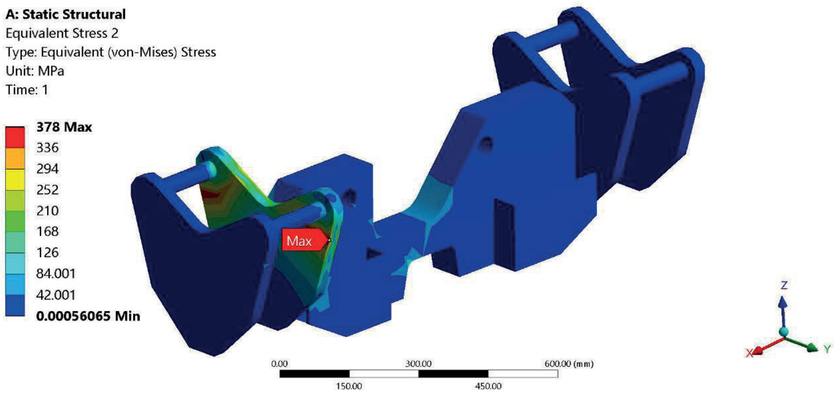
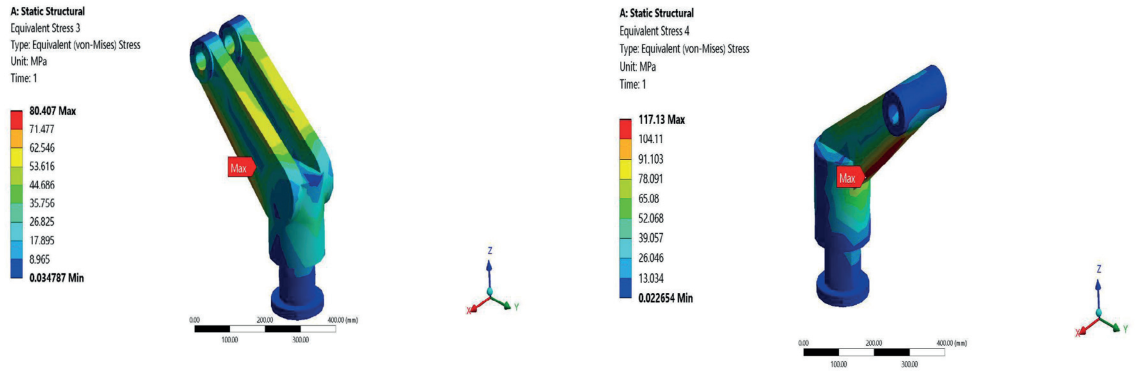



***Figure 11*** *Stress distribution according to Mises*

$$L = \sqrt[4]{\frac{4EI}{k}}. \tag{6}$$

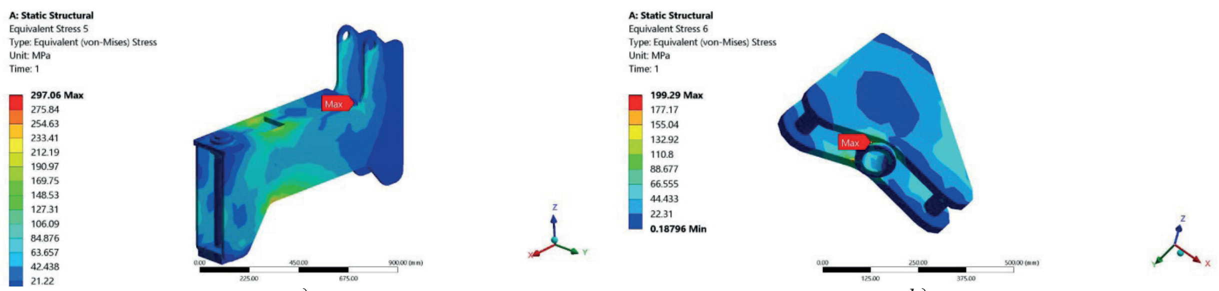
A point on the track, subjected to a load moving at a constant speed $v$, experiences this deflection as a function of time t = $x/v$. The solution for the time-varying displacement of the track at a point, due to a train of moving loads (Figure 9 (b)), each separated from the first load by a distance $x_n$, can be found by summing the effect of each wheel load:

$$w(t) = \sum_n \frac{F}{2kL} e^{-\frac{\left|t - \frac{x_n}{v}\right|}{L}} \cdot \left(\cos\left(-\frac{\left|t - \frac{x_n}{v}\right|}{L}\right) + \sin\left(-\frac{\left|t - \frac{x_n}{v}\right|}{L}\right)\right). \tag{7}$$



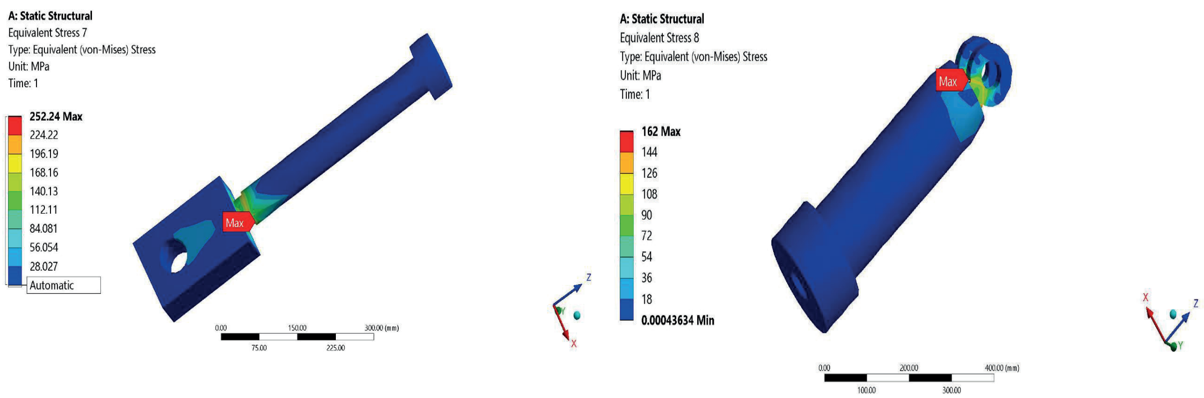

*a)* *b)*

***Figure 12*** *Stress distribution on grippers according to Mises: a) front right gripper; b) front left gripper*




*a)* *b)*

***Figure 13*** *Stresses according to Mises: a) front right gripper; b) front left gripper*




*a)* *b)*

***Figure 14*** *Stress distribution of hydraulic cylinder according to Mises: a) rod; b) cylinder*

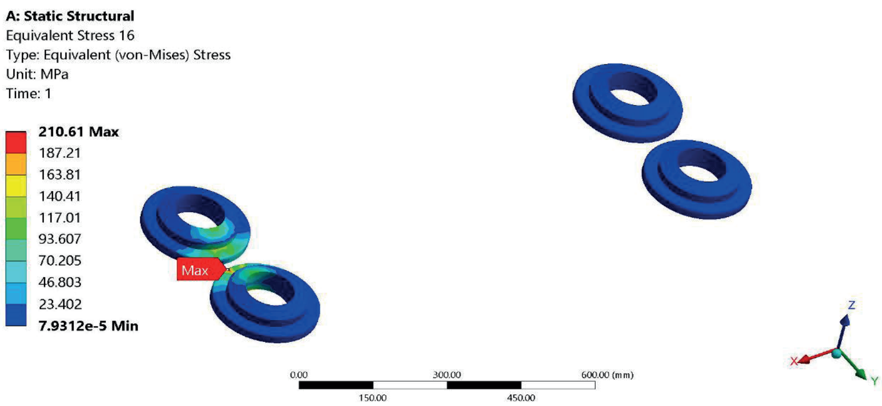



***Figure 15*** *Stress distribution of the support roller according to Mises*

If measurements are made on the sleeper instead of on the rail, the sleeper deflection $w_s$ has the same pattern but with a reduced amplitude that depends on ratio of the rail pad modulus $k_p$ to the total system support modulus $k$

$$w_x = w\left(1 - \frac{k}{k_p}\right). \tag{8}$$

As a result of calculation, the nature of the Mises stress change and strain in elements during the operation of the LSD were obtained.

Figure 10 shows changing the vertical strain of the R75 rail.

From the strain pattern and the strain value indicator, one notes that the vertical strain at the end of the rail was 124 mm, which does not exceed the maximum permissible value.

Then, in Figure 11, one can observe symmetrical stress concentrations of 378 MPa on the grippers enclosing structure, which requires use of a material that provides strength for this design.

Figures 12 a, b show stress distribution according Mises of the most loaded front grippers. In these elements, strength is provided with a margin. On the left gripper, the stress is higher than on the right one.

The largest stress concentrations, according to Mises in Figures 13 a, b, arise due to abrupt transitions in the geometry of elements. This problem is fixed by the geometry adjustment.

Figures 14 a, b show the stress state of the hydraulic cylinder.

The maximum stress concentration in Figure 13 a is explained by a sharp transition.

Figure 15 shows the contact stresses of the support roller.

This stress can be varied by changing the gripping power of the R75 rail. Strength and rigidity of the LSD design are provided.

## 4 Conclusions

1. For the first time, the spatial stress-strain state of a lifting-straightening device has been studied.
2. The numerical and analytical strength assessment, used in scientific and industrial practice, cannot be reliable without any additional experimental studies.
3. Accumulation of the long-term static and low-cycle damage in the material can lead to premature destruction of the machines.
4. Strength and rigidity of the lifting-straightening device is provided overall.
5. The convergence of the nonlinear (contact) problem is achieved by eliminating the motion of loose bodies, reducing the stiffness of the contact elements and by sealing the CEs in the contact zone.

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Barbara Lisiecka - Agata Dudek - Robert Ulewicz

# ATMOSPHERIC PLASMA SPRAYING (APS) AND ALLOYING AS METHODS TO MODIFY PROPERTIES OF THE SSS SURFACE LAYERS

*Use of the powder metallurgy (PM) in production of various components has been growing in the automotive industry, including production of sintered stainless steels (SSSs). This study aims to improve the functional properties of SSSs by formation of the Cr3C2-NiCr coating by APS method. The next stage involved alloying of the surface of SSSs using the gas tungsten arc welding (GTAW). Analysis of microstructures was carried out using microscopy (metallographic microscope and scanning electron microscope). Furthermore, the study presents XRD (X-ray powder diffraction) examinations, mechanical properties and surface roughness measurements. The presented modification improved properties of the surface layers examined in the study and enabled a reduction in the wall thickness of the detail, which is important factor in the automotive and transport industry.*

***Keywords:*** *(SSS) steel, Cr3C2-NiCr coating, APS, GTAW, surface layer alloying*

## 1 Introduction

Due to the wear observed during use, the surface of the solid body has been a subject of the frequent tests. This surface can be repeatedly modified in physical and chemical terms, which results in obtaining the desired functional properties that are better than the properties of the native material [1-3]. The surface layer alone plays mostly a technical role. It has to show very high requirements for increased durability of consumable machine parts and tools designed and intended for operation in the conditions of friction and fatigue. Appropriate surface modification has a significant impact on functional properties (e.g. significant extension of the durability of tools, machine parts and devices, especially in terms of tribological properties) and the final use of objects and finished products [4-6]. Duplex steels are increasingly used in the automotive industry for catalyst housing components, turbochargers and rotors [7]. They are also susceptible to automation of production processes [8].

The coating application and surface treatments have been among the methods that are the most commonly used to improve the surface properties of SSSs. The creation of the coating increases, among others, the surface resistance to oxidation or abrasion. The mechanical properties of the coating, e.g. interfacial adhesion and fracture behaviours, can be criteria when choosing a coating for a given application [7-11]. Creation of the transition metal carbides based coatings is a very interesting and well-known modification. Transition metal carbides are characterized by a very high melting point, hardness and strength at high temperatures. Furthermore, they show improved properties related to electrical and thermal conductivity, which ensures that they are widely used in metallurgy. Due to their high strength at high temperatures compared to other carbides, chromium carbides are the most often used in surface modification [12-15].

Chromium carbides can occur in three polymorphic structures: cubic ($Cr_{23}C_6$), hexagonal ($Cr_7C_3$) and orthorhombic ($Cr_3C_2$). Considering the appropriate adhesion to the substrate and the best mechanical properties (e.g. higher hardness, wear resistance and strength, high melting point, high elastic modulus, great chemical corrosion resistance), chromium carbide ($Cr_3C_2$) is the most frequently chosen for the surface modification through deposition of coatings. Nowadays, chromium carbide coatings have been known to improve resistance to high-temperature oxidation (up to 750°C) and prevent the coating properties from deterioration, which is related to formation of the $Cr_2O_3$ layer on its surface [16-17]. Thermal spraying of $Cr_3C_2$-NiCr is successfully used for protecting and modification of the surface in the aerospace, automobile or energy sectors. Among the methods used to obtain the $Cr_3C_2$-NiCr coatings are such methods like electron beam physical vapour deposition (EB-PVD), atmospheric plasma spraying (APS) and high-velocity oxy-fuel (HVOF) [18-21].

Atmospheric plasma spraying (APS) continues to attract much interest and is successfully used to deposit chromium carbide coatings. As is known, the deposition of powders as dense and homogeneous coatings is possible using the thermal spraying using the APS method. In this process, the powder of $Cr_3C_2$-NiCr is introduced into the plasma jet and heated to a molten state. Then, the heated material is propelled towards a native material. The result

**Barbara Lisiecka[1,*], Agata Dudek[1], Robert Ulewicz[2]**
[1]Department of Material Engineering, Faculty of Production Engineering and Materials Technology, Czestochowa University of Technology, Poland
[2]Department of Production Engineering and Safety, Faculty of Management, Czestochowa University of Technology, Poland
*E-mail of corresponding author: lisiecka.barbara@wip.pcz.pl

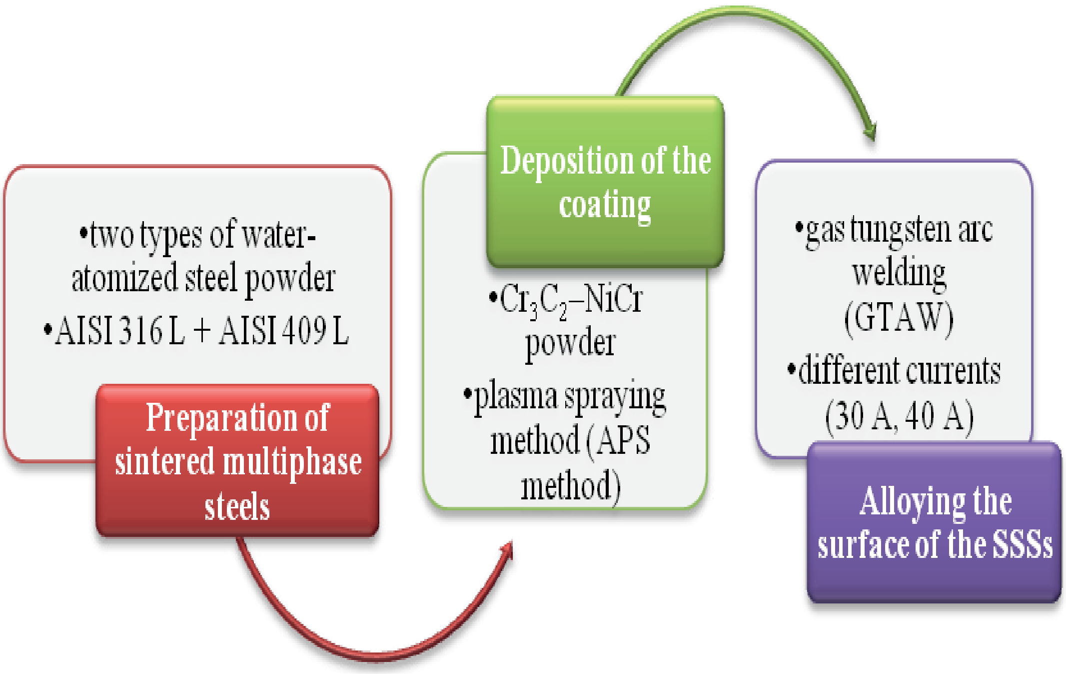


***Figure 1*** *The purpose of research*

***Table 1*** *Elements contained in powders studied (% wt.)*

| Powder grade | Cr | Ni | Mo | Si | Mn | C | S | Fe |
|---|---|---|---|---|---|---|---|---|
| AISI 316L | 16.80 | 12.00 | 2.00 | 0.90 | 0.10 | 0.022 | 0.005 | Balance |
| AISI 409L | 11.86 | 0.14 | 0.02 | 0.82 | 0.14 | 0.020 | 0.010 | Balance |

***Table 2*** *Proportion of individual powders used to make the series of samples (% wt.)*

| Series of samples | Powder grade | |
|---|---|---|
| | AISI 316L | AISI 409L |
| 1 | 80% | 20% |
| 2 | 50% | 50% |
| 3 | 20% | 80% |

***Table 3*** *Sinters forming parameters*

| Parameters | Description/values |
|---|---|
| Compact | uniaxially |
| Lubricant | 1% Acrawax C |
| Pressing pressure | 720 MPa |
| Sintering temperature | 1250°C |
| Sintering time | 30 minutes |
| Cooling rate | 0.5°C/s |

is a coating formed from adhering powder particles. The metallurgical properties do not change after the deposition of the coating (no regular heating). Plasma spray coatings are extremely interesting in terms of their capability of giving specific properties (e.g. porosity, roughness)[22-27].

The welding techniques that are based on concentrated thermal energy are increasingly used to modify the surface of the SSSs. One of the most widespread and interesting methods in surface processing with alloys are laser technologies. As laser technologies are expensive, alternative technologies are increasingly being sought. The GTAW method offers a great alternative here, and it is very commonly used to modify surface layers, including the SSSs surfaces described here. The GTAW method is easy to use and is characterized by a low cost equipment. Furthermore, use of the GTAW method allows the functional properties of the surface to be modified [28-32].

***Table 4** APS process parameters*

| Parameters | Ranges |
|---|---|
| Voltage ($U_r$) | 50 (V) |
| Current intensity ($I_r$) | 45 (A) |
| Spray distance | 120 (mm) |
| Primary plasma gas Ar | ~ 45 (l/min) |
| Secondary plasma gas $H_2$ | ~ 12 (l/min) |

***Table 5** X-ray diffractometer parameters*

| Parameters | Ranges |
|---|---|
| Angle range (2θ) | 10-120° |
| Tube voltage ($U_r$) | 40 (kV) |
| Tube current ($I_r$) | 40 (mA) |
| Step-scan mode | 0.1° |
| Step size | 0.1° |
| Pulse integration time ($t_r$) | 10 (s) |

The authors of the present study proposed to improve functional properties, mainly hardness and wear resistance. Several modifications were made and the purpose of the research is shown in Figure 1.

## 2 Experimental

Preparation of the multiphase sinters, used for examinations, was described in detail in the paper [33]. Table 1 shows the contents of individual elements in the powders used to obtain sinters. The nominal particle size of both powders is 130-150 µm.

Three different sinters were used in examinations, formed by mixing the two powders in different proportions (i.e. austenite and ferrite). Three series of samples were obtained (see Table 2).

Table 3 presents parameters affecting the production of sintered samples. To reduce oxidation of the batch and to protect it from a decline in chromium concentration, the process was performed in the reduction atmosphere using 100% hydrogen.

The next stage of examinations consisted of modification of the surface layer by deposition of a coating using the plasma spraying (APS method). To improve the functional properties of the analysed steels, it was decided to deposit a chromium carbide coating. To prepare a suitable powder mixture for the coating, the chromium carbide was mixed mechanically, at a ratio of 75% wt. $Cr_3C_2$ and 25% wt. NiCr. Table 4 presents parameters of the coating spraying process. A 60 µm coating was obtained as a result of the modifications.

Gas tungsten arc welding (GTAW) has been used for surface layer treatment, used for the coatings of sintered stainless steels. Alloying of sintered stainless steels was performed at a constant surface scanning rate of 340 mm/min and welding at a current intensity of 30 A and 40 A and voltage parameters. Argon was used in the process as a shielding gas. Its flow rate was set at ~ 14 l/min.

The stereo microscope Olympus SZ61 has been used for the macroscopic evaluation of sintered stainless steels after application of $Cr_3C_2$-NiCr powder and after the surface alloying process. Analysis of the microstructure was performed using microscopy (i.e. an Olympus GX41 metallographic microscope and a JSM-6610LV scanning electron microscope Jeol). Analysis of the chemical composition was carried out using a Jeol JSM-6610LV scanning electron microscope. The microhardness measurements for the SSSs were carried out using the Vickers method under a load of 980.7 mN.

The X-ray Seifert 3003 T-T diffractometer, with a cobalt lamp $\lambda_{cok\alpha}$ = 0.17902 nm, was used for identification of the phase composition of the alloyed surface of specimens. All the measurement parameters are presented in Table 5.

A Hommel T1000 contact profilometer was used to evaluate roughness parameters ($R_a$, $R_z$, $R_{max}$) on the surface of samples. Three measurements were made, with each measurement consisting of the contact of a stylus with the analysed surface, using a differential measuring system.

The scratch resistance test (Revetest XPress Plus with Rockwell indenter) was used to evaluate the coefficient of friction. Measurements consisted of the mechanically induced damage to the surface obtained by scratching. A constant load of 10N, scratch length of 5 mm and the scratch velocity of 5 mm/min were used. The main purpose of the scratch test was to determine the relationship between the direction of the scratch and the surface orientation depending on the penetration depth and to evaluate the coefficient of friction.

## 3 Results and discussion

The $Cr_3C_2$-NiCr powder used for spraying and deposition of the coating is shown in Figure 2.

Figure 3 presents the microstructure of the surface of the coating (before the alloying process) recorded using scanning electron microscopy.

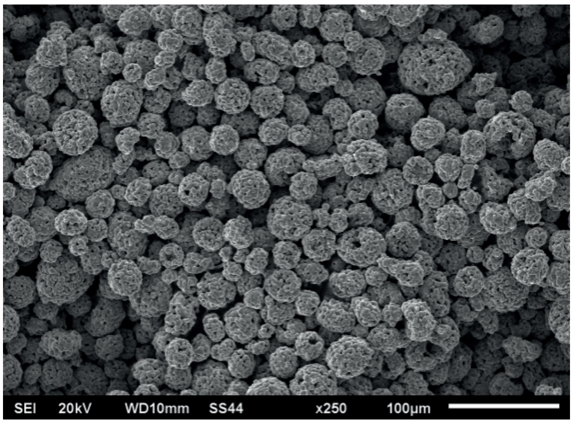


***Figure 2*** *Grains of the $Cr_3C_2$-NiCr powder*

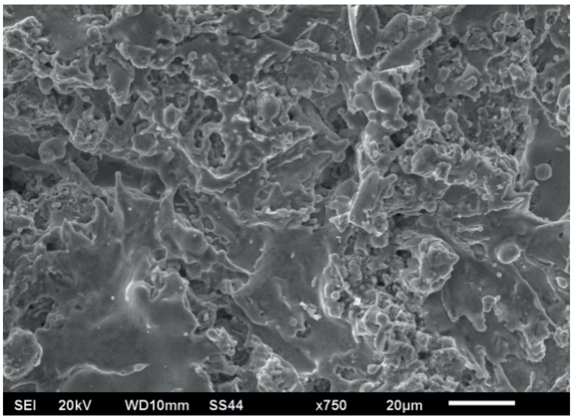


***Figure 3*** *SEM image of the coating deposited on SSS after APS*

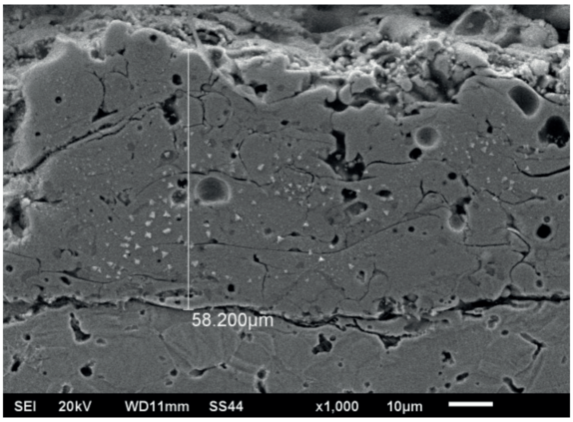


***Figure 4*** *SEM image of the coating after APS*

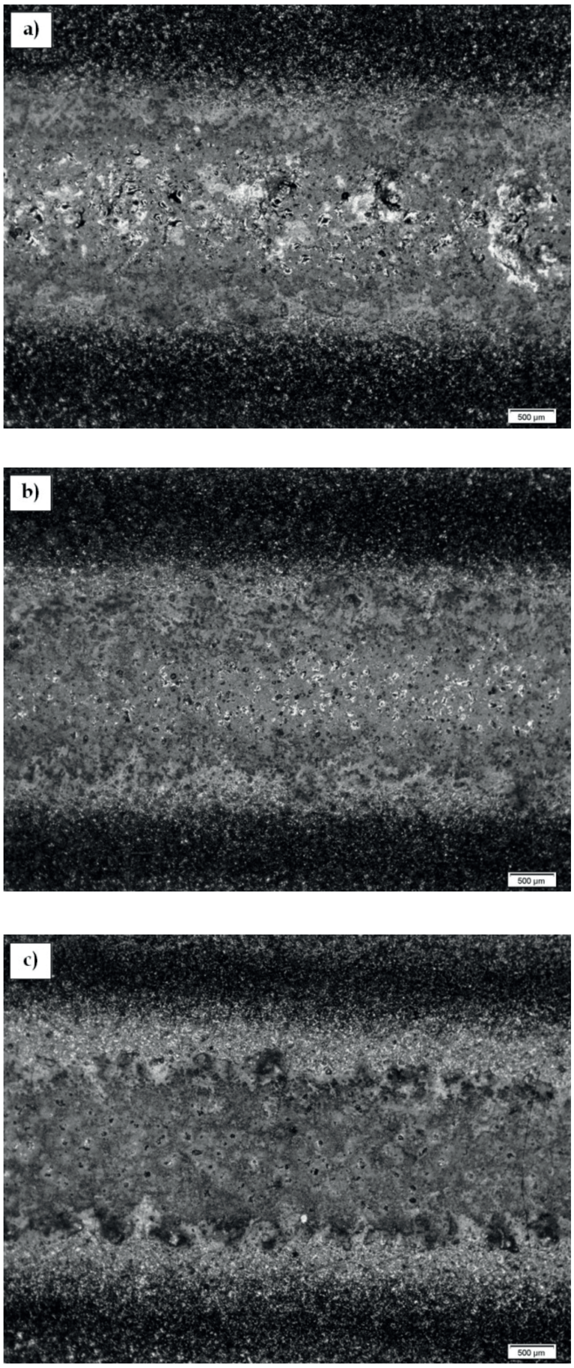


***Figure 5*** *Images of the surface of the SSSs after alloying at 30 A for samples: a) 1, b) 2, c) 3*

The cross-section of the $Cr_3C_2$-NiCr coating obtained using the scanning electron microscope is presented in Figure 4. Thickness of the obtained $Cr_3C_2$-NiCr coating was also marked (cca. 60 μm).

The resulting $Cr_3C_2$-NiCr coating is characterized by structural elements that are typical for this deposition method (APS). This coating exhibits a porous lamellar structure with visible cracks and particles that have not melted.

After the surface treatment, the macroscopic examinations were performed to assess the effect of alloying on quality of the steel surface. The main criteria of evaluation were the continuity of the band, similar width and a relatively smooth surface that did not contain any craters. Figure 5 presents images of the surface after alloying of the SSSs at current intensity 30 A obtained using an Olympus SZ61 microscope.

The metallographic sections were prepared by etching with a mixture of nitric acid and hydrochloric acid (i.e. aqua regia). Figure 6 shows an image of the microstructure obtained for sample 1 after the surface alloying at 40 A using the metallographic microscope Olympus GX41.

The microstructure analysis confirmed the presence of a homogeneous cellular-dendritic structure resulting

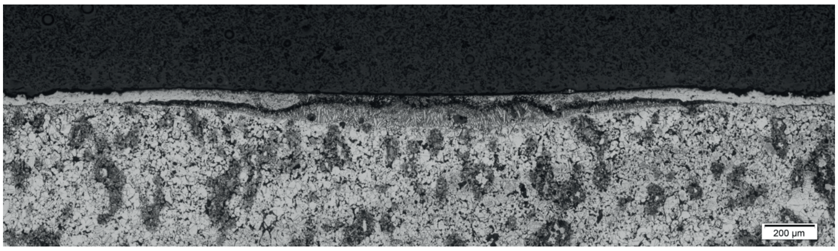

*Figure 6* Cross-section of the alloyed zone (sample 1 afteralloying at 40 A)

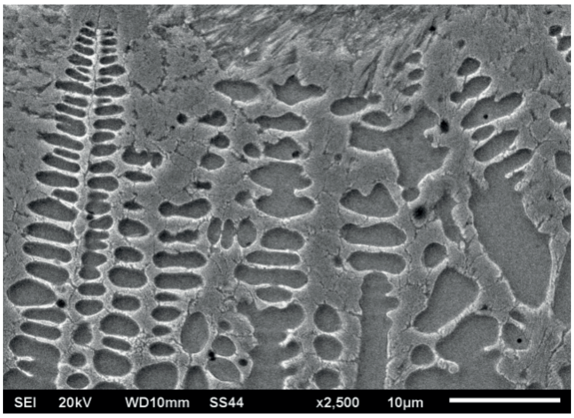


*Figure 7* Image showing the alloyed zone (sample 2 after alloying 40 A)

***Table 6*** *EDX-analysis after alloying at a current intensity of 30 A (AZ-alloying zone, HAZ- heat affected zone, NM-native material)*

| Series of samples | Element | Weight (%) | | |
|---|---|---|---|---|
| | | AZ | HAZ | NM |
| 1 | Cr | 48.27 | 22.22 | 17.26 |
| | Ni | 6.97 | 8.33 | 11.87 |
| | Mo | 1.47 | 2.41 | 2.27 |
| | Fe | 29.05 | 53.34 | 67.78 |
| | Si | 0.38 | 0.58 | 0.83 |
| | C | 13.49 | 13.12 | - |
| 2 | Cr | 32.09 | 20.45 | 14.86 |
| | Ni | 8.00 | 7.55 | 5.43 |
| | Mo | 1.22 | 0.69 | 0.95 |
| | Fe | 46.29 | 65.79 | 77.24 |
| | Si | 0.52 | 0.79 | 1.52 |
| | C | 11.89 | 4.72 | - |
| 3 | Cr | 74.94 | 28.52 | 15.26 |
| | Ni | 6.43 | 7.48 | 5.82 |
| | Mo | - | 0.46 | 1.38 |
| | Fe | 8.66 | 55.70 | 76.87 |
| | Si | - | 0.64 | 0.69 |
| | C | 9.96 | 7.19 | - |

from the alloying process. The crystalline columns, arranged along the heat exchange direction, were observed. Contact of a layer after the alloying with the core material led to formation of a transient zone, in which nucleation and an increase in the primary structure crystals were observed.

Figure 7 presents an example of a microstructure that was obtained by the surface alloying for the SSSs. Observations were made using a scanning electron microscope.

Table 6 presents the chemical composition for the surface layers in the SSSs after alloying at a current

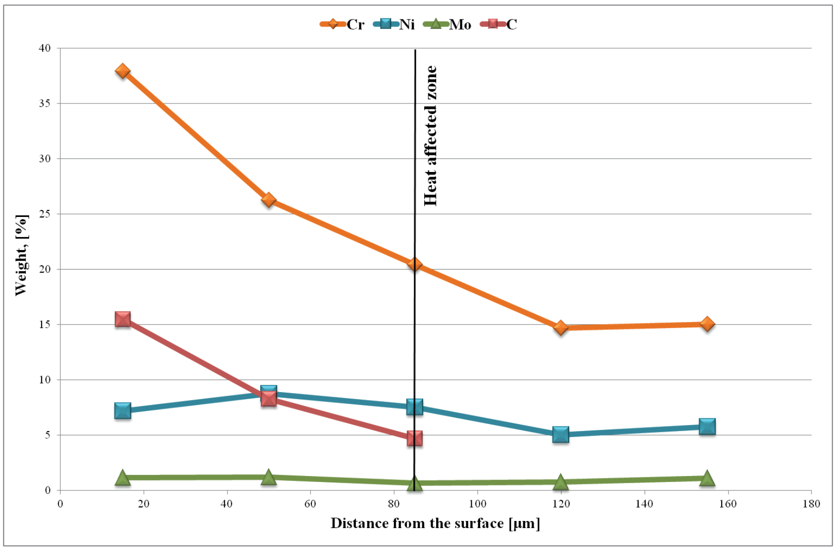


***Figure 8*** *Linear chemical composition analysis for sample 2 after alloying at current intensity 30 A*

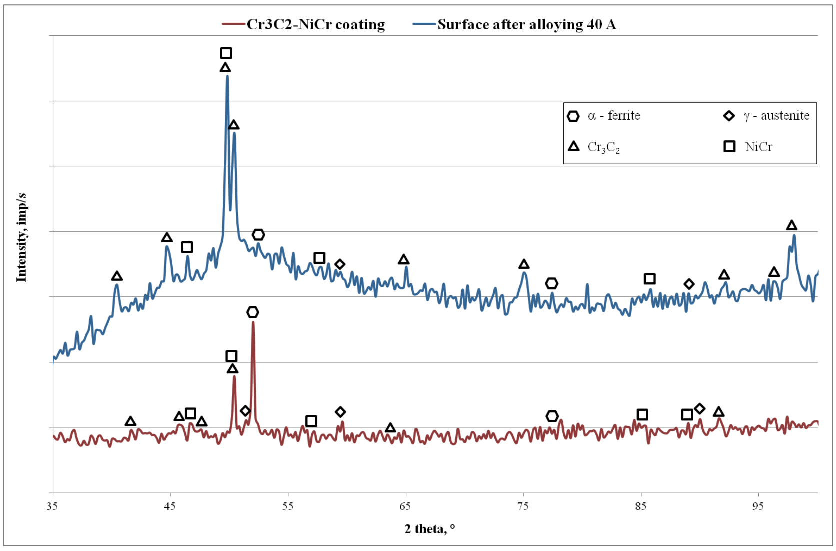


***Figure 9*** *Diffractograms of sample 3 with $Cr_3C_2$-NiCr coating after alloying (40 A)*

intensity of 30 A using the GTAW method. The main purpose of this analysis was to compare the presence of selected elements in the areas studied after the surface treatment. Analysis allowed for determination of the migrating alloying elements and thus observation of diffusion occurring in the alloying process. Furthermore, homogeneity of the chemical composition was determined in the obtained surface layers. Analysis of changes in the content of elements showed migration of the diffusing elements (i.e. chromium, nickel). Diffusion occurred between the ferritic and austenitic phases. An intermediate zone was formed as a result of nickel dispersion in austenite. All the samples used in the study showed different contents of the alloying elements.

Figure 8 shows results of the linear analysis of the chemical composition for sample 2 after the GTAW alloying at a current intensity of 30 A. Linear chemical analysis was carried out so that it was possible to present distribution of selected elements vs. distance from the surface, taking into account the modified alloy zone, heat-affected zone and native material. Diffusion of chromium to ferrite and nickel to austenite was confirmed. Consequently, formation of the phase transformations on the boundary of the analysed areas was observed.

The X-ray phase analysis was performed to identify the phase composition on the alloyed surface layer. Figure 9 presents identification of the phase composition for sample 3 with a $Cr_3C_2$-NiCr coating and after the alloying process (40A). The phase analysis for individual specimens revealed the presence of austenitic and ferritic phases, which was proportional to the contents of the powders used.

Phases, obtained during the phase composition analysis of the SSSs, are shown in Table 7. The peak intensities obtained on the diffractogram depend on the content of individual phases in the SSSs.

To analyse the geometric structure, profilometric tests were carried out and the profiles, yielding roughness parameters of steel surface layers, were obtained. Table

***Table 7** Results of the phase composition analysis*

| Phases | Cell | Cell parameters |
|---|---|---|
| $Cr_3C_2$ | orthorhombic | a = 0.55 nm, b = 1.14 nm, c = 0.28 nm, $\alpha = \beta = \gamma = 90°$ |
| NiCr | cubic | a = b = c = 0.45 nm, $\alpha = \beta = \gamma = 90°$ |
| $\alpha$ - ferritic | cubic | a = b = c = 0.28 nm, $\alpha = \beta = \gamma = 90°$ |
| $\gamma$ - austenite | cubic | a = b = c = 0.35 nm, $\alpha = \beta = \gamma = 90°$ |

***Table 8** Roughness parameters of the analysed samples*

| Series of samples | Current intensity (A) | Roughness parameter [µm] | | |
|---|---|---|---|---|
| | | $R_a$ | $R_z$ | $R_{max}$ |
| $Cr_3C_2$-NiCr coating | | 4.79 ± 0.45 | 27.35 ± 3.35 | 32.28 ± 0.48 |
| 1 | 30 | 3.73 ± 0.01 | 22.94 ± 0.51 | 31.98 ± 0.31 |
| | 40 | 3.51 ± 0.28 | 20.93 ± 0.09 | 30.29 ± 0.47 |
| 2 | 30 | 3.95 ± 0.19 | 22.24 ± 0.71 | 31.12 ± 0.62 |
| | 40 | 3.73 ± 0.18 | 22.45 ± 0.38 | 33.06 ± 0.80 |
| 3 | 30 | 3.78 ± 0.29 | 21.60 ± 0.70 | 28.92 ± 0.34 |
| | 40 | 3.40 ± 0.37 | 24.88 ± 0.06 | 36.06 ± 0.55 |

***Table 9** Hardness measurements of specimens (AZ - alloying zone, HAZ - heat affected zone, NM - native material)*

| Series of samples | Current intensity (A) | Hardness (HV 0.1) | | |
|---|---|---|---|---|
| | | AZ | HAZ | NM |
| 1 | 30 | 283.67 ± 0.98 | 231.00 ± 0.10 | 128.67 ± 0.62 |
| | 40 | 347.00 ± 0.05 | 226.33 ± 0.33 | |
| 2 | 30 | 388.00 ± 0.30 | 272.00 ± 0.33 | 138.00 ± 0.82 |
| | 40 | 443.00 ± 0.28 | 277.00 ± 0.31 | |
| 3 | 30 | 686.50 ± 0.50 | 453.00 ± 0.01 | 142.00 ± 0.00 |
| | 40 | 602.00 ± 0.02 | 354.00 ± 0.12 | |
| $Cr_3C_2$-NiCr coating | | | 1065.67 ± 0.71 | |

8 illustrates the roughness parameters for the $Cr_3C_2$-NiCr coating and surface of the SSSs after alloying. The following parameters were selected for analysis: $R_a$, $R_z$ and $R_{max}$.

Considering the first stage of modification, i.e. deposition of the $Cr_3C_2$-NiCr coating, the roughness parameter on the surface of sinters was measured ($R_a$ = 4.79 µm). Application of the GTAW method for the alloying surface treatment led to improvement in roughness. The parameters obtained (e.g. $R_a$, $R_z$ and $R_{max}$) are lower than before the modifications. Along with an increase in the current intensity, the sintered surface was smoothed (lower values of $R_a$). This is associated with the linear energy of the arc applied to the steel surface during the alloying.

Mechanical properties were evaluated based on hardness measurements by the Vickers method. Table 9 presents hardness of the $Cr_3C_2$-NiCr coating, alloying zone, heat-affected zone and native material obtained after alloying at different current intensities. Three measurements were performed, and their means are shown in the table below.

The proposed modification with the $Cr_3C_2$-NiCr coating and GTAW alloying led to homogenization of the microstructure, as confirmed by the hardness tests. Contents of individual phases had a direct effect on the mechanical properties of sinters. Formation of the $Cr_3C_2$-NiCr coating dramatically improves the strength properties of the SSSs. Furthermore, analysis of hardness revealed that the GTAW method led to improvement in mechanical properties of the samples.

The scratch test under the constant load was conducted to determine the coefficient of friction (COF) and wear resistance. Table 10 shows the friction coefficients for the SSSs, as obtained during the scratch test. Figure 10 shows a diagram of the normal load and friction for sample 1 after alloying (at 40 A) obtained after the scratch test.

Resistance to friction depends on many factors. Scratch tests confirmed that the applied surface treatment reduces the coefficient of friction of sintered steels (SSS) modified with chromium carbide. This coefficient depends on the current-voltage parameters used during the remelting.

***Table 10** Coefficients of friction for the analysed samples (AZ - alloying zone, NM - native material)*

| Series of samples | Current intensity (A) | Coefficient of friction | |
|---|---|---|---|
| | | AZ | NM |
| 1 | 30 | 0.18 | 0.14 |
| | 40 | 0.14 | |
| 2 | 30 | 0.15 | 0.13 |
| | 40 | 0.12 | |
| 3 | 30 | 0.17 | 0.15 |
| | 40 | 0.14 | |
| $Cr_3C_2$-NiCr coating | | 0.30 | |

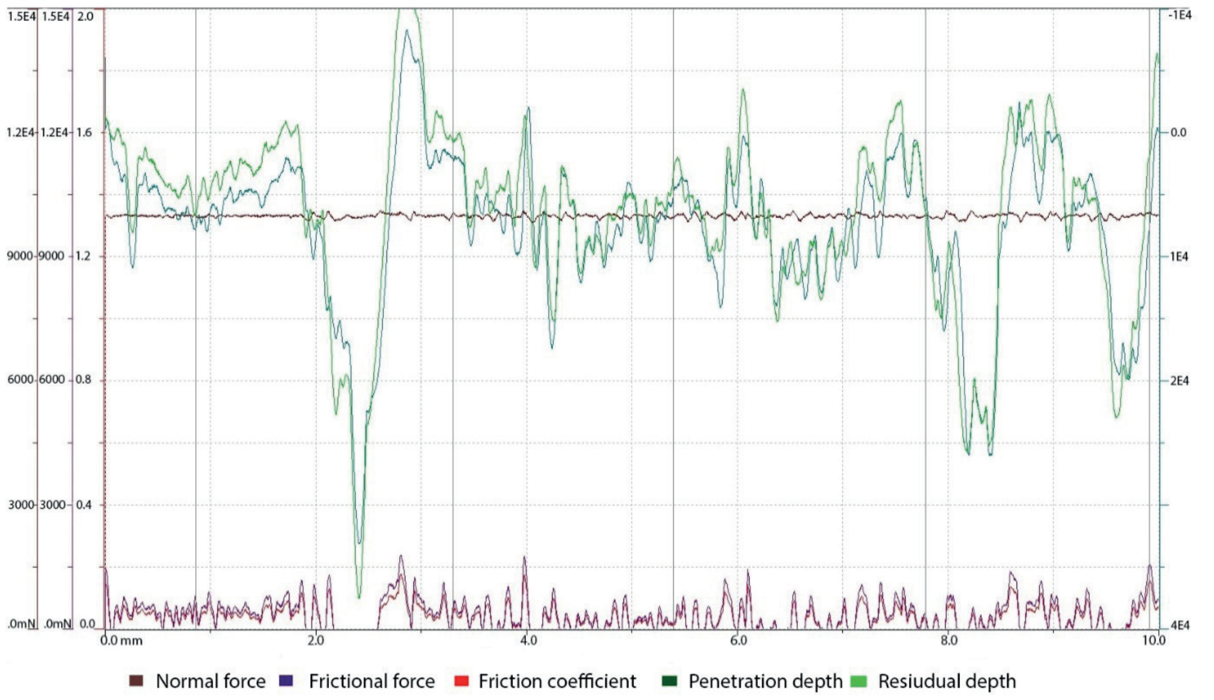


***Figure 10** The effect of alloying (40A) on coefficient of friction for sample 1*

Based on results, it can be concluded that the greater the resistance to abrasive wear, the lower the coefficient of friction. The method of surface modification, discussed in the present study, allowed for improvement of the mechanical properties of the samples studied.

## 4 Conclusions

Sintered stainless steels are mainly used in the automotive industry, which is open to new material solutions to meet the growing needs and expectations of customers, e.g. in reducing mass of details, especially in electric cars [34]. This is followed by proposals of material engineers aimed to continuously modify and improve the materials used. Modification of the surface layer of the SSSs, proposed in this paper, represents a proposal to apply the two-stage surface treatment (spraying and remelting) to improve the functional properties of the parts. The authors of the paper proposed the modification of the surface of the sintered two-phase steels (AISI 316L and AISI 409L) by introducing $Cr_3C_2$ carbide into the surface layer of steel. The most important problem was to choose melting parameters to ensure the change in the physical and chemical properties of the steel surface. Results presented in this study are part of advanced research conducted by the authors [6, 12, 26, 31, 33].

Alloying the surfaces of sintered stainless steels yielded a gradual change in the chemical composition of the surface layer vs. distance from the surface of the modified materials. The depth of the modified zone was on average 100 µm for samples remelted at 30A and 130 µm for those remelted at 40A. The change in the chemical composition and internal stresses that occur in the remelted material resulted in improved strength properties expressed in hardness (a twofold increase in hardness of the modified layer was obtained compared to the unmodified material). Use of the concentrated energy source (GTAW method) and appropriate choice of melting parameters resulted in reduction in the specific surface area of steel compared to the $Cr_3C_2$ coating. This result is very important from the standpoint of abrasive wear resistance and corrosion resistance of these materials. An increase in abrasive wear resistance of the modified steels was confirmed by the analysis of the coefficient of friction (during the scratch test). As the current-voltage parameters, used in the remelting process, increased, the coefficient of friction decreased compared to the coefficient of friction of the carbide coating, which can be associated with a change in chemical composition and hardness of the modified layer.

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Norbert Radek - Renata Dwornicka

# FIRE PROPERTIES OF INTUMESCENT COATING SYSTEMS FOR THE ROLLING STOCK

*This paper presents results of the experimental research aimed at fire and smoke properties of rolling stock coating system. The overriding research task was to meet current European requirements in the field of fire properties with maintaining the desired performance parameters, such as protective and decorative properties. The research determined parameters such as flame spreading over the surface and heat emission of coating system prepared on steel substrate. Research was carried out to find the optimum thickness of intumescent layer. The tests have shown the effectiveness of use of a protective paint that allows meeting the requirements in the field of fire safety.*

***Keywords:*** *fire properties, flame propagation, heat emission, smoke properties, intumescent paint*

## 1 Introduction

Coating systems for the rolling stock must fulfill mechanical, protective and decorative properties maintenance longer on the vehicle. These requirements include: adhesion, abrasion resistance, hardness, chemical resistance, resistance to weather conditions (humidity, UV, corrosion). Coating systems intended for the rolling stock in addition to the above-mentioned requirements, as well as ease of application, must also have adequate fire performance [1-3]. Strong emphasis on safety in railway transport caused intensive development of requirements and methods in this area and as a consequence contributed to development of materials and products. There was a research to develop new and modify existing materials used in rail vehicles, which reduce the risk of people being threatened and improve the overall safety. Table 1 presents requirements for the coating systems of the rolling stock, both inside (R1) and outside (R7). The coating systems for rail vehicles must meet as the minimum, the requirements specified by the HL2 hazard. An important effect of the existing fire (posing a deadly threat to passengers and impeding evacuation) is the spread of flame on the surface as a result of the combustion of materials used on railway vehicles [4]. The most important element of effective fire protection is use of the fire-resistant materials limiting the spread of fire and smoke in the rolling stock. However, values of the specified parameters CFE and MARHE were significantly different from the admissible criteria. Therefore, an intumescent layer was introduced into the system in order to limit the impact of the ignition source operation on the lower layers, especially on the putty. The effect of thickness of the intumescent layer on the fire and smoke properties of the entire system was determined.

## 2 Experimental procedures

All the tested coatings were applied to 1 mm thick S355 carbon steel plates with a SATA spray gun; prior to application the surface of steel was polished with 80-grit sandpaper. Coating systems consist of the following layers: anti-corrosion epoxy primer, putty, primer filler, basecoat and anti-graffiti clear coats BO100-AGR. Each layer is applied and dried in accordance with requirements of the technological cards. The prepared samples were conditioned at 23 °C and 50% humidity for minimum 7 days in order to perform tests on dry coating. The thickest layer in the coating systems, applied to the external walls of rail vehicles is a putty. The above results from the desire to hide all inequalities and obtain the maximum flatness of the painted surface of the vehicle body shells.

To assess the fire resistance, these fire parameters were selected that characterize the material's resistance to external fire sources, i.e.:

1) CFE - Critical Flux at Extinguishment, kW/m$^2$ (the lower its value, the greater the fire hazard) according to ISO 5658-2 [6] (Figure 1).
2) The side flame spread test was performed by exposure of a vertically arranged sample to external heat flux with a standardized density distribution (50 kW/m$^2$). At the end of the test, the length of the burned part of the sample is determined and entered into the program to calculate the Critical Flux at Extinguishment CFE [kW/m$^2$] by the control program.

MARHE - maximum average rate of heat release kW/m$^2$ - (the higher its value, the greater the fire hazard), according to ISO 5660-1 [7] (Figure 2).

Measurements of maximum heat generated were made using a conical calorimeter using the oxygen consumption

**Norbert Radek[1,*], Renata Dwornicka[2]**
[1]Faculty of Mechatronics and Mechanical Engineering, Kielce University of Technology, Poland
[2]Institute of Applied Informatics, Faculty of Mechanical Engineering, Cracow University of Technology, Poland
*E-mail of corresponding author: norrad@tu.kielce.pl

***Table 1** Numerical values for each test specified in EN 45545-2 [5]*

| Parameter | Requirement | Values required for a specific HL threat | | |
|---|---|---|---|---|
| | | HL1 | HL2 | HL3 |
| CFE ($kWm^{-2}$) ISO 5658-2 | R1, R7 | ≥20 a | ≥20 a | ≥20 a |
| | R17 | 13 a | 13 a | 13 a |
| MARHE ($kWm^{-2}$) ISO 5660-1 | R1, R7, R17 | a - | ≤90 | ≤60 |
| | R8 | - | ≤50 | ≤50 |
| $D_s(4)$ (-) EN ISO 5659-2 | R1 | ≤600 | ≤300 | ≤150 |
| $D_s$max (-) EN ISO 5659-2 | R7, R8, R17 | - | ≤600 | ≤300 |
| | R10 | ≤600 | ≤300 | ≤150 |
| $VOF_4$ (min) EN ISO 5659-2 | R1 | ≤1 200 | ≤600 | ≤300 |
| $CIT_G$ (-) EN ISO 5659-2 | R1, R17 | ≤1.2 | ≤0.9 | ≤0.75 |
| | R7, R8, 10 | - | ≤1.8 | ≤1.5 |

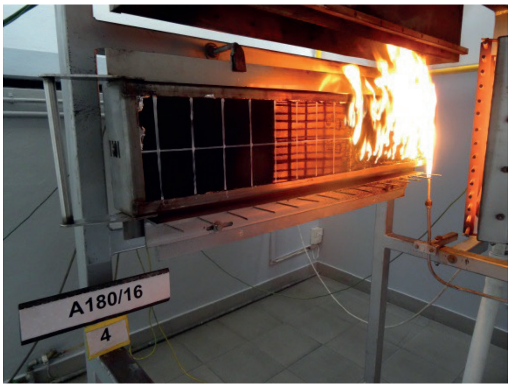


***Figure 1** Determinationof Critical Flux at Extinguishment- CFE according to ISO 5658-2*

***Figure 2** MARHE determination using a cone calorimeter according to ISO 5660-1*

calorimetry principle: For most materials per kilogram of oxygen consumed by burning material, 13.1 MJ of heat is released to within ± 5%. Use of the precision oxygen measurement equipment in gas extraction and gas flow measurement in the extract, allow for a very precise determination of oxygen consumption and at the same time to accurately calculate the value of the released heat and its rate of release.

To assess the fire resistance, these further fire parameters were selected that characterize the material's resistance to external fire sources, as well, i.e.:

1) $D_s$(max) (maximum optical density of smoke) (-), Ds(4) (-) (specific optical density of smoke in the 4th min), $VOF_4$ (min) (blackout in the 4th min) - according to EN ISO 5659-2 [8] (Figure3).
2) The tests determining the optical density of smoke were carried out with a set thermal flow of 50 kW / $m^2$ without a pilot burner. The attenuation of the white light beam passing through the smoke was measured.

$CIT_G$ (Conventional Index of Toxicity determined in the 4th min and in 8 min) (-) - according to EN ISO 5659-2 [8] and EN 45545-2 [5] Annex C (Figure 3).

The toxicity tests were carried out with a given heat flux of 50 kW/$m^2$, no pilot burner, sampling at 4 and 8 minutes. The FTIR (Fourier Transform Infrared Spectroscopy) was used for the determination of gases.

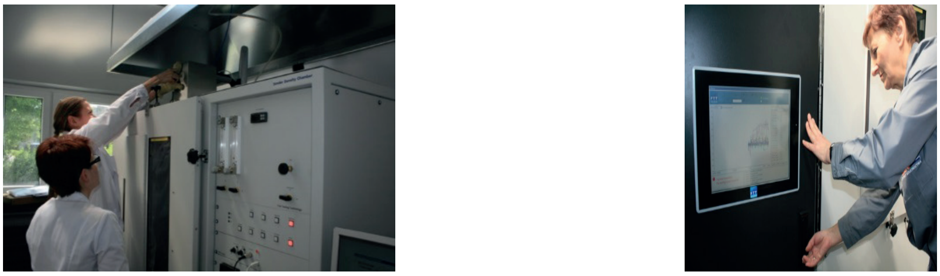

***Figure 3*** *Determination of smoke properties using a smoke chamber according to EN ISO 5659-2 and a toxicity index when connected to the FTIR analyzer chamber (on the right) according to EN 45545-2 Annex C*

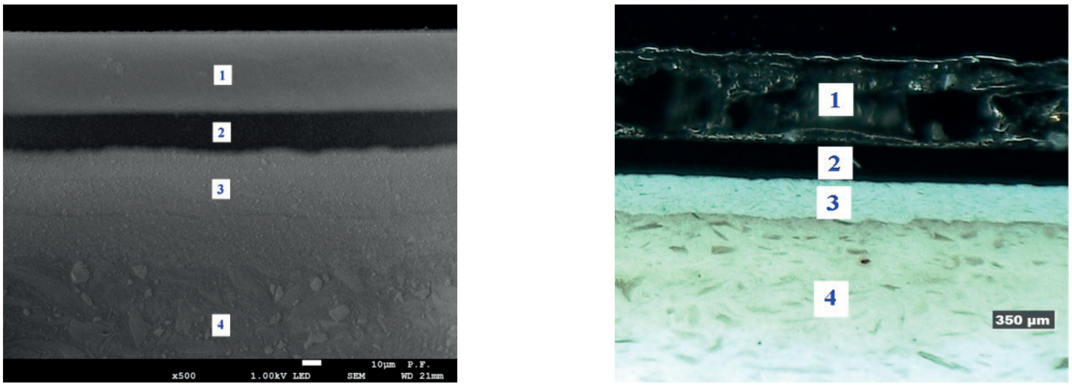


***Figure 4*** *SEM (left) and LM (right) micrographs of the polished cross-section through a coating system on S355 carbon steel substrate: 1- clear coat, 2 - base coat, 3 - filler, 4 - putty*

***Table 2*** *Results of the flame spread test of the rolling stock coating system*

| Sample | Spread of flame (mm) | Burning time (s) | CFE (kWm$^{-2}$) | Mean CFE (kWm$^{-2}$) | Standard deviation CFE (kWm$^{-2}$) |
|---|---|---|---|---|---|
| 1 | 447 | 755 | 13.6 | | |
| 2 | 469 | 680 | 11.6 | 12.4 | 1.1 |
| 3 | 466 | 670 | 11.9 | | |

The previous tests of the paint systems showed that the first two parameters were the most difficult to fulfill, so the tests were started from this two parameters [9-10]. The tests were performed at the Materials & Structure Laboratory of the Railway Research Institute in Warsaw. In the next stage of the work, an intumescent layer was introduced into the system in order to limit the impact of the ignition source operation on the lower layers, especially on the putty. Then, further research was undertaken to determine the required thickness of the intumescent layer to meet requirements for the CFE. The tests were carried out for the thickness from 200 to 1000 µm.

## 3 Results and discussion

### 3.1 Microstructure analysis

A microstructure analysis was conducted for anti-graffiti coating systems using the *JEOL* JSM-*7100F* scanning electron microscope with field emission and the Hirox KH-8700 light microscope.

Thickness of the obtained coating systems was from approx. 2300 to approx. 2500 µm. There are clear boundaries between the individual layers. Figure 4 shows the clear boundary between the varnish layers and the putty. Also, the varnish layers are free of pores and microcracks.

### 3.2 Measurement of flammability properties

The CFE test according to ISO 5658-2 is carried out on three samples with dimensions of 155 mm x 800 mm x 1.5 mm. This method involves exposed the vertical sample to an external heat stream with a standard density distribution. Results of the test are presented in Table 2.

Samples with an anti-graffiti coating system were treated with a cone-shaped electric radiator with a radiation intensity of 50 kW/m$^2$. The ignition was initiated by the spark and combustion was carried out in air atmosphere (0.024 m$^3$/s). Classification according to EN 45545-2 defines the MARHE parameter, which represents the maximum average rate of heat release (ARHE) over a 20 minute test. The ARHE value is calculated according to the following formula:

$$ARHE(t_n) = \frac{\sum_2^n (t_n - t_{n-1}) \times \frac{q_n + q_{n-1}}{2}}{t_n - t_{n-1}}, \qquad (1)$$

***Table 3** Results of the maximum average heat release of the rolling stock coating system*

| Sample | MARHE ($kWm^{-2}$) | Mean value of MARHE ($kWm^{-2}$) | Standard deviation MARHE ($kWm^{-2}$) |
|---|---|---|---|
| 1 | 208.1 | | |
| 2 | 196.8 | 198.1 | 9.4 |
| 3 | 189.4 | | |

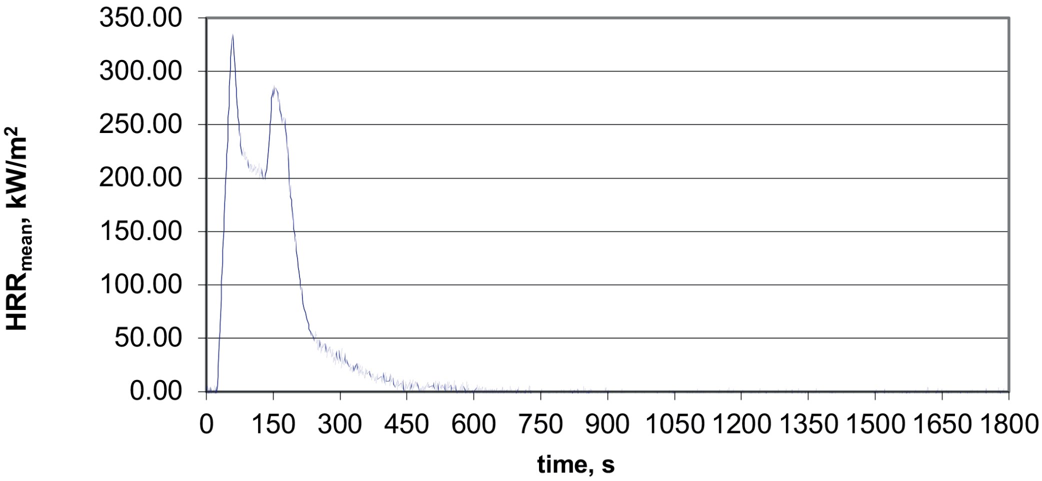


***Figure 5** Example of the HRR heat releasing curve for the coating system*

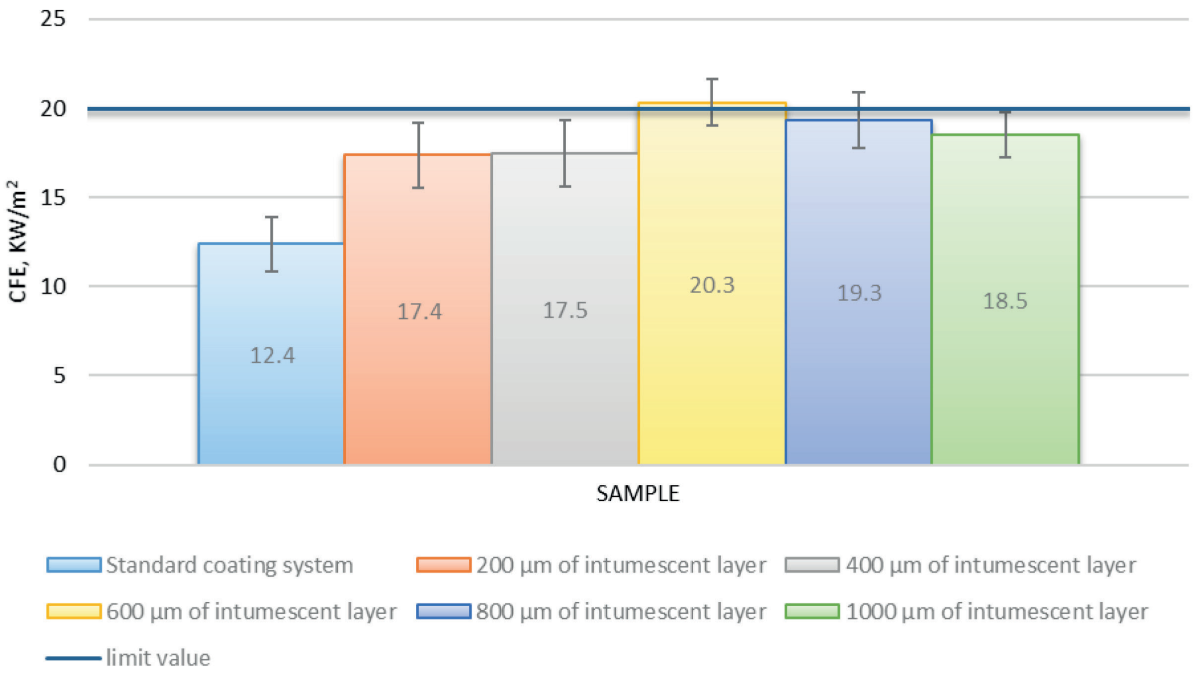


***Figure 6** Results of the critical heat flux of the coating system after applying a fire protection layer of varying thickness*

where:
$t$ -time, mostly $t_1 = 0$,
$q$ – the rate of heat release, mostly $q_1 = 0$.

The test is carried out according on three weighted sample of dimension 100mm x 100mm x 1mm. The test result are presented in Table 3. The Figure 5 presents example of the heat release rate curve (HRR) depending on the energy emitted from a specific surface to duration of the test.

Result sof the conducted tests definitely differed from requirements of the EN 45545-2 standard. Thickness of each layers (mostly putty) had a significant influence on results of the fire properties. The newly developed protective layer (intumescent layer) was designed to improve the flammability, while maintaining durability of the coating system. Intumescent layer, developed by Barwa laboratory, was tested in scope of impact its thickness on fire and smoke properties. The purpose of using the intumescent layer was to slow down the spread of fire, reduce the

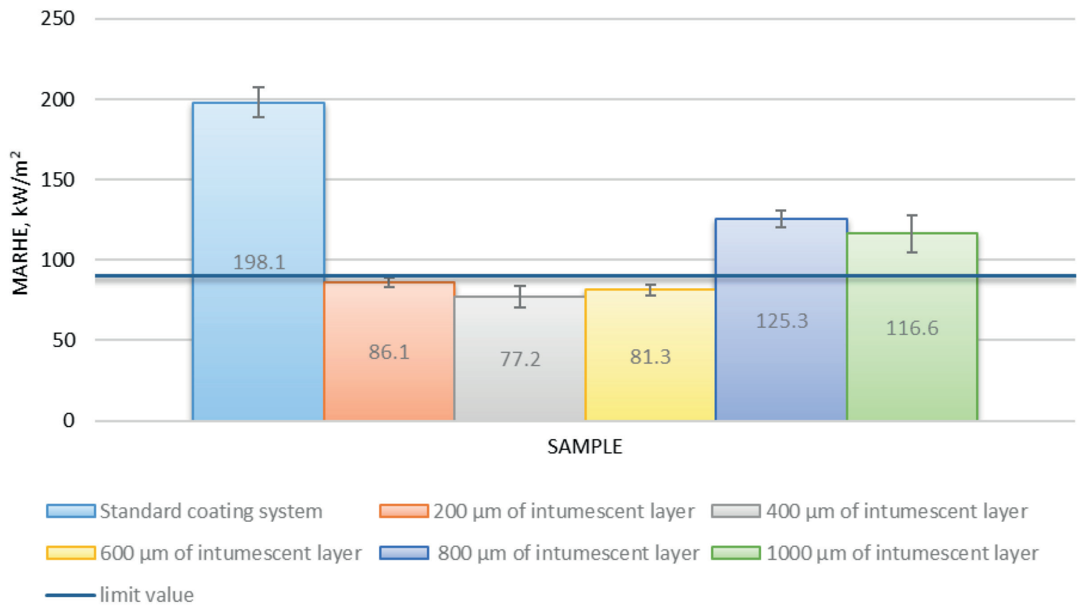


***Figure 7** Results of the maximum average heat release of the coating system after application of a fire-resistant layer of varying thickness*

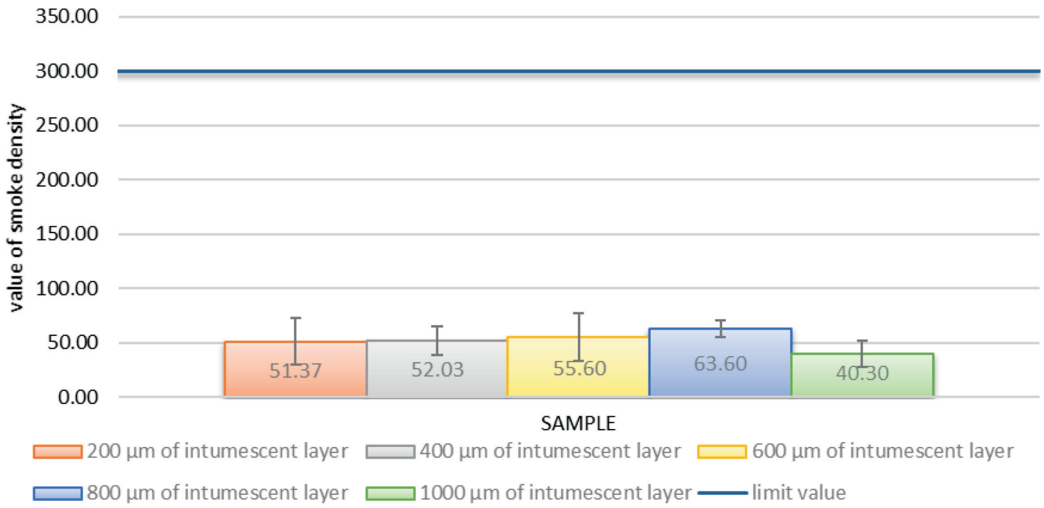


***Figure 8** Smoke optical density at 4 minutes of the coating system test with an intumescent layer*

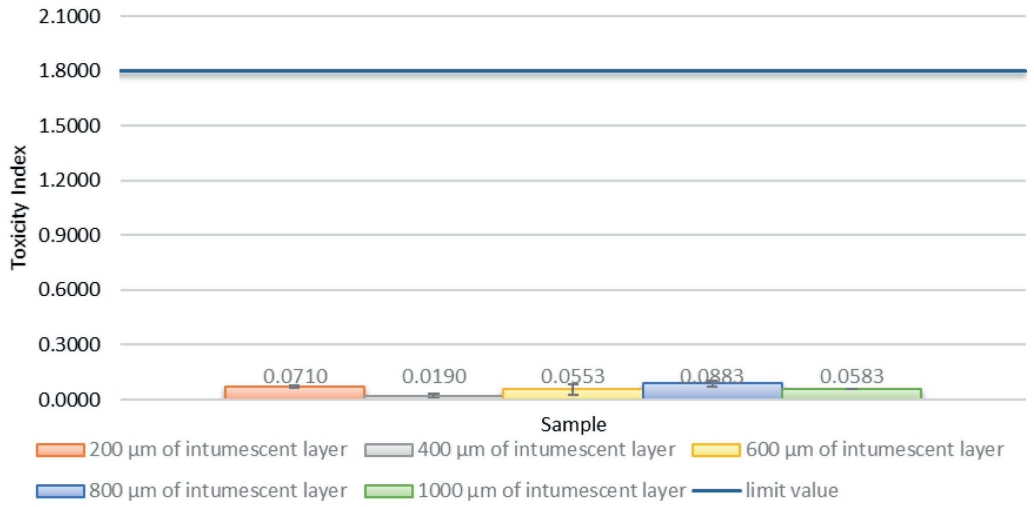


***Figure 9** Toxicity results of a coating system with an intumescent layer at the 8th minute of the test*

amount of heat released and reduce the fumes emitted during the burning of the coating.

The mean values of the next thicknesses of the intumescent layer were compared to the initial results for the parameter of the Critical Flux at Extinguishment CFE (Figure 6) and for the parameter of the maximum average heat release MARHE (Figure 7). Studies of the CFE and MARHE parameters confirmed the beneficial properties of applying a protective layer to coating systems. In addition, thickness of the fire protection layer was determined, which translated into the best results. Both in the study determining the fire spreading parameter and the maximum average heat release, the most preferred thickness of the intumescent layer was about 600 µm thickness. In the next investigated case, with a thickness of 800 µm of intumescent layer, both parameters assumed less desirable values in relation to requirements of the EN 45545-2 standard.

### 3.3 Smoke properties

A large volume of smoke can limit visibility and confuse passengers at a time when every second is important. Another aspect is also the toxicity of smoke. Toxic gases cause poisoning and long health treatment. Therefore, use of agents from the group of halogens and bromides as flame retardants are not recommended. The coating system with an intumecent layer of various thicknesses was measured. Samples were prepared according to a technological process. The samples dimensions were 75 mm x 75 mm x 1 mm. The tests were carried out together with the smoke analysis determining the toxic substances contained in it. Figure 8 shows results of the optical smoke density in the 4th minute of the test for different thicknesses of the intumescent coating included in the coating system.

$$CIT_G = \frac{0.51m^3 \times 0.1m^2}{150m^3 \times 0.004225m^2} \times \sum_{i=1}^{i=8} \frac{c_i}{C_i}, \quad (2)$$

where:
*0.1 $m^2$* - surface area of burning sample,
*150 $m^3$* - the gaseous effluents disperse into standard vehicle volume,
*0.51 $m^3$* - smoke chamber volume,
*0.004225 $m^2$* - the exposed surface area of the test specimen,
$c_i$ - the concentration measured in mg/m$^3$ of the i-th gas in the EN ISO 5659-2 smoke chamber,
$C_i$- the reference concentration measured in mg/m$^3$ of the i-th gas.

To assessthe toxicity of materials used in the railway industry, a standard toxicity index, calculated based on the obtained data, was introduced. The tests should determine the presence and concentration of eight substances in the gases from the burning sample. The gases were: $CO_2$, CO HF, HCl, HBr, HCN, $SO_2$, $NO_x$ (NOx as the sum of NO and $NO_2$). Conventional Index of Toxicity for generic products $CIT_G$ is calculated according to Equation (2).

Both in the 4 and 8 minute gas sampling each of the tested coating systems was characterized by negligible values of the general toxicity parameter. Figure 9 presents the results of the general toxicicty in the 8th minute sampling.

Thickness of the intumescent layer did not influence the value of the optical smoke density of the coating system at the 4th minute of the test and results obtained were within limits of measurement error. The obtained results deviated significantly from the value required by the EN 45545-2 standard. The results obtained in the measurement of smoke properties met the requirements of the EN 45545-2 standard, for each thickness of the applied intumescent layer in the coating system. There was no correlation between the thickness of the intumescent layer of coating systems and values obtained in smoke measurements and toxicity.

## 4 Conclusions

Tested coating system has homogeneous structure and is free of defects. Laboratory tests confirmed the positive effect of the intumescent layer on flammable properties of the coating system. The tests determined the optimal thickness of the protective layer of 600 µm. Deterioration of the flammability characteristics, when increasing the intumescent layer (above 600 µm), can be explained by delivery of a combustible substance to the system in the form of a polyurethane resin, which ensured the appropriate structure of this layer. Use of the intumescent layer in coating system allows to meet the requirements of the EN 45545-2 standard and apply the developed coating system in the production of rolling stock. Use of an intumescent layer does not have the negative effect on the smoke emission during a fire. No additional toxic gases are emitted during the fire compared to a standard coating system. The next step will be tests of resistance to aggressive environmental factors and corrosion resistance.

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Daniel Varecha - Slavomir Hrcek - Otakar Bokuvka - Frantisek Novy - Libor Trsko - Ruzica Nikolic - Michal Jambor

# FATIGUE SAFETY COEFFICIENTS FOR ULTRA - HIGH REGION OF LOAD CYCLES

*In this paper the authors introduce results from the field of the fatigue safety of selected steels in the region of ultra - high number of loading cycles. The fatigue tests were carried out at high frequency tension - compression loading (f = 20 kHz, T = 20 ± 5°, R = -1) in the region from N = $10^6$ to N = $10^9$ cycles. The fatigue safety coefficients were calculated by four methods (Goodman, Gerber, ASME elliptic and Soderberg). The percentage reduction of the fatigue safety coefficients (N = $10^9$ vs. N = $10^6$ cycles) was at Goodman, 7.99 ÷ 10.83 %, Gerber, 5.27 ÷ 8.26 %, ASME, 1.89 ÷ 6.42 % and Soderberg, 6.51 ÷ 10.25 %.*

***Keywords:** structural steels, ultra - high cycles fatigue, safety coefficients*

## 1 Introduction

Fatigue is the dominant degradation mechanism during the operation of components and mechanical constructions. More than 90 % of all the fractures are caused by fatigue of the applied material. Targeted research, both theoretical and experimental, of the low - cycle and high - cycle fatigue of structural steels, began in the mid - 19th century. For the area of the high cycle fatigue, the fatigue limit $\sigma_c$ was defined as the largest fluctuating stress at certain mean stress $\sigma_m$ that the structural steel withstands for an infinite number of cycles. For steels, the so - called basic number of cycles $N_c$, in the range from $N_c = 10^6$ to $10^7$ cycles, was recommended for an infinite number of cycles. However, research institutes have demonstrably noticed that fractures caused by fatigue occur in structural steels far beyond the so - called basic number $N_c = 10^7$ cycles. Conclusions on the safe loading and permanent fatigue strength beyond this cycle limit are inaccurate and incomplete. In view of this fact, at the end of the 20th century, both theoretical and experimental research of ultra - high - cycle fatigue, in the range from N = $10^7$ to N = $10^{10}$ loading cycles, began. Questions are being verified, such as what is the course of dependence $\sigma_a = f(N)$, the physical nature of the fatigue limit $\sigma_c$, the existence of the fatigue limit, degradation fatigue mechanisms at very low values of the plastic deformation amplitude, propagation of short fatigue cracks at extremely low rates, the role of inclusions, long grain boundaries, pores, surface and subsurface initiation of fatigue cracks, etc. after the so - called basic number $N_c = 10^7$ load cycles in structural steels. The course of the dependence $\sigma_a = f(N)$, including the step - wise or duplex curves with a "plato" is discussed [1-7]. High - graded steels of medium and high strengths are used in various industries. They have a specific place in the field of rails, tires, wings and hull transport. With regard to this state area of application, these steels are required to have a long service life and high reliability and safety, [8]. Determining the fatigue safety factor is important both from a theoretical point of view and from a practical point of view [9-13]. In this paper the authors introduce their own results from the field of the fatigue safety of selected steels in the region of ultra - high number of loading cycles.

## 2 Experimental

Experimental works, the qualitative and quantitative chemical analysis, tensile tests, fatigue test and the fatigue coefficient $k_u$ calculations, were carried out on eight structural steels including high strength steels (DOMEX 700MC, HARDOX 400, HARDOX 450). Chemical analysis was performed with help of the emission spectrometry on an ICP (JY 385) emission spectrometer, using a fast recording system Image. Tensile tests were carried out on a ZWICK Z050 testing machine at ambient temperature of T = 20 ± 5 °C, with the loading range in interval F = 0 - 20 kN and the strain rate of $\dot{\varepsilon}_m = 10^{-3}s^{-1}$. The round cross - section specimens were used, the shape and dimension of specimens have met requirements of the EN 10002 - 1 standard (3 specimens for each steel were used). The fatigue tests were carried out at high - frequency sinusoidal cyclic tension - compression loading (f = 20 kHz, T = 20 ± 5 °C, R = - 1, cooled by distilled water with anticorrosive inhibitor) and with use of the ultrasonic fatigue testing device. Smooth round bar specimens (minimum 10 pieces) with diameter of 4 mm, ground and polished by metallographic procedures, were used for the fatigue test [14-15]. The investigated

**Daniel Varecha[1,*], Slavomir Hrcek[1], Otakar Bokuvka[1], Frantisek Novy[1], Libor Trsko[2], Ruzica Nikolic[2], Michal Jambor[3]**
[1]Faculty of Mechanical Engineering, University of Zilina, Slovak Republic
[2]Research Centre, University of Zilina, Slovak Republic
[3]Institute of Physics of Materials, Brno, Czech Republic
*E-mail of corresponding author: daniel.varecha@fstroj.uniza.sk

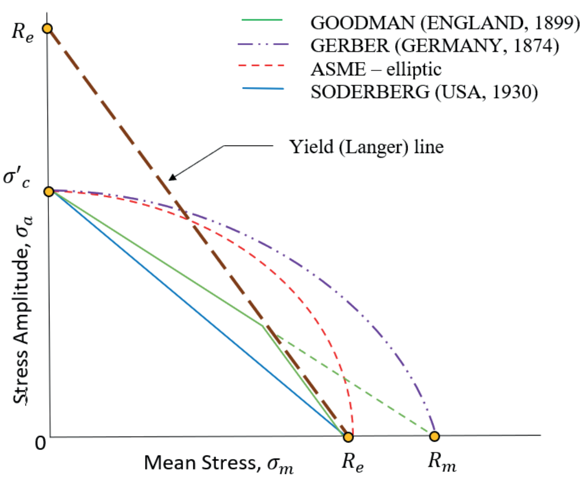


***Figure 1*** *$\sigma_a = f(\sigma_m)$ [12]*

***Table 1*** *Mechanical properties of tested structural steels*

| Steel | $R_e$ (MPa) | $R_m$ (MPa) | $\sigma_a$, $10^6$ (MPa) | $\sigma_a$, $10^9$ (MPa) |
|---|---|---|---|---|
| 1 | 340 | 446 | 285 | 201 |
| 2 | 376 | 564 | 352 | 210 |
| 3 | 251 | 773 | 408 | 288 |
| 4 | 796 | 850 | 425 | 265 |
| 5 | 710 | 867 | 390 | 288 |
| 6 | 750 | 952 | 548 | 350 |
| 7 | 1226 | 1257 | 500 | 352 |
| 8 | 1425 | 1560 | 551 | 400 |

***Table 2*** *Chemical composition (in weight %) of tested structural steels*

| Steel | C | Mn | Si | N | Ti | Al | Mo | Cr | Ni | Cu | P | S | Nb | V | B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.17 | 0.51 | 0.17 | - | - | - | - | 0.03 | 0.04 | 0.06 | 0.013 | 0.013 | - | - | - |
| 2 | 0.18 | 1.47 | 0.03 | - | - | - | - | 0.03 | 0.02 | 0.04 | 0.015 | 0.011 | - | - | - |
| 3 | 0.058 | 1.63 | 0.81 | - | 0.37 | - | 2.54 | 17.55 | 12.96 | - | 0.033 | 0.037 | - | - | - |
| 4 | 0.08 | 1.67 | 0.35 | - | 0.015 | 0.015 | - | - | - | - | 0.018 | 0.0037 | 0.06 | 0.014 | - |
| 5 | 0.08 | 1.62 | 0.12 | 0.061 | 0.17 | 0.049 | 0.14 | - | - | - | 0.030 | 0.025 | - | - | - |
| 6 | 0.52 | 0.70 | 0.34 | - | - | - | - | 0.16 | 0.06 | 0.15 | 0.008 | 0.005 | - | - | - |
| 7 | 0.13 | 0.95 | 0.30 | - | - | - | 0.04 | 0.25 | 0.06 | - | 0.012 | 0.002 | - | - | 0.002 |
| 8 | 0.20 | 0.80 | 0.39 | - | - | - | 0.01 | 0.45 | 0.05 | - | 0.005 | 0.005 | - | - | 0.001 |

region of number of cycles ranged from $N \approx 10^6$ to $10^9$ cycles of loading.

The fatigue safety coefficient was calculated with regard to work [12], Figure 1, with the using equations: (1) Goodman, (2) Gerber, (3) ASME and (4) Soderberg.

$$k_u = \frac{1}{\frac{\sigma_a}{\sigma'_c} + \frac{\sigma_m}{R_m}}, \tag{1}$$

$$k_u = \frac{1}{2}\left(\frac{R_m}{\sigma_m}\right)^2 \frac{\sigma_a}{\sigma'_c}\left[-1 + \sqrt{1 + \left(\frac{2 \cdot \sigma_m \cdot \sigma'_c}{R_m \cdot \sigma_a}\right)}\right], \tag{2}$$

$$k_u = \sqrt{\frac{1}{\left(\frac{\sigma_a}{\sigma'_c}\right)^2 + \left(\frac{\sigma_m}{R_e}\right)^2}}, \tag{3}$$

$$k_u = \frac{1}{\left(\frac{\sigma_a}{\sigma'_c}\right) + \left(\frac{\sigma_m}{R_e}\right)}, \tag{4}$$

where:
$\sigma_a$ is the stress amplitude,
$\sigma_m$ is the mean stress,
$\sigma'_c$ is the fatigue limit,
$R_m$ is the ultimate tensile strength,
$R_e$ is the yield point.

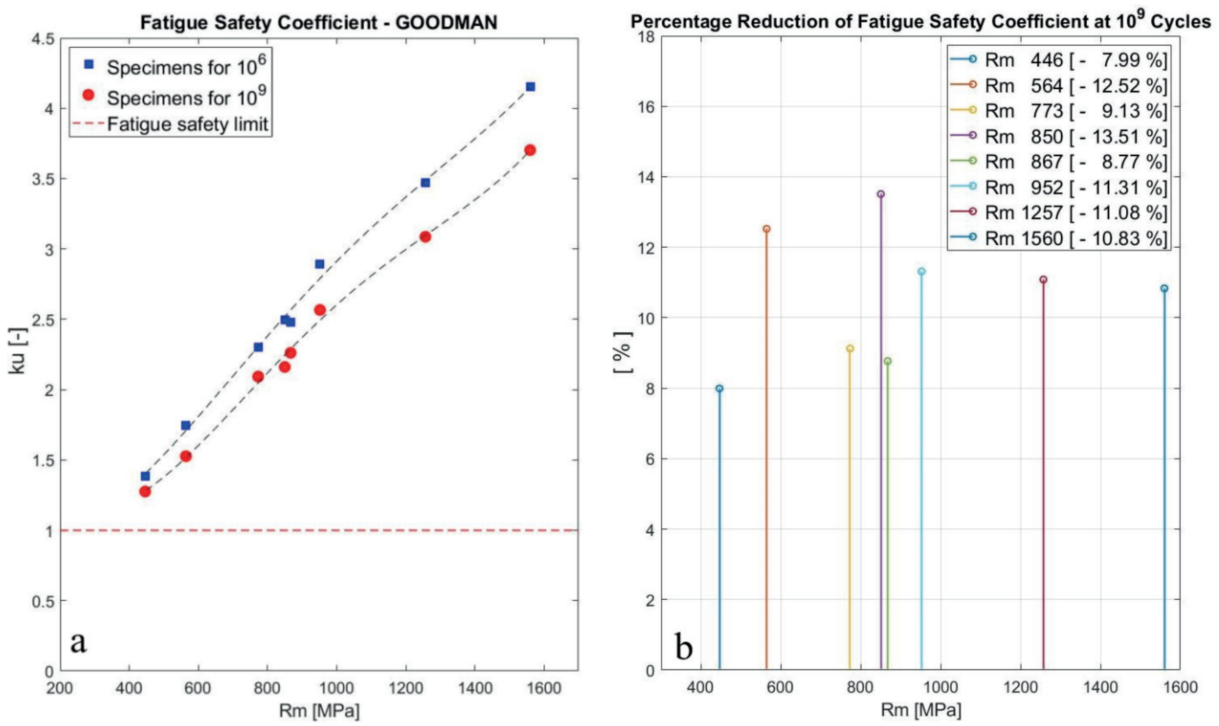


***Figure 2*** *Fatigue safety coefficient $k_u$ (a) and percentage reduction of $k_u$ (b) - Goodman*

***Table 3*** *Specimens for the safety coefficient $k_u$ for Goodman*

| Specimens | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| $k_u$ for $10^6$ | 1.39 | 1.75 | 2.3 | 2.5 | 2.48 | 2.89 | 3.47 | 4.15 |
| $k_u$ for $10^9$ | 1.27 | 1.53 | 2.09 | 2.16 | 2.26 | 2.57 | 3.08 | 3.70 |
| % Reduction $k_u$ | - 7.99 | - 12.52 | - 9.13 | - 13.51 | - 8.77 | - 11.31 | - 11.08 | - 10.83 |

Application of the above described experimental work was executed on a screw joint, which is, during the operation, loaded by a cyclic stress in superposition with the preload. The material parameters of the screw were taken from Table 1, where values of $R_e$ and $R_m$ of experimental materials are given.

## 3 Results and discussion

Results of qualitative and quantitative chemical analysis (chemical composition), tensile tests (ultimate tensile strength $R_m$, yield point $R_e$) and high - frequency fatigue tests $(\sigma_a, 10^6, \sigma_a, 10^9)$, are shown in Tables 1 and 2, respectively. Results of the fatigue safety coefficient $k_u$ calculations are shown in Figures 2 to 5 and also in Tables 3 to 6.

Material fatigue tests have demonstrably confirmed a continuous decrease in fatigue strength in the investigated range of the number of the loading cycles. The step - wise or duplex $\sigma_a = f(N)$ curves were not observed. The observed values of $\Delta\sigma_a$ ranged from $\Delta\sigma_a$ = 84 MPa to $\Delta\sigma_a$ = 198 MPa. Values $\Delta\sigma_a$ in the region of the ultra - high number of loading cycles for steels range from $\Delta\sigma_a$ = 20 MPa to $\Delta\sigma_a$ = 200 MPa. Higher values of $\Delta\sigma_a$ were exhibited by the structural steels of higher strength, what is related to their higher sensitivity to both surface and internal defects (micro - impurity, microstructural heterogeneity, pores, grain size, inclusions). These statements are in accordance with the works of the authors [1-7, 9].

It is clear from results (Figures 2 to 5, Tables 3 to 6) that Goodman and Soderberg methods are suitable methods (criteria) for evaluation of the fatigue safety of selected structural steels in the region of the high number of cycles. The Soderberg criterion checks the occurrence of any deformation. Lower values of $k_u$ ensure that no fatigue failure or accidents would occur during the considered ultra - high number of load cycles. The Goodman criterion is very strict, but it is one of the best known criteria that allows for a simple analytical solution of fatigue tasks. The American Society of Mechanical Engineers (ASME) has addressed the issue of fatigue safety, which is a more conservative criterion but does not have sufficient margin to determine the fatigue safety coefficient for an ultra - high number N = $10^9$ of cycles. The Gerber criterion seems to be the least suitable, because approaching the limit state of fatigue safety and at an ultra - high number of cycles fatigue fracture accidents can occur [9-13].

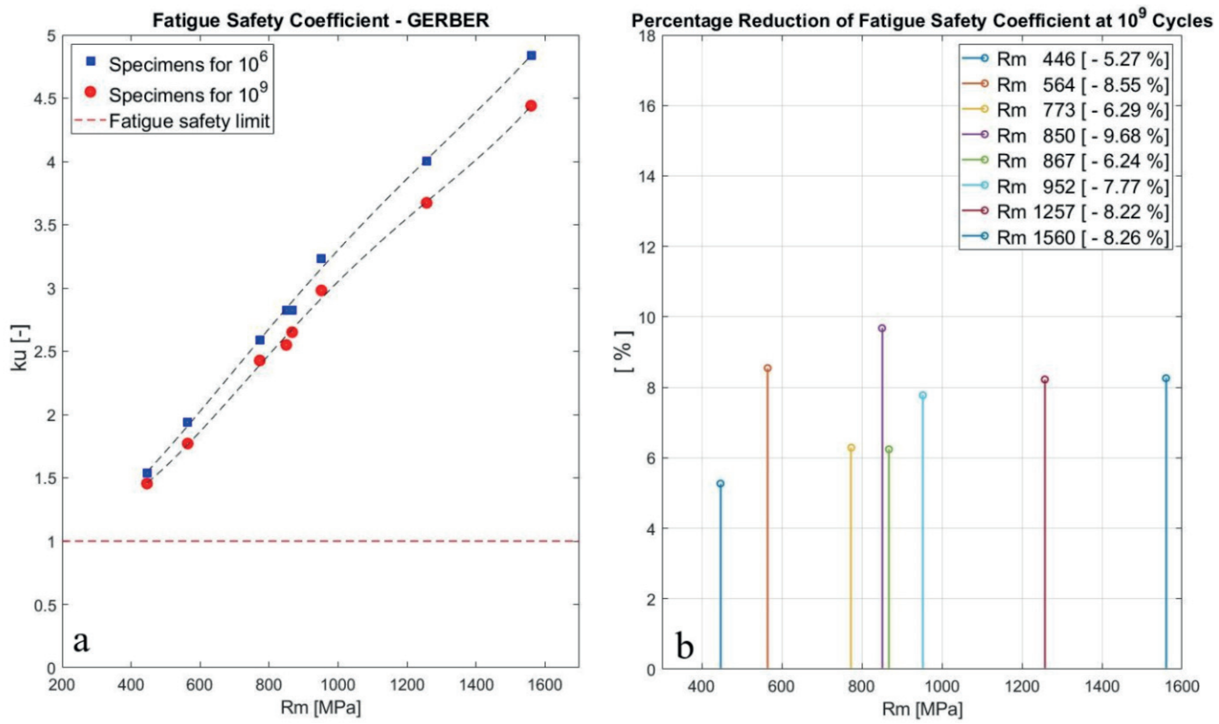


***Figure 3*** *Fatigue safety coefficient $k_u$ (a) and percentage reduction of $k_u$(b) - Gerber*

***Table 4*** *Specimens for the safety coefficient $k_u$ for Gerber*

| Specimens | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| $k_u$ for $10^6$ | 1.54 | 1.94 | 2.59 | 2.82 | 2.82 | 3.23 | 4.0 | 4.84 |
| $k_u$ for $10^9$ | 1.45 | 1.77 | 2.43 | 2.55 | 2.65 | 2.98 | 3.67 | 4.44 |
| % Reduction $k_u$ | - 5.27 | - 8.55 | - 6.29 | - 9.68 | - 6.24 | - 7.77 | - 8.22 | - 8.26 |

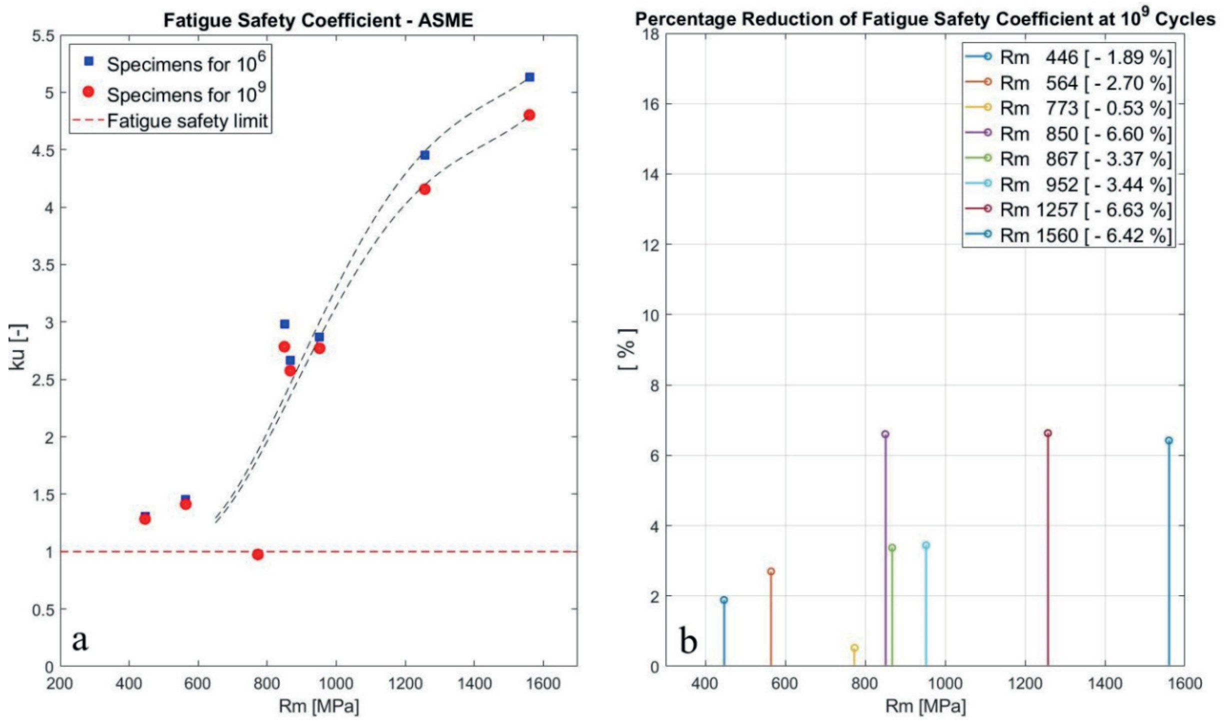


***Figure 4*** *Fatigue safety coefficient $k_u$ (a) and percentage reduction of $k_u$ (b) - ASME*

***Table 5*** *Specimens for the safety coefficient $k_u$ for ASME*

| Specimens | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| $k_u$ pre $10^6$ | 1.31 | 1.45 | 0.98 | 2.98 | 2.67 | 2.87 | 4.45 | 5.13 |
| $k_u$ pre $10^9$ | 1.28 | 1.41 | 0.97 | 2.78 | 2.58 | 2.77 | 4.16 | 4.80 |
| % Reduction $k_u$ | - 1.89 | - 2.7 | - 0.53 | - 6.60 | - 3.37 | - 3.44 | - 6.63 | - 6.42 |

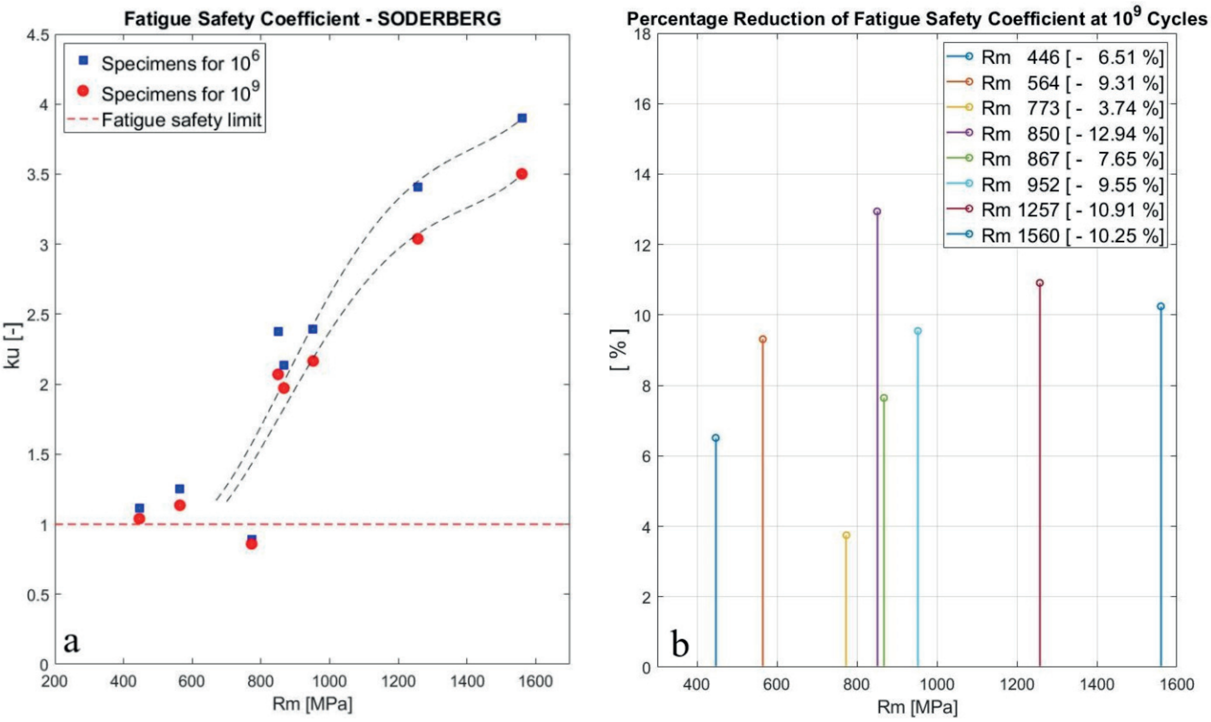


***Figure 5*** *Fatigue safety coefficient $k_u$ (a) and percentage reduction of $k_u$ (b) - Soderberg*

***Table 6*** *Specimens for the safety coefficient $k_u$ for Soderberg*

| Specimens | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| $k_u$ for $10^6$ | 1.11 | 1.25 | 0.89 | 2.38 | 2.14 | 2.39 | 3.41 | 3.90 |
| $k_u$ for $10^9$ | 1.04 | 1.14 | 0.86 | 2.07 | 1.97 | 2.17 | 3.04 | 3.5 |
| % Reduction $k_u$ | - 6.51 | - 9.31 | - 3.74 | - 12.94 | - 7.65 | - 9.55 | - 10.91 | - 10.25 |

## 4 Conclusions

Taking into account the performed experimental work, the following can be stated:

- Dependence $\sigma_a = f(N)$ shows a decreasing character after the so - called basic number of cycles $N_c = 10^6$ to $10^7$ cycles.
- The obtained values of the fatigue limit $\sigma_c$ at the so - called basic number of cycles are overestimated.
- Determining the fatigue safety coefficient beyond the so - called basic number of cycles $N_c$ is therefore desirable.
- These facts must be respected in a qualified choice of structural steel if the component or equipment will work in real operation in the region of ultra - high numbers of load cycles.

## Acknowledgements

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Pawel Zmarzly

# EXPERIMENTAL ASSESSMENT OF INFLUENCE OF THE BALL BEARING RACEWAY CURVATURE RATIO ON THE LEVEL OF VIBRATION

*Raceway curvature ratio is a very important parameter, because its values influence the performance characteristics of rolling-element bearings, their durability and the level of generated vibrations. However, the level of generated vibrations is one of the most important operating parameters of the rolling-element bearings. Excessive vibrations generated by rolling-element bearings affect the operation of the whole mechanism. The article presents experimental studies aimed at evaluation of influence of the inner and outer raceway curvature ratios of 6304-type rolling-element bearings on generated vibrations values. The raceway curvature ratio was determined based on results of metrological measurements. For this purpose, the radii of the inner and outer raceways as well as the diameters of the balls were measured. Design and principle of operation of an innovative system for analysis of the raceway geometry of the rolling bearing rings was presented. The vibration analysis was carried out in three frequency ranges, i.e. low (50-300 Hz), medium (300-1,800 Hz) and high (1,800-10,000 Hz). Values of measured vibrations were expressed in Anderon units. The test results showed that increase in the raceway curvature ratio causes a moderate decrease in the value of the generated vibrations. The research results presented in this article will serve as a guidance to designers and manufacturers of the rolling-element bearings on how to modify the geometry of raceways and balls to obtain bearings that generate low vibration values. That is very important in car transportation.*

***Keywords:*** *rolling-element bearings, raceway curvature ratio, vibration, Anderon unit*

***Nomenclature***

$f_i$ - *bearing curvature ratio for the inner raceway,*

$f_o$ - *bearing curvature ratio for the outer raceway,*

$f_t$ - *total curvature ratio,*

$r_i$ - *radius of inner raceway,*

$r_o$ - *radius of outer raceway,*

$D_w$ - *ball diameter,*

*V - vibration velocity,*

*N - radian,*

*N - number of octave,*

$f^h$ - *the upper limit of the frequency band in Hz,*

*fl - the lower limit of the frequency band in Hz,*

*And - Anderon unit.*

## 1 Introduction

The rolling-element bearings are a large group of mechanical elements involved in torque transmission, while minimizing friction and the rolling resistance. The rolling-element bearings have found application in various branches of industry, as well as transportation [1]. Increasing demands for improved efficiency of equipment and mechanisms, while, at the same time, reducing energy consumption, require the rolling-element bearings to have a long service life, low running noise and low frictional moment [2]. This is particularly important in mechanisms produced using additive technologies [3-4]. The ball bearings are constructed in the following way: rolling elements are placed between the two rings. The ball moves on the surface of the raceway of the rings to minimize friction and rolling resistance [5-6]. Depending on the type and application, the ball bearings can be equipped with raceways with different radii. The contact surface of rolling elements and raceways depends on their mutual geometry. Moreover, the way balls interact with the bearing ring raceway surfaces influences significantly the bearing performance characteristics. The ratio of the radius of the inner raceway $r_i$ or outer raceway $r_o$ to the diameter of the balls $D_w$ is called the raceway curvature ratio.

**Pawel Zmarzly**
Department of Mechanical Engineering and Metrology, Kielce University of Technology, Poland
E-mail of corresponding author: pzmarzly@tu.kielce.pl

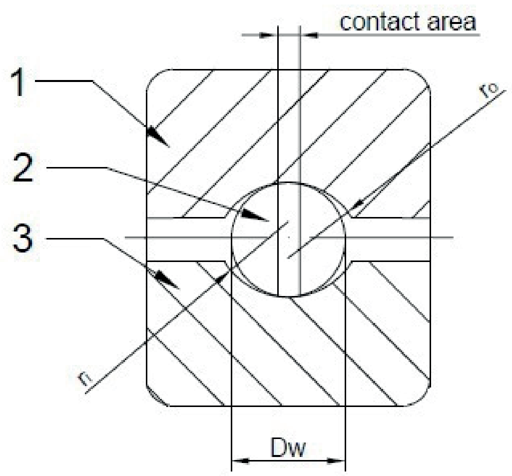


***Figure 1*** *Ball bearing cross-section: 1 - outer ring, 2 - ball, 3 - inner ring*

Despite the fact that the raceway curvature ratio is one of the most important design parameters for the ball bearings, there is very little research dedicated to its analysis. In the paper [7], the influence of the raceway curvature ratios of 6203-type ball bearings on the value of frictional moment was studied. Studies have shown that even a small change in the raceway curvature ratio has a significant effect on the frictional moment value. The author of this paper [8] carried out a study to determine how the raceway geometry (described by the raceway curvature ratio) affects the service life of the rolling-element bearings. He demonstrated that reduction of the raceway curvature ratio extends the service life of bearings. Zhu and Haung analyzed the relationship between the contact surface roughness statistical parameters and the bearing ratio curve in [9]. The research made it possible to evaluate how the roughness of slide connections affects the friction and wear of the bearings. The study [10] demonstrated influence of the ball bearing raceway roughness on motions of the balls, skidding, lubrication performance and the stress fluctuation in the substrate. However, the authors did not take the raceway curvature ratios into account. The authors of paper [11] analyzed the phenomena occurring in the contact zone of the balls with raceways in slewing bearings. In addition, they proposed modifications to the raceways of the slewing bearings in order to increase their service life. The paper [12] presents computer models investigating, among others, the influence of rolling element contact mechanic on the moment of friction occurring in slewing bearings. Simulation tests assessing the change in the ball contact zone with the inner raceway of ball bearings due to load changes were presented in [13].

In the first stage of operation of the rolling-element bearings, the friction coefficient depends, among others, on the contact area size and roughness of the cooperating raceway surfaces and rolling elements. Furthermore, excessive friction between the active surfaces of the rolling-element bearings, apart from reducing their service life, also affects values of generated vibrations. Therefore, it can be concluded that the raceway curvature ratios have a direct and indirect influence on values of generated vibrations. There are many publications describing vibration analysis of rolling-element bearings in terms of their wear [14-15]. There are also many papers which present the influence of various factors on the values of generated vibrations, e.g. roughness or waviness of the raceway [16-18], radial clearance [19-20], raceway defects [21]. However, there are no commonly available studies evaluating influence of the raceway curvature ratios on the generated vibrations. In addition, there are no studies, which describe how the raceway geometry of bearings and balls can be evaluated to determine the raceway curvature ratios. In most cases, the raceway radius is tested using universal measurement systems such as contour measuring instruments or profilometers. However, there is no description of the principle of operation and the construction of specialized systems for analysis of the bearings raceway geometry.

Therefore, experimental testing was conducted to determine the curvature ratios for the inner and outer raceways on new 6304-type rolling-element bearings. Next, the vibration analysis of the tested bearings was carried out and the influence of the raceway curvature ratios on the vibrations generated in specific frequency bands was evaluated. The tests presented in this article will serve as a guidance to designers and manufacturers of the rolling-element bearings on how to modify the geometry of raceways and balls to obtain bearings that generate low vibration values.

## 2 Raceway curvature ratio

The raceway curvature ratio determines the percentage degree of contact (fit) between the ball surface and the raceway surfaces (see Figure 1).

The bearing curvature ratio can be determined for the inner raceway as $f_i$, Equation (1), the outer raceway as $f_o$, Equation (2). The total curvature $f_t$, Equation (3) is defined as a sum of curvature ratios determined for the inner and outer raceways:

$$f_i = \frac{r_i}{D_w}, \quad (1)$$

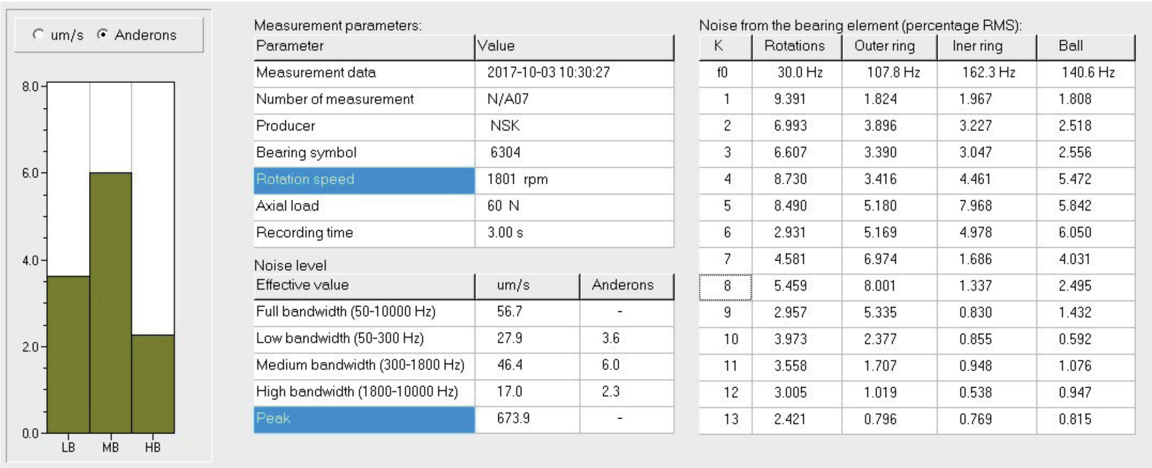


***Figure 2** Measurement report obtained from Anderonmeter software*

$$f_o = \frac{r_o}{D_w}, \tag{2}$$

$$f_t = f_i + f_0 - 1. \tag{3}$$

The raceway curvature ratios for most ball bearings fall within the range of 52% to 58%. As the raceway curvature ratio increases, the contact area between the ball and the raceway decreases. The rolling-element bearings with smaller raceway curvature ratio are suitable for carrying heavier loads. However, too small raceway curvature ratios (less than 50%) result in excessive ball rolling resistance on the raceway surface, which is detrimental to operation. The rolling-element bearings with high raceway curvature ratios have lower frictional moment. Because of low energy losses, this type of bearing is especially recommended for mechanisms which are activated and stopped repeatedly. It should be added that too high raceway curvature ratios (above 58%) are also detrimental. In such bearings inner stresses are more frequent, which significantly reduces their service life.

## 3 Experimental procedure

Experimental studies carried out for the purposes of this research were divided into several stages. Fifty new, 6304-type single row ball bearings were used in these studies. The open ball bearings were used in order to eliminate the damping influence of grease on vibration. The research was carried out in Rolling Bearing Laboratory located in Kielce University of Technology.

### 3.1 Vibration measurement

The first step in the study consisted of vibration velocity measurement using the Anderonmeter. A detailed description of the structure and principles of operation of the used measurement system was presented in papers [16] and [22]. The system uses a measuring sensor for vibration velocity. The most significant advantage of using such a sensor is the ability to measure low vibration frequencies, as low as 30 Hz. It should be noted that the low-frequency vibration can be caused, among other things, by incorrect geometry of balls and bearing raceways. Therefore, in terms of assessment of influence of the raceway curvature ratios on the generated vibration values, this range should be analyzed with particular care. The signal from the sensor is amplified, filtered and divided into appropriate frequency bands. The filtration procedure was carried out based on the guidelines presented in the international standard ISO 15242-1. An analogue-digital card PCI-1716L Advantech Company was used to record the measuring signal. Then, the digital wave filter was used for separating oscillations based on their frequency. The band-pass filter has a single transmission band extending from a lower cut-off frequency greater than zero to finite upper cut-off frequency. Signal sampling frequency was 25 600 Hz. Number of samples for FFT was 16 384. Using the appropriate software measured signal is filtered and vibrations analysis was carried out for each bearing in three frequency ranges: low (LB) 50-300 Hz, medium (MB) 300-1,800 Hz and high (HB) 1,800 - 10,000 Hz. In order to maintain constant measuring conditions and to meet the standard requirements for vibration analysis, the rolling-element bearings were tested at a constant speed of 1,800 rpm. An axial load of 60 N was used to remove the backlash by means of pneumatic pressure. Fifty rolling ball bearings 6304 types were used for research. Measurement practice has shown that the bearing vibration value changes with the change in the measurement location on the outer ring. Therefore, the vibration was measured at three points distributed evenly at 120° on the race circumference. The measurements were carried out for two sides of the bearing, which allowed to obtain six sets of results for each bearing. The mean values from the set of results obtained for each bearing were determined for analysis. Figure 2 shows an example of a measurement report obtained from the Anderonmeter system software.

Values of measured vibrations were expressed in Anderon units, which are closely related to the vibration velocity and rotational velocity of the tested rolling-element bearing [16, 23]. An Anderon unit is approximately 7.698

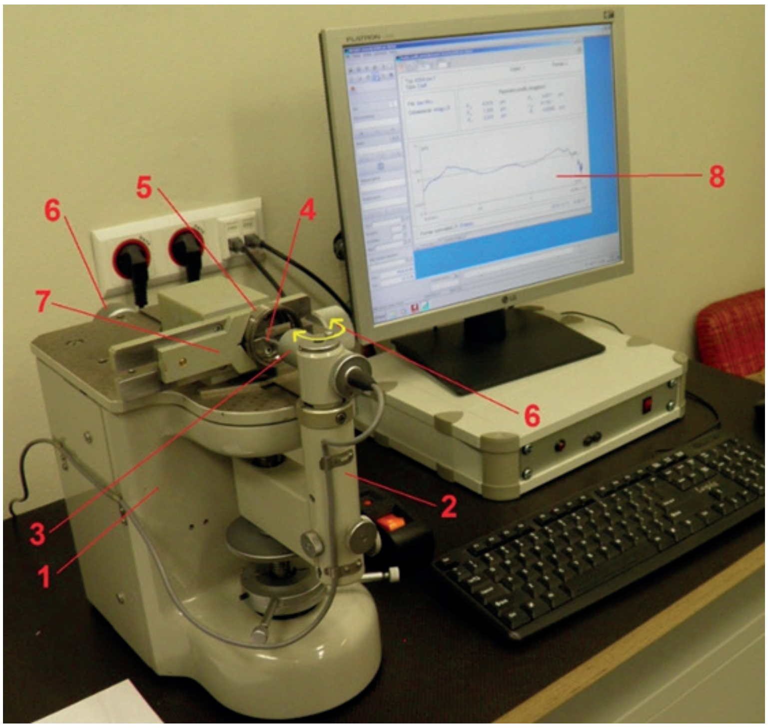


***Figure 3*** *STPP measuring system for analysis of the geometry of bearing raceways: 1 - body, 2 - rotating clamp, 3 - measuring head, 4 - measuring tip, 5 - rolling-element bearing outer ring, 6 - adjustment supports, 7 - magnetic holder, 8 - CYFORM software interface*

µm/s. Mathematical interpretation of the Anderon unit is presented in Equation (4):

$$1And = \frac{V}{n\sqrt{N}} = 2\pi \cdot 30\sqrt{\log_2 \frac{f_h}{f_l}}, \tag{4}$$

where:
$V$ - vibration velocity,
$n$ - radian,
$N$ - number of octave,
$f_h$ - the upper limit of the frequency band in Hz,
$f_l$ - the lower limit of the frequency band in Hz.

### 3.2 Geometry measurement

After the disassembly of each bearing, the geometry of the inner and outer ring raceways was analyzed, constituting the second stage of the study. The STPP system (Figure 3) developed at the Kielce University of Technology was used to measure the raceway radius.

In addition to measuring the raceway radius, STPP can also be used to analyze the roughness and waviness of bearing raceways. A cast iron body, to which the drive system and measuring system are mounted, is the main element of the instrument. Vertical spindles, mounted in the front part of the body (1), together with the rotating clamp (2) can rotate in ±60° angle (see yellow arrow in Figure 3). The measuring head (3) is mounted at the end of the spindle. By using the plain bearings, the measuring head (3) together with the measuring tip (4) can accurately move along the raceway curve of the bearing ring (5). The correct settings of the measuring tip movement are regulated by the supports (6). For the fast and accurate positioning of the bearing rings to be measured, a magnetic holder (7) is used. The signal from the measuring head is amplified and filtered accordingly. Analysis of the measurement results is performed by the CYFORM software (8).

In most contour measuring stations and profilometers used to analyze the rolling-element bearings raceway geometry, the measuring tip is always perpendicular to the raceway surface and moves along its axis (see Figure 4). Therefore, the measurement is carried out in relation to rectangular coordinates. This can be considered as a simplification and a potential source of errors, as the angle of application of the tip to the raceway surface changes in structures of this type. In addition, when measuring the rounded surfaces, the point of contact of measuring tip with the surface is different each time. In the case of damaged or worn measuring tips, this can have a significant impact on the end result. An example of a rolling-element bearing raceway measurement using the Form Talysurf PGI 1230 profiler is shown in Figure 4.

In the case of the STPP system, measurements were made in polar coordinates along the arc with a defined curvature (radius). The reference radius was set by measuring the standard setting ring before proceeding further. Therefore, the STPP measurement system uses the differential measurement method, i.e. the difference between the actual raceway radius and the standard ring radius is measured at each point. This solution allowed to avoid the complicated calculations, which can result in additional errors. In addition, the tip is always set perpendicular to the raceway curvature, therefore it always measures at a specific point. Due to its compact design,

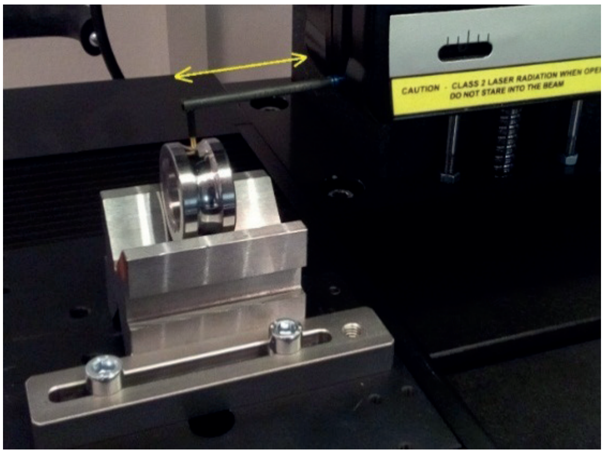


***Figure 4*** *Measurement of radius of the inner ring raceway using the PGI 1230 Form Talysurf system*

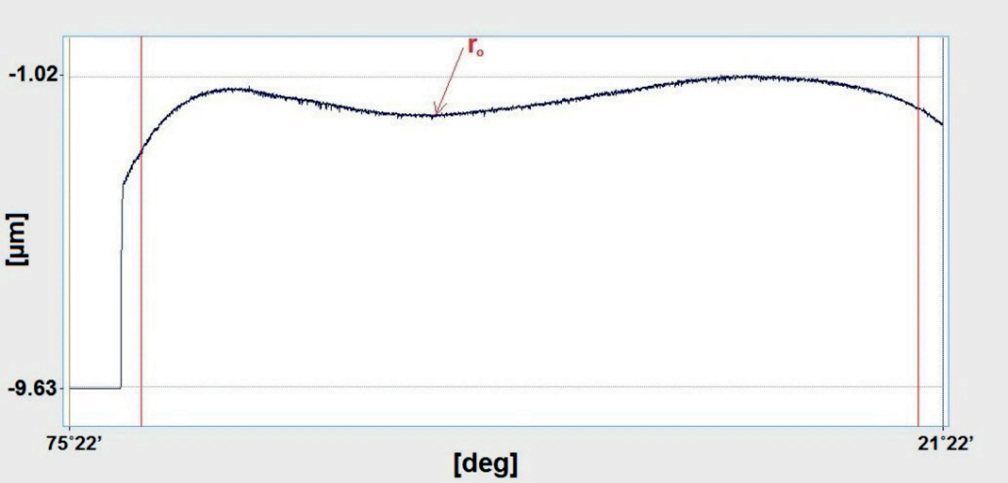


***Figure 5*** *Outer race profile measured using the STPP system*

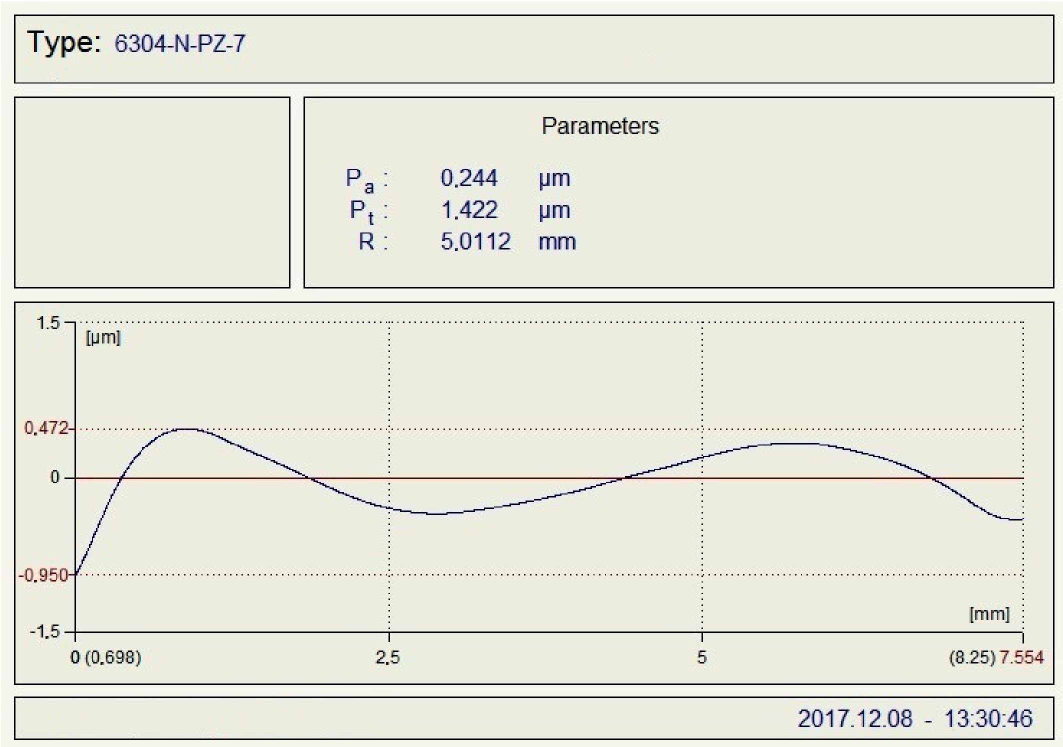


***Figure 6*** *Outer race profile after filtration*

***Table 1** Summary of results*

| | Vibration values, And | | | Raceway curvature ratio, % | |
|---|---|---|---|---|---|
| | LB | MB | HB | $f_i$ | $f_o$ |
| Numbers of samples | | | 50 | | |
| $\bar{x}$ | 8.81 | 9.10 | 8.53 | 51.85 | 52.73 |
| $x_{max}$ | 15.37 | 17.53 | 13.93 | 52.79 | 52.96 |
| $x_{min}$ | 4.52 | 5.12 | 3.33 | 51.54 | 52.40 |
| $R$ | 10.85 | 12.41 | 10.61 | 1.25 | 0.56 |
| $s$ | 2.504 | 2.973 | 2.364 | 0.002 | 0.002 |
| $V$ | 0.284 | 0.327 | 0.277 | 0.00004 | 0.00004 |

***Table 2** Vibrations values calculated for particular selection groups of the rolling-element bearings (for outer raceway curvature ratios $f_o$)*

| Selection group No | Range of outer raceway curvature ratios $f_o$, % | Vibration values, And | | | | | |
|---|---|---|---|---|---|---|---|
| | | LB | | MB | | HB | |
| | | $\bar{x}$ | $s$ | $\bar{x}$ | $s$ | $\bar{x}$ | $s$ |
| 1 | <52.40,52.57> | 8.47 | 2.46 | 8.18 | 1.89 | 8.52 | 1.12 |
| 2 | <52.58,52.73> | 9.68 | 3.34 | 9.19 | 2.42 | 8.15 | 2.15 |
| 3 | <52.75,52.80> | 8.55 | 1.91 | 9.30 | 3.54 | 8.35 | 2.82 |
| 4 | <52.81,52.86> | 8.42 | 1.61 | 8.42 | 3.18 | 7.77 | 2.48 |
| 5 | <52.87,52.96> | 9.04 | 2.82 | 8.87 | 3.70 | 7.20 | 2.95 |

the measuring instrument can be used directly in industrial conditions, for example at measuring workstations. Single, precise adjustment of the measuring instrument according to the standard allows for fast and easy measurements, which is particularly desirable in series production such as rolling-element bearings manufacturing. Figure 5 shows an example of the outer race profile measured using the STPP system, while Figure 6 presents the filtered profile together with calculated measurement parameters (radius of the outer race $R$ = 5.0112).

The next step in the study was to measure the diameter of the balls using a horizontal length measuring device KLM 60.01 from Steinmeyer. Based on the measured values, i.e. the radius of the outer and inner raceway and the diameters of the balls, the raceway curvature ratios for the outer and inner raceways were determined.

## 4 Results and discussion

A vibration analysis was carried out for each bearing. Vibration values were determined for three frequency ranges, i.e. low (LB), medium (MB) and high (MB). Then, for each bearing inner raceway $f_i$ and outer raceway $f_o$ curvature ratios were determined. The group of fifty rolling bearings was examined. Due to the large number of measurement results, Table 1 presents only results of statistical calculations obtained from all the measurement results, i.e. the average value ($\bar{x}$), maximum value ($x_{max}$), minimum value ($x_{min}$), mean squared error ($s$), range ($R = x_{max} - x_{min}$), and coefficient of variation $\left( V = \frac{s}{\bar{x}} \right)$.

Analyzing the results presented in Table 1, it can be concluded that the vibration values expressed in Anderon units (And) are characterized by increased variability in comparison to the raceway curvature ratios. However, considering the average values of vibrations in relation to specific frequency ranges (LB, MB, HB), it can be stated that the highest vibrations were recorded in the average frequency range of vibrations, i.e. 300 - 1,800 Hz. The lowest values were recorded for the high frequency range. However, one can see that the average values were similar for all the analyzed frequency ranges. High values of the mean squared error ($s$), determined for vibrations values, are indicative of the high variability of the measurement results. This indicates a large discrepancy in values of the vibrations generated by the tested bearing. For the average vibration frequency range, for example, the range was $R$ = 12.41 And. This is also confirmed by the high values of the coefficient of variation $V$ (see the last row in Table 1). For all the tested frequencies these coefficients were higher than 27%, which proves that the analyzed characteristics are statistically significant and have average variability. However, when considering the static values calculated for the raceway curvature ratios, it can be concluded that the results were more consistent when compared. For both the inside and outside raceway curvature ratios, the mean squared error values were very small ($s$ = 0.002%). Coefficients of variation demonstrated that the inner raceway curvature ratios were more differentiated than those of the outer raceway. In addition, it can be stated that the average the outer raceway curvature ratios were higher

***Table 3** Vibrations values calculated for individual selection groups of rolling-element bearings (for inner raceway curvature ratios $f_i$)*

| Selection group No | Range of inner raceway curvature ratios $f_i$, % | Vibration values, And | | | | | |
|---|---|---|---|---|---|---|---|
| | | LB | | MB | | HB | |
| | | $\bar{x}$ | $s$ | $\bar{x}$ | $s$ | $\bar{x}$ | $s$ |
| 1 | <51.54,51.62> | 8.24 | 2.09 | 8.89 | 2.73 | 9.80 | 2.59 |
| 2 | <51.66,51.78> | 8.77 | 2.86 | 9.51 | 2.68 | 9.21 | 2.06 |
| 3 | <51.79,51.89> | 9.22 | 3.37 | 8.61 | 3.72 | 8.75 | 1.98 |
| 4 | <51.92,52.01> | 9.22 | 2.43 | 9.22 | 3.27 | 8.20 | 2.83 |
| 5 | <52.05,52.79> | 8.48 | 1.46 | 9.47 | 3.08 | 7.71 | 2.76 |

than those of the inner raceway. However, these values are very close ($f_i$ = 51.85%, $f_o$ = 52.73%).

Due to the very small spread (variability) of raceway curvature ratios and in order to simplify analysis of influence of the raceway curvature ratios on values of the generated vibrations, the tested bearings were divided into 5 selection groups. In each group, ten bearings were analyzed. The divisions were made according to the obtained curvature ratios of the outer raceway $f_o$ (see Table 2) and inner raceway $f_i$ (see Table 3). For each selection group the average vibration values measured for the rolling-element bearings in a given selection group were calculated.

By analyzing the test results presented in Table 2, it can be concluded that an increase in curvature ratios $f_o$ determined for the outer raceway, results in a slight increase in the vibration values for low and medium frequencies. Looking at the results presented in Table 2, an increase in the outer raceway curvature ratios in the $f_o \in$ <52.40%,52.80%> (selection groups 1 to 3) causes a rapid increase in the vibrations recorded in the medium range of the MB vibration frequency. Then a decrease in the vibration values was observed. The situation is similar for the HB high frequency vibration range, where the increase in the raceway curvature ratio after the initial increase in vibration values from 2 to 3 selection group, causes a decrease in vibrations for the 3-5 selection group.

Analyzing the research results presented in Table 3, one can see that the increase in the inner raceway curvature ratio $f_i$ causes a moderate increase in the value of generated vibrations recorded in the low (LB) and medium (MB) frequency range. However, by analyzing the vibrations tested in the high frequency range (HB), a downward trend was observed, with an increase in the inner raceway curvature ratios. Nonetheless, similarly to the results obtained for the $f_o$, the initial increase in vibrations values is followed by a downward trend. It should be added that as the value of the curvatures ratios increases, the contact area of the ball with the raceways surface decreases. Then the rolling resistance decreases, which may result in a decrease in the value of generated vibrations. In addition, by analyzing the average values and standard deviations obtained for vibration values (see Table 3), one can see that these values are similar to each other for each frequency bands. This means that examined bearings types 6304 do not have significant manufacturing defects.

## 5 Conclusions

In the case of precise and important machine parts, proper operation of the rolling-element bearings is a critical factor that often affects the condition of entire devices or mechanisms. In many cases, manufacturers do not provide detailed information about the operating parameters of rolling-element bearings, such as vibration values, frictional moment values or the raceway curvature ratios. The rolling-element bearings of the same type can have considerably different parameters. It should be added that the values of generated vibrations are the basic parameter describing the technical conditions of new and used bearing assemblies. Excessive vibration values may indicate bearing defects, but they may also result from their design characteristics, e.g. the geometry of raceway and balls. Therefore, the article analyzes influence of the raceway curvature ratios on values of generated vibrations.

The tests presented in the paper demonstrated that the outer raceway curvature ratios reached higher values than those of the inner raceway. However, the results are very close, and for the analyzed bearings the values of the raceway curvature ratios did not exceed 53%. This type of bearings is designed to carry heavier loads, however, the frictional moment can be higher, which can directly influence values of generated vibrations. Vibration analysis showed that the highest values of vibrations were recorded for the average MB frequency range of vibrations, i.e. 300 - 1,000 Hz. However, the vibrations results for all the analyzed frequencies were characterized by a large discrepancy, which may indicate manufacturing defects, especially in light of the fact that the new rolling-element bearings were used in the tests. An increase in both outer and inner curvature ratios causes an initial increase in vibrations values and then their decrease. The only exception is in the high frequency band, where an increase in the inner raceway curvature ratio resulted in decreased vibrations. By analyzing the test results, it can be stated that with an increase of the raceway curvature ratio the coefficient of friction between the raceways and the rolling element decreases, which in turn may cause a decrease in the vibrations value.

Besides, it should be added that the vibrations values recorded in the low and medium frequency range depend, among others, on shape errors in the balls and raceways, lubricant contamination or incorrect assembly. Therefore, when examining the effect of the values of raceway curvature ratio on values of generated vibrations that were analyzed in the frequency range 50 - 1800 Hz it should be consider the impact of these factors on the final measurement result.

However, the vibrations values analyzed in the high frequency ranges, i.e. above 1 800 Hz, result from the bearing operation characteristics. Therefore, this frequency range should be analyzed in details in terms of assessing the impact of the bearing curvature ratio value on the generated vibrations values.

The research results presented in the paper provide some guidelines for manufacturers of low-noise rolling bearings that it is recommended to design the rolling bearings with higher values of the curvature ratio, as this reduces the values of generated vibrations and reduces the rolling resistance.

The studies presented in the article are preliminary for a broader assessment of the influence of selected factors on the level of generated vibrations. It should be noted that the tested bearings were obtained directly from the manufacturer, so the raceway curvature ratios were in the narrow range of 51.54% to 52.96%. In further research, the author will examine bearings with a broader range of raceway curvature ratio. Other types of bearings will undergo testing, as well. The results presented in this article will be used to develop mathematical models allowing for the assessment of influence of selected factors on values of vibrations generated by the ball bearings.

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Jozef Matuszek - Tomasz Seneta - Luboslav Dulina - Eleonora Bigosova

# MANUFACTURABILITY ASSESSMENT OF THE PRODUCT ASSEMBLY PROCESSES DESIGN IN THE AUTOMOTIVE INDUSTRY

*The paper presents a methodology for the design of the production process of a new product from the point of view of manufacturability criterion assembly operations (Design for Assembly - DFA) in the automotive industry. Methods and techniques, used in implementation of the DFA method to produce a new product, are mentioned. Impact of those methods on improving the assembly technology of a complex product is described. Suggestions for improving the abovementioned methods are presented, as ell. The examples given illustrate the proposed procedures.*

***Keywords:*** *production process design, design manufacturability*

## 1 Introduction

In modern market conditions, enterprises, introducing new products and innovative solutions in production processes, use various methods and techniques to rationalize the activities that make up the concept of production preparation. The issue has extensive literature in which project management methods are presented and various approaches assessing the process of production preparation using the philosophy of Design for Six Sigma, Implementation of the quality function - QFD, Value engineering VE, Design for assembly/ design for production - DFA/DFM, Target Costing [1]. As a result of technical progress in the conditions of the large production volume, when implementing new products, relatively less attention is paid to ever-wider technological possibilities: modern workstations, workshop aids, automation - to achieve the high efficiency and relatively low costs of process components of the final production. Hence, the advanced methods, described in the literature for assessing the possibilities of manufacturing products, are oriented on assembly processes and are adapted to assess implementation of a new product in conditions of high - volume and mass production.

This is due to the high proportion of manual work compared to machining, the significant share in the costs of the entire production process, the high labour intensity and high costs of the assembly process.

## 2 Production preparation processes

To describe the processes of mass production a new product implementation model is used, proposed by AAIG (Automotive Action Industry Group - Automobile Manufacturers Association), described in the APQP manual - Advanced Product Quality Planning (Figure 1) [2-4].

There are many proposals in the automotive industry for use of the design-oriented assembly assessment methods. Design for Assembly - DFA, are described by G. Boothroyd and P. Dewhurst in [5]. The concept of Design for Assembly can be defined in a variety of ways, from the relatively narrow meaning of product design from the point of view of assembly technology criteria to the broader term associated with the term product design and process flow from the point of view of the cost-effective and reliable manufacturing criterion for ensuring customer satisfaction and achieving financial success [6]. Many DFA methods are presented in the literature. The chronology of these methods development and their brief description characterizing their use is presented in Table 1 [7].

The first two methods are presented in the paper due to the greatest practical application. Competition on the market forced companies to take a comprehensive approach to rationalizing the design and marketing of a new product [8-9]. This situation evoked the need for a broader view on the assessment of the technology of the structure, including this problem, considering many other aspects; this way of design is illustrated in Figure 2.

Other methods - QFD (Quality Function Deployment) [10-11] have also found application in the processes of designing products that complement or support the DFA methods. [11] - used to implement customer requirements in initial product assumptions, FMEA (Failure Mode and Effect Analysis) [12] - predicting and preventing product failure at the design stage, DFX (Design for X) [13-14] - e.g. Design for Manufacturing (DFM) means the design

**Jozef Matuszek[1], Tomasz Seneta[1], Luboslav Dulina[1], Eleonora Bigosova[2,*]**
[1]Katedra Inzynierii Produkcji, Wydzial Budowy Maszyn i Informatyki, Akademia Techniczno-Humanistyczna w Bielsku-Bialej, Poland
[2]Department of Industrial Engineering, Faculty of Mechanical Engineering, University of Zilina, Slovakia
*E-mail of corresponding author: eleonora.bigosova@fstroj.uniza.sk

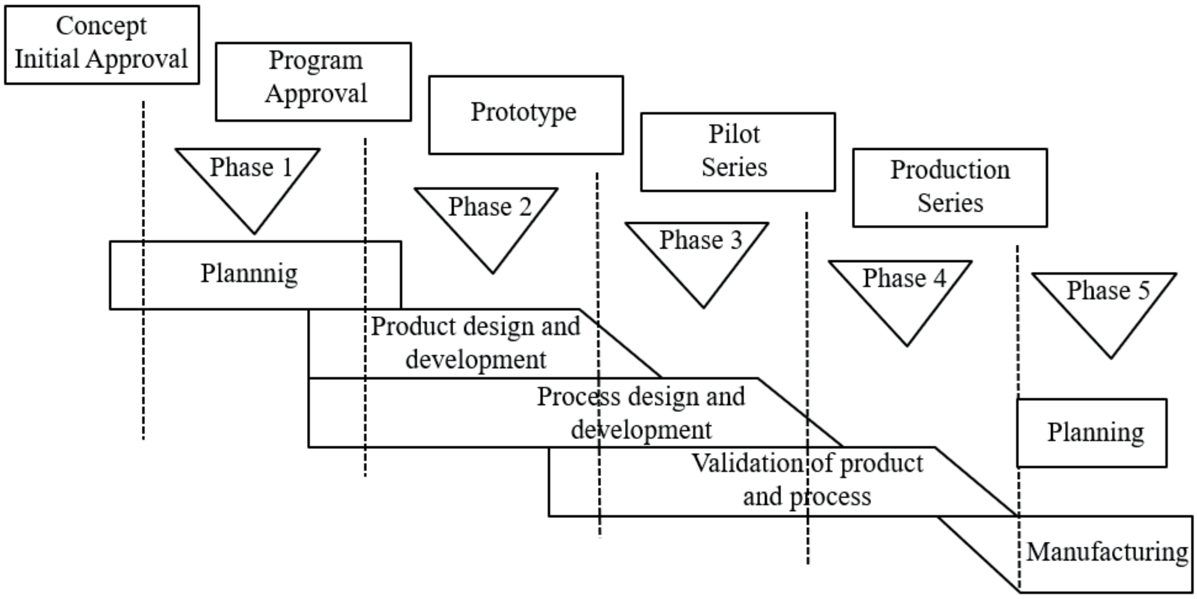


***Figure 1*** *Model of implementing a new product according to AAIG [2-4]*

***Table 1*** *Summary and description of the methodology of selected Design of Assembly methods [1]*

| Nr | Method | Year | Discoverers | Description |
|---|---|---|---|---|
| 1 | Lucas DFA | 1980 | Redford A. H., Swift K. G. | It is based on Assembly Sequence Diagram, evaluating the assembly design. Evaluates and adds penalty points related to product design issues. |
| 2 | Hitachi Assemblability Evaluation Method (AEM) | 1986 | Miyagawa S., Ohashi T. | This method evaluates the product's assemblability and cost index to identify weaknesses associated with the project design. |
| 3 | Product Assemblability Merit Analysis Tool (PDM) | 1986 | Zorowski C. F. | The method issues opinions on product and component assembly problems and an oversizing indicator. |
| 4 | Boothroyd and Dewhurst | 1988 | Boothroyd G., Dewhurst P. | The method is based on an experimental study of the costs associated with a manual or automatic assembly process and has three criteria for limiting the number of components. |
| 5 | Integrated Design for Assembly Evaluation and Reasoning System | 1991 | Sturges R. H. Jr, Kilani M. I. | The method built on the existing solid modelling package examines the product's assemblability. |
| 6 | Fuzzy Product Assemblability Merit Analysis Tool | 1993 | Jackson S. D., Sutton J. C., Zorowski C. F. | PDM developed with fuzzy logic. |
| 7 | DFA REV-ENGE | 1994 | Kim G. J., Bekey G. A. | DFA method considering reverse engineering. |
| 8 | Constraints Network System | 1995 | Oh J. S., Grady P. O., Young R. D. F. | The method of related restrictions. |
| 9 | Virtual Disassembly Evaluation | 1998 | Srinivasan H. | Method considering virtual disassembly. |

of many structural elements that shape the production process [15-16]. These methods are related to concepts, such as simultaneous engineering, Six Sigma, Lean, WCM (World Class Manufacturing) and others. Decisions taken at the product design stage do not have a significant impact on production costs only, but on the production efficiency and quality, as well. Supporting methods such as modelling are of great importance in carrying out these works, simulation and animation of production processes and systems and ideas stimulating innovation such as brainstorming, TRIZ (Theory of solving innovative tasks) and others.

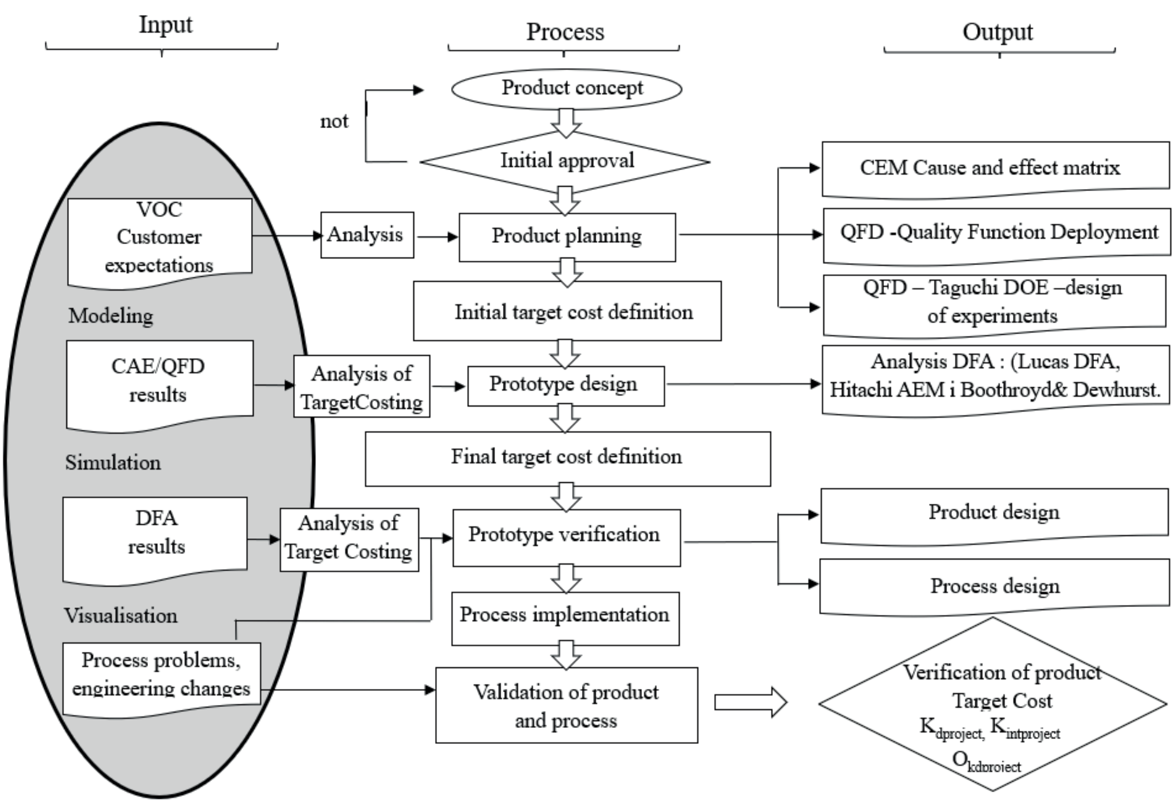


*Figure 2* *Use of methods supporting the design of the production process of a new product*

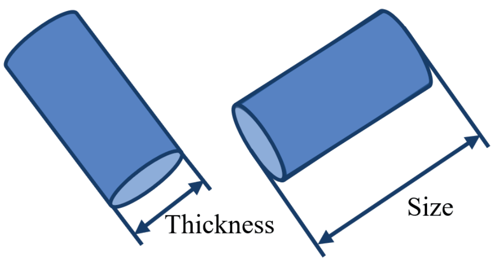


*Figure 3* *Determining the thickness and size of parts [3]*

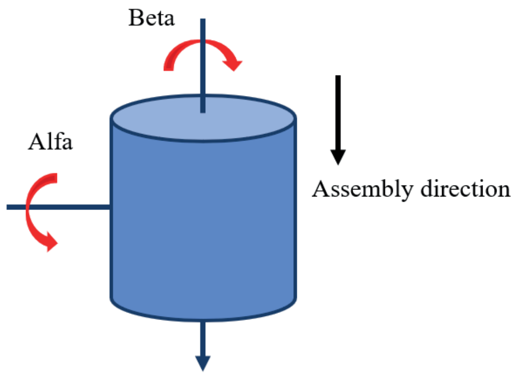


*Figure 4* *Determining alpha and beta angles [3]*

## 3 Production manufacturability assessment methods

### 3.1 Boothroyd Dewhurst method

The method was developed in the late 1970s. by Geoffrey Boothroyd at the University of Massachusetts in Amherst in cooperation with the University of Salford in England. The method contains eight principles aimed at: reducing the number of components, eliminating corrections, using self-positioning and self-embedding components, ensuring adequate access and unrestricted field of view, ensuring ease of assembling parts with looseness, minimizing the need for reorientation during the assembly, eliminating parts, that cannot be installed incorrectly, maximizing symmetrical parts, if possible, or if not clearly asymmetrical. The method assumes that the part is a permanent or non-permanent element of the assembly process. A subassembly is considered as a part if it is added during the assembly. However, glues, fluxes, fillers, etc., used to connect parts are not considered parts. Each part has two parameters - thickness and size. The thickness is the length of the shortest side of the smallest cuboid that surrounds the element. If the element has a cylindrical or regular polygonal shape, e.g. a section with five or more sides, the thickness is defined as the radius of the smallest cylinder that surrounds the element (Figure 3). The size is the length of the longest side of the smallest cuboid that can surround the part.

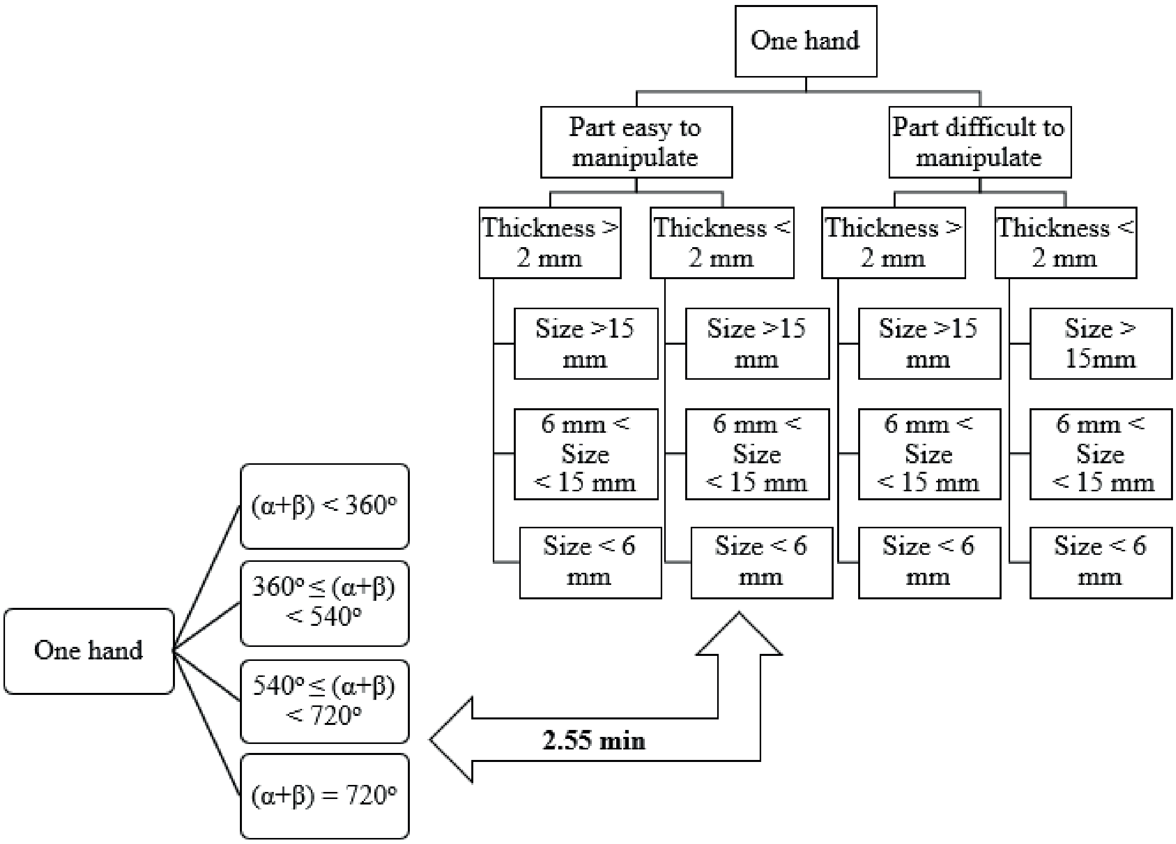


***Figure 5*** *Diagram for determining the index of manipulation with one hand [17]*

The next step is to evaluate the symmetry of the element and determine the number of degrees of rotation around both axes for proper orientation and alignment, Figure 4, [3].

BETA is the symmetry of the part relative to the insertion axis, i.e. the smallest rotation angle for correct insertion. ALFA is the symmetry of the part about the axis perpendicular to the insertion direction - the smallest angle between alternative insertion directions [3]. After determining the thickness, size, BETA and ALFA angles, the next step is to formulate the indexes of handling time and the time of inserting / assembling individual components. To this end, use schemes and tables prepared by Boothroyd and Dewhurst (Figure 5).

The total number of operations to assembly product is:

$$L_o = l_{o1} + l_{o2} + \ldots . l_{oi} + \ldots . l_{on}, \tag{1}$$

where:
$l_{oi}$ - i-th assembly operation.

The total product assembly time is calculated as:

$$T_o = \Sigma t_{oi} = I_{ma} + I_{mo}, \tag{2}$$

where:
$t_{oi}$ - duration of the i-th assembly operation,
$I_{ma}$ - part handling index, $I_{mo}$ - part assembly index.

Total costs of assembly product is:

$$K_o = \Sigma k_{oi}, \tag{3}$$

where:
$l_{oi}$ - i-th assembly operation,
$k_{oi}$ - unit cost of i-th assembly operation [17].

When determining the time index for manipulation of a part, it should be determined whether manipulation can be performed: with one hand, one hand with an auxiliary handle, two hands, two hands with mechanical assistance. Knowing the assembly times, one can proceed to process analysis, e.g. whether one should reduce the number of assembled parts, replace them with other, more complex ones. Lowering the number of components of a product may increase their complexity and increase their manufacturing costs. The final product can be easy to assemble and expensive to process its components. This method is used to analyse manual assembly; separate variants of the method are used to analyse automatic assembly. The final stage is calculation of a sum of the number of operations, total operation time, total operation costs, theoretical minimum number of parts and the DFMA index illustrating the state of the product technology. The next stage of analysis is to check whether a given part can be eliminated. A diagram of the course of proceedings regarding the elimination of parts is given in Figure 6 (assessment of possibility for occurrence of several parts in the form of one whole).

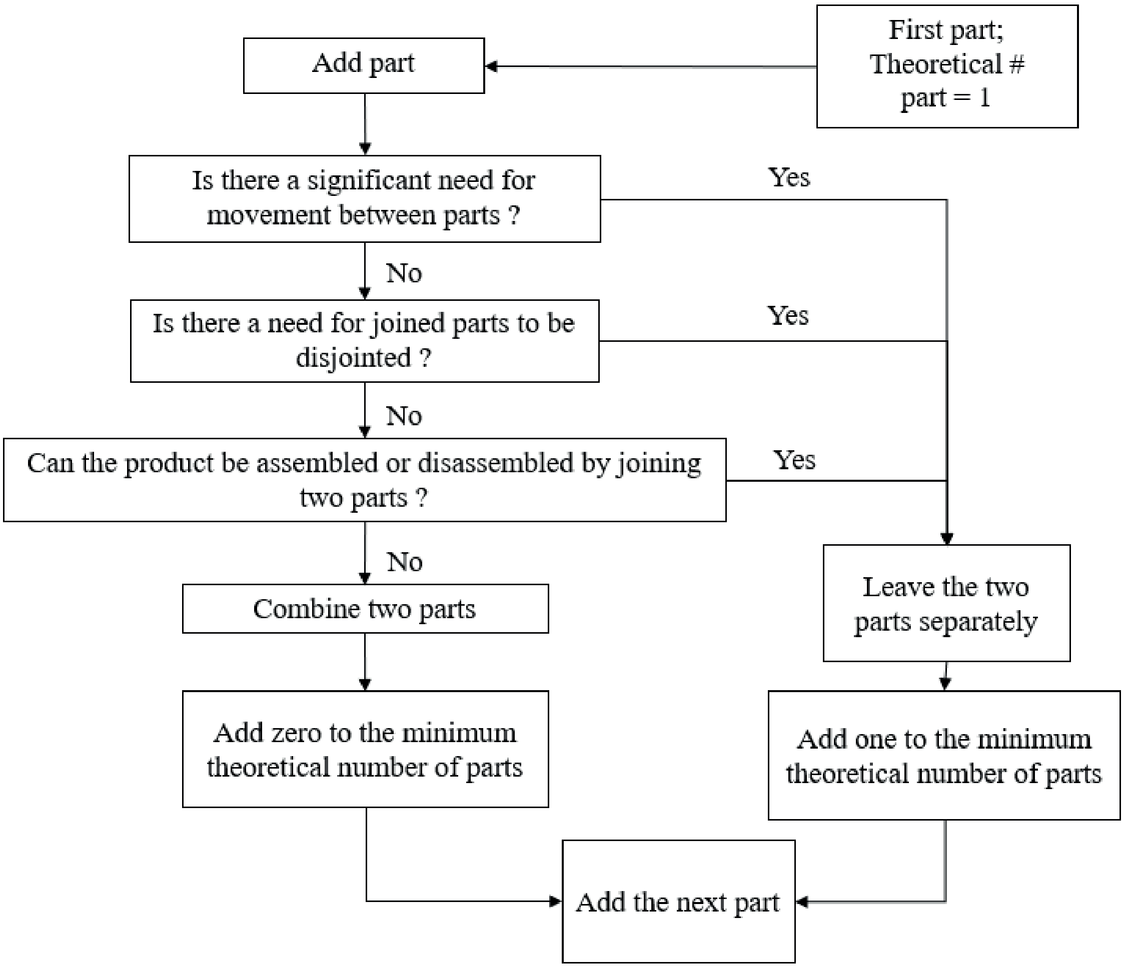


***Figure 6*** *Design for Assembly B & D components elimination diagram [17]*

The theoretical minimum number of parts is:

$$C_t = C_{pe} - C_{ae}, \tag{4}$$

where:
$C_{pe}$ - number of parts before elimination analysis,
$C_{ae}$ - number of parts eliminated as part of the elimination analysis.

The final stage is determining the DFMA indicator, while considering the costs of the assembly operation being carried out:

$$DFMA_{index} = (3 \cdot L_o)/T_o, \tag{5}$$

for many parts, it can be assumed that: $L_o = A$ and where:
$DFMA_{index}$ -*DFMA* index,
$A$ - the number of parts necessary for the product to function (the study assumes that: $L_o = A = C_t$),
$T_o$ - total product assembly time) [17].

### 3.2 Lucas DFA method

The method was developed in 1980. by Lucas research teams and University of Hull researchers, [17]. The method is used to analyse manual or automatic assembly. In the Lucas DFA method, three indicators determine the measure of mounting difficulty. The procedure is as follows. The prepared project is subjected to functional analysis, which determines whether individual components are needed and what their functions are (Figure 7).

A feasibility analysis is then conducted consisting of manoeuvring analysis and assembly analysis. Data for analysis can be read for specific installation conditions from tables developed by the authors of the method [18].

The project effectiveness index $W_{ep}$, based on functional analysis, is determined by the formula:

$$W_{ep} = [L_{kA}/(L_{kA} + L_{kB})]100\ \%, \tag{6}$$

where:
$L_{kA}$ - number of components A (fulfilling the functions of a product),
$L_{kB}$ - number of components B (characterized by a lack of product function e.g. rivets, washers) [18].

Based on the analysis carried out in this way, it is possible to combine some separate components into one whole, thereby reducing the number of individual components that make up the final product, change design solutions that eliminate components that do not fulfil

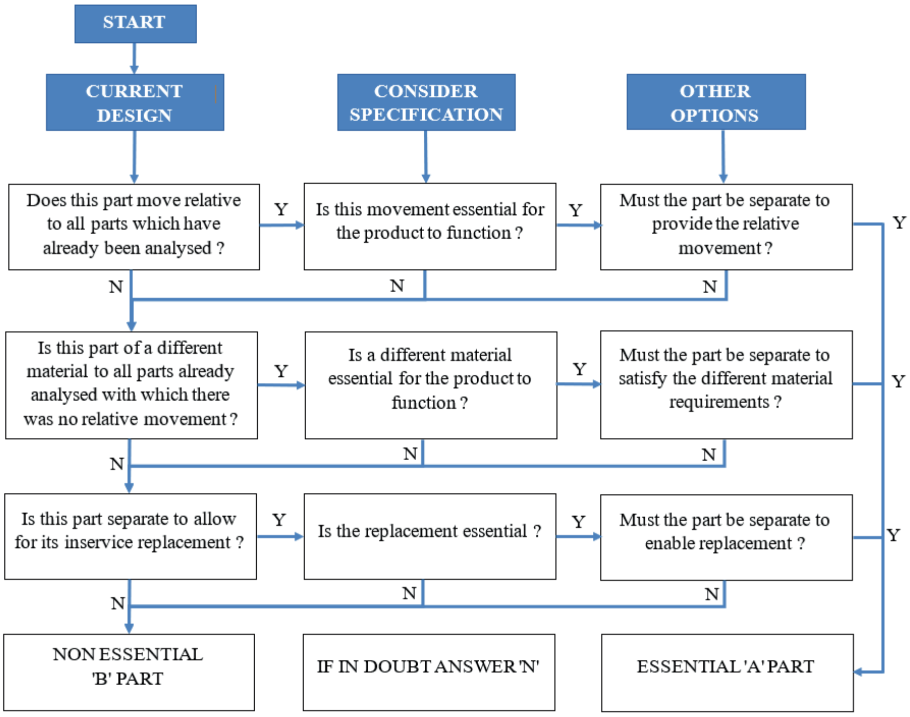


***Figure** 7 Diagram of functional analysis in LUCAS Design for Assembly [18]*

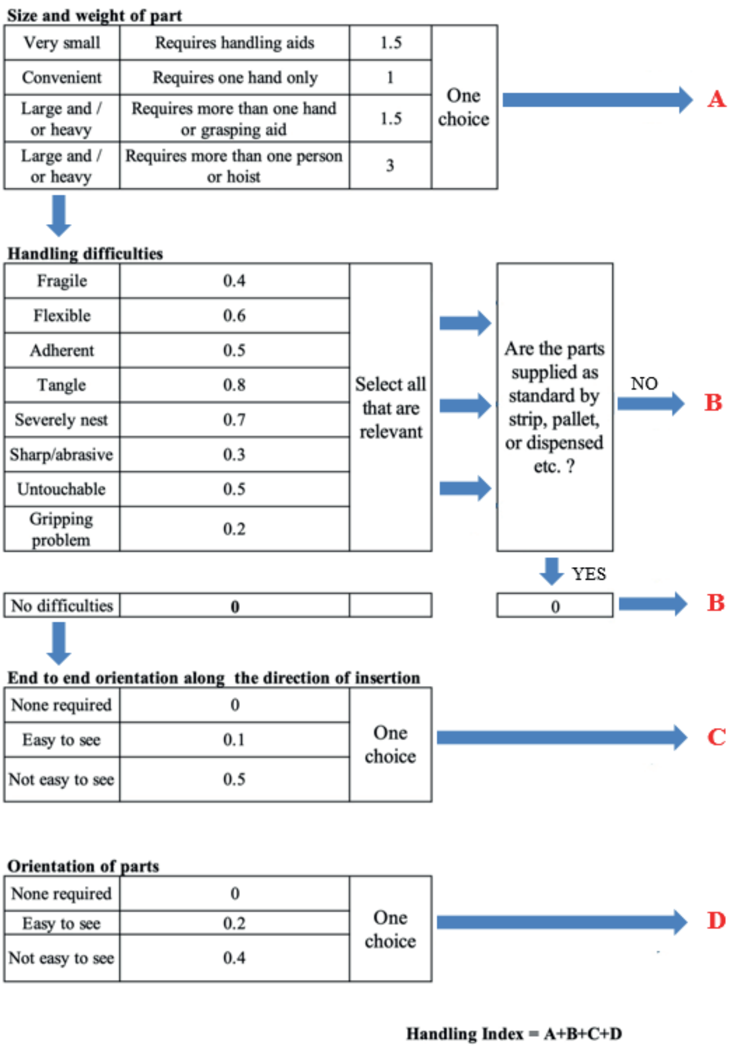


***Figure** 8 Manoeuvring analysis scoring diagram in LUCAS DFA [18-19]*

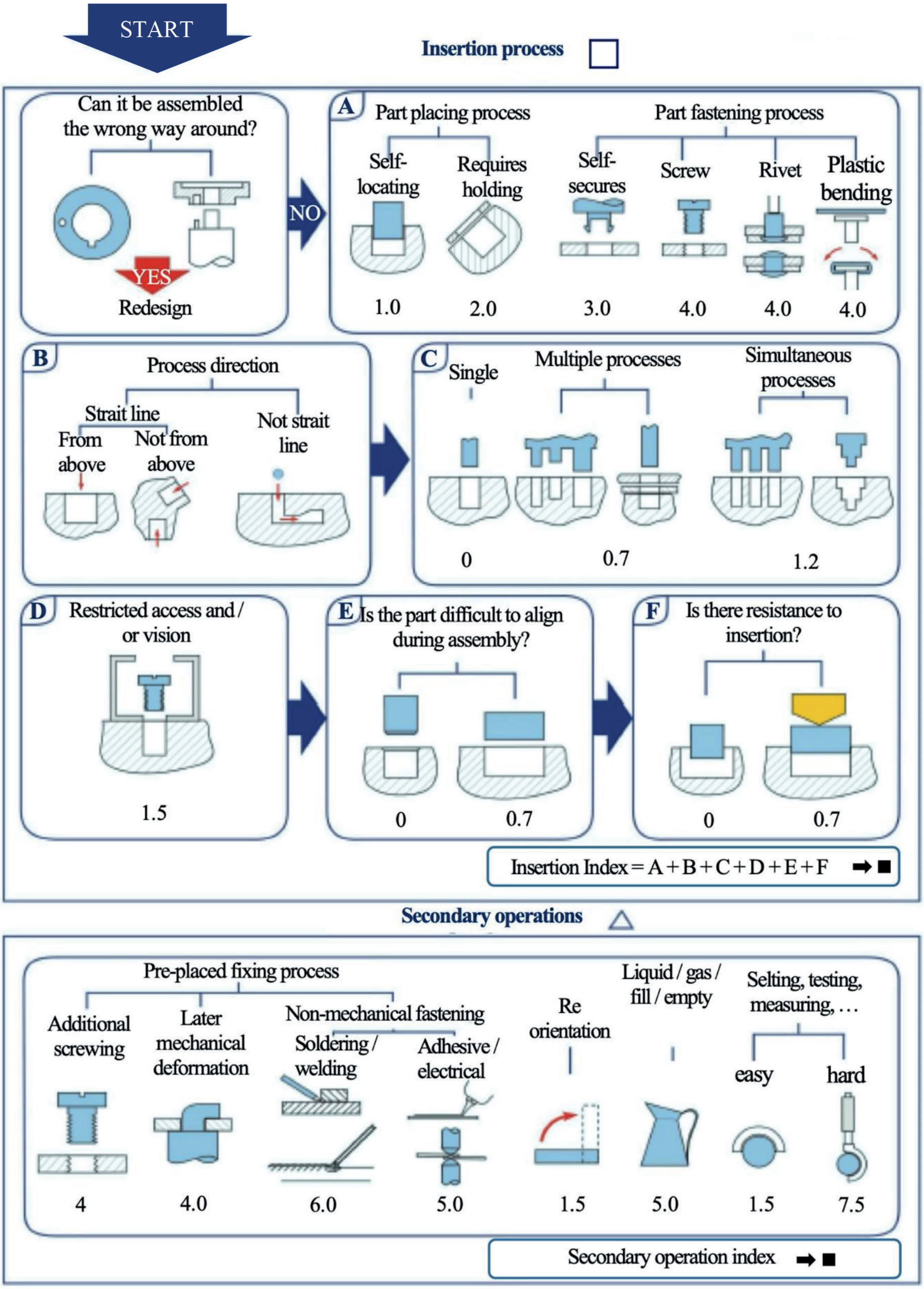


***Figure 9*** *Assembly analysis scoring diagram in LUCAS DFA [18]*

the function of the product. Then, an analysis is carried out consisting of an analysis of the displacement of the mounted components, their manoeuvring and the method of assembly itself. The manoeuvring assessment of the assembled product components is determined based on Figure 8.

Manoeuvring factor $W_{man}$ is given by the formula:

$$W_{man} = I_{man} / L_{kA}, \tag{7}$$

where $W_{man}$ is the manoeuvring factor and

$$I_{man} = L_{pA} + L_{pB} + L_{pC} + L_{pD}, \quad (8)$$

where:
$I_{man}$ - manoeuvring index,
$L_{kA}$ - number of type A parts.

Values of $L_{pA}$, $L_{pB}$, $L_{pC}$, $L_{pD}$ are specified from tables provided by the authors of the method [18].

The analysis also makes it possible to make structural changes to the product and its components improving the efficiency of assembly processes and the method of assembly technology designed (e.g. use of the special equipment to facilitate manoeuvring of the assembled component).

Another element of the technology assessment is assessment of the errors risk in individual assembly operations and impact of the adopted construction solutions on the labour intensity of individual assembly operations. Assessment of the assembly operations progress, from the feasibility point of view, is carried out based on Figure 9.

The formula describing results of the analysis of the $W_{mon}$ assemblability coefficient according to the Lucas DFA method is:

$$W_{mon} = (W_m + W_d)/L_{kA}, \quad (9)$$

where:
$W_m$ - main activity indicator wherein, $W_m = L_{mA} + L_{mB} + L_{mC} + L_{mD} + L_{mE} + L_{mF}$,
$W_d$ - indicator of additional activities, values making up the $W_m$ and $W_d$ parameters are specified in tables provided by the authors of the method,
$L_{kA}$ - number of the type A parts [18-19].

## 4 Conclusions

The B&D and Lucas DFA methods are methods developed for the needs of assembly operations in the conditions of mass production. By analysing the obtained values of assembly efficiency assessment parameters in both methods it is possible to:

- Reduce times, eliminate of errors, reduce the process costs.
- consider, in addition to assembly, many other various factors, e.g. availability of spare parts, mass production, production conditions in the form of equipment types, available assembly techniques, level of automation, scope of external cooperation orders, etc.

The conditions of modern production, striving to manufacture products tailored to the individual wishes of the customer, with the largest possible serial production of component parts causes the need to modify or develop new methods for analysing the product design technology. The assessment should consider many other factors, sales, servicing, spare parts availability, production series, types of equipment, available assembly techniques, level of automation, cooperative services, possibilities of using commercial components, technical culture of the crew, etc. The new methods developed should also be used for smaller series of manufactured products in the case of the production of a group of technologically similar products. A helpful action in the assessment of the structure is use of standardization of machining and assembly operations, which makes it easier to determine the times of performing those operations. The assessment of the construction arouses the creativity of designers, the course of action can be carried out for the product, its components such as assemblies, subassemblies, etc.

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Matus Danko - Juraj Adamec - Peter Drgona - Michal Frivaldsky

# RECOVERY PROCEDURE FOR DEEPLY DISCHARGED $LiFePO_4$ TRACTION BATTERY

*Presented paper deals with possibility of recovery of damaged traction batteries by deep discharge. For the test of proposed charging algorithm, new, unused cell was selected, the deeply discharged condition of which was caused by the self-discharge during the improper storage. The cell had significant damage of package in the central part. For the battery testing, experimental set-up was realized for automated recovering procedure and other tests of cells. For verification of the proposed algorithm, a recovered cell was compared to a reference/new cell by testing the delivered ampere-hours for various discharging current. The final evaluation shows that the proposed algorithm for recovery of the deeply discharged cell can recover up to 70% of the nominal cell capacity.*

***Keywords:*** *traction battery, deep discharge, battery recovery,* $LiFePO_4$

## 1 Introduction

Lifetime of lithium batteries can be divided into four phases. The first phase starts at production, where batteries are made and tested. If the test failed, batteries are directly recycled. Batteries are produced as uncharged, whereupon batteries must be charged before the first use, which is the next and most important phase of the battery lifetime. Initial charging and discharging are called formatting and has significant impact on the battery performance. The most important parameters during the formation are number of charging/discharging cycles, battery current and battery voltage. This process is executed by the manufacturer during the manufactured batteries testing. Those tests are performed in order to detect bad batteries with lower capacity. Most often, batteries are discharged to 50% of capacity and stored several weeks for testing the self-discharge and open circuit voltage (OCV) is measured. Batteries, capacity of which falls below 47%, fails the test and are recycled. The next phase is using batteries in application, which has significant impact on the battery lifetime, based on charging/discharging current, charging voltage and other parameters, [1-3]. The next conditions, which can impact the battery lifetime are overcharging or over-discharging. End of the battery lifetime is the last phase and usually occurs at 80% of state of health of a battery. Batteries can be recycled by various methods, based on the battery chemistry. For the lead acid batteries, about 99% of lead from used batteries is reclaimed. From the lithium-ion batteries, lithium-iron-phosphate (LiFePO4) is possible to recycle for up to 80% of the batteries' material, [4-6]. Depending on the battery active materials, it is possible to recover cobalt, manganese and nickel for reuse in producing new batteries. However, manufacturing batteries from the recycled materials is five times more expensive than manufacturing from the new ones, so for many manufacturers it is more cost-effective to produce batteries from the new materials, [7-10].

After the battery's state of health falls to 80% and battery is not suitable for original application, it is possible to continue using it in other application where demands on battery performance are not high, for example in storage for photovoltaics, [9-11]. Recovery of damaged batteries as well as recycling is therefore a topic, which must be accepted if sustainability related to environment and costs are considered, [12-14]. Therefore, within the presented paper, the experimental methodology for deeply discharged battery recovery is being introduced.

## 2 Selected cell and test-stand

For testing of the battery recovery algorithm, WINA 3.2V 60Ah LiFePO4 cell was selected. Parameters of the cell are listed in Table 1. This cell has significant damage of package in central part of the cell. The width of the cell reached 43.8 mm while the width of the new cell, specified by manufacturer is 36 mm, (Figure 1). The deep discharge condition was confirmed by measurement of the open circuit voltage, which was only 2.04V. The minimal voltage of the selected cell in datasheet is 2.5V. Selected cell was new, unused and its deep discharge was caused by improper storage and cell voltage decreased below the minimal cell voltage because of the self-discharge. The permissible self-discharge, specified by the cell manufacturer is a loss of 3% of capacity over a month period, [15].

**Matus Danko, Juraj Adamec, Peter Drgona, Michal Frivaldsky***
Department of Mechatronics and Electronics, Faculty of Electrical Engineering and Information Technologies, University of Zilina, Slovakia
E-mail of corresponding author: michal.frivaldsky@feit.uniza.sk

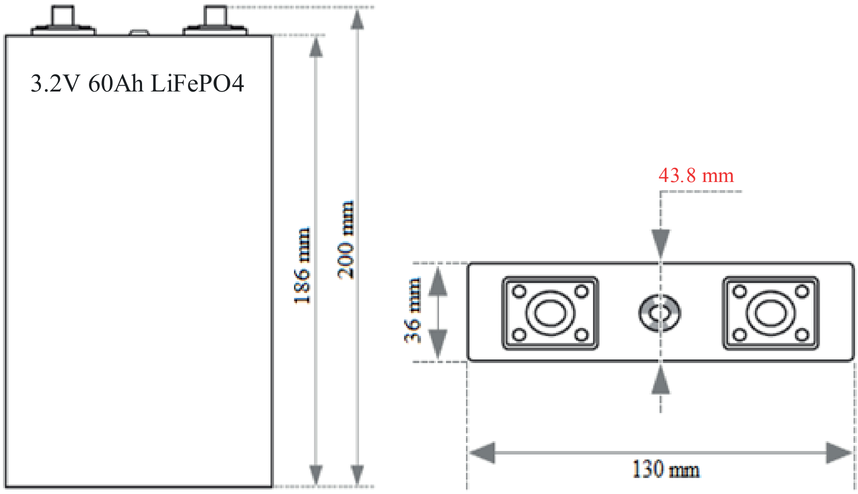


***Figure 1** Dimensions defined by manufacturer and change of width in the central part*

***Table 1** Technical parameters of investigated cell WINA $LiFePO_4$ 3.2 V 60 Ah*

| Parameters | Value | unit |
|---|---|---|
| Nominal voltage | 3.2 | [V] |
| Maximum charging voltage | 3.8 | [V] |
| Minimum voltage | 2.5 | [V] |
| Maximum discharge current (continuous) | 3 | [C] |
| Optimal discharge current | 20 | [A] |
| Maximum charging current | 90 | [A] |
| Optimal charging current | 20 | [A] |
| Operating temperature | -20 to +50 | [C°] |
| Capacity | 60 | [Ah] |
| Shell material (package) | aluminum | [-] |

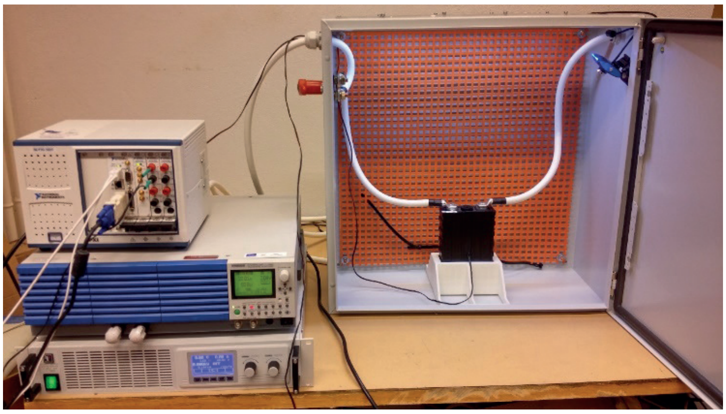

***Figure 2** Experimental test-stand for the traction batteries recovery*

### 2.1 The test-stand for battery recovery testing

To secure safety, the recovery procedure and other tests of traction batteries were executed on a designed test stand, which can be seen in Figures 2 and 3. The test stand consists of a metal box where the battery is located, programmable power supply EA PSI 8080-60, programmable electronic load KIKOSUI PLZ 100W and NI PXI-1031 for control, temperature measurement and logging (current/voltage/temperature). To prevent the hazardous situation, the power line of a battery is protected by a mechanical switch. By using the LabVIEW application of NI PXI it is possible to create a sequence of charging or discharging of the cell.

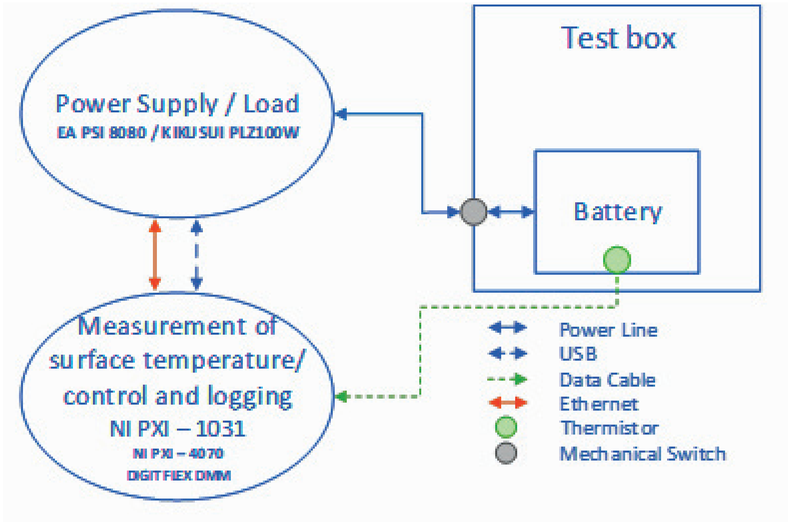


***Figure 3** Block diagram of **the** test-stand for the traction batteries recovery*

***Table 2** Setting of sequences of regeneration algorithm for deeply discharged cell*

| | Duration | Amplitude of charging current | Charging voltage |
|---|---|---|---|
| Sequence | 126 min<br>consists of subsequences 1 and 2 | 20 A | 3.65 V |
| Subsequence 1 | 30 charging pulses<br>30 pause pulses<br>alternating<br>one pulse = 1 second | | |
| Subsequence 2 | Regeneration period<br>5 min | | |

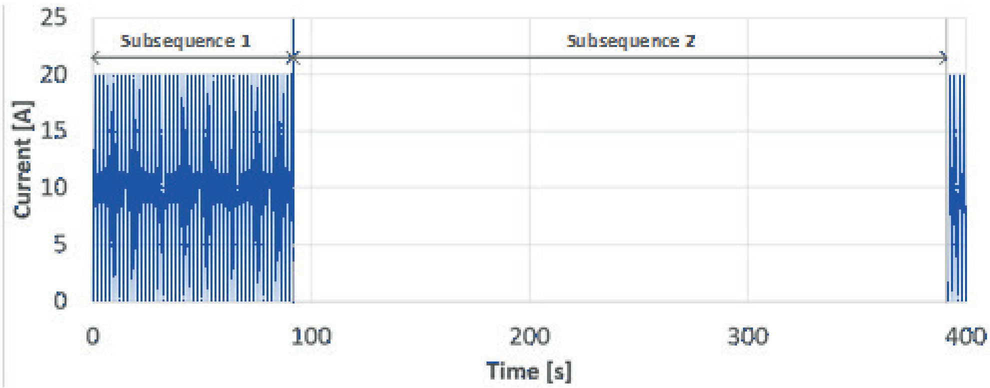


***Figure 4** Graphical interpretation of proposed regeneration sequence for deeply discharged cells*

## 3 Charging algorithm for recovery of the deeply discharged cells

Algorithm for recovery of the deeply discharged cells consists of 30 steps of charging and 30 steps of pause, mutually alternating, while each steps lasts 1 second (Figure 4). After that, battery is resting for 5 minutes for a cell to regenerate. The whole algorithm lasts 126 minutes; it consists of 21 sequences, as can be seen in Table 2. Amplitude of the charging current was selected, following recommendation from manufacturer, to 20 A, which is 1/3 of capacity of a cell. Maximum of charging voltage was selected to 3.65 V. For the given battery, application of six sequences was realized in order to achieve required OCV on the device, while 16 hours of resting period was applied between individual sequences.

Figures 5-7 show time waveform of the cell voltage during each sequence application. It is seen that voltage increased from 2.04 V up to 3.19 V at the end of the first sequence, while during the last sequence the voltage level

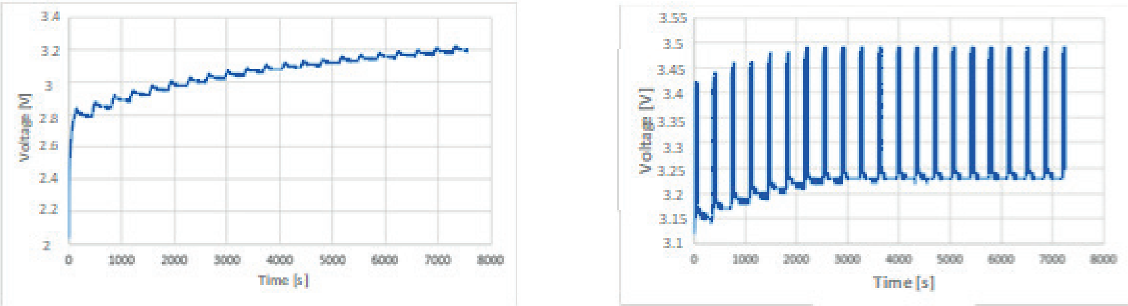


***Figure 5*** *Voltages of cells during the first sequence (left) and second sequence (right) charging*

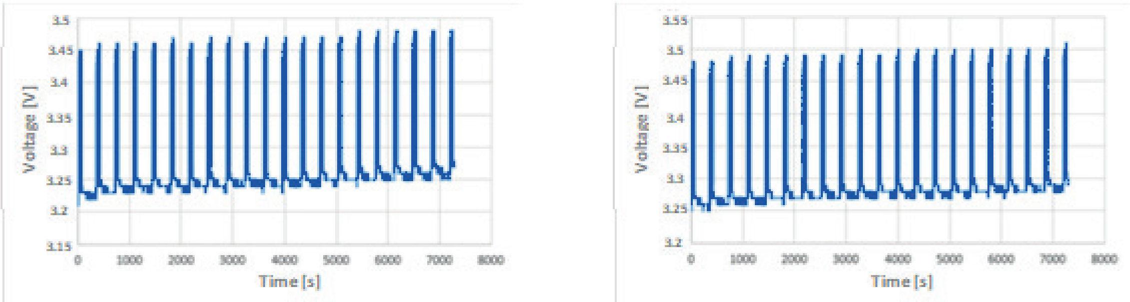


***Figure 6*** *Voltages of cells during of the third sequence (left) and fourth sequence (right) charging*

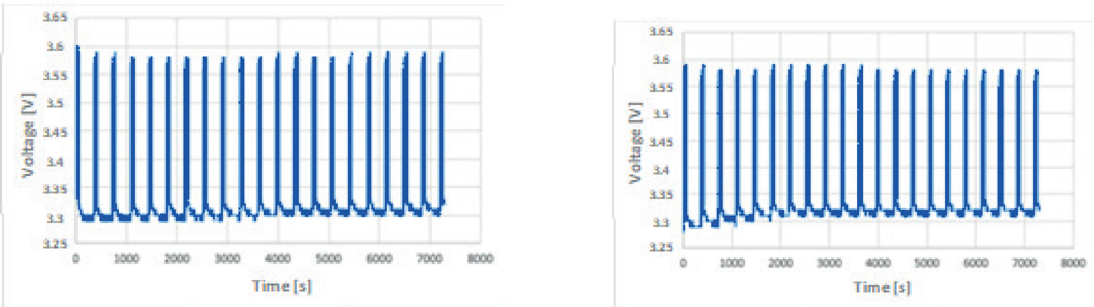


***Figure 7*** *Voltages of cells during the fifth sequence (left) and sixth sequence (right) charging*

***Table 3*** *Voltage levels before and after each regeneration sequence of deeply discharged cell*

| Sequence | Voltage on a cell before the sequence | Voltage on a cell after the sequence |
|---|---|---|
| 1 | 2.04 V | 3.19 V |
| 2 | 3.12 V | 3.21 V |
| 3 | 3.19 V | 3.27 V |
| 4 | 3.21 V | 3.28 V |
| 5 | 3.24 V | 3.29 V |
| 6 | 3.26 V | 3.31 V |

on the cell exceeded 3.3 V. Voltage of all the sequences are listed in Table 3. The temperature on the cell surface during each sequence was within 25.38 ˚C - 26.18 ˚C.

## 4 Verification of the recovery algorithm

Recovery was tested trough delivered ampere-hours. Before the testing, it is required to fully charge the recovered cell. Selected cell was charged by the CC&CV (Constant Current and Constant Voltage) method, with parameters for optimal charging from datasheet. Maximal charging current was 20 A as 1/3 of capacity of cell and maximum charging voltage of cell 3.65 V. The recovered cell is verified in a way of delivered ampere-hours test (test of capacity), whereby the new un-damaged cell has been used as a reference device for comparison and evaluation. For the test of the recovered cell capacity, five discharging currents have been verified i.e. 20 A, 40 A, 60 A, 80 A. After each test, the cell was re-charged to full capacity, as mentioned above.

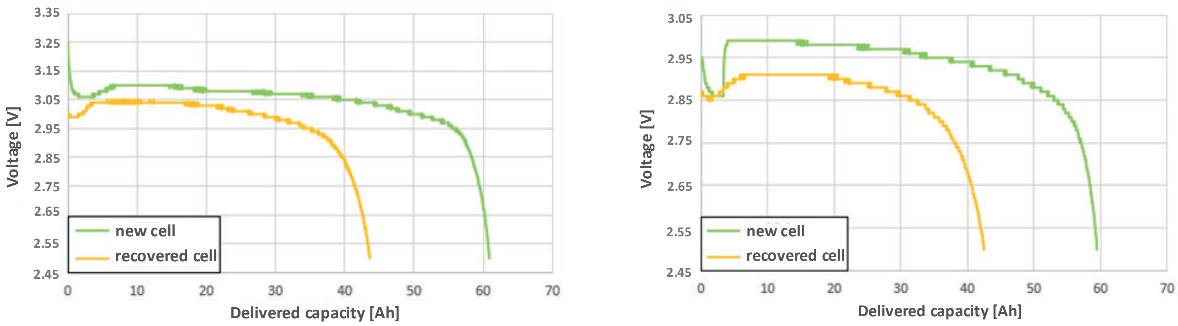


***Figure 8** Cell voltage during the discharge by 20 A (left) and 40 A (right) for regenerated (yellow) and referenced cell (green)*

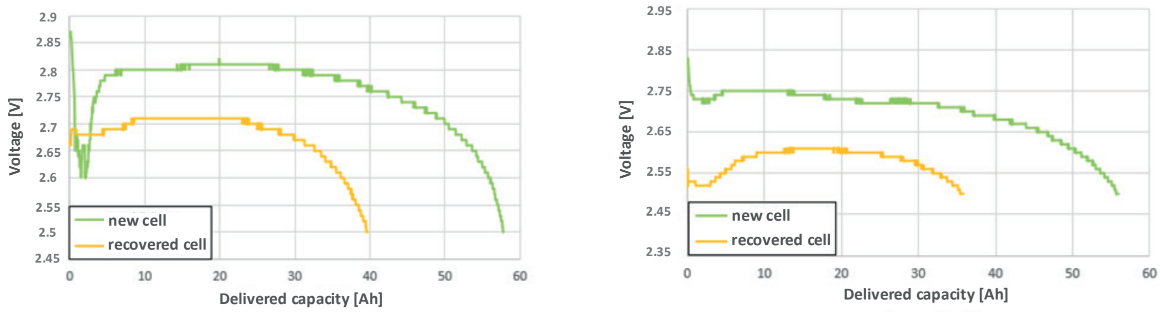


***Figure 9** Cell voltage during the discharge by 60 A (left) and 80 A (right) for regenerated (yellow) and referenced cell (green)*

***Table 4** Summary of results of verification test of the deeply discharged cell*

| Battery cell model | 3,2V, 60Ah, $LiFePO_4$ | |
|---|---|---|
| Cell status | Recovered after deep discharge | New cell |
| | Discharge CC 20 A | |
| discharge time | 2 h, 8 min, 18 s | 3 h, 2 min, 46 s |
| maximal surface temperature | 31.293 °C | 35.397 °C |
| delivered Ah | 43.608 Ah | 60.869 Ah |
| | Discharge CC 40 A | |
| discharge time | 1 h, 2 min, 40 s | 1 h, 27 min, 18 s |
| maximal surface temperature | 35.703 °C | 39.158 °C |
| delivered Ah | 42.536 Ah | 59.486 Ah |
| | Discharge CC 60 A | |
| discharge time | 38 min, 58 s | 57 min, 47 s |
| maximal surface temperature | 38.403 °C | 41.502 °C |
| delivered Ah | 39.709 Ah | 57.826 Ah |
| | Discharge CC 80 A | |
| discharge time | 26 min, 22 s | 41 min, 4 s |
| maximal surface temperature | 40.881 °C | 44.168 °C |
| delivered Ah | 35.886 Ah | 55.965 Ah |

Delivered ampere-hours of the new cell, discharging with current 20 A, was slightly higher than the nominal capacity of a cell, 60.869 Ah and the surface temperature reached 35.397 °C. Delivered ampere-hours of the recovered cell was only 43.608 Ah, which is for 17.261 Ah less than the nominal capacity (Figure 8, left). The maximal temperature during the discharging was 31.293 °C. At discharging current of 40 A, the new cell delivered 49.468 Ah and the surface temperature during the test was 39.158 °C, while the recovered cell delivered only 42.536 Ah (Figure 8, right), which is for 16.932 Ah less and surface temperature reached was 35.703 °C.

The third discharging current for the test was 60 A (Figure 9, left). At this discharge current, the new cell was able to deliver 57.862 Ah, while the recovered cell was able delivered only 39.709 Ah. The surface temperature of the new cell during the test was 41.502 °C and temperature of the recovered cell was 38.403 °C. Difference of delivered ampere-hours in this case was 18.117 Ah. The last test was realized with discharging current 80 A (Figure 9, right). In this case, the new cell delivered 55.965 Ah and the recovered cell delivered only 35.886 Ah. Temperature of the new cell during the test was 44.168 °C and temperature of the recovered cell was 40.881 °C. Results of the tests are listed in Table 4.

## 5 Conclusions

This paper deals with the recovery algorithm of the lithium-iron-phosphate traction battery damaged by the deep discharge. Deeply discharged condition was caused by improper storage and it was confirmed by measurement of the open circuit voltage (OCV), which was only 2.04 V, while the minimal voltage, specified by the manufacturer, should not drop below 2.5 V. The traction cell also had visible deformation in the central part, width in this part was 43.8 mm, while width of the new cell, specified by the manufacturer, is 36 mm. The recovery procedure is based on the charging process, whereby the deeply discharged cell uses short duration peak charging pulses. This charging algorithm was verified by test of the delivered ampere-hours. This test was realized with various discharging currents, i.e. 20, 40, 60 and 80 A. The proposed recovery algorithm achieved almost 70%, if the discharge currents were within 20-40 A (0.3 C-0.6 C). For the higher currents, the voltage drop of the battery represents the limiting parameters as it reached the minimum allowable operational value. The surface temperature of the recovered cell during the test was approximately for 10% lower than temperature of the new cell. During the recovery process and during the ampere-hours test, the battery deformation did not change.

## Acknowledgments

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Peter Drgona - Rastislav Stefun - Slavomir Kascak - Jan Morgos

# DEMONSTRATION OF A SYSTEM IDENTIFICATION ON REAL STEP-DOWN POWER CONVERTERS

*System identification is a scientific field with a wide range of applications, including transport and transportation systems. Automotive industry has a growing trend of power converters implementation. In addition, intelligence of converters is developing. Thus, the power electronics and autotronics are application areas where identification can also be applied. Since buck (step-down), boost (step-up) and buck-boost are the most common topologies of the converters in automobiles, this article aims to demonstrate possibilities of using the identification procedure on the synchronous buck converter. The objective is to obtain a parametric model that could be further useful in analysis and other work with the converter.*

***Keywords:*** *identification, automotive, buck converter, step-down converter, transfer function*

## 1 Introduction

System identification is very interesting nowadays as it can improve and reduce system design time. The aim of identification is to analyze the essential properties and parameters as accurately as possible and to express them in the form of a mathematical model. The best way to analyze a system is to measure it physically, but that is not always possible. During the identification, the parasitic effects and various inaccuracies, neglected in the design, are included, as well, as it is carried out directly on the measured samples from the system. The identification can be used to monitor the condition of the system and its aging, as well as in creation of the adaptive control.

System identification can be implemented also in the power electronics and autotronics, as well, since intelligence in motor vehicles has a growing trend at the present time. Various support systems and electronic assistants are added. They need a stabile voltage to work properly. Therefore, in the current vehicle, one can also find many switched mode power supplies (SMPS), which ensure the supply of electricity to the circuits. These are mainly of the buck, boost, and buck-boost topology. Development of converters is constantly moving forward and intelligent controllers are coming to the forefront. Ability of a converter to recognize its parameters extends the possibilities to improve its dynamic properties and better and more stable control. Ideally, the SMPS regulator should detect changes in the load in real time and adapt its control laws. Such regulators are named as adaptive or self-tuning regulators and should quickly identify their loads, more accurately place poles, better enable transient-suppressing circuits and calculate optimal switching trajectory paths [1].

Methods that aim to determine the transfer function, or the corresponding impulse responses, by direct techniques without selecting a continued set of possible models, are called nonparametric methods. In majority of cases, they are used to obtain the frequency spectrum of the system. Sine-wave testing, or the frequency analysis by the correlation method, take a long time because the methods must be repeated for multiple input frequencies [2]. Identification using the parametric models is motivated by the fact that in many applications and in many situations when one needs to represent a dynamic system in terms of a model, the non-parametric representations, e.g. the Bode plots, Nyquist plots, step responses, etc., are not sufficient. The key step is to select the appropriate model from the model set. A suitable model produces the least possible predictive deviations from the measured data.

In terms of data processing, while minimizing the loss function, one can recognize the one-time identification (offline) methods, where computational operations are performed on a complete data set. The model is created by processing the entire data set. The second group is continuous identification methods (online). They are characterized by a recursive approach to data processing, where the information brought by new - fresh data is only used to correct (update) the original model. The new model is created by repairing the original model [3]. Parameter values estimated using online estimation can vary with time, but parameters estimated using offline estimation do not [4].

In this paper, two experiments on non-isolated digitally controlled DC-DC synchronous step-down converters are presented to demonstrate possibilities of identification. The first converter is C2000™ Digital Power BoosterPack from Texas Instruments (TI). Its parameters are: $f_{SW}$ = 200 kHz,

**Peter Drgona, Rastislav Stefun*, Slavomir Kascak, Jan Morgos**
Department of Mechatronics and Electronics, Faculty of Electrical Engineering and Information Technology, University of Zilina, Slovakia
*E-mail of corresponding author: rastislav.stefun@feit.uniza.sk

L = 4.8 μH, $C_O$ = 396 μF, $U_{IN}$ = 9 V, R = 1.58 Ω. The second converter has parameters: $f_{SW}$ = 10 kHz, L = 1 mH, $C_O$ = 470 μF, R = 3.3 Ω, $U_{IN}$ = 9 V. Both converters were connected to evaluation kit containing the TMS320F28069F processor for digitally controlling the converter.

## 2 Currently used identification methods

### 2.1 Frequency domain data

Significant work in this area was published by authors of [5-6]. They first started with non-parametric online identification of the step-down converter, then added the forward topology in their work, focused to acquiring characteristics in the frequency domain. They used the cross-correlation method, effectively modified for FPGA circuits. Gradually, it passed from the open loop, where the PRBS signal injected into the fixed duty cycle into the characteristics obtained for the closed-loop control circuit. Very good results in identification field authors obtained also in [6]. Paper deals with parametric online identification implemented on the FPGA circuit. Authors applied the least squares (LS) logarithmic method to the obtained frequency domain data.

### 2.2 Recursive least square methods

Authors used the recursive least square (RLS) method in [1] for online parametric identification of an open-loop synchronous step-down converter. Their goal was to monitor the inverter load in real time using a fixed-point processor. Their method can be used for cases where the load stays fixed from the start-up and changes slowly. For example, RLS could identify a battery charger SMPS whose cell count is fixed throughout charging. However, the proposed RLS method, in its most basic form, did not work well for abrupt parameter change, which however, is desired. [1]

In [7], the authors improved the work of authors of [1] in identifying the buck topology converter. The authors designed the fuzzy RLS adaptive method (FRLS). The forgetting factor  is continually updated based on the squared prediction error  2(k) and the change of squared prediction error Δ 2(k) using fuzzy logic. Authors simulated the algorithm on both open-loop and closed-loop buck converter. They concluded that the method is relatively simple and is able to estimate accurately parameters during the step load change before the output voltage reaches the maximum allowable value.

In another work [8], the authors again focused on online identification using the RLS using a forgetting factor (referred to as the exponentially weighted least squares method, ERLS). The aim was to create the cheapest and competitive solution for active load identification for the most efficient control of SMPS. The team was the first to apply the dichotomous coordinate descent algorithm (DCD-RLS) for power electronics in the ERLS method. The DCD is widely used for computationally efficient solution of the system of linear equations, since in the classical RLS approach computationally intensive matrix inversion is required. The authors concluded that the method proposed by them is a suitable alternative to the classical RLS approach in industrial and commercial applications, especially for applications with less powerful processors. The proposed method achieves high accuracy of parameter estimation and low predictive error value. However, compared to conventional RLS techniques, it achieves a slower convergence and is therefore not very suitable for the step load changes.

### 2.3 Kalman filter

Authors proposed in [9] a new parametric system identification method based on a self-tuned Kalman filter (KF). They implemented it into the embedded processor, which controlled the DC-DC synchronous buck converter. In the paper authors concluded that although the RLS methods, especially ERLS, often have satisfactory properties, the KF method is considerably more efficient. It achieves better parameter estimation accuracy and a higher degree of convergence. Moreover, the KF is less influenced by the measurement noise in the practical implementation compared to the ERLS. The KF method is also stable and does not suffer from a windup effect. The code execution time for the KF was 3 μs longer than for the ERLS method. The team also tested the behavior of the algorithm in a step change of load with positive result. The proposed method has potential for practical implementation in real-time applications, especially in adaptive control systems of SMPS [9].

### 2.4 Fast affine projection

In [10], the scientific team applied an algorithm called the fast affine projection (FAP) to a simulated buck topology converter. Affine projection (AP) algorithms are a group of configurable algorithms designed to improve a performance of other adaptive algorithms, especially the least mean square (LMS). The method proposed by the authors achieved very good results compared to the classical RLS or LMS method. The authors achieved the FAP better accuracy, speed of convergence and especially lower computational demands.

### 2.5 Steiglitz - McBride algorithm

Authors led by Peretz researched signal-based identification in the time domain in [11]. Specifically, they applied a step perturbation in the duty cycle command on the buck and the boost converters and sensed output voltage. They used the Steiglitz - McBride algorithm to

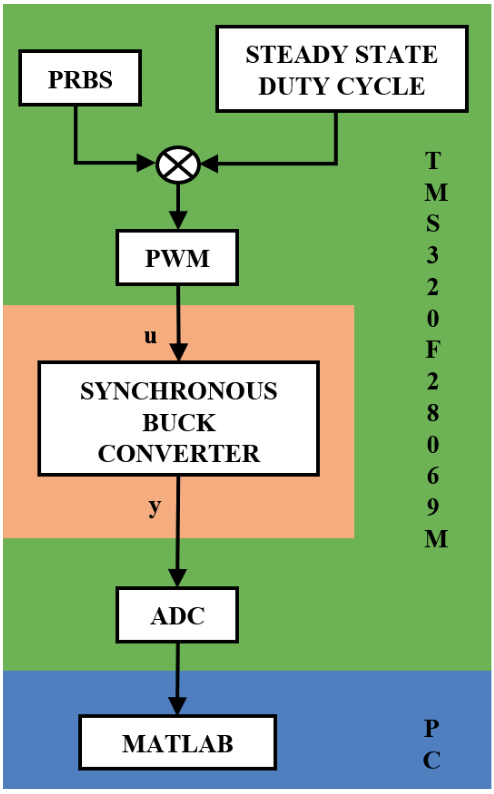


***Figure 1*** *Block schematics of the experiment, where u is input and y is output of the system*

determine the system model parameters by iterative the least squares method. The identification procedure was also implemented on digital signal processors (DSP). The method has the advantage that it uses a relatively small number of measured input and output samples sampled at a suitable time. As stated in the paper, the method can be used for direct design of a discrete controller or for determining the output impedance of a converter.

### 2.6 Limit cycle oscilations (LCOs)

Authors that focused on hardware-efficient identification in [12] introduced a method in which the LCOs are used to identify some converter parameters. The method was directly tested on topologies of step-down and step-up converters. The LCOs are an undesirable phenomenon in normal operation but carry useful information about the system. By examining the LCOs amplitude and frequency, it is possible to determine the load R and Q factor. Authors used these parameters for adaptive control and the look - up table to speed up the determination of new regulator coefficients. The presented method of identification is also applicable to the low-cost processors, but the method is not very accurate and has many limitations.

### 2.7 Component parameters detection

System identification can also be applied in the field of monitoring the aging of individual components of the converter, or for detecting a fault in the circuit. In a paper [13], authors proposed a method with a non-invasive online way of determining the value of capacity C and the equivalent series resistance (ESR) of the output capacitor of the buck topology converters. Although the method requires additional circuits, it is very easy to implement. However, it is necessary to know the output inductance of the converter.

## 3 Identification verification on real data

For identification process, it is very important that the input signal meet the excitation stability requirements, because if the system is at a steady state, the information value of the inputs is minimal. Continuous excitation at the system input means that the inputs have such an informative value that the identification algorithm can run smoothly. Otherwise, instability of identification may occur. In practice, this means that the identification algorithm will not be able to capture dynamics of the system and problems of numerical character may occur; exponential convergence of the searched parameters will not be guaranteed. A controlled system becomes unstable, which can lead to serious consequences. Therefore, the pseudo random binary signal (PRBS) was chosen as the excitation signal for the experiment. The PRBS is rectangular pulse sequence modulated in width and appropriately digitally approximates the white noise. It has very similar spectral properties to white noise. It is rich in frequency content. The advantage is also that this signal is periodical and

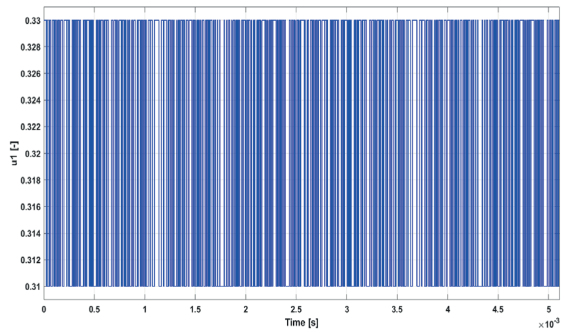


***Figure 2** Input signal (u1) of the first converter - duty cycle*

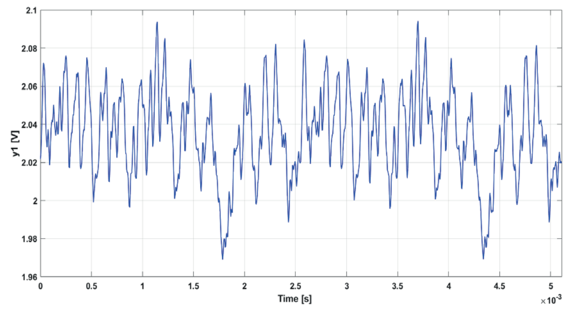


***Figure 3** Output signal (u1) of the first converter - output voltage*

deterministic, so that the experiment is repeatable. It is important to choose a sufficiently long period of the PRBS compared to the plant impulse response time [14]. For experiment, 9-bit PRBS with a frequency of 200 kHz or with 10 kHz respectively, were chosen in order not to take up too much memory but at the same time to excite sufficiently the converter. The PRBS frequencies are the same as switching frequencies of the converters. The PRBS had maximum length L = 511 and was generated in the C language by iteratively performing the XOR operation between the 5th and 9th bit. The Block schematics of experiment is shown in Figure 1.

The impulse response of the first converter lasts 0.25 ms and the actual injections of perturbation lasts for 5.1 ms. The impulse response of the second converter lasts 6 ms and the actual injections of perturbation lasts for 102.2 ms. Thus, both systems were sufficiently excited. To collect the input and output data a program was written for the processor in CodeComposer.

The input data represents the duty cycle and the output data represents the voltage at the converter output. Two periods of input signal and response to it were sensed. Input and output data were then exported to a PC and analyzed offline in the MATLAB System Identification Toolbox (SIT). Due to the effort to suppress partially the noise, collections of input - output data were repeated 5 times and the data were averaged. The amplitude of the PRBS was set to 0.01 and varied around the steady-state duty cycle value of 0.32. Thus, the duty cycle values were either 0.31 or 0.33 (Figure 2). This represents a voltage oscillation of $125\,\mathrm{m\ V}$ at the converter output (Figure 3). The steady-state output is 2.04 V, so the perturbation reaches a maximum of ±3% for both converters. Subsequently, the data were subjected to offline analysis to find a suitable model describing the converter.

In the case of the first converter several models and order variants were tested. The best results were obtained by estimating the state space model of the third order with the noise component **K**. It represents the noise matrix of the model and it is used for modelling of noise contribution to the model output and for modelling the noise dynamics [4]. Identified discrete-time state-space model is represented by equations and matrices:

$$x[n+1] = Ax[n] + Bu[n] + Ke[n], \tag{1}$$

$$y[n] = Cx[n] + Du[n] + e[n], \tag{2}$$

where the vectors x[n], u[n], y[n] and e[n] are the state, input, output and error vectors for the nth sample. State (or system) matrix **A**, input matrix **B**, output matrix **C**, feedthrough (or feedforward) matrix **D** and noise component **K** are:

$$A = \begin{bmatrix} 0.8772 & 0.4141 & 0.4774 \\ 0.00217 & 0.8659 & -0.137 \\ -0.01965 & -0.1107 & 0.6019 \end{bmatrix},$$
$$B = \begin{bmatrix} 0.1686 \\ 0.08249 \\ 0.6404 \end{bmatrix},$$
$$C = [1.741 \;\; 0.7932 \;\; -0.3212],$$
$$D = [0],$$
$$K = \begin{bmatrix} 0.3944 \\ 0.1851 \\ -0.03969 \end{bmatrix}.$$

The state space model was consequently converted to control-to-output transfer function using MATLAB command "ss2tf" and it is:

$$F(z) = \frac{0.1532z^{-1} + 0.3574z^{-2} - 0.4814z^{-3}}{1 - 2.3456z^{-1} + 1.802z^{-2} - 0.4524z^{-3}}, \tag{3}$$

where $z$ is the complex operator of z-transform.

The match of the measured values with the values generated by the model is 90.14%. In comparison, the classical small signal model of the researched converter showed a match of only 61.69%. Identified model was generated by the method of regularized reduction. This method is noniterative. The method works on discrete time-domain data and frequency-domain data. It first estimates a high-order regularized autoregressive model with exogenous inputs (ARX) or finite impulse response (FIR) model, converts it to a state-space model and then performs balanced reduction on it. This method provides improved accuracy on short, noisy data sets [4]. In described experiment, ARX model was used.

It is often necessary to apply a regularization when identifying the higher order models. Regularization is the technique for specifying constraints on a model's flexibility, thereby reducing uncertainty in the estimated parameter values. The kernel is used for regularized estimation of impulse response. The kernel contains information about

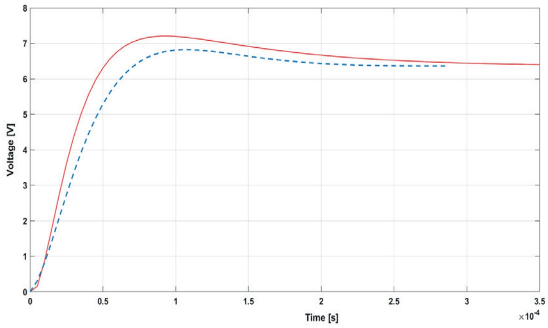


*Figure 4* *Step response of the first converter - real (blue dashed line) and its identified model (red solid line)*

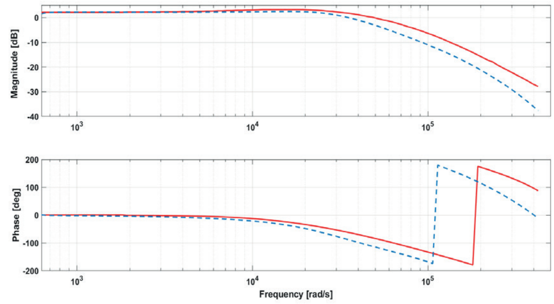


*Figure 6* *Frequency characteristics of the first converter - real (blue dashed line) and its identified model (red solid line)*

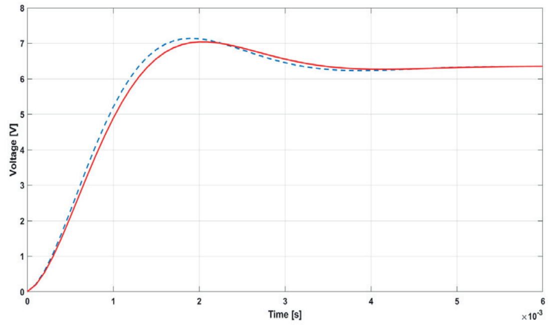


*Figure 5* *Step response of the second converter - real (blue dashed line) and its identified model (red solid line)*

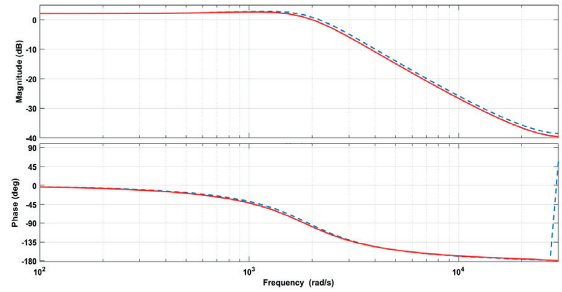


*Figure 7* *Frequency characteristics of the second converter - real (blue dashed line) and its identified model (red solid line)*

parameterization of the prior covariance of the impulse response coefficients. Regularization reduces variance of estimated model coefficients and produces a smoother response by trading variance for bias. The SIT offers a few options of selection. In the experiment, High frequency (HF) stable spline kernel was chosen as regularization kernel [4].

Identification of the second converter was a simpler task due to fewer passive components present in the converter. Models of the higher orders did not have to be tried. A suitable model was identified directly in the form of the transfer function of the second order:

$$TF(z) = \frac{0.00274 + 0.1893z^{-1}}{1 - 1.779z^{-1} + 0.8096z^{-2}}. \quad (4)$$

The match of the measured values with the values generated by the model is 93.55%. The classical small signal model of the researched converter showed a match of 83.18%.

Both identified models are stable - its poles are located inside unit circle. According to [2] it is very important to check not only match of the real data and data produced by the model but the correlations of residuals - differences between the one-step-predicted output from the model and the measured output from the validation data set, as well. Residuals represent the portion of the validation data not explained by the model [4]. Residuals for both converters are inside the confidence interval of the corresponding estimates, indicating that the residuals are uncorrelated.

The identified models were also confronted to the real step-down converters. The step responses of real converters were measured and compared to step responses of identified models. As can be seen in Figures 4 and 5, they are very similar.

The comparison of frequency characteristics is also very important mainly for the control purposes. Software Frequency Response Analyzer (SFRA) library developed by the TI for obtaining frequency characteristics of converters was used to collect frequency response data of real buck converters. It is based on injecting a sinusoidal signal into the duty cycle and measuring the response of the system [15]. Characteristics of the researched converters were compared to the frequency characteristics of the models (Figure 6, Figure 7). They have a high match.

## 4 Conclusion

The article deals with demonstration of identification possibilities applied in the field of power electronics and autotronics. In addition to mapping the currently used methods, the article deals with the offline identification of the real step-down converters. Identification was performed offline on real measured input and output data, which were subsequently processed in MATLAB. Suitable models, describing the converters, were found. In the case of the first converter, model was found in the state-space form of the third order, which was subsequently transformed into a transfer function. The identified model shows a higher match with the measured data than the standard small signal model. In the case of the second converter, it was possible to find the simpler model of the second order. Both models have very similar properties for the real step-down converters and can be used as mathematical models of the real converters. Proposed identification procedure could be applied in automotive industry.

**Acknowledgment**

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Juraj Pancik - Peter Drgona - Marek Paskala

# FUNCTIONAL SAFETY FOR DEVELOPING OF MECHATRONIC SYSTEMS - ELECTRIC PARKING BRAKE CASE STUDY

*The electric parking brake (EPB) system as the complex mechatronic system consists of the actuators that generate the clamping force necessary to hold the vehicle safe, the conventional calipers that convert clamp force into brake torque, electronic hardware with the Electronic Control Unit (ECU), cable harness and switches and especially the control software providing the functions that the driver will experience. Like most of the modern automotive components, the EPB is equipped with embedded electronic systems that include ECU, electronic sensors, signals, bus systems, and coding. Due to the complex application in electrical, electronics and programmable electronics, the need to carry out detailed safety analyses that are focused on the potential risk of malfunction is crucial for automotive systems. This paper describes a possible division of the EPB sub-functions between the supplier the wheel brakes and the supplier which supplying the ECU. Functional safety must be a guarantee with concerning the overall vehicle system. Functional safety is according to the requirements of the ISO 26262 standard and in the context of this paper relates solely to the E/E components (electrical and/or electronic) of the EPB. This paper covers the hazard analysis and risk assessment relevant to the EPB control software, and the derived allocation of ASIL risk levels to the EPB software elements of the functional architecture of the EPB.*

***Keywords:*** *functional safety management, ISO26262, ASIL, electric parking brake*

## 1 Electric parking brake (EPB) systems

The automotive market globally demands Electric Parking Brake Systems (EPB) in the goal to improve the overall safety, performance, and comfort of passenger cars on the path to autonomous driving and braking. Therefore, the market share for EPB systems is continuously growing from year to year. Figure 1 shows how the fitment rate of the EPB develops compared to conventional options. The production of the 60 millionth EPB caliper in 2015 was a remarkable milestone and the market share will most likely reach 30% within the next years. Meanwhile, the EPB is available in all major vehicle platforms and produced globally while the share of conventional park brake systems is getting smaller. Even in the segments of small cars and light trucks the demand for EPB systems increases. The forecast shows that the fitment rate could nearly reach half of the market within a decade. While the overall volume demand for EPB Systems is growing additional EPB suppliers entered the market in recent years. This is associated with more diversity regarding system layout and design. Vehicle manufacturers developed individual requirements to specify their needs and system suppliers reacted with individual specifications for test and release.

The efforts required to test and release a safe EPB system significantly contribute to the overall engineering costs. Hence, there is a growing need to establish globally harmonized standards and rules for collaboration between OEM and OES and avoid distortion of competition.

### 1.1 The EPB functionality

The release process for EPB systems represents its main functionality. Since the EPB was first launched in 2001, several of EPB functions continue to rise significantly. The EPB offers by far more than the basic application and release of a conventional parking brake. It interacts with several other driver assistance systems. Figure 2 gives some examples of typical functions of actual EPB systems.

The EPB offers the driver a comfortable hold and launch on gradients not only on a hill but also in daily car park situations. It can safely hold the vehicle in all situations, for example, when the engine start-stop automatic is active even if the driver leaves the car on a gradient. This is a common situation for delivery service drivers who frequently leave their cars. The EPB satisfies legal requirements regarding the holding ability of a vehicle on inclined surfaces and guarantees safe parking even when all other assistance systems are in sleeping mode and the main power supply is off. If the hydraulic system fails, the EPB allows an emergency stop by applying the EPB switch (following standard ECE-R13H [2-3]).

**Juraj Pancik*, Peter Drgona, Marek Paskala**
Department of Mechatronics and Electronics, Faculty of Electrical Engineering and Information Technology, University of Zilina, Slovak Republic
*E-mail of corresponding author: juraj.pancik@fel.uniza.sk

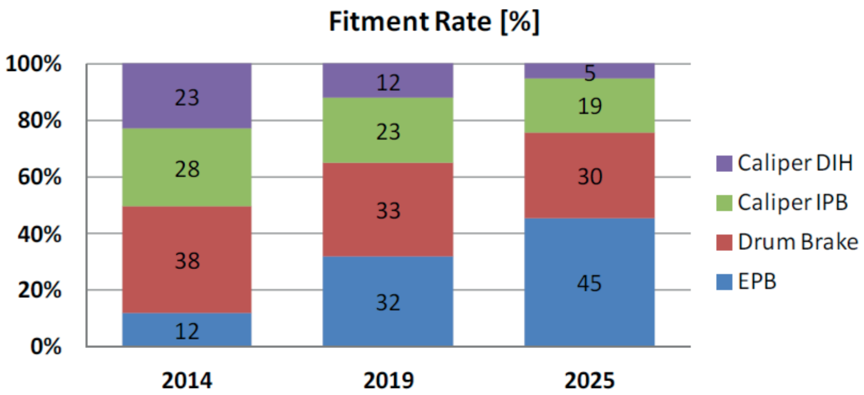


***Figure 1*** *EPB fitment rate [%], actual and forecasted [1]*

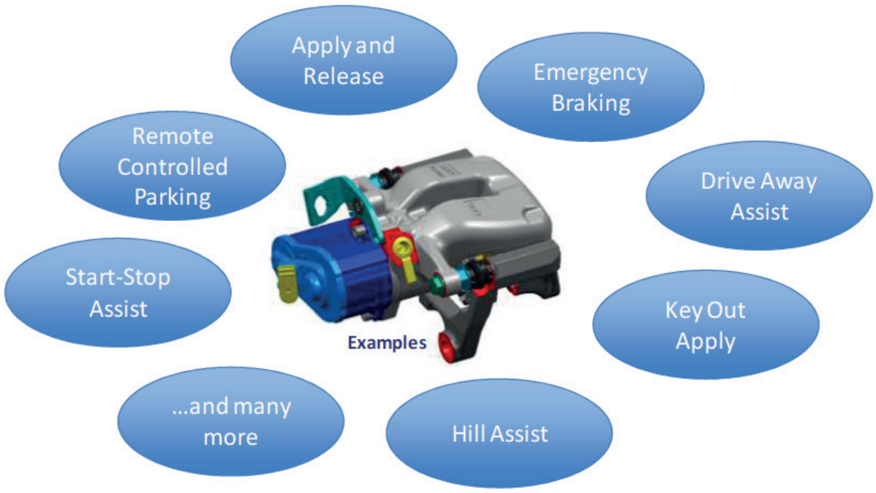


***Figure 2*** *Functionalities of the Electric Parking Brake*

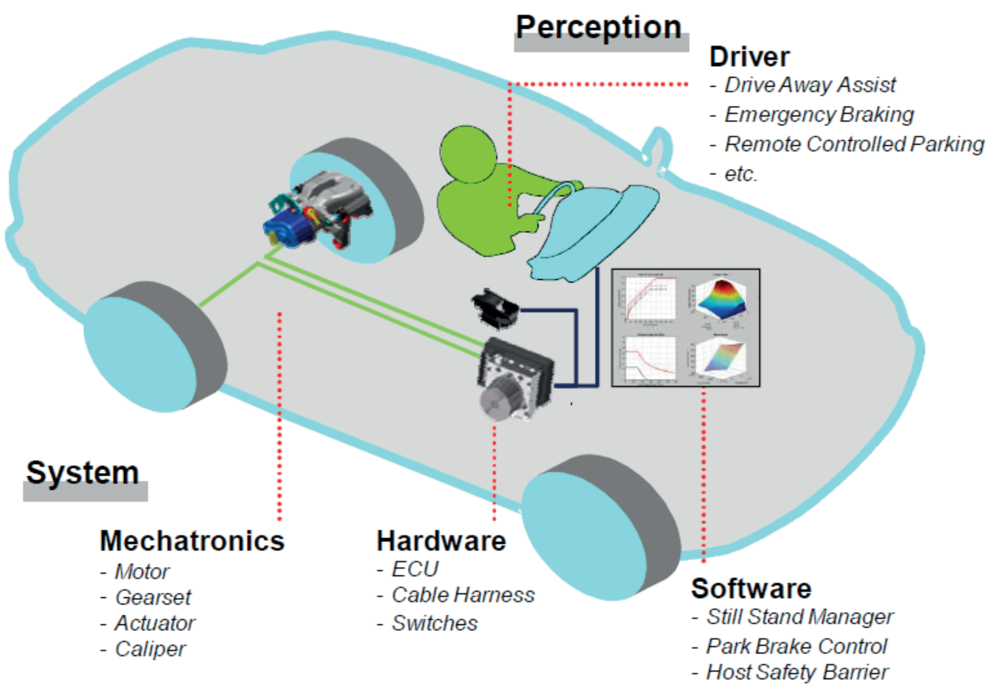


***Figure 3*** *Electric Parking Brake System (EPB)*

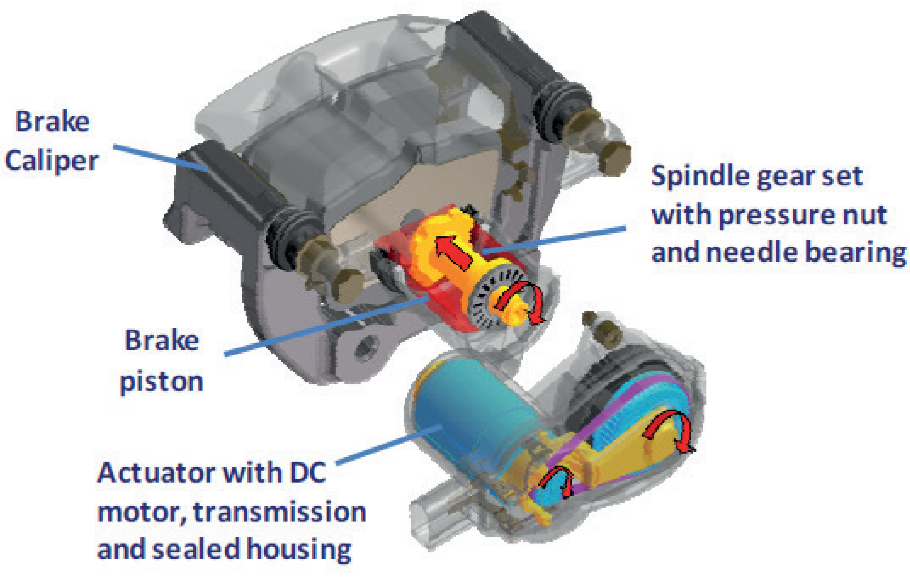


***Figure 4*** *Mechatronic EPB actuator and caliper assembly [1]*

### 1.2 The EPB system

Figure 3 gives an overview of the EPB system with the functionality perceived by the driver on the one hand and the components with their technical characteristics on the other hand.

The EPB system consists of the actuators that generate the clamping force necessary to hold the vehicle safely, the conventional calipers that convert clamp force into brake torque, electronic hardware with the Electronic Control Unit (ECU), cable harness and switches and especially the control software providing the functions that the driver will experience.

Figure 4 shows a typical EPB actuator and caliper assembly. The actuator is screwed on the brake caliper. The spindle gear set converts rotational torque coming from the motor, belt drive and planetary gear set into translational clamp force that is applied to the conventional piston. Brake fluid is present in the piston chamber and separated from the sealed actuator. This is just an example as there are also other designs on the market.

### 1.3 EPB crosswise integration projects

Let introduce the definitions OES and OEM abbreviations. An original equipment manufacturer (OEM) is a company that produces parts and equipment that may be marketed by another manufacturer. The OES (Original Equipment Supplier part) is made by the manufacturer who made the original factory part for the vehicle model. On the other hand, an Original Equipment Manufacturer may not have made that specific part (e.g. EPB) for vehicle originally, but has an official contract history with the automaker [4]. The integrated EPB system can be divided into two parts:

OES-EPB supplier: One part of the EPB system contains the parking brake actuator, the parking brake caliper and the actuation logic (Park Brake Control PBC) which can be represented in our case by PBC software library

OES-ESC supplier: The second part of the EPB system, also called the host, contains the EPB power electronics and necessary peripherals and controls the functions

In addition to the independent EPB control unit, it is possible to integrate the EPB control unit into the ECU with the name Electronic Stability Control (ESC) system. The state of the art is to integrate the EPB control unit into the electronic stability control (ESC) system. On the market, there are OES - specific solutions as well as OES - independent combinations from different ESC and EPB suppliers. The latter case OES - independent is commonly called crosswise integration. In crosswise integration projects, the OES-EPB supplier is responsible for the first part and the OES-ESC supplier is responsible for the second part. The aims of this division are:

- encapsulation of knowledge about particular components
- clearly defined areas of responsibility
- independent testing and approval of components from the different suppliers
- enabling manufacturer-specific levels of functionality of the individual components.

The development and release of such integrated systems need clear requirements for the interfaces and rules for collaboration between the development partners.

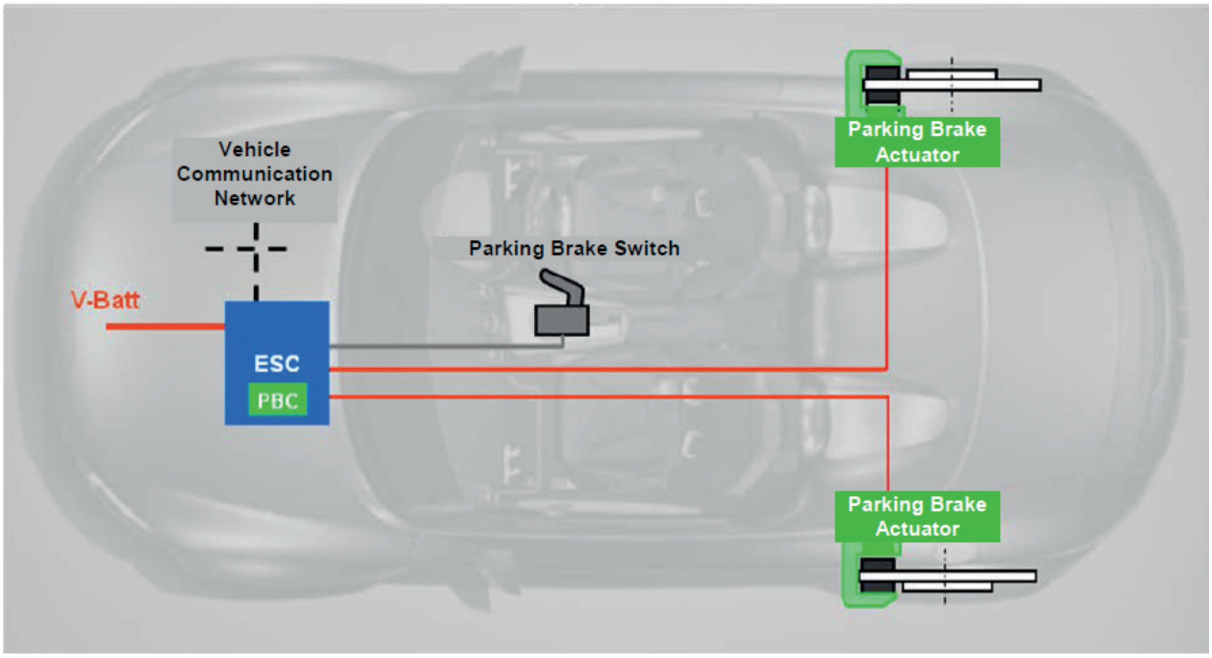


***Figure 5*** *Schematic diagram of the integrated electric parking brake when it is produced by two suppliers (EPB system green and ESC system as blue) [6]*

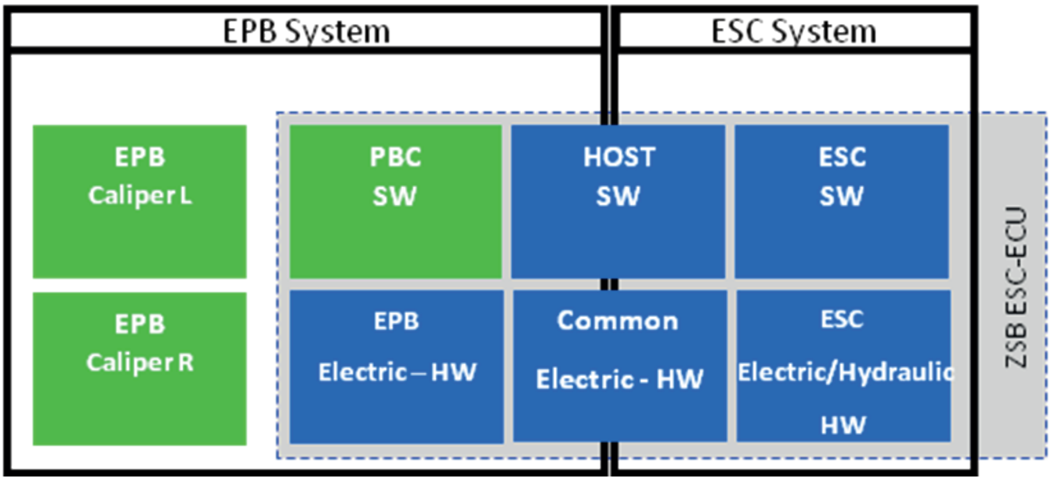


***Figure 6*** *System network of the integrated electrical parking brake when it consists of two suppliers (EPB system green and ESC system as blue) [6]*

### 1.4 EPB integration into host ECU according to the VDA recommendation 305-100

Within the VDA [5] working groups were formed who elaborate relevant recommendations to harmonize requirements and procedures between the development partners for braking systems in case of EPB crosswise integration projects. VDA recommendation 305-100 [6] defines the integration of the EPB control unit into an ESC type control unit from different manufacturers. For such a crosswise integration the work products of functional safety of each part need to be distributed on both OES to realize a systematic verification and validation. The content of this recommendation has been selected such that the constraints permit combining EPB and ESC but without restricting further product - specific development by these different OES.

The VDA Recommendation 305-100 describes and defines the integration of the control of caliper-integrated parking brake actuators into an ESC control unit from a different manufacturer. The Brake Assembly supplier (brake or OES-EPB supplier) is responsible for the parking brake actuator, the parking brake caliper and the actuation logic (parking brake controller, PBC) (see Figure 5; green). The ESC supplier (host or OES-ESC supplier) is responsible for the EPB power electronics and necessary peripherals and the functions that the driver can experience (see Figure 5; blue).

The PBC is a software component designed specifically for the parking brake actuator and is integrated into the host. The integration of the EPB as described in this VDA recommendation 305-100 is distinguished by the use of a single ESC control unit. The logical representation of the

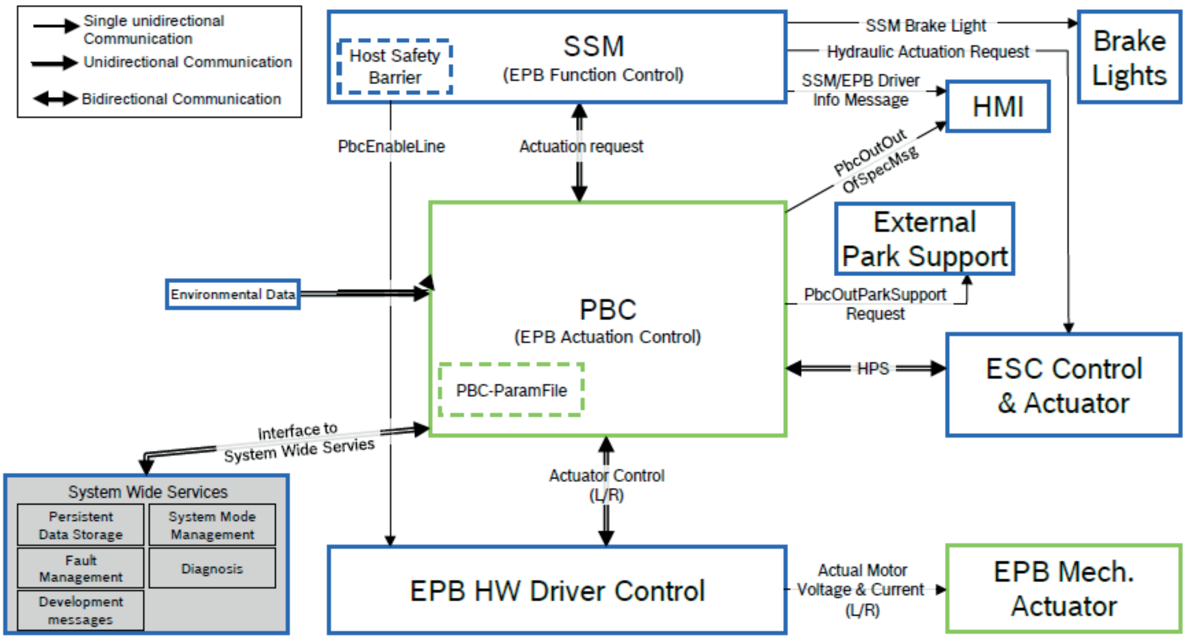


***Figure 7** Overview of the functional architecture of the integrated EPB system including interfaces [6]*

***Table 1** List of the functional architecture blocks of the integrated EPB*

| Function block | Task |
|---|---|
| PBC | Proper control of the EPB Mech. Actuator for safe parking of the vehicle and releasing of the parking brake, arbitration between actuation requests from diagnosis and SSM, control of the dynamic deceleration actuation via the parking brake actuators. The PBC parameter file (PBC-ParamFile) contains specific parameters of the PBC. |
| EPB HW Driver Control | Activation unit for the parking brake actuators (acc. requested direction) and providing electric measurements to the PBC. |
| EPB Mech. Actuator | Providing and archiving the electromechanical clamping force; reducing the electromechanical clamping force. |
| System Wide Services | Providing services for data storage, diagnosis and monitoring of the system modes; fault management; communication of development messages. |
| HOST Safety Barrier | Safety mechanism to enable the EPB hardware drivers to avoid PBC safety-critical activations of the parking brake actuators. |
| HMI | Control logic and actuation of driver information (e.g. warning lamps, status lamps and text messages). |
| Brake Lights | Control logic and request for brake lights |
| ESC Control & Actuator | Control logic and hardware of the hydraulic actuator. |
| Environmental Data | Collecting, preparing and providing environmental data to the PBC. |
| External Park Support | Control logic for requesting external parking support (depending on available parking support actuators). |

components used and their allocation to the EPB and ESC systems are shown in Figure 6.

### 1.5 Functional architecture of EPB

The functional architecture of EPB with the marked system boundaries is shown in Figure 7

*Figure* . Green boundaries specify the subject of interest in this work. Table 1 describes functional architecture blocks of the integrated EPB and Table 2 describes interfaces between the function blocks.

## 2 Functional safety for PBC - EPB software part of the electric parking brake

Functional safety management (FSM) in general represents planning, coordinating, and documenting activities related to functional safety. The FSM implements of the management plan for all phases of the safety lifecycle, including:

- Overall safety management
- Project dependent safety management
- Safety management for production, operation, service and decommissioning

***Table 2*** *List of interfaces between the function blocks [6]*

| Interface | Task |
|---|---|
| SSM ←→<br>“Actuation Request” | SSM →PBC: actuation request<br>PBC →SSM: status information from the Brake Assy |
| PBC ←→EPB HW Driver Control “Actuator Control L/R” | PBC →EPB HW Driver Control: actuation command from the PBC.<br>EPB hardware driver control →PBC: status information, current and voltage of the hardware driver for the parking brake actuators. |
| EPB HW Driver Control →EPB Mech. Actuator<br>“Actuator Voltage & Current” Supply” | EPB HW Driver Control →EPB Mech. Actuator: activation of the parking brake actuators in the direction requested, separate for L/R, by supplying current and voltage. |
| PBC ←→System Wide Service “Interface to System Wide Services” | PBC →System Wide Service: providing internal PBC data for the ECU Diagnostic Interface, fault manager (FM) interface, providing data to be stored<br>System Wide Service →PBC: providing stored data, transferring diagnostic requests, FM interface |
| PBC →HMI “PbcOutOutOfSpecMsg” | Display indication of Brake Assy operation outside the specification range. |
| PBC ←→ ESC Control & Actuator “HPS” | PBC →ESC Control & Actuator: hydraulic support request from the PBC to ensure Park brake hold capability.<br>ESC Control & Actuator →PBC: status information |
| Environmental Status Information →PBC | Providing environmental data to the PBC |
| SSM →HMI “SSM/EPB Driver Info Message” | Request driver information relevant to EPB (e.g. EPB status information, EPB fault information, function-based text messages) |
| SSM →Brake Lights<br>“SSM Brake Light” | Request brake lights during an emergency brake request via the parking brake control unit |
| SSM →ESC Control & Actuator “Hydraulic Actuation Request” | Requests for holding (e.g. Auto Hold) and hydraulic dynamic deceleration via the hydraulic actuator. |
| HOST Safety Barrier →EPB HW Driver Control<br>“PbcEnableLine” | Enabling the “EPB HW Driver Control” for each direction separately (apply/release), for driving the parking brake actuators. |
| PBC →External Park Support “PbcOutParkSupportRequest” | Requests for external parking supp |

## 2.1 Standard ISO 26262 - functional safety for road vehicles

The only widely/internationally recognized standard for functional safety management (FSM) in the automotive industry is the ISO 26262 [7]. This standard must be followed for all development, production and service activities of safety - related electrical and electronic components and systems (E/E-components/-systems) in the automotive industry. Though currently there does not seem to be any direct legal requirement it is nevertheless mandatory to develop E/E - systems according to the ISO 26262 standard because this is considered to be “state-of-the-art” in product development at present and this legal standard is a requirement of legislation in general. Additionally, increasingly many customers in automotive explicitly demand ISO 26262-compliant development and corresponding contracts and agreements are undoubtedly legally binding.

### 2.1.1 Automotive Safety Integrity Level (ASIL)

The standard ISO 26262 defines functional safety as “the absence of unreasonable risk due to hazards caused by malfunctioning behavior of electrical or electronic systems.” ASILs establish safety requirements - based on the probability and acceptability of harm - for automotive components to be compliant with ISO 26262. There are four ASILs identified by ISO 26262 - A, B, C, and D. ASIL A represents the lowest degree and ASIL D represents the highest degree of automotive hazard. Systems like airbags, anti-lock brakes, and power steering require an ASIL - D grade-the highest rigor applied to safety assurance-because the risks associated with their failure are the highest. On the other end of the safety spectrum, components like rear lights require only an ASIL - A grade. Headlights and brake lights generally would be ASIL - B while cruise control would generally be ASIL - C. ASILs are established by performing hazard analysis and risk assessment. For each electronic component in a vehicle, engineers measure three specific variables:

- Severity (the type of injuries to the driver and passengers)
- Exposure (how often the vehicle is exposed to the hazard)
- Controllability (how much the driver can do to prevent the injury)

Each of these variables is broken down into sub-classes. Severity has four classes ranging from “no injuries”

***Table 3*** *Safety goals of the EPB system according to VDA recommendation 305-100 Chapter 4*

| Case (operational situations and operating modes) | Hazard | Risk assessments |
|---|---|---|
| Too high or unintended braking torque while the vehicle is in motion (max. ASIL D) | 1a) Incorrect actuation of EPB in the locking direction when v > vcrit. | ASIL D |
| | 1b) Execution of the function 'Dynamic deceleration' intended by the driver leads to vehicle instability when v > vcrit. | ASIL B |
| | 1c) Execution of the function 'Dynamic deceleration via the parking brake actuators intended by the driver' leads to vehicle instability when v > vcrit. | ASIL A |
| | 1d) Incomplete release of the EPB with residual braking torque. | ASIL B |
| Unintended braking torque while the vehicle is stationary (max. QM) | 2a) EPB cannot be released. | QM |
| Too low braking torque while the vehicle is stationary (max. ASIL C) | 3a) Incorrect EPB actuation in the releasing direction (driver absent, vehicle parked, ignition off). | ASIL C |
| | 3b) Too low build-up of EPB holding force (driver absent, road slope ≤ 8%). | ASIL B |
| | 3c) Incorrect release of the EPB (driver absent, vehicle held, ignition on). | ASIL B |
| | 3d) Required EPB function 'proactive re-clamping' is either not executed, or is executed insufficiently (driver absent, vehicle parked). | ASIL A |
| | 3e) Required EPB function 'hydraulic support' is either not executed, or is executed insufficiently (driver absent, vehicle held). | ASIL A |
| | 3b) Too low build-up of EPB holding force (driver absent, road slope > 8%). | ASIL A |
| Incorrect driver information (max. ASIL A) | 4a) EPB specific driver information on the EPB function status incorrectly signals EPB status 'locked' (EPB opened). | ASIL A |

(S0) to "life-threatening/fatal injuries" (S3). Exposure has five classes covering the "incredibly unlikely" (E0) to the "highly probable" (E4). Controllability has four classes ranging from "controllable in general" (C0) to "uncontrollable" (C3). All variables and sub-classifications are analyzed and combined to determine the required ASIL. For example, a combination of the highest hazards (S3 + E4 + C3) would result in an ASIL D classification. Given the guesswork involved in determining ASILS, the Society of Automotive Engineers (SAE) drafted J2980, "Considerations for ISO 26262 ASIL Hazard Classification" in 2015 [8]. These guidelines provide more explicit guidance for assessing Exposure, Severity, and Controllability for a given hazard.

#### 2.1.2 Benefits of ASILs

ISO 26262 is a goal-based standard that's all about "preventing harm." Despite their challenges, ASIL classifications are intended to "prevent harm" and help us achieve the highest safety rating possible for myriad automotive components across a long and often disjointed supply chain. Key benefits of ASIL include:

- Establishing safety requirements to mitigate risks to acceptable levels
- Managing and tracking safety requirements
- Ensuring that standardized safety procedures have been followed in the final product

### 2.2 Functional safety solution for PBC software

#### 2.2.1 Management of functional safety of PBC software

A central functional safety department inside of an organization manages the functional safety process area in the EPB system development. The safety - lifecycle requirements for automotive products are defined in the specific FSM guidelines, which assign the safety activities required by ISO 26262. The functional safety management within the project is carried out by a project-specific team, which is supported by the central functional safety department of developing an organization. The team must prepare prescribed documents (work products) that are related to developing. The PBC software development process has to follow the requirements of the Automotive SPICE Process Reference Model Process Assessment Model Version 3.1 [9] and should be tailored in the system development manual prepared by the organization. Implementation ASPICE in the software development of

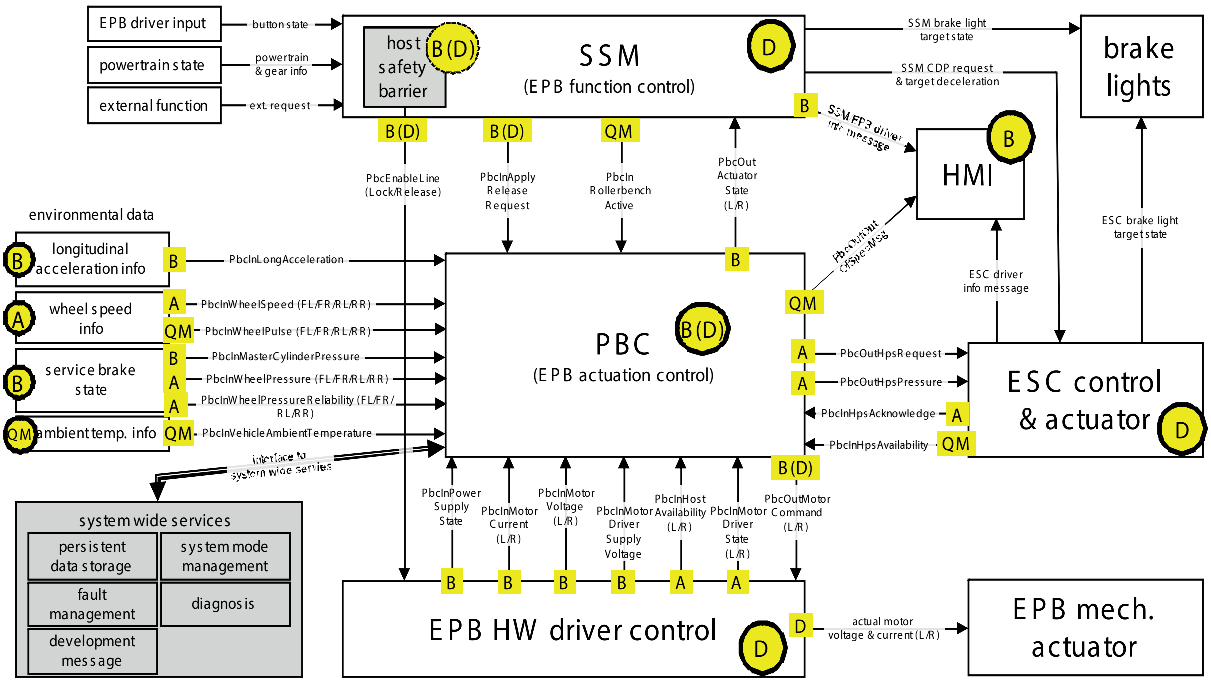


***Figure 8*** *Overview of EPB functional architecture with relevant ASIL levels (maximum overall hazards, hazard 1a) according to ASIL B(D) and ASIL B(D) decomposed) signals*

***Table 4*** *ISO 26262 recommended rules that govern ASIL decomposition [11-12]*

| ASIL before decomposition | ASIL after decomposition |
|---|---|
| ASIL D | ASIL D(D) + ASIL quality management (QM) (D) |
| | or |
| | ASIL C(D) + ASIL A(D) |
| | or |
| | ASIL B(D) + ASIL B(D) |
| ASIL C | ASIL C(C) + ASIL QM(C) |
| | or |
| | ASIL B(C) + ASIL A(C) |
| ASIL B | ASIL B(B) + ASIL QM(B) |
| | or |
| | ASIL A(B) + ASIL A(B) |
| ASIL A | ASIL A(A) + ASIL QM(A) |

automotive parts with embedded software is recommended by standard IATF 16949:2016 [10].

### 2.2.2 Hazard Analysis and Risk Assessment (HARA) for the parking brake assembly

Even if the brake assembly is only a part of the parking brake system, a hazard analysis as specified work product has been carried out by the team for the overall parking brake system on vehicle level. All possible hazards have been analyzed by taking account of the operational situations and operating modes according to ISO 26262-3. The resulting hazardous events have been classified and the corresponding safety goals have been defined. Table 3 shows the safety goals for the electric parking brake with the resulting ASIL classification according to VDA recommendation 305-100, Chapter 4 [6] and standard J2980 [8].

### 2.2.3 Functional safety concept

Based on the safety goals, the functional safety concept has been specified by deriving the functional safety requirements in the document PBC SRS2 Safety and allocating them to the item architecture elements in the PBC system architecture. The specification of the functional safety requirements considers the parking brake realization concept, which unifies the host part and the brake assembly part. The functional safety requirements allocation in the SRS2 Safety document and the ASIL allocation to the host part and the assembly brake part comply with the contents of chapter 4 of the VDA recommendation 305-100.

### 2.2.4 Technical safety concept

The technical safety concept work product has been derived from the functional safety concept, considering the interchangeability concept described in the VDA recommendation 305-100. In this document, ASIL decompositions at the interface between the host and the brake assembly are determined for the fulfillment of the safety goals and the technical safety requirements concerning the interfaces between the host and the brake assembly are specified and addressed to the responsible part(s). Furthermore, the interface signals between the host and the brake assembly are defined and specified in the VDA recommendation 305-100. The corresponding ASIL classifications are also assigned to the interface signals where are described in the EPB functional architecture (Figure 8). The maximum overall hazard is hazard 1a with ASIL D (Table 3). In other words, the parking EPB brake assembly is an item with ASIL D risk.

### 2.2.5 PBC software safety requirements

Software safety requirements are derived from the technical safety concept and the system architectural design specification (inherit the ASIL). The EPB safety requirements implemented in the PBC software module must not be greater than ASIL B. To ensure this, the method of ASIL decomposition is applied for all hazards classified as ASIL C or ASIL D. The confirmation measures for park brake assembly system were estimated in the HARA work product (chapter 3.2.2) with ASIL D and used accordingly (ISO 26262-2, chapter 6.4.7). The used process for decomposition can be found in ISO 26262-9, chapter 4. In general, an ASIL D functional safety requirement can be decomposed into ASIL B (in support of D) + ASIL B (in support of D) - see Table 4. The PBC software is part of the ASIL decomposition with the Host safety barrier (ASIL D => ASIL B (D) + ASIL B (D)) and fulfills, therefore, ASIL B (D).

## 3 Conclusion

The electric parking brake (EPB) system is a complex mechatronic system. In our work possible hazards for the EPB system have been analyzed with taking account of the operational situations and operating modes according to ISO 26262. We presented an overview of the EPB functional architecture with relevant ASIL levels (maximum overall hazards for EPB system is ASIL D). Software safety requirements for the PBC software module are following the ASIL B(D). The PBC software safety requirements can be applied to software development, integration, testing and used tools for EPB software development and they were not a subject of our research.

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Matej Kucera - Milan Sebok - Matej Kubis - Daniel Korenciak - Miroslav Gutten

# ANALYSIS OF THE AUTOMOTIVE IGNITION SYSTEM FOR VARIOUS CONDITIONS

*Paper presents diagnostic analysis of automotive ignition system for various working and adverse conditions in laboratory. Description and importance of basic diagnostics of automotive ignition system are examined in the first part of the paper. In the second the focus is placed on the basic principles and solution of the spark plug model. The test laboratory device is proposed in the following and the specialized measurements were executed by the proposed measurement system. The faults were simulated by application of oil and gasoline between the electrodes and failing by the driver to make the ignition contact on the spark plug.*

***Keywords:*** *ignition system, conditions, diagnostics, measurement, LabVIEW*

## 1 Introduction

Recent trends in the automotive industry lead to an increase in performance and a reduction in the production of pollutants contained in the exhaust gas, while simultaneously reducing the fuel consumption. This is also associated with a huge development in the field of ignition systems of internal combustion engines.

The ignition systems, even in their simplest form, represent an electrical system producing high voltage waveform in the form of complicated impulses. The essence of the fully electronic ignition system is to distribute high voltages for individual spark plugs for creating the ignition mixture.

Ignition systems are among the most important in the field of engine management, thus the great emphasis is placed on the diagnostics itself and determination of the exact failure [1].

Currently, the control circuits check the condition of electronic components, mainly by monitoring the voltage levels, calculating and estimating value limits during the diagnostic mode of the element. The diagnostics of these systems also requires diagnostic systems that allow to record these processes for further analysis. The current value of the jumping spark voltage in the individual cylinders must be determined by the separate switching control of the primary circuits of the high voltage transformers (spark ignition coils) [1-2].

The engine operating parameter signals are input to the control unit by means of which the control unit generates the control pulses for the end stages of the individual ignition coils. Operational parameter signals are needed to calculate the exact moment in which the high-voltage pulse has occurred.

Figure 1 shows an example of voltage and current waveforms of the transformer primary side.

The ignition coil (high voltage transformer) produces high-voltage pulses on the spark plug electrodes for ignited mixture in the combustion chamber of the engine (Figure 2) [3].

Conventional measurement diagnostic systems enable, based on the analysis of the primary and secondary high voltage waveforms, to evaluate measurement of the ignition systems for obtaining a more comprehensive overview of examined electric system [1].

Diagnostics of the ignition systems using the conventional diagnostic systems enables, based on analysis of the primary and secondary high-voltage waveforms, to detect failures in the diagnostics of the measurement system under examination. When locating the fault states of electronic ignition systems, possibilities of the non-destructive diagnostics of ignition systems, based on voltage, current or thermo-vision analysis, are analyzed, as well [4].

## 2 Theoretical analysis

The distributorless ignition system (DIS) is an ignition system, which distributes high voltage to each spark plug without using the mechanical distributor. The high voltage shall be achieved to create a spark at the spark plug igniting the mixture through a high-voltage coil (transformer). The high-voltage outlets in the distributorless ignition system are directly applied to plugs, thus increasing the number of ignition coils [5].

**Matej Kucera, Milan Sebok, Matej Kubis, Daniel Korenciak, Miroslav Gutten***
Department of Measurements and Applied Electrical Engineering, Faculty of Electrical Engineering and Information Technology, University of Zilina, Slovakia
E-mail of corresponding author: miroslav.gutten@uniza.sk

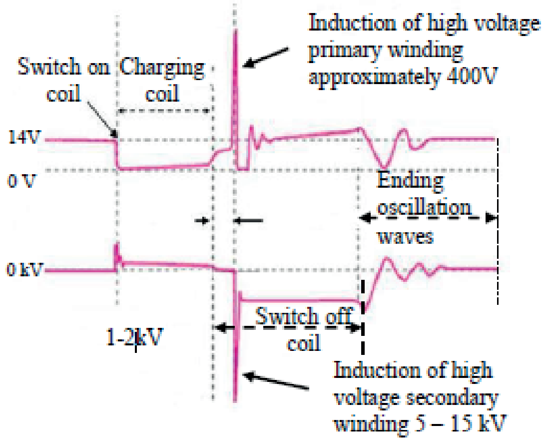


**Figure 1** *Voltage waveforms of the primary side of the transformer winding*

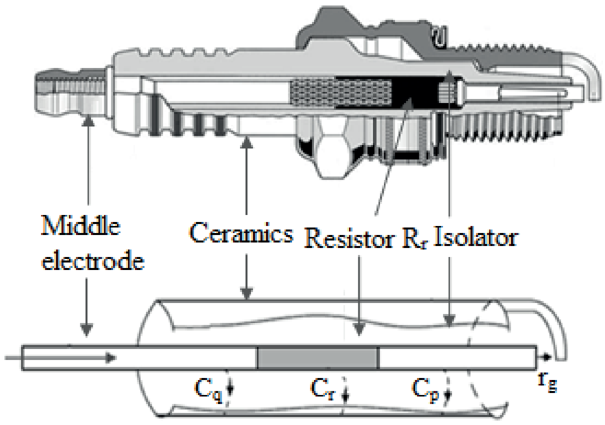


**Figure 2** *The spark plug model*

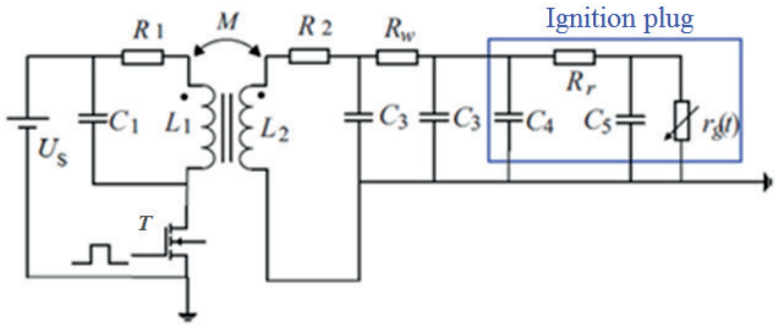


**Figure 3** *The replacement model of the ignition assembly*

An immediate flashover in the cylinders must be determined by a separate switch controlling the transformer primary circuits.

The ignition system is equipped by an ignition module (high-voltage transformer), power electronics (transistors with protective circuits) and a spark plug. The ignition system is controlled by generating signals by the control unit, which are led to the power module. Based on the signals, the transistors are opened, thanks to which the current flows through the primary side of the ignition transformer. When the transistor is closed, the energy is transferred from the primary side to the secondary side. Modelling of the spark plug during the discharge of the ignition transformer is problematic. The current passing between the electrodes is the dominant ignition current. The corresponding spark plug design is shown in Figure 2, [5-6].

A replacement model of the ignition assembly is constructed by using the Figure 3 spark plug model, where $R_r$ is a series resistance and its value depends on the design solution, $r_g$ is the spark plug air gap resistance, and $C_q$, $C_r$ and $C_p$ are parasitic capacities between the middle electrode and the sheath.

The following equations can be derived from Figure 2

$$C_4 = C_q + \frac{C_r}{2},\quad C_{45} = C_p + \frac{C_r}{2},\quad C_3 = \frac{C_w}{2}. \qquad (1)$$

The DC power supply voltage is marked $U_S$, $R_1$ and $R_2$ are respectively the primary and secondary winding resistances, $L_1$ and $L_2$ are respectively the primary and secondary winding inductance, $R_w$ is the high-voltage conductor resistance and $M$ is the mutual inductance coefficient between the primary and secondary sides. It is obvious from the replacement ignition circuit that the transition from the steady state is associated with a change in the electromagnetic energy $W(t)$ in the circuit [7-8].

This energy is accumulated by the electric field of the capacitor and the magnetic field of the inductor

$$W(t) = \sum_{k=1}^{n1} W_{ek}(t) + \sum_{k=1}^{n2} W_{mk}(t), \qquad (2)$$

where $n_1$ is the number of capacitors and $n_2$ is the number of coils.

## 3 Test laboratory device

Currently, the control circuits check the condition of electronic components mainly by monitoring the voltage levels, calculating and estimating value limits during the diagnostic mode of the element.

In order to evaluate the correct operation of the ignition system, it is necessary to check the time course of the voltage and current of the high-voltage

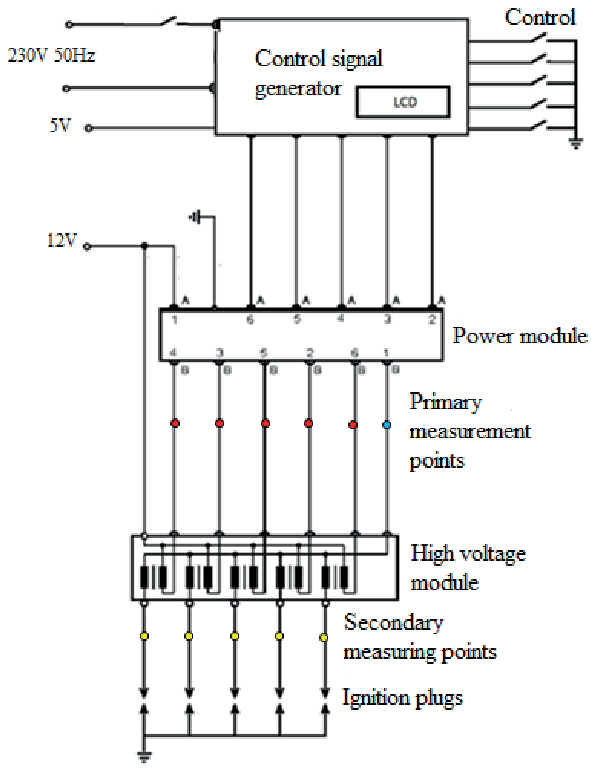


***Figure 4*** *Ignition system wiring diagram*

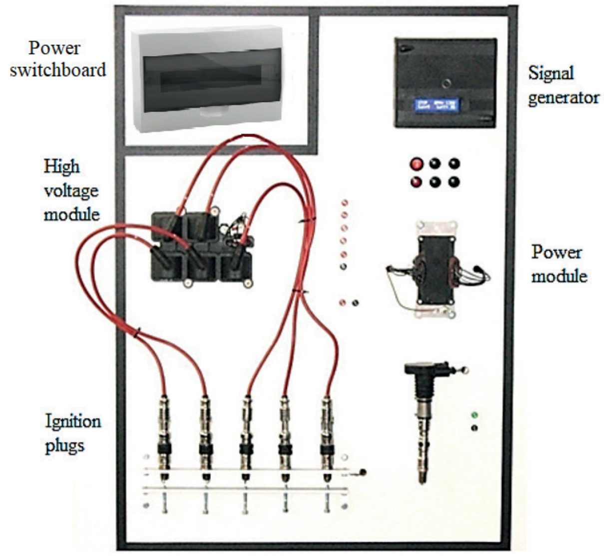


***Figure 5*** *The ignition system test equipment*

module by measurement., It is possible to determine the state of the ignition system and to determine the reduced functionality by measuring and evaluating the characteristics.

A laboratory device has been created to obtain the necessary signals. The device allows for creating the fault states and monitoring changes in output characteristics. Based on this device, it is possible to physically simulate possible faults, copy them to a database and compare them to the actual ones in the car based on files.

Figure 4 shows a wiring diagram of a test device that includes a control signal generator, power module, high voltage module and spark plugs. The diagram also contains measuring points for direct connection of oscilloscope and capacitive probe.

The signal generator replaces the motor control unit in a simplified form. It is a programmed 8-bit microprocessor DC9S08QE. It is possible to activate the generator by use of buttons and change the time intervals during which the energy accumulates on the primary side of the ignition coils.

For information on the set signal generation mode, the generator also includes an LCD display. The signal generator allows generating a switch-on time $t_{on}$ ranging from 0 to 9 ms and a switch-off time $t_{off}$ between 10 and 500 ms in 1 ms steps. Generation is performed for five channels. The display unit shows the mentioned times, the generator activation status and the estimated four-stroke engine speed. The generator produces 5 V voltage levels. The output circuits contain opto-couplers for galvanic isolation. The power module converts the low-power 5 V voltage signals to power. It is powered from a 12 V power supply. The component contains a charging current limitation, which can also be seen in the current characteristics.

The current limitation is to prevent the ignition coil from being supersaturated. The high voltage module is a block containing the high voltage ignition coils. They are voltage transformers whose primary tents resistance is approximately 1.5 Ω and secondary 5-10 kΩ. The primary sides of the coils are connected all together to the 12 V voltage and by means of transistors the connection is made to the ground (vehicle ground).

Spark plugs must be designed to withstand the aggressive working environment of the combustion chamber and to ignite the mixture. Ignition of the fuel mixture is accomplished by creating an electric arc between the contacts. Connection between the high voltage module and spark plugs is made by the high voltage conductors with increased resistance from 5 to 10 kΩ.

Spark plugs also have an increased resistance, which amounts to 3 to 6 kΩ, depending on the design type. As the temperature rises, the plug resistance decreases. The measuring points are placed in such a way that important signals can be detected, which give information about the state of the ignition system. The constructed device is shown in Figure 5.

The device allows to create fault states in individual blocks, which also affects the change of electrical quantities, which can be subsequently measured and evaluated.

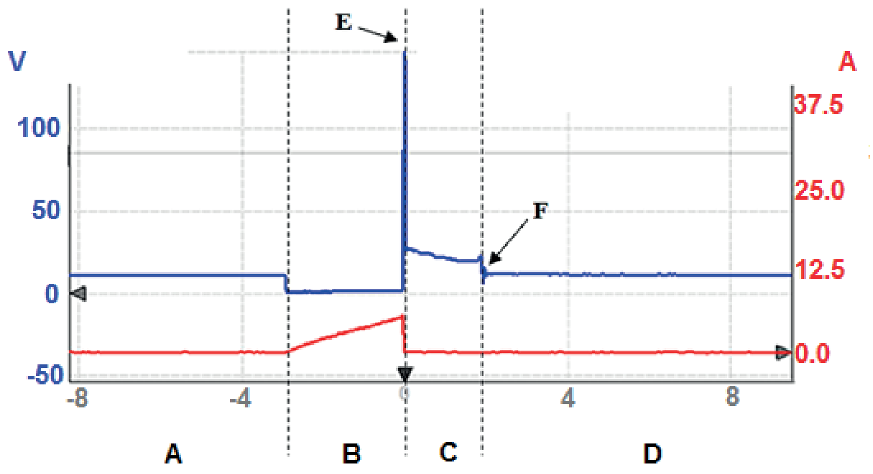


***Figure 6*** *Current and voltage waveforms on the primary side of the ignition module:*
*A - ignition module inactivity, B - energy storage interval, C - arc burning time, D - ignition module inactivity,*
*E - Initialization of the arc burning, F - ignition transformer oscillations.*

## 4 Processing of results

Let the time behaviour be considered as a measurable quantity. If that signal is then compared to the desired signal, one can evaluate the residue based on the difference. Failure assessment, using a residual assessor, not only allows detecting the component failures but can provide information about the component degradation. The best solution for detecting a failure and possibly making a component prognosis is to monitor the behaviour course of the arc burning on the spark plug. By measuring the voltage on the primary or secondary side one obtains information about the arc burning or eventually the inactivity of the ignition system.

Figure 6 shows the current and voltage waveforms on the primary side of the ignition module for the set interval $t_{on}$ = 3 ms. The voltage characteristics shows influence of the secondary side, where it is possible to observe the initial impulse for arc formation and burning time, which in this case is approximately 2 ms.

By using the ADC converter of the engine control unit to monitor the signals on the primary side of the ignition module and then applying a suitable algorithm, it is possible to increase the diagnostics of the ignition system. If one observes the signal in the interval A (or D,) one can evaluate whether the primary winding of the ignition module is damaged by interruption or whether the supply voltage has been disconnected. During the energy storage period B, the transistor in the power module opens. At this interval, the voltage is equal to the voltage drop across the transistor. The current increases depending on parameters of the ignition transformer. By evaluating the current increase and the maximum value, it is possible to determine the short in the winding, which would result in a change in inductance and a decrease in series resistance.

The interval C is essential for determining the arc burning condition. If there was a significant failure during A and B, there would be no burning interval. In this mode, the transistor is closed and the energy stored on the primary side of the ignition coil is transferred to the secondary part. Voltage greater than 10 kV is required for the initial combustion of the arc in the combustion chamber. This voltage is more than a hundred volts on the primary side. Each diagnostic system works by evaluating the measured signals in certain modes and comparing them to the desired signals [9-10].

According to Figure 7 the waveform can be divided into six periods, which are then mathematically spread (interval $t_1$ until $t_5$):

Interval $t_1$: $u(t) = 0$

Interval $t_2$: $u(t) = l \cdot \cos(n \cdot t) e^{-d \cdot t}$

$l$ - voltage in the steady state is voltage constant,

$n$ - determines the number of amplitudes,

$k$ - amplitude,

$d$ - specifies the attenuation.

Interval $t_3$: $u(t) = a \cdot t + c_1$

$a$ - is a constant of the line inclination,

$c_1$ - determines the initial state (final state in the interval $t_2$).

Interval $t_4$: $u(t) = \dfrac{1}{b\sqrt{\pi}} \cdot e^{-t^2/b^2} + c_2$

$b$ - amplitude constant,

$c_2$ - determines the initial state (final state in the interval $t_3$).

Interval $t_{5\text{-}1}$: $u(t) = -m \cdot t + c_3$

$m$ - is a constant of the line inclination,

$c_3$ - determines the initial state (final state in the interval $t_4$).

Interval $t_{5\text{-}2}$: $u(t) = k \cdot \cos(n \cdot t - h) e^{-d \cdot t} + c_4$

$n$ - determines the number of amplitude,

$d$ - specifies the attenuation,

$h$ - shift of course,

$c_4$ - determines the initial state (final state in the interval $t_5$).

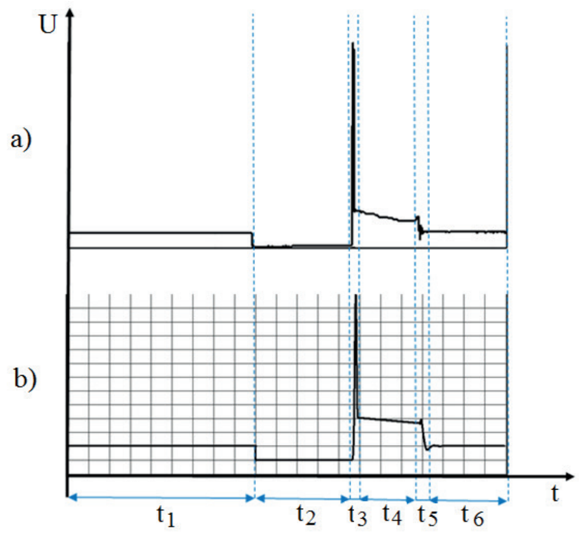


***Figure 7*** *Voltage waveform on the primary part of the ignition module: a - real, b - simulated*

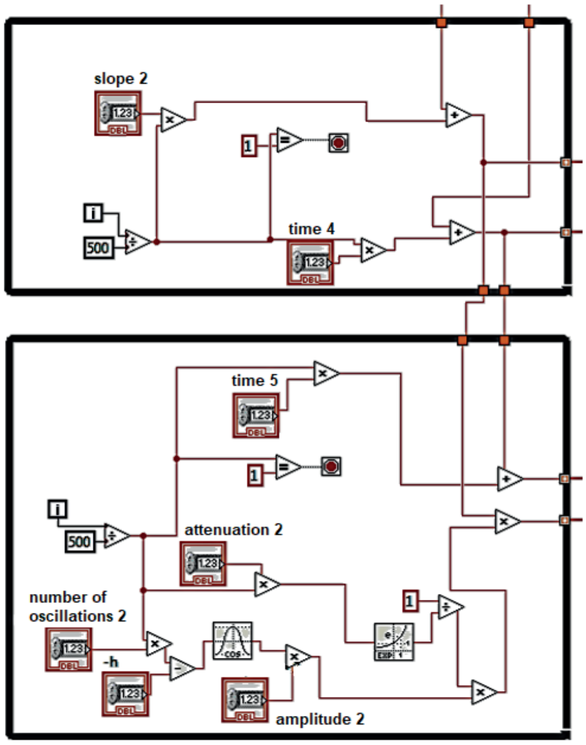


***Figure 8*** *Part of the block diagram from LabVIEW to simulate intervals $t_4$, $t_5$ and $t_6$*

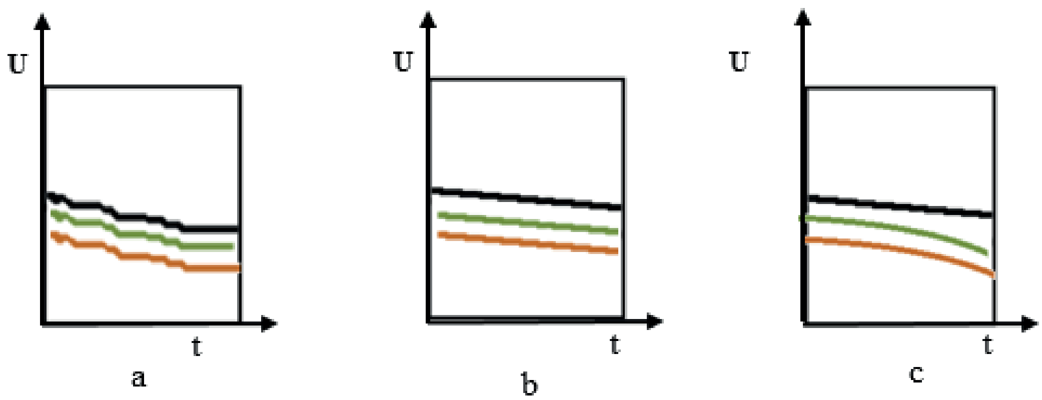


***Figure 9*** *Arc burning interval $t_4$ with tolerance zones: a - real, b - simulated, c - simulated with adjusted tolerance zones*

Voltage simulation was created in LabVIEW environment (Figure 8), where individual time periods are described by mathematical functions.

For a deeper analysis, a simulation by programming environment NI Labview in mathematical mode can be used, where one can set up such operations during the subsequent simulation of error conditions spark pulses through the mathematical model, Figure 8.

LabVIEW allows to export the simulated waveform to a spreadsheet program. Thus, the waveform can be used as a reference for signal testing. If one can determine the reference course of combustion, one can then further introduce tolerance zones to detect partial and permanent failure [11].

The first tolerance band may be for detecting a partial fault (Figure 9 green).

The second tolerance zone (orange color) is intended to determine the inactivity of the ignition system. At least two measurements should be made during the intervals depicting the arc burning. The length of the arc burning is almost 2 ms. In about 0.5 and 1.5 ms. for the built-in online diagnostics, a test cycle would also have to be created, allowing for example to be checked only after the car has warmed up to operating temperature and partially loaded at medium engine speed with a minimum of 5 test cycles over 10 minutes.

Figure 10 illustrates the sampling of arc burning that must be performed from time $t_{0.}$ It is possible to realize only one measurement at time $t_{z2}$, which is sufficient for the arc burning evaluation.

In Figure 11 is presented a sequence program of high voltage waveform ignition model EFS with a faulty diode

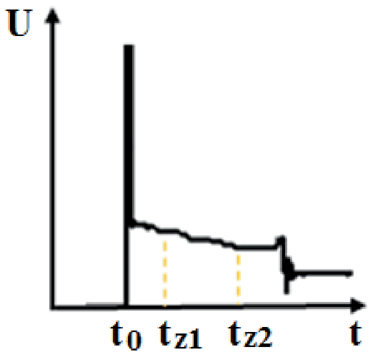


***Figure 10*** *Arc burning interval with two sampling points*

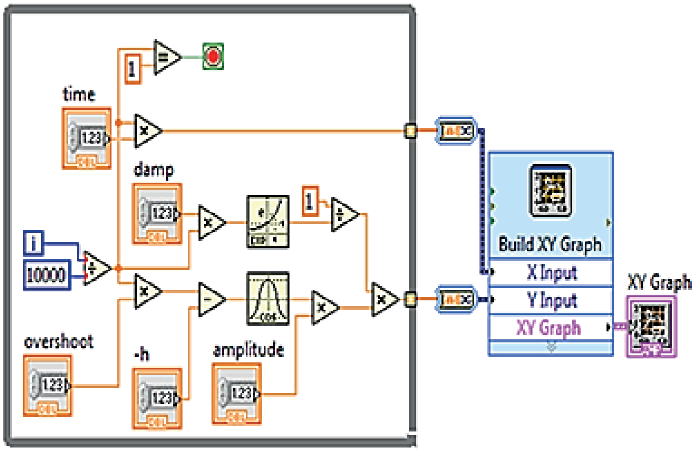


***Figure 11*** *The program sequence in Labview*

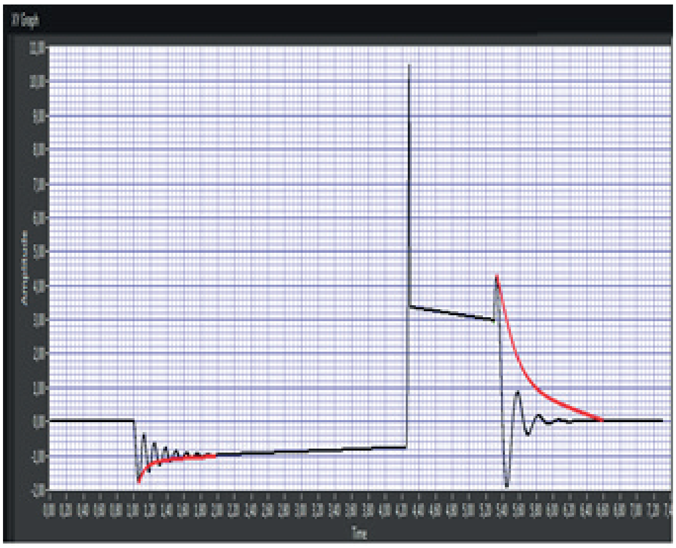

***Figure 12*** *Simulating spark waveforms during the correct and incorrect operation*

and simulation graph in Figure 12., It shows comparison of the malfunctioning ignition coil - sinusoidal course with decreasing amplitude at switching on the primary part of transformer and switching off secondary part of transformer the shutdown transformer (faulty diode) and graph with the end of burning sparkle with-out damped oscillations (correct operation of the ignition coil).

## 5 Measured results with simulated faults

The measurement was performed at atmospheric pressure and on a four-electrode spark plug. The oscilloscope sampling was set to 100 kS/s (time between samples is 10 μs). The transformer charging phase was set to 6ms. The measurement was repeated and recorded five times. Figure 13 is a characteristics,

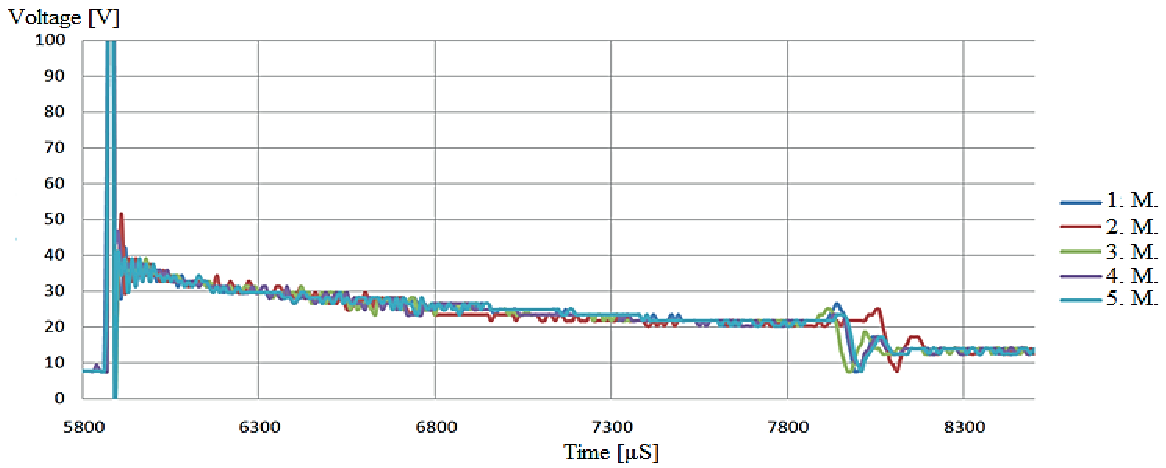


***Figure 13*** *The course of voltage during the arc burning*

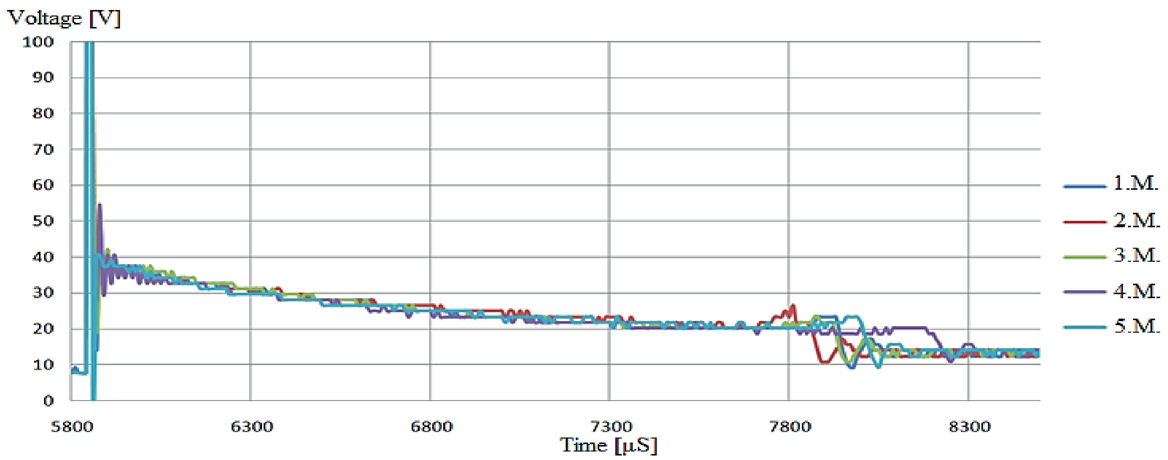


***Figure 14*** *The course of voltage during the arc burning by applying gasoline*

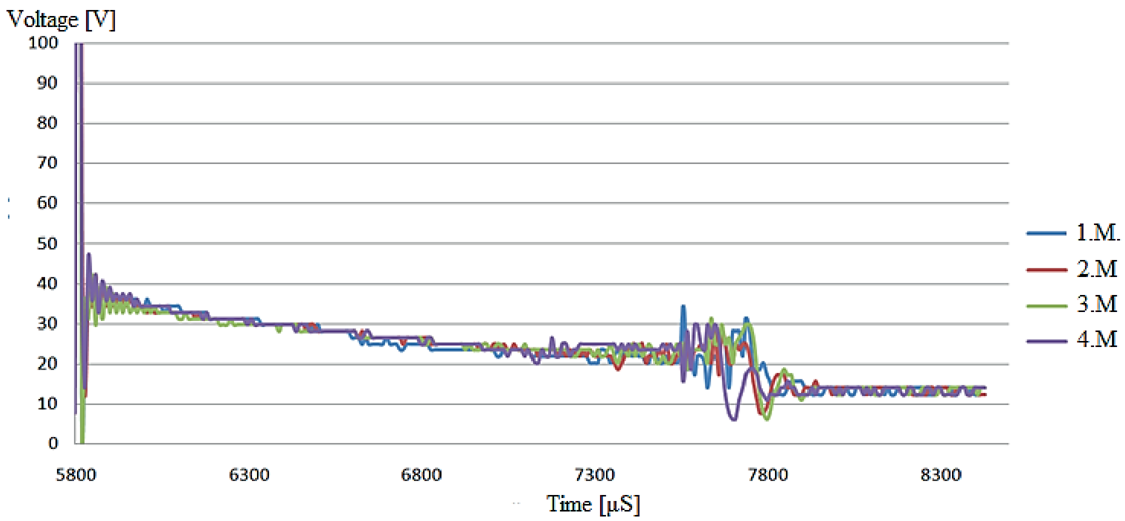


***Figure 15*** *The course of voltage during the arc burning by applying oil*

showing the voltage on the primary side of the ignition module.

By applying a small amount of gasoline to the spark plug, the arc fading scattering occurred (Figure 14). Petrol changed the air gap properties between the electrodes.

The oil was more radical in the characteristic (Figure 15). The reverberation of the arc burn was more oscillated, and the burn time was also reduced by 250 ± 100 µs.

Figure 16 shows a simulated failure of the ignition contact of the driver to the spark plug. The gap distance

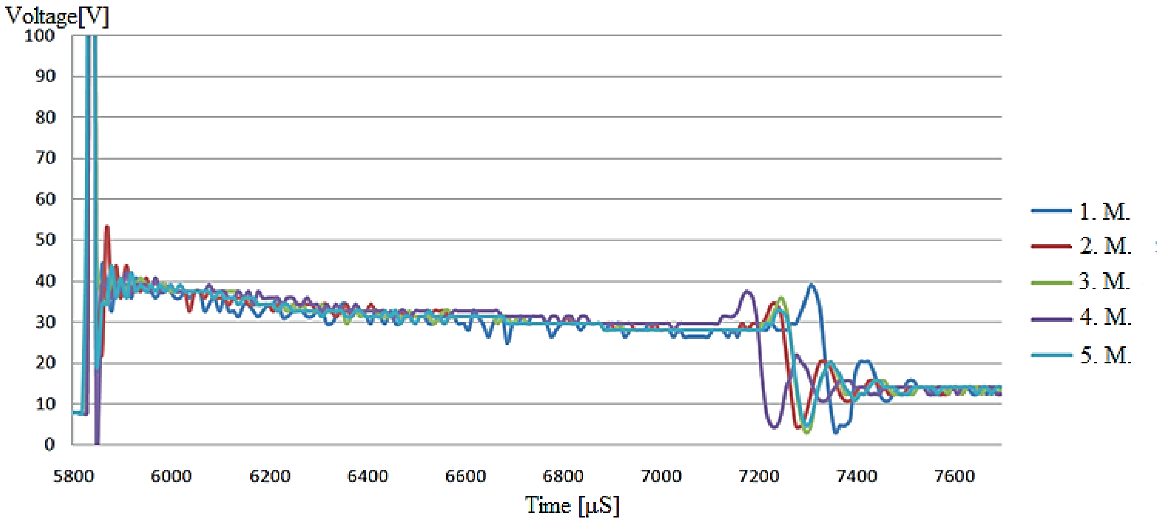


***Figure 16*** *The course of voltage during the arc burning with failure*

was 400 ±100 µm. Burning time was reduced by 750 ± 150 µs. During the burning, the voltage was for about 10 V higher. Higher overshoot was reflected in the decay of the arc, as well.

## 6 Conclusion

Diagnostics of ignition systems by diagnostic systems allows measurement of the primary and secondary high-voltage waveforms. Programming environment of Labview allows to evaluating adequately the waveforms to obtain a comprehensive overview of the examined system based on the simulation analysis.

Ignition system with dual spark coils represents a simple variant without mechanical distribution of ignition. The negative aspect is the limitation of time adjustment due to the exhaust sparks.

A device was designed on which one can test individual components of the ignition systems, monitor their functionality and measure the influence of the ignition arc on different components. Based on this device, it is possible to physically simulate possible faults, copy them to a database and compare them to the actual ones in the car based on files.

Measurements have elucidated the phenomena and effects that affect the arc burning. After the application of oil and gasoline between the electrodes and the failure of the spark plug connection, the time characteristics of the voltage differed from the base. The most significant differences were found during the arc burning with failure.

In the abovementioned analysis of the voltage waveform, when the spark burns out, it is evident that the finishing phase of the burning sparks is missing and instead of damped oscillations course gradually declined. This effect is caused by the high-voltage diode. If a spark goes off, the current stops flowing in the secondary circuit and diode closes and electrically disconnects the secondary circuit section.

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Renato Filjar - Ivan Sklebar - Marko Horvat

# A COMPARISON OF MACHINE LEARNING-BASED INDIVIDUAL MOBILITY CLASSIFICATION MODELS DEVELOPED ON SENSOR READINGS FROM LOOSELY ATTACHED SMARTPHONES

*General mobility estimation is demanded for strategy, policy, systems and services developments and operations in transport, urban development and telecommunications. Here is proposed an individual motion readings collection with preserved privacy through loosely fit smartphones, as a novel sole inertial sensors use in commercial-grade smartphones for a wide population data collection, without the need for the new infrastructure and attaching devices. It is shown that the statistical learning-based models of individual mobility classification per means of transport are capable of overcoming the variance introduced by the proposed data collection method. The success of the proposed methodology in a small-scale experiment for the Individual Mobility Classification Model development, using selected statistical learning methods, is demonstrated.*

***Keywords:*** *mobility classification, smartphone, inertial sensor, statistical learning*

## 1 Introduction

Mobility may be seen as the level of one's ability to move physically, easily and without restrictions in a given framework of the individual and collective transportation infrastructure, that involves different means (modes) of transport and walk. The mobility estimation is a mathematical process of the evidence-based estimation of the level of mobility within the given spatio-temporal constraints. It is considered as a result of integration of the individual mobilities observations.

Modern information and communications systems provide foundation for the information and services provision in relation to user whereabouts. The mobile telecommunications Location-Based Services (LBS) started to exploit the case [1]. This trend expanded to other disciplines including Intelligent Transport Systems, general human activity recognition [2-3], mobile health, medical diagnostics and convalescence [4]. The provision of information and services relies upon user's position determination [5-6], followed by sub-setting the contextual information to the estimated position of the user served. Authors of [1] proposed the now accepted LBS model that facilitate the position-location duality, through recognition of position as a place of existence determined in the physical world, and location as a place of existence in the world of context (the world of information). It clarified the need for the context recognition, as an alternative to position determination and contribution to establishment of location intelligence. Location intelligence is understood as a discipline addressing discovery, identification, exploration and exploitation of common patterns in location (i.e. context-related) dynamics. The term localisation will comprise a set of methods for determination of location relation classes. This may include identification of the mobility patterns (classes of location-related behaviour). Formal description of human mobility has been addressed from biological and medical [7], to mathematical [8] perspectives.

A number of studies addressed exploitation of position and location for location intelligence, utilising increasingly smartphone sensors readings and records of telecommunication activity as data sources. In the now landmark manuscript, authors defined the statistical model of human mobility in the physical (material) world, [9]. Hausmann in [10] outlined the mathematical framework for studying human mobility. Researches showed that position awareness is not a necessary requirement for (human) mobility classification. Gustafsson established the framework and demonstrated the approach in the position estimation through sensor data fusion for requirements-defined classes of Location-Based Services, [5]. In [3] is defined a generalised framework for human mobility classification based on various sets of motion activity observations, while in [11] methodologies for position determination using wearable sensors were surveyed. A smartphone sensors-based position estimation method for constrained in-doors environments is presented in [12]. The selected machine learning methods performance in recognition of individual human motion detection were

**Renato Filjar[1,*], Ivan Sklebar[2], Marko Horvat[3]**
[1]Krapina University of Applied Sciences, Krapina, Croatia
[2]Catholic University of Croatia, Zagreb, Croatia
[3]Department of Applied Computing, Faculty of Engineering and Computing, University of Zagreb, Croatia
*E-mail of corresponding author: renato.filjar@vhzk.hr

surveyed in [2]. The group mobility has been addressed as well in a number of studies, as outlined in [13].

Smartphones have come equipped with a set of high-precision motion sensors and introduced them for everyday utilisation in a modern society. Disciplines ranging from location intelligence and telecommunications to medicine, benefit from data science methods applications on massive position- and location-related observation data collection. The smartphone opportunistic sensor approach is on the rise to integrate physical sensors with the context [14]. Ahmed and Song developed and demonstrated a Bayesian method for human motion classification, which includes the learning process of new classes of motion unknown to the system, based on the utilisation of smartphone accelerometers, [15]. Performance of four machine learning methods in resolution of the problem of the human motion class identification, based on bespoke inertial sensors set on human limbs (i.e. not smartphone ones), with the k-Nearest Neighbour method presenting the best performance for the set-up were examined in [16]. Authors of [17] gave a general overview of the machine learning methods for classification of human motion using smartphone-based sensors, along with recommendations on the experimental studies design. Sama demonstrated the approach in human activity recognition using observations from smartphone sensors, [18] while in [19] application of feature selection methods for human activity recognition using bespoke wearable sensors is discussed. Smartphone sensor data were associated with driver environment descriptors to accomplish machine learning-based driver behaviour profiling in [20]. In [21] is demonstrated a method for seamless rover tracking based on the internet activity data collection. [Benefits of context awareness for indoors localisation were examined in [22]. The smartphone-based opportunistic sensing still fails in expansion beyond the physically attached-to-body devices and the infrastructure-related context (availability and quality of the network communications signals, or a number of infrastructure-based sensors such as CCTV). The majority of utilisations rely on satellite navigation, at least partially, rendering the approach limited to spaces with the GNSS signals available in required quality.

Numerous studies consider smartphone sensor readings in medical applications and services especially as diagnostic tool in neurology, orthopaedic and sport medicine. Haines et al. addressed the global health observations using smartphone sensor readings and modern internet-based communication technology, [23], while in [24] a case of mobility characterisation using wearable sensors in healthy, elderly and stroke patients was examined. Authors of [25] assessed mobility sensors, including those in smartphones, as sources of diagnostic and status information, requiring physical attachment to the patient's body for the alignment of the reference systems.

Machine learning methods have been used for navigation and mobility modelling scenarios. Still, the traditional approaches failed to loose requirements on smartphone sensor deployment and to consider a wider integration with context. Palaghias reviewed and deployed machine learning methods for interpretation of human behaviour, depending on the complex set of various on-body or external infrastructure-related sensors, [26]. Authors of [27] presented a method for Origin-Destination Matrices (ODMs) estimation, as an indicator of general mobility, from the mobile communications activity records, without utilisation of the smartphone inertial sensors and without consideration of individual mobility, for privacy reasons.

The studies presented here rely upon the physical attachment of a motion sensor on the individual's body using a dedicated additional attaching device. Such an assemblage should be operated in a prescribed manner by trained users. Observations are then utilised for mobility classification as inputs for model development methods, selected according to statistical properties of observations [28]. A complexity of deployment reduces prospects of the wide application in a more objective population sample and scenarios of usage. Dependence on position determination renders many methods inconsistent and unusable without the high-quality position estimation.

This study was aimed at recognition and classification of the means of travel based on observations from smartphone sensors through utilisation of machine learning-based classification model development methods for experimental data-based individual mobility classification, [28]. The means of travel are defined as the manner in which an individual using a smartphone roams within the given transportation infrastructure (including pedestrian areas) utilising either a transport device, or simply walking. This research hypothesises that: (i) the novel method for the individual mobility data collection provides observations of the quality and resolution sufficient for mobility classification task and (ii) the methods for the individual mobility classification model development exist that utilise observations from the proposed novel method for the individual motion data collection of the sufficient model performance. The objectives of this study are, as follows: (i) development of the motion data collection method based on the loosely attached smartphone inertial sensors (accelerometers, gravity sensors, magnetometers, gyros) with the embedded reference frames alignment, to serve the mobility classification (estimation) model development, (ii) the mobility classification method selection that will exploit potentials of the loosely attached smartphone sensor observations and (iii) comparison of the mobility estimation and classification models developed using the presented methodology to provide the best practice for the mobility estimation studies of different scales. This research does not aim at development of the overall mobility model. It proposes the methodology for collection of the representative massive dataset and the statistical learning-based methods for development of the individual mobility classification model. The results have the potential of utilisation in Location-Based Services (LBS), urban and transport strategic planning, location intelligence, medical diagnostics and conditions' observation, (urban)

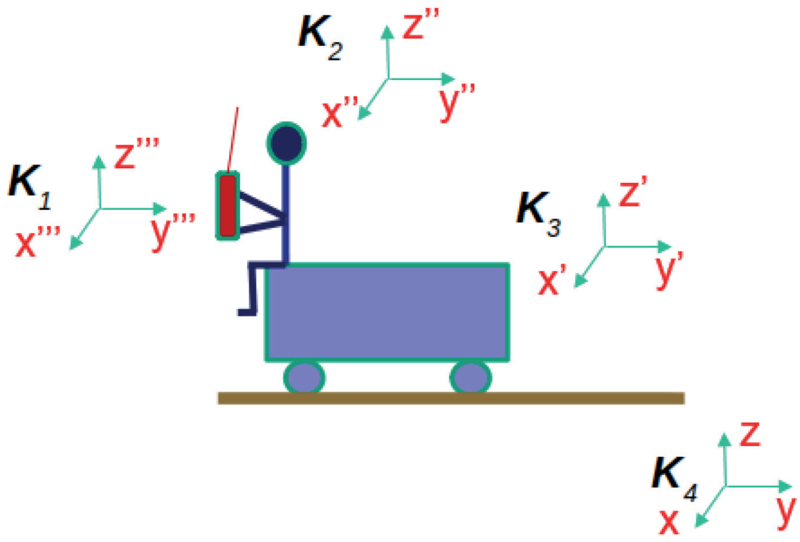


***Figure 1*** *Requirement for the reference frames alignment*

operational mobility management, Intelligent Transport Systems and emergency relief.

The manuscript maintains a simple structure, as follows. Section 1 (this section) states the problem, surveys the research state-of-the-art, and outlines aims and objectives of the research presented in the manuscript. Section 2 formalises the problem of reference frameworks alignment, proposes the novel method for the loosely fit smartphone data collection, describes the experimental smartphone motion data collected using the proposed method in Krakow, Poland, and Zagreb, Croatia. Description includes the exploratory statistical analysis. Finally, a selection of statistical learning methods for the individual mobility classification model development is introduced, based on the statistical properties of experimental motion data. Section 3 outlines the individual mobility classification models developed using the selected statistical learning methods and experimental data and examines their performance for decision on the most suitable individual mobility classification model. The concluding Section 4 summarises the study's results and contributions, the benefits and shortcomings identified and outlines subjects of the future research.

## 2 Method and material

Inertial sensors measure motion properties very accurately, while retaining a low-cost investments of measurements [6]. The smartphone inertial sensors allow for the low-cost high-precision (i.e. with the consistent repeatability) observations of the motion variables (linear acceleration, direction of movement etc.). The high accuracy is accomplished by simple calibration procedures, already conducted by users without the need for further education, or with the sensor information fusion processes [29]. The accuracy levels differ slightly, depending on the actual smartphone realisation [29-30]. The slight differences in the motion sensor accuracy are considered acceptable in classification modelling scenarios, since the model development methods anticipated the existence of variance in observations and addressed them in the model development process.

However, the measurement methodology must ensure that the reference frames (coordinate systems) of all the components of the system comply with each other [31]. Mobility estimation problem concerns the measurement environment that comprises components depicted in Figure 1, as follows: (i) measuring unit (smartphone equipped with inertial motion sensors), (ii) measurement object (mobile individual), (iii) transport device (if a mobile individual is assisted in his or her mobility by train, tram, car, bicycle or some other device), (iv) stationary mobility infrastructure (road, pavement).

Each component of mobility estimation environment utilises its own spatial reference frame (co-ordinate system) $\boldsymbol{K}_{(l)}$, $l = 1, \ldots, 4$, respectively. Measurements taken by measuring unit may be considered in relation to the other components of the mobility estimation environment only if at least one of the presumptions are fulfilled, as follows:

*P1*: Spatial reference frames of a measuring unit ($\boldsymbol{K}_1$), measurement object ($\boldsymbol{K}_2$), transport device ($\boldsymbol{K}_3$) and mobility infrastructure ($\boldsymbol{K}_4$) are correspondent (equal),

P2: a set of transformations $\boldsymbol{f}_{i,j}$, $i = 1, \ldots, 4, j = 1, \ldots, 4, i \neq j$, that transform positions and measurements taken in one spatial reference frame into another, exists.

The P1 presumption is addressed with a tailored physical fitting of a mobile device to a measurement object's body. The attachment means assures that the sensors in a mobile unit are measuring the same motion as the individual's one. The need for an additional, often costly, infrastructure (fitting device and method) and user training in operation emerge as a drawback of this approach, preventing its wider use and affecting the quality of representation of a targeted population. Here, a novel method for motion readings collection, using inexpensive and accurate inertial sensors in a widespread and frequently used smartphones, is proposed. The proposal results from the statistical analysis of inertial sensors readings and common practices in smartphone utilisation.

Modern smartphone application usage often requires the end-user's attention and machine-to-individual communication through an application interface. The common practice of a smartphone application utilisation results in the common pose in which an individual is loosely fixed with his or her smartphone. A loose (approximate) compliance between a mobile measurement's devices (inertial sensor in a smartphone) and measurement object (an end-user) is accomplished without the need for physical fitting or training the end-user. The proposed method assures at least a loose compliance between the spatial reference frames of measured object (an individual using a smartphone) and of a transport device, considering an end-user would utilise his or her smartphone while standing or being seated in a transport device (car, taxi, train, tram etc.).

A simple algorithm is developed to identify a common pose of a smartphone utilisation that involves comparison of the rate of change of the inertial sensor readings. Inertial sensor readings are collected when taken during the interaction with a smartphone in a characteristic pose. The proposed method opens prospects for a wide-spread anonymised individual mobility data collection using commercial-grade smartphones without additional equipment or operational training.

The proposed motion data collection method was demonstrated in the solution of the individual mobility classification problem. The individual motion smartphone data sets were collected by the team members volunteering to utilise the proposed loose-fit smartphone in a small-scale experiment. It intended to serve as the proof-of-principle and as the motivation for a wider data collection for the mobility estimation for targeted regions in the future. Volunteering data collectors followed the proposed methodology and behaved like ordinary smartphone users, frequently utilising various applications. A dedicated smartphone application and the data post-processing identified scenarios of the attention given to interactions with smartphones and recorded the inertial sensors reading for the individual mobility classification model development. The proposed methodology was used in three common cases of urban mobility, with overlapping nature of descriptors: (i) walking (walk), (ii) travelling by bus (bus), (iii) travelling by tram (tram). The cases selected in this research are to be expanded in the future further to various means (modes) of transport. Overlapping statistical characteristics arise inevitably from the similarity of movement in urban traffic, especially during the rush-hours, thus reflecting the variance added to the original data.

The problem of the added variance in data was addressed by utilisation of the supervised machine learning-based methods for classification model development, selected for their nominal capacity in addressing data with statistical properties of the same nature as those collected with our experiment [28, 32], as follows: (i) Random Forest (RF) method, (ii) k-Nearest Neighbours (KNN) method, (iii) Least Square Support Vector Machine with Radial Kernel Function (LSSVMR) method, (iv) Support Vector Machine with Radial Kernel Function (SVM) method, (v) Linear Discriminant Analysis (LDA) and (vi) Classification and Regression Tree (CART) method.

A comprehensive overview of the methods involved, their characteristics, ranges of applications and details of implementation in the open-source R framework for statistical computing [33] may be found elsewhere [28, 34-35].

The classification statistical learning methods for the model development were deployed using resampling approach [28, 35] to mitigate randomness (variance) in data split and method. The cross-validation-based approach was determined as required after significant differences in models performances were found, resulting from the particular means of the original data set division into training and test sets. A dedicated software was developed in the open-source R environment for statistical computing, using the R libraries: *caret* [35] and *forecast* [36] and their dependencies. The used R software integrated statistical learning methods for the model development with those aimed at developed models performance assessment. Model performance was examined through the performance metrics involving Confusion Matrix and Classification Accuracy and Kappa parameters [28, 35].

The smartphone inertial sensor readings were collected in the identified application usage pose from smartphone inertial sensors, as follows:

(i) *Accel_x*, denotes accelerometer readings of the acceleration vector x-component, in [mm/s$^2$],

(ii) *Accel_y*, denotes accelerometer readings of the acceleration vector y-component, in [mm/s$^2$],

(iii) *Accel_z*, denotes accelerometer readings of the acceleration vector z-component, in [mm/s$^2$],

(iv) *Gyro_x*, denotes gyroscope readings of the angular velocity vector x-component, in [rad/s],

(v) *Gyro_y*, denotes gyroscope readings of the angular velocity vector y-component, in [rad/s],

(vi) *Gyro_z*, denotes gyroscope readings of the angular velocity vector z-component, in [rad/s],

(vii) *Magnetic_x*, denotes magnetic sensor readings of the geomagnetic field density vector x-component, in [nT],

(viii) *Magnetic_y*, denotes magnetic sensor readings of the geomagnetic field density vector y-component, in [nT], and

(ix) *Magnetic_z*, denotes magnetic sensor readings of the geomagnetic field density vector z-component, in [nT].

The variables above served as predictors (features) of the Individual Mobility Classification Model.

The actual Category in which readings were taken was set the response (outcome) of the model.

Readings were collected using the Android application AndroSensor [37] on a Motorola G5 smartphone and stored internally for the post-processing during the experiment conducted in cities of Krakow, Poland and Zagreb, Croatia in Winter of 2018.

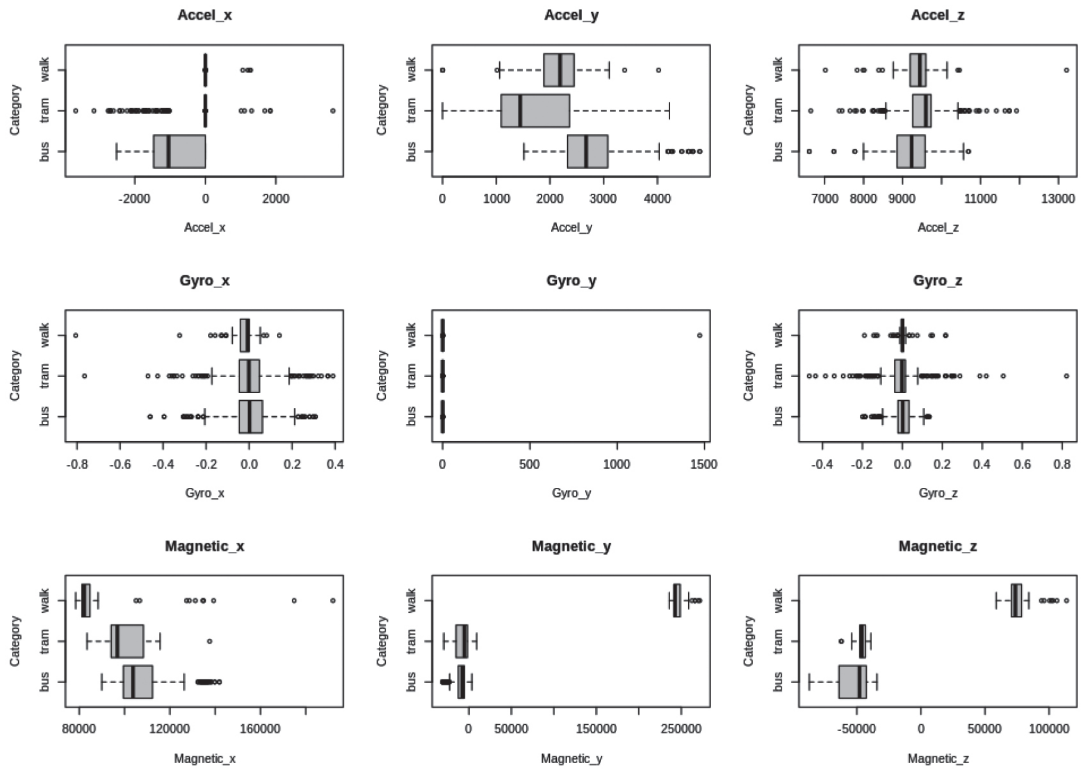


*Figure 2* *Boxplots of original readings (predictors)*

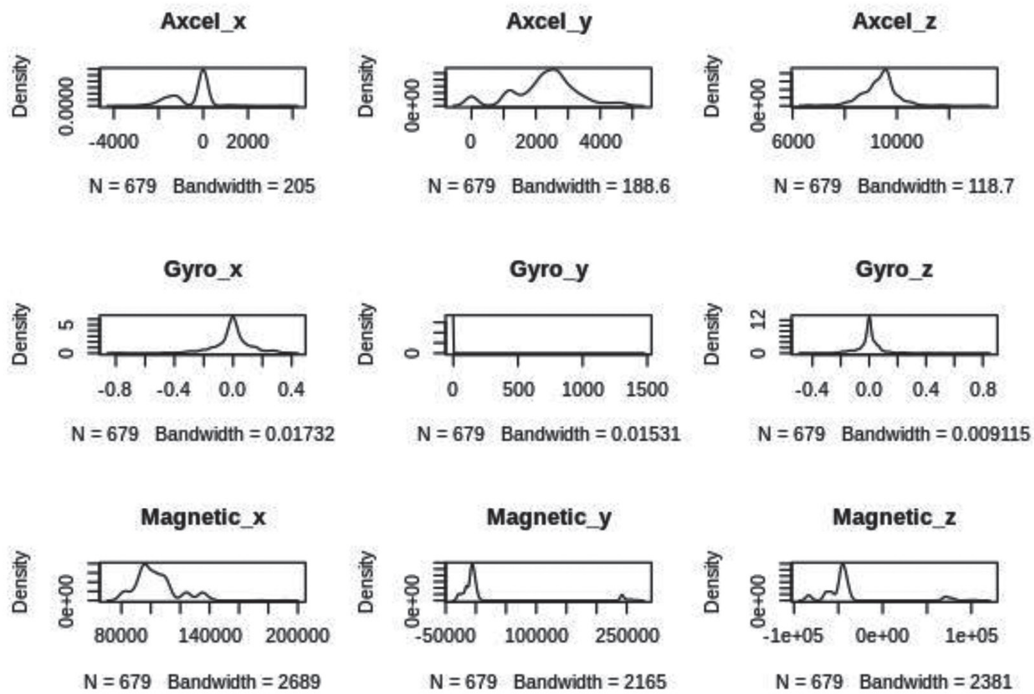


*Figure 3* *Experimental statistical distribution density functions of predictors (features)*

An intentionally unbalanced set of readings was collected, (Figure 2), to examine robustness of the statistical learning classification methods in the specific scenario under consideration. Overlapping of statistical distribution density functions of predictors is observed and a wide range of statistical properties of predictors are evident from the exploratory data analysis. The variety of individual predictors variances results in the complexity of the process modelled. That fact leads to selection of the model development methods capable of encompassing the complexity of variances, including those generated by the loosely attached smartphone sensors data collection method [32].

The original data set was split into training (80%) and test (20%) sets in a randomised manner, utilising the common statistical learning practice based on the Pareto

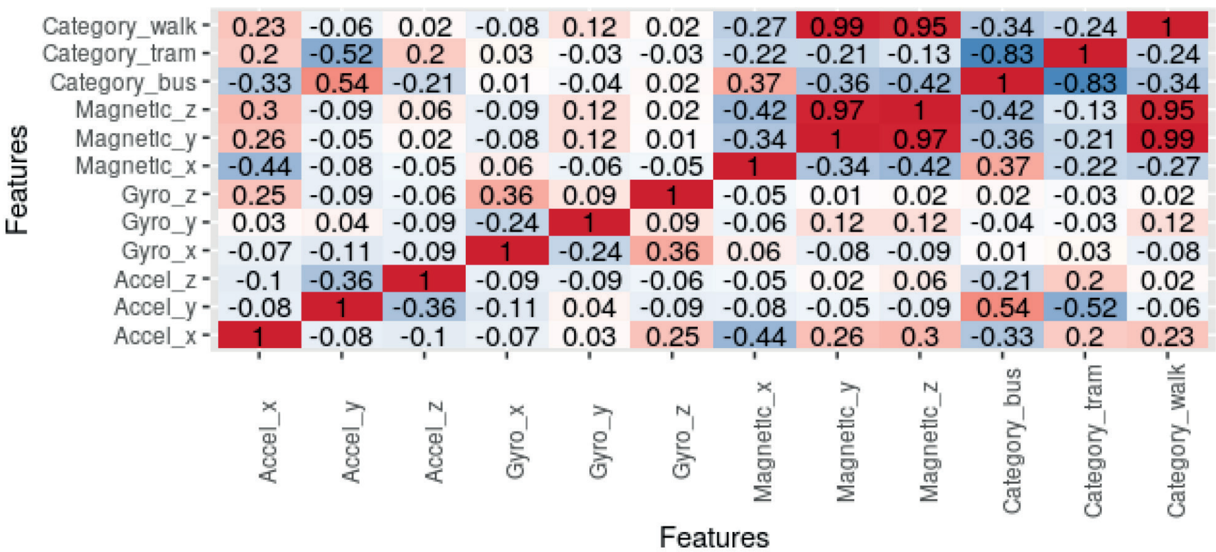


***Figure 4*** *Correlation matrix of nine predictors in the experimental data set*

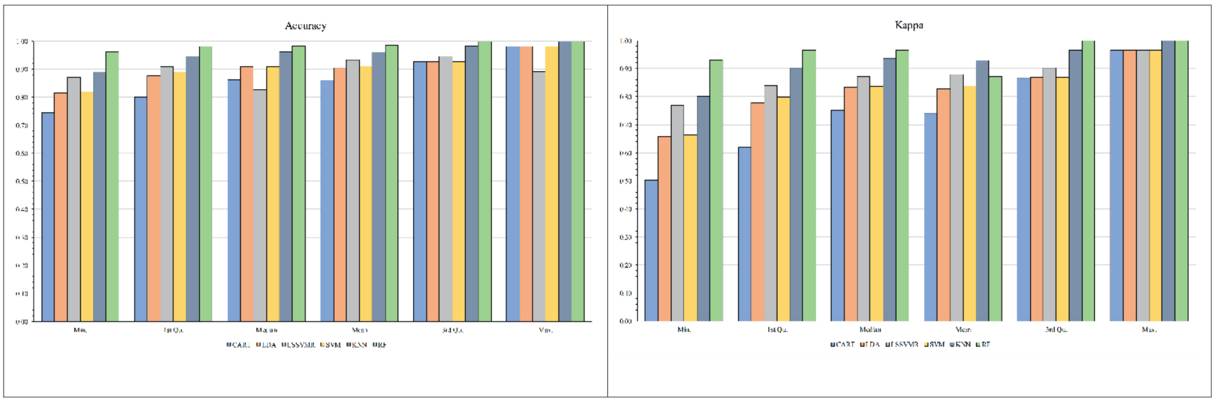


***Figure 5*** *Comparison of the accuracy (left) and kappa (right) model performance statistics for the six models: CART, LDA, LSSVMR, SVM, KNN and RF*

principle [28]. Cross-validation was utilised to compensate for the randomised original data split and for the optimised model development, as an another common statistical learning practice [32].

## 3 Research results

This research aimed at developing the method for massive data collection in different scenarios across the population and at justifying utilisation of statistical learning methods in mitigation the additional variance imposed by the process. The experimental data set collected extends a wide variety of statistical properties, as evident in estimates of experimental density functions depicted in Figure 3. The predictors (features) in the experimental data set were mostly uncorrelated, as evident from the correlation matrix in Figure 4.

The proposed loose-fitted smartphone procedure is more contextually oriented, compared with the traditional approach of the tight physical fitting. As a result, the experimental results (readings) encompassed a larger variance, due to: (i) loose fitting (approximate equality between the reference frames) and (ii) introduction of complex parameter-overlapping classification scenarios.

It was intended to tackle the problems with the dedicated statistical and statistical learning methods for model development, as outlined in Section 2. Despite the differences in statistical properties observed in data, it was proceeded by modelling the development without deployment of any data preparation activity (transforms, feature reduction, or normalisation). Introduction of the resampling procedure was the only modification of the original method implementation that was used to mitigate randomness introduced by the very methods and variance inherited in data. The caret R package allowed for a targeted model developments, and assessment of their performance. The resampling procedure was optimised using the Kappa parameter [35]. Statistical analysis of model performance parameters is presented in Figure 5 and box-plots of the same performance parameters in Figure 6.

Two model development strategies were examined for their difference in classification approach, and results of their models are addressed and presented here in more details. The Support Vector Machine (SVM) approach is recognised widely as a very robust method for the

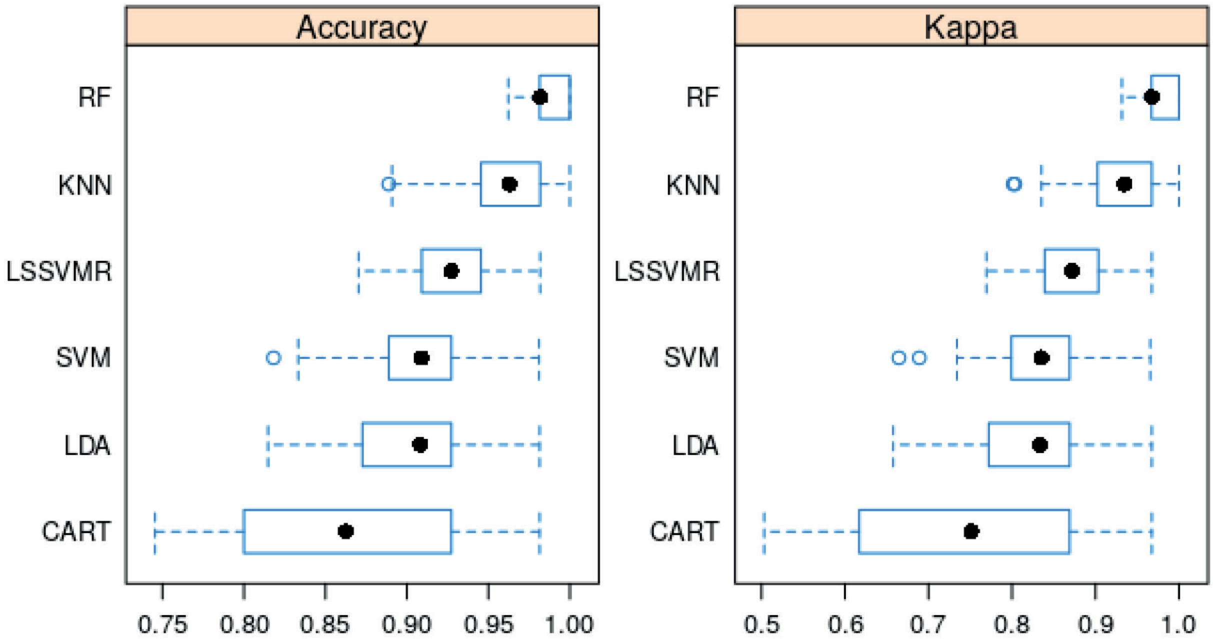


***Figure 6** Boxplots of model performance parameters*

***Table 1** Confusion matrix of the Support Vector Machine with the Radial Kernel Function (SVM) Mobility Classification model*

| Prediction/Reference | bus | tram | walk |
|---|---|---|---|
| bus | 73 | 11 | 0 |
| tram | 1 | 38 | 2 |
| walk | 0 | 0 | 10 |

***Table 2** Confusion matrix and statistics of the Random Forest (RF) Mobility Classification model*

| Prediction/Reference | bus | tram | walk |
|---|---|---|---|
| bus | 72 | 2 | 0 |
| tram | 2 | 47 | 0 |
| walk | 0 | 0 | 12 |

***Table 3** The overall statistics of the two competing models*

| Overall statistics | SVM | RF |
|---|---|---|
| Accuracy | 0.8963 | 0.9704 |
| 95% CI | (0.8321, 0.9421) | (0.9259, 0.9919) |
| Kappa | 0.8087 | 0.9471 |

classification model development. With a range of their kernel function, the SVM allows for fine-tuning of the models developed, and yields well-behaving models [28]. The Random Forest (RF) approach tackles easily a large-variance data, encompassing well the extended variance. Additionally, the RF models are not prone to overfitting [28]. Both approaches were exploited, with the resampling procedure deployed in both cases.

The Support Vector Machine with the Radial Kernel Function (SVM) model performed as depicted in Table 1. While providing good accuracy and fair Kappa parameter, the SVM model struggles in recognition of the transport means in low-level dynamics conditions, as seen from the confusion matrix. The SVM model failed in recognition of tram travel and even walk, during the low-speed and low-dynamics travels. Utilisation of the Random Forest approach yields the RF Mobility Classification Model of a far better performance, as shown in Table 2.

The RF Mobility Classification Model reached better accuracy of more than 97% and improved the Kappa parameter value. Its confusion matrix contains just four instances of the bus-tram misclassification, apparently in the very similar dynamical conditions. Walk is identified correctly.

Table 3 outlines the overall statistics (model performance parameters) for the two competing models extending the best performance.

The z-statistics yields the statistical significance of the accuracy difference between the SVM and the RF models at $p = 0.02811$ ($\alpha = 0.05$).

## 4 Conclusion

The problem of general mobility estimation is addressed here with introduction of an inexpensive method for individual mobility data collection using wide-spread utilisation of commercial-grade smartphones. With the loose smartphone attachment to user in a common pose of a smartphone usage, the correspondence of the all the reference frames involved was accomplished. This accomplishment allows for utilisation of the smartphone inertial sensor readings for the individual mobility classification. The use of inertial sensor readings establishes a foundation for anonymised mobility data collection, thus allowing for sustained privacy of individual users. Additionally, the proposed methodology does not rely upon the high-precision absolute position determination, often unavailable in a number of high-population scenarios (indoors, city centres) where the individual mobility assessment is particularly needed.

The acceptable extent of additional variance in data resulting from the loose-attachment approach was shown and the effectiveness of the statistical learning approach in the Individual Mobility Classification Model development under the circumstances of the enlarged variance in data was demonstrated. In comparison of various classification models approaches examined, it was found that the Random Forest Individual Mobility Classification Model is the best performer, with the development and performance assessment conducted with the tailored software, developed in the R environment for statistical computing. The RF Individual Mobility Classification Model has returned the 95% confidence interval of $0.0305 \pm 0.0290$, for the $N = 135$ testing sub-set of the sparse and unbalanced original data. The methodology proposed and models developed here form a foundation for expanding the crowdsourcing efforts in experimental data collection for the individual mobility classification based on the widespread set of scenarios of smartphone usage while travelling. The general nation-wide, regional, or city-wide mobility estimation will emerge from information fusion of the individual mobility classification models.

The intention is to pursue this research with assemblage of the loosely attached smartphone sensor observation database with different mobility scenarios and a wider range of individual mobility means (transportation modes) involved and with examination of potentials for utilisation of refined statistical learning-based classification model development methods.

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Jan Dvorsky - Jaroslav Belas - Ivana Novotna - Martin Fero - Zora Petrakova

# QUALITY OF BUSINESS ENVIRONMENT OF THE SME: A SECTORAL VIEW

*The aim of the article is to find out differences in the perception of selected factors that determine the business environment among selected groups of small and medium-sized enterprises (SMEs), divided according to the sector of the national economy they belong to. The first group included SMEs from the sector of transport and services. The second group included SMEs from the construction, manufacturing and agriculture sectors. The questionnaire was completed by 459 SMEs in the Czech and the Slovak Republics. To evaluate the formulated hypotheses, the Chi-square test and the Z-score were used. The case study showed interesting findings. The SMEs in transport and services perceive the competitive environment as more acceptable than the SMEs in construction, manufacturing and agriculture. In addition, the SMEs in transport and services are of the opinion that customers accept prices of their products and services to a greater extent than the SMEs in construction, manufacturing and agriculture. There are also significant differences between selected groups of SMEs in assessing the quality of the judicial system in commercial law and the view that the current level of macroeconomic indicators supports entrepreneurship and creates interesting business opportunities. The national economy sector is not an important criterion in assessing financing, the family environment, R&D infrastructure, the quality of the business environment or the quality of education. The paper brings interesting findings and new incentives for small and medium-sized enterprises; for organizations supporting the business environment; for further research and discussion on the cross-sectoral assessment of the business environment quality and its important factors.*

***Keywords:*** *transport, national economy, SME, case study, Czech Republic, Slovak Republic*

## 1 Introduction

Continuous changes in the business environment are forcing businesses to make permanent changes and innovations [1]. The ability of an enterprise to adapt to continuous changes in the business environment depends on its ability to adapt business objectives to conditions in the business environment [2]. Attitudes of owners and top managers towards determinants of the quality of the business environment are a valuable source of information for state, private and non-profit organizations. However, the primary beneficiaries are the small and medium-sized enterprises themselves, which can benefit from the knowledge gained in managing SMEs [3-4]. The structure of SMEs by sector of the national economy is one of the criteria that can cause different perceptions of factors determining the quality of the business environment as well as the perception of the quality of the business environment itself [5]. The sectoral view of the assessment of business environment quality factors by the SMEs in the transport and services sector provides important information not only for the companies concerned [6-7].

The article deals with the detailed comparison of evaluation of selected factors of the quality of the business environment by the group of the SMEs from the transport and services sector in comparison to the SMEs from the construction, manufacturing and agriculture sectors. The subject of comparison consists of selected economic, legislative, social, technological factors and competitive environments. The case study was carried out in 2017 and 2018 on a sample of 459 small and medium-sized enterprises in selected sectors of the national economy.

The article has the following structure. The first part presents current knowledge in the segment of small and medium-sized enterprises in given sectors of the national economy. In the second part, the aim of the article is determined; statistical hypotheses are formulated; methodology of data collection and sample structure of respondents and statistical methods used are presented. The next section presents the most important empirical results of the case study and evaluation of statistical hypotheses. The discussion summarizes the most important outcomes and compares the results to conclusions of articles from other authors in a similar field of research. In conclusion, there are limitations of the results as well as the future direction of research.

**Jan Dvorsky[1,*], Jaroslav Belas[1], Ivana Novotna[2], Martin Fero[2], Zora Petrakova[3]**
[1]Department of Business Administration, Faculty of Management and Economics, Tomas Bata University in Zlin, Czech Republic
[2]Department of Languages and Humanities, Faculty of Materials Science and Technology, Slovak University of Technology Trnava, Slovakia
[3]Institute for Forensic Engineering, Faculty of Civil Engineering, Slovak University of Technology, Bratislava, Slovakia
*E-mail of corresponding author: j1dvorsky@utb.cz

## 2 Literature background

The business environment or the quality of the business environment is a broad term. The term business environment is used by the United Nations Conference on Trade and Development (UNCTAD). Formankova, Vajcnerova, Ryglova, Chladkova, Stojanova and Adrasko [8] state that the quality of the business environment is primarily determined by national legislation and national economic aspects that ultimately affect all the sectors of the national economy. In general, one can generalize that the SMEs are very sensitive to quality of the business environment.

The quality of the business environment plays an important role in the national economic sector - in the country's economic system [9-10]. This concept and its certain measurement or evaluation depend on values of the individual components. According to Kozubikova, Kotaskova, Dvorsky and Kljucnikov [11], the following factors are the legal form of the enterprise, the business activities of the corporation, the sources of financing (if at all and to what extent the corporation uses these funds), market, taxation and domestic taxation rate in the country, the rate of economic growth and development, the rate of inflation, the legal system in the country, the nature of accounting rules, social values, international factors (harmonization factors in certain areas), but also the country's culture and others [12]. This is also due to internal factors, e. g. property-legal relations in the company, activity of the corporation - e. g. in the context of corporate social responsibility, etc. Civelek, Kljucnikov, Dobrovic and Hudakova [13] also focus on the entrepreneur's personality in terms of their creativity and ability to be or to become an entrepreneur. Probably the oldest form of measuring the quality of the business environment in different countries is the Competitiveness Index of the Countries, published by the World Economic Forum (WEF).

In assessing the quality of the business environment, Viturka [14] assigns the greatest importance to business factors. Their partial factors are the proximity of the market - the geographical location of regions in interaction with the economic potential of the best available markets, the factor of concentration of major companies - in the context of location of major customers represented by economic or non-economic entities, presence of foreign enterprises - assessing the positive impact of foreign investment on integration of the host country into the global economy and the factor of supported services - higher demand for highly specialized services (Knowledge Intensive Services).

In the context of small and medium-sized enterprises (SMEs), their role is considered by many authors to be very important in the effective functioning of the economic system [15-16]. Chladkova [17] states that SME share unique characteristics that are determined by their nature and that also enable them to take a special position in the economic system. On the one hand, the SMEs generally have limited capital resources that adversely affect corporate governance and development, on the other hand, these companies are very flexible in responding to changes that occur in the economic system or they operate in a sector that is not of interest to large enterprises.

Transport has several functions. According to Eisler [18], in addition to its dominant function, which is transport or the movement of goods and persons, it further has a stimulating function, reflecting investment in transport infrastructure, which ultimately initiates the country's economic growth, the social stabilizing function – Fabus and Csabay [19] is of the opinion that transport has a significant political-social dimension and each disorder - the mismatches have a significant impact on the stability and development of the economy and society. Another function is the substitution function - e.g. with the Just in Time system in place, it replaces storage in the context of freight transport. The supply of transport is also closely related to other services, especially tourism, where it affects the structure of consumption and the size of services.

Surovec [20] further states that transport must, in addition to its main function - ensure the transport demand of society, contribute optimally to the national economic development and to the growth of the population living standard. This effect will only be achieved if the transport is understood as a coherent system involving all the types of transport of persons and goods. Novack, Gibson, Suzuki and Coyle [21] cite a well-functioning transport system as a requirement of an economically developed country. Transport is, according to authors, based on the historical, economic, social and political perspective, the most important industry in the world.

Novack, Gibson, Suzuki and Coyle [21] also draw attention to the negative aspect of malfunction or insufficient functionality of the transport system, which causes frustration of population and with it possible economic losses. In the case of a well-functioning system, there is an opportunity and reward for each user in different forms. Transport plays an important role in helping to bridge the gap in demand and supply as a part of a mass-production approach. Looking at services, many authors unite in their definition. For instance, Tuckova [22] defines service as an activity, or the advantage offered by one party to another, which is essentially intangible without customer ownership. According to Tuckova [22], the customer buys only the right to perform the service. Service production may or may not be associated with a particular tangible product. In addition, the author presents the features of services towards which the individual opinions of the author are converging. According to Bryson and Daniels [23], these are the following: intangible, inseparability, heterogeneity, difficulty in expressing value, destructibility (services cannot be deferred - stored, e.g. missed flight) and the impossibility of ownership.

Research and innovation are moving at a high pace. Product innovations go hand in hand with development of services and the constant impetus for more specific and knowledge-intensive services - services that require obtaining the knowledge needed to deliver them. Bryson and Daniels [23] classify Knowledge Intensive Services as services where some greater knowledge of the selected field to which the service relates is required, e.g. in the context of scientific and technical knowledge, research and development activities, etc. Those services require people with higher education and professional qualifications who can provide the client with a solution to their complex or narrowly specific needs. Those services play an important role in the innovation process of companies as these activities maintain interaction with the knowledge providers [24].

The constant diversity of services requires their arrangement - classification according to certain characteristic groups based on common features. Bryson and Daniels [23] defines division of services e. g. by nature of activities (NACE classification), by function performed (production, distribution, personal and social services), by mode of implementation (market services, social and economic needs), by target services market, by COPNI classification (classification of services by purpose).

## 3 Aim, methodology and methods

The aim of the article was to find out differences in perception of selected factors that determine the business environment among selected groups of small and medium enterprises (SMEs) according to the sector of the national economy. The first group included the SMEs from the transport and services sector (T+S). The second group included the SMEs from the construction, manufacturing and agriculture sectors (C+M+A). The authors of the article assume that the perception of top managers or owners of the SMEs (herein after as respondent) to the evaluation of selected factors will be different.

During the calendar years 2017 and 2018, more than 17,200 SMEs from the Czech and Slovak Republics were asked to complete an online questionnaire. The total number of addressed SMEs represented more than 5% of all the SMEs in selected countries (CR: 9,400 SMEs, SR: 7,800 SMEs). The respondents were approached with the Bisnode Albertine database (CR) and the Cribis database (SR) by random sampling. The basic criterion for determining the total set of SMEs in selected countries was the number of employees of the enterprise (from 1 to 250 employees). The number of respondents who responded positively to the application was 641 SMEs (3.7% return on questionnaires). Respondents were addressed by e-mail with a structured request to fill in a questionnaire. The questionnaire consisted of 82 assertions. The questionnaire was created in two versions according to the nationality of the respondent. The questionnaires are available on the following websites:

**Czech version:**
https://docs.google.com/forms/d/e/1FAIpQLSdTbrl5oKX93-hFY2deUAOYeWHWgI-tBa3zPape_FiJAmI-Dg/viewform

**Slovak version:**
https://docs.google.com/forms/d/1_H7WSPiVJZkEXdQx3VlGV0iJ_4ppDKRIQMXL6F8Vn-4/edit

The questionnaire was divided into three parts: *i) socio-demographic characteristics* - region of operation of the enterprise, national economy and size of enterprise; gender, age and educational attainment of the respondent; *ii) business environment factors* - economic, political, social, technological and competitive factors; *iii) business environment quality contentions (QBE)*. The questions in the questionnaires were randomly formulated in order to really find out the respondent's opinion. The questionnaire also contained a control question to prevent the questionnaire from being filled by computer. The authors of the article evaluated 26 assertions (31.7%) from all the questionnaire assertions to fulfil the objective. Respondents were able to comment on the claims by one of five options: totally disagree (A1), disagree (A2), cannot answer (A3), agree (A4) and totally agree (A5). The following arguments were the subject of the examination of attitudes:

**F1: Macroeconomic environment**: I evaluate the macroeconomic environment as friendly for business activity (F11); the state of the macroeconomic environment in our country promotes business start-ups (F12); the current macroeconomic environment supports innovative business activities (F13); the current level of basic macroeconomic variables (GDP, employment, inflation) supports entrepreneurship and creates interesting business opportunities (F14).

**F2: Financing enterprises:** Companies have good access to bank loans (F21); credit terms of banks are acceptable to companies (F22); the price of loans is acceptable to firms (F23); banks have a positive impact on the quality of the business environment (F24).

**F3: Legal environment:** I rate the level of legislation in business as good (F31); the commercial justice system works well (F32); law enforcement is good in our country (F33); the legislative environment in our country is stable (F34).

**F4: Quality of education:** I rate higher education in our country as good quality (F41); I evaluate the secondary school education as a quality one (F42); the state can prepare quality people for us (F43); school graduates have good knowledge and skills (F44).

**F5: Infrastructure in the area of research and development:** R&D infrastructure in our country is well built (F51); state support for R&D in the country is at a good level (F52); R&D results in our country help entrepreneurs; government support for R&D has an upward trend (F54).

**F6: Family environment:** Family environment motivates people to do business (F61); it is easier to do business if one of the close relatives is doing business (F62); in the family, I have gained a lot of knowledge that helps me do business (F63); my family helps me do business (F64).

**F7: Competitive environment:** The risk of new competitors entering the sector in which I operate is appropriate (F71); the intensity of competition in the

***Table 1*** *Evaluation of indicators of macroeconomic environment*

| F11 | T+S | C+M+A | F12 | T+S | C+M+A |
|---|---|---|---|---|---|
| A1+A2 | 136 | 101 | A1+A2 | 131 | 100 |
| [%] | 52.7 | 50.2 | [%] | 50.8% | 49.8% |
| V3 | 41 | 42 | V3 | 58 | 54 |
| A4+A5 | 81 | 58 | A4+A5 | 69 | 47 |
| [%] | 31.4 | 28.9 | [%] | 26.7% | 23.4% |
| Chi-square | | 1.937 | Chi-square | | 1.419 |
| P-value | | 0.379 | P-value | | 0.492 |
| F13 | T+S | C+M+A | F14 | T+S | C+M+A |
| A1+A2 | 78 | 62 | A1+A2 | 80 | 76 |
| [%] | 30.2 | 30.8 | [%] | 31.0 | 37.8 |
| V3 | 108 | 87 | V3 | 77 | 67 |
| A4+A5 | 72 | 52 | A4+A5 | 101 | 58 |
| [%] | 27.9 | 25.9 | [%] | 39.1 | 28.9 |
| Chi-square | | 0.240 | Chi-square | | 5.431 |
| P-value | | 0.886 | P-value | | 0.049 |

industry in which I operate is normal (F72); my customers accept the prices of my products and services (F73); my suppliers demand reasonable prices for their products and services (F74).

**F8: Quality of business environment:** The business environment in our country is of good quality and suitable for business (F81); business environment in our country is reasonably risky and allows business (F82); conditions for doing business in our country have improved in the last five years (F83); business environment in our country is suitable for starting a business (F84).

The following hypotheses have been formulated to meet the main objective of the article:

*H: There are statistically significant differences in the perception of the macroeconomic environment (H1); business finance (H2); legislative environment (H3); quality of education (H4); R&D infrastructure (H5); family environment (H6), competitive environment (H7) and quality of business environment (H8) among selected groups of respondents (1st group: transport and services; 2nd group: construction; production and agriculture).*

Statistically significant differences between selected groups of SMEs by national economy were compared using the Pearson statistics at a significance level of 5%. If the calculated p-value was less than 5% [25], an alternative statistical hypothesis of significant differences in the number of respondents to the claim was accepted. The calculations were performed using free software (www.socscistatistics.com/tests). Statistically significant differences in individual reactions were examined by the Z-score. The calculations were performed using free software (www.socscistatistics.com/tests/ztest/Default2.aspx).

The structure of the sample according to nationality: CR (312) and SR (329). The structure of the sample according to the size of the company was as follows (CR/SR): micro (258/234), small (43/71) and medium (11/24) of the companies in the Czech Republic. The questionnaires were responded to (CR/SR): by 236/251 of men's and 76/78 women's. One of the factors was also the age of the company. Most respondents have had his business for more than 10 years (CR/SR: 208/147), 48/78 of entrepreneurs 5-10 years and the rest (56/104) of the entrepreneurs have operated their business 1-5 years. The survey involved all regions of the Czech Republic and the Slovak Republic. Regions representation of Czech Republic was as follows: Zlin Region (49), Moravian-Silesian Region (17), Olomouc Region (26), South Moravian Region (22), Liberec Region (28), Prague (17), Pardubice (17), Pilsen Region (22), Central Region (14), Hradec Kralove (17), Highlands (25), South Region (16), Usti Region (27) and Karlovy Vary (15). Regions representation of Slovak Republic was as follows: Presov Region (76), Kosice region (75), Bratislava region (56), Banska Bystrica region (30), Zilina region (28), Trnava region (27), Trencin region (20), Nitra region (17). Education (CR/SR): university education (127/224), higher education (135/95) and higher education without graduation (50/10). Questionnaires were addressed to entrepreneurs from different areas of the economy (CR/SR): 109/122 were from service companies, 73/69 were from commercial companies, 53/51 from manufacturing companies, 29/39 from the construction, 19/11 from transportation, 9/20 from agriculture and the rest belonged to "other" (industry not mentioned in the questionnaire).

***Table 2** Evaluation of indicators of financing enterprises*

| F21 | T+S | C+M+A | F22 | T+S | C+M+A |
|---|---|---|---|---|---|
| A1+A2 | 77 | 57 | A1+A2 | 98 | 65 |
| [%] | 29.8 | 28.4 | [%] | 38.0 | 32.3 |
| V3 | 58 | 48 | V3 | 70 | 58 |
| A4+A5 | 123 | 96 | A4+A5 | 90 | 78 |
| [%] | 47.7 | 47.8 | [%] | 34.9 | 38.8 |
| Chi-square | | 0.181 | Chi-square | | 1.610 |
| P-value | | 0.913 | P-value | | 0.447 |
| F23 | T+S | C+M+A | F24 | T+S | C+M+A |
| A1+A2 | 85 | 58 | A1+A2 | 84 | 56 |
| [%] | 32.9 | 28.9 | [%] | 32.6 | 27.9 |
| V3 | 71 | 62 | V3 | 98 | 79 |
| A4+A5 | 102 | 81 | A4+A5 | 76 | 66 |
| [%] | 39.5 | 40.3 | [%] | 29.5 | 32.8 |
| Chi-square | | 1.054 | Chi-square | | 1.258 |
| P-value | | 0.591 | P-value | | 0.526 |

***Table 3** Evaluation of indicators of legal environment*

| F31 | T+S | C+M+A | F32 | T+S | C+M+A |
|---|---|---|---|---|---|
| A1+A2 | 184 | 137 | A1+A2 | 147 | 93 |
| [%] | 71.3 | 68.2 | [%] | 57.0 | 46.3 |
| V3 | 27 | 24 | V3 | 73 | 71 |
| A4+A5 | 47 | 40 | A4+A5 | 38 | 37 |
| [%] | 18.2 | 19.9 | [%] | 14.7 | 18.4 |
| Chi-square | | 0.551 | Chi-square | | 5.541 |
| P-value | | 0.759 | P-value | | 0.047 |
| F33 | T+S | C+M+A | F34 | T+S | C+M+A |
| A1+A2 | 161 | 125 | A1+A2 | 139 | 106 |
| [%] | 62.4 | 62.2 | [%] | 53.9 | 52.7 |
| V3 | 57 | 45 | V3 | 59 | 50 |
| A4+A5 | 40 | 31 | A4+A5 | 60 | 45 |
| [%] | 15.5 | 15.4 | [%] | 23.3 | 22.4 |
| Chi-square | | 0.005 | Chi-square | | 0.256 |
| P-value | | 0.997 | P-value | | 0.879 |

## 4 Results

The total number of respondents in the sectors of the national economy, such as transport, services, construction, manufacturing and agriculture was 459 SMEs. Of these, 216 were from the Czech Republic and 243 from Slovakia; by national economy: 258 (T+S) and 201 (C+M+A); by sex: 356 men and 103 women; by education: 247 higher education, 212 other education; by time of business: 258 more than 10 years, 201 less than 10 years.

Table 1 summarizes the perception of the macroeconomic environment by the SME respondents by sector of the national economy.

The structure of respondents' responses to the current level of basic macroeconomic variables (GDP, employment, inflation) supports entrepreneurship and creates interesting business opportunities (F14) is statistically significant (P-value of the Chi-square test is 0.049). There are statistically significant differences in positive responses (V4 + V5) in the perception of the indicator "F14" according to selected groups of respondents (P-value of Z-score (2.299) is 0.029). The hypothesis H1 was partially accepted.

Table 2 summarizes the perception of the SME financing by enterprises by sector of the national economy.

The structure of respondents' responses to business finance indicators (F21, F22, F23, F24) is not statistically significant (P-values of the Chi-square test are greater than the level of significance - 0.05). There are no statistically significant differences in the perception of business finance indicators by selected groups of respondents (P-values are greater than 0.05). The hypothesis H2 was rejected.

*Table 4 Evaluation of indicators of quality of education*

| F41 | T+S | C+M+A | F42 | T+S | C+M+A |
|---|---|---|---|---|---|
| A1+A2 | 100 | 70 | A1+A2 | 120 | 84 |
| [%] | 38.8 | 34.8 | [%] | 46.5 | 41.8 |
| V3 | 63 | 55 | V3 | 61 | 52 |
| A4+A5 | 95 | 76 | A4+A5 | 77 | 65 |
| [%] | 36.8 | 37.8 | [%] | 29.8 | 32.3 |
| Chi-square | | 0.882 | Chi-square | | 1.021 |
| P-value | | 0.643 | P-value | | 0.600 |
| F43 | T+S | C+M+A | F44 | T+S | C+M+A |
| A1+A2 | 178 | 122 | A1+A2 | 134 | 104 |
| [%] | 69.0 | 60.7 | [%] | 51.9 | 51.7 |
| V3 | 47 | 46 | V3 | 59 | 55 |
| A4+A5 | 33 | 33 | A4+A5 | 65 | 42 |
| [%] | 12.8 | 16.4 | [%] | 25.2 | 20.9 |
| Chi-square | | 3.438 | Chi-square | | 1.815 |
| P-value | | 0.179 | P-value | | 0.403 |

*Table 5 Evaluation of indicators of infrastructure in the area of research and development*

| F51 | T+S | C+M+A | F52 | T+S | C+M+A |
|---|---|---|---|---|---|
| A1+A2 | 110 | 81 | A1+A2 | 111 | 85 |
| [%] | 42.6 | 40.3 | [%] | 43.0 | 42.3 |
| V3 | 99 | 79 | V3 | 103 | 73 |
| A4+A5 | 49 | 41 | A4+A5 | 44 | 43 |
| [%] | 19.0 | 20.4 | [%] | 17.1 | 21.4 |
| Chi-square | | 0.287 | Chi-square | | 1.519 |
| P-value | | 0.866 | P-value | | 0.468 |
| F53 | T+S | C+M+A | F54 | T+S | C+M+A |
| A1+A2 | 73 | 54 | A1+A2 | 69 | 51 |
| [%] | 28.3 | 26.9 | [%] | 26.7 | 25.4 |
| V3 | 124 | 87 | V3 | 117 | 103 |
| A4+A5 | 61 | 60 | A4+A5 | 72 | 47 |
| [%] | 23.6 | 29.9 | [%] | 27.9 | 23.4 |
| Chi-square | | 2.296 | Chi-square | | 1.792 |
| P-value | | 0.317 | P-value | | 0.408 |

Table 3 summarizes the perception of the legislative environment by S the ME respondents by sector of the national economy.

The structure of respondents' responses to the business justice system works well (F32) is statistically significant (P-value of the Chi-square test is 0.047). There are statistically significant differences in positive responses (V4 + V5) in the perception of the indicator "F32" according to selected groups of respondents (P-value of Z-score (2.184) is 0.039). The hypothesis H3 was partially accepted.

Table 4 summarizes the perception of the quality of education by the SME respondents by sector of the national economy.

The structure of respondents' responses to the quality of education indicators (F41, F42, F43, F44) is not statistically significant (P-values of the Chi-square test are greater than the level of significance - 0.05). There are no statistically significant differences in the perception of indicators of quality of education by selected groups of respondents (P-values of Z-score are greater than 0.05). Hypothesis H4 was rejected.

Table 5 summarizes the perception of R&D infrastructure by the SME respondents by sector of the national economy.

The structure of respondents' answers to the infrastructure indicators in the area of research and

***Table 6*** *Evaluation of indicators of family environment*

| F61 | T+S | C+M+A | F62 | T+S | C+M+A |
|---|---|---|---|---|---|
| A1+A2 | 55 | 39 | A1+A2 | 31 | 30 |
| [%] | 21.3 | 19.4 | [%] | 12.0 | 14.9 |
| V3 | 53 | 38 | V3 | 42 | 36 |
| A4+A5 | 150 | 124 | A4+A5 | 185 | 135 |
| [%] | 58.1 | 61.7 | [%] | 71.7 | 67.2 |
| Chi-square | | 0.594 | Chi-square | | 1.123 |
| P-value | | 0.743 | P-value | | 0.540 |
| F63 | T+S | C+M+A | F64 | T+S | C+M+A |
| A1+A2 | 54 | 39 | A1+A2 | 22 | 15 |
| [%] | 20.9 | 19.4 | [%] | 8.5 | 7.5 |
| V3 | 57 | 34 | V3 | 24 | 22 |
| A4+A5 | 147 | 128 | A4+A5 | 212 | 164 |
| [%] | 57.0 | 63.7 | [%] | 82.2 | 81.6 |
| Chi-square | | 2.505 | Chi-square | | 0.467 |
| P-value | | 0.285 | P-value | | 0.791 |

***Table 7*** *Evaluation of indicators of competitive environment*

| F71 | T+S | C+M+A | F72 | T+S | C+M+A |
|---|---|---|---|---|---|
| A1+A2 | 53 | 42 | A1+A2 | 49 | 49 |
| [%] | 20.5 | 20.9 | [%] | 19.0 | 24.4 |
| V3 | 27 | 36 | V3 | 33 | 22 |
| A4+A5 | 178 | 123 | A4+A5 | 176 | 130 |
| [%] | 69.0 | 61.2 | [%] | 68.2 | 64.7 |
| Chi-square | | 5.617 | Chi-square | | 2.068 |
| P-value | | 0.042 | P-value | | 0.355 |
| F73 | T+S | C+M+A | F74 | T+S | C+M+A |
| A1+A2 | 24 | 30 | A1+A2 | 41 | 28 |
| [%] | 9.3 | 14.9 | [%] | 15.9 | 13.9 |
| V3 | 24 | 23 | V3 | 49 | 30 |
| A4+A5 | 210 | 148 | A4+A5 | 168 | 143 |
| [%] | 81.4 | 73.6 | [%] | 65.1 | 71.1 |
| Chi-square | | 4.415 | Chi-square | | 1.981 |
| P-value | | 0.041 | P-value | | 0.371 |

development (F51, F52, F53, F54) is not statistically significant (P-values of the Chi-square test are higher than the level of significance - 0.05). There are no statistically significant differences in the perception of infrastructure indicators in the area of research and development according to selected groups of respondents (P-values of Z-score are greater than 0.05). The hypothesis H5 was rejected.

Table 6 summarizes the perception of the family environment by the SME respondents by sector of the national economy.

The structure of respondents' responses to family environment indicators (F61, F62, F63, F64) is not statistically significant. There are no statistically significant differences in the perception of family environment indicators by selected groups of respondents (P-values of Z-scores are greater than 0.05). Hypothesis H6 was rejected.

Table 7 summarizes the perception of the competitive environment by the SME respondents by sector of the national economy.

The structure of respondents' responses to the risk of new competitors entering the SME industry (F71) and the fact that customers accept the prices OF products and services (F73) are statistically significant (F71: P-value of Chi-square test is 0.042; F73: P-value of Chi-square test is 0.041). There are statistically significant differences in positive responses (V4 + V5) in the perception of indicators "F71 and F73" according to selected groups of respondents

*Table 8 Evaluation of indicators of quality of business environment*

| F81 | T+S | C+M+A | F82 | T+S | C+M+A |
|---|---|---|---|---|---|
| A1+A2 | 156 | 124 | A1+A2 | 78 | 61 |
| [%] | 60.5 | 61.7 | [%] | 30.2 | 30.3 |
| V3 | 36 | 36 | V3 | 37 | 31 |
| A4+A5 | 66 | 41 | A4+A5 | 143 | 109 |
| [%] | 25.6 | 20.4 | [%] | 47.7 | 47.8 |
| Chi-square | | 2.458 | Chi-square | | 0.119 |
| P-value | | 0.292 | P-value | | 0.942 |
| F83 | T+S | C+M+A | F84 | T+S | C+M+A |
| A1+A2 | 142 | 103 | A1+A2 | 119 | 85 |
| [%] | 55.0 | 51.2 | [%] | 46.1 | 42.3 |
| V3 | 45 | 42 | V3 | 42 | 45 |
| A4+A5 | 71 | 56 | A4+A5 | 97 | 71 |
| [%] | 27.5 | 27.9 | [%] | 37.6 | 35.3 |
| Chi-square | | 1.021 | Chi-square | | 2.758 |
| P-value | | 0.600 | P-value | | 0.252 |

(F71: P-value of Z-score (1.979) is 0.044; F73: P-value of Z-score (1.991) is 0.047). The hypothesis H7 was partially accepted.

Table 8 summarizes the perception of the quality of the business environment by the SME respondents by sector of the national economy.

The structure of respondents' responses to business environment quality indicators (F81, F82, F83, F84) is not statistically significant (P-values of the Chi-square test are greater than the level of significance - 0.05). There are no statistically significant differences in the perception of business environment quality indicators by selected groups of respondents (P-values of Z-score are greater than 0.05). The hypothesis H8 was rejected.

## 5 Discussion

The results show that seven out of ten respondents agree (agree or fully agree) with the indicators of the competitive environment (entrepreneurs consider the risk of entry of competition in the business sector appropriate; intensity of competition in the industry is normal; customers accept prices for products and services; the adequacy of the prices of their suppliers' products and services). The findings concerning intensive competition as a factor that impacts business environment are consistent with previous studies [26-27].

On the other hand, six out of ten respondents disagree (totally disagree or disagree) with the legislative environment indicators (good level of business legislation; quality of the judicial system in the area of commercial law; law enforcement is good; stability of the legislative environment). The findings concerning the legislative environment as a factor that impacts business environment are consistent with previous study [28].

It has also been shown that entrepreneurs are of the opinion that the state is not able to prepare quality people for companies (more than 60% of respondents). Also, entrepreneurs think that school graduates do not have good knowledge and skills (more than 50% of respondents).

A comparison of respondents' attitudes, divided into two groups according to the national economy sector, shows that there is no difference in perception of factors such as the family environment, the quality of the business environment, the quality of education, business financing and R&D infrastructure.

On the other hand, differences in the assertion that the current value of macroeconomic indicators (GDP, unemployment and others) support entrepreneurship have been shown. Up to 39.1% of the SMEs in the transport and services sectors agree with this statement, compared to 28.9% of the SMEs in the construction, manufacturing and agriculture sectors. There are also significant differences in the argument that the judicial system in commercial law works well. Up to 57.0% of the SMEs in the transport and services sector disagree with this statement, compared to 46.3% of the SMEs in the construction, manufacturing and agriculture sectors.

The greatest lack of consistency among the selected SME groups is when assessing the factor of the competitive environment. The SMEs in the transport and services sectors are more in agreement with the claim (81.4%) that the customers accept the prices of products and services compared to the SMEs in the construction, manufacturing and agriculture sectors (73.6%). The findings concerning the comparison of the competitive environment between the T+S (the transport and service sector) and the C+M+A (the construction, manufacturing and agriculture sector) are not consistent with the study [29]. The results of this research are less consistent.

## 6 Conclusions

The aim of the article was to identify differences in the perception of selected factors that determine the business environment among selected groups of small and medium-sized enterprises (SMEs) according to the sector of the national economy.

The results showed interesting findings. The SMEs in transport and services perceive the competitive environment as more acceptable than the SMEs in construction, construction and agriculture. In addition, the SMEs in transport and services are of the opinion that customers accept the prices of their products and services to a greater extent than the SMEs in construction, manufacturing and agriculture. There are also significant differences between selected groups of the SMEs in assessing the quality of the judicial system in commercial law and the view that the current level of macroeconomic indicators (GDP, unemployment, etc.) promotes entrepreneurship and creates interesting business opportunities. The sector of the national economy is not an important criterion when assessing the financing of businesses; family environment; R&D infrastructures; the quality of the business environment and the quality of education.

The authors are aware of the limitations of the case study (e.g. the local nature of the study - 2 Central European countries; the number of SMEs - only 459; verification of results using one methodology; application of selected statistical methods). The authors believe that the paper may bring some interesting findings and new incentives for further research and discussion on the cross-sectoral assessment of the business environment quality and its important factors.

The future research will focus on comparing other factors that determine the quality of the business environment among selected groups of SMEs. Those are mainly the areas of monetary policy and interest rates; state regulation and business support; state bureaucracy; availability of human capital; private-public cooperation; media and communication environment, or narrower business environment. It is assumed that the attitudes of SMEs towards the above factors will bring different perceptions.

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Pawel Gromek - Rafal Wrobel

# RISK ASSESSMENT IN ROAD TRANSPORT. OPERATIONAL PERSPECTIVE OF THE FIRE SERVICE IN POLAND

*The paper presents a fire service determined picture of road safety in Poland in its operational (non-system and system) dimensions. It focuses on the road risk assessment, using data related to interventions conducted in 2015-2019 by entities of the State Firefighting Rescue System. The database of the Main Headquarters of the State Fire Service in Poland is adopted and 661,775 emergency road interventions are taken into account.*

*The results state general framework for procedures, resource allocation and training for fire services. The framework is determined by the riskiest kinds of events on the Polish roads. It refers to micro scale (in relation to operational procedures, tactics and strategies, allocation of equipment and training programs) and macro scale (regarding to emergency system, central-planned equipment procurements and training framework).*

***Keywords:*** *risk, risk assessment, road, transport, fire service, safety, security*

## 1 Introduction

Road transport plays a significant role in every modern society [1]. Consequently, the road safety inscribes to fundamental issues of human operation that is emphasized at national and European levels [2-5]. Notably, that summary value of road collisions and accidents consequences can exceed total consequence value of disasters (floods, hurricanes, wildfires, etc.) [6].

Researchers have been analyzing the road safety phenomena for many years. The studies cover different and partially referenced problematic aspects, which concern (i.a.) statistics of accidents [5], risk factors and risk assessment [7-8], subjectivity of passengers' safety [9], emergency service operations in terms of traffic accidents [10], resource scheduling [11] and response simulation [12]. Among many different road safety perspectives, one seems to be especially influential and more cognitively valuable that the others. In addition, it is relatively rarely taken into consideration in the literature. It is an emergency service perspective, which reflects the most important values to be protected (people life and health) in difficult circumstances of direct danger to people life. Focusing on the road collisions and accidents, when emergency services are involved to rescue people, allows to put a special attention on events with the highest influence on safety. It is caused by the events mediumistic and mass influence, as they refer to safety sense of individuals and entire society. More, a distinct possibility to get a new knowledge for practitioners (public administration, public services) is noticed.

From the practitioners' perspective, it is crucial to assess the road safety level in terms of different kinds of vehicles, considering such fundamental organizational issues as procedures, resource allocation and training. Furthermore, only the real data-based assessment can ensure that the results will state a realistic input for decision makers who manage these issues on the n micro scale (in relation to operational procedures, tactics and strategies, allocation of equipment and training programs) and macro scale (regarding to emergency system, central-planned equipment procurements, training framework). As risk is dealt with as the safety measure [13-15], road risk assessment in analyzed context is particularly desired.

This study focuses on the road risk assessment, using data related to interventions conducted in 2015-2019 by entities of the State Firefighting Rescue System (SFRS). The time horizon provides to the most actual data and is related to the current SFRS evaluation. The evaluation regards implementation of lessons-learned collected during 25 years of the system operation and takes into consideration actual operational tendencies (especially the increase of SFRS operational domain regarding the chemical, biological, radiological and nuclear issues; CBRN issues, also related to the road risk) [16-18]. The database of the State Fire Service (SFS) in Poland is adopted and 661,775 emergency road interventions are analyzed. The results are referred to current road safety determinants on the micro and macro scale. Thus, the study presents a fire service determined picture of the road safety in Poland in its operational (non-system and system) dimensions.

## 2 Methodology

### 2.1 Data source description

The SFS is a primary firefighting rescue entity in Poland. It states a core of SFRS. The institution organizes

**Pawel Gromek*, Rafal Wrobel**
The Main School of Fire Service, Warsaw, Poland
*E-mail of corresponding author: pgromek@sgsp.edu.pl

*Table 1 Road events when SFRS entities operated in 2019*

| Size category for F/LH | Category of transportation mean (*j*) | | | | |
|---|---|---|---|---|---|
| | Sum | T1 - motorcycles, bikes | T2 - buses, trolley buses | T3 - lorries, heavy traffic machines, tanks, lorry trailers | T4 - cars, light traffic machines, car trailers |
| F | | | | | |
| Small (F/S) | 9843 | 132 | 185 | 1091 | 8306 |
| Medium (F/M) | 65 | 1 | 3 | 25 | 32 |
| Big (F/B) | 2 | 0 | 1 | 0 | 0 |
| Very big (F/VB) | 0 | 0 | 0 | 0 | 0 |
| Sum (F): | 9910 | 133 | 189 | 1116 | 8338 |
| LH | | | | | |
| Small (LH/S) | 3558 | 204 | 57 | 393 | 2806 |
| Locally limited (LH/L) | 62364 | 2898 | 507 | 4507 | 53942 |
| Medium (LH/M) | 2948 | 50 | 67 | 504 | 2252 |
| Big (LH/B) | 24 | 0 | 8 | 3 | 10 |
| Catastrophic (LH/C) | 0 | 0 | 0 | 0 | 0 |
| Sum (LH): | 68894 | 3152 | 639 | 5407 | 59010 |

the system and makes the relevant coordination at all the operational levels (intervention, tactical and strategic) [19]. When serious road accident occurs and people life, health, property and environment are in danger, SFRS entities (SFS, voluntary fire services, etc.) are dispatched. The SFS plays there a leading role, having to its disposal a wide spectrum of legal tools and direct access to specialized resources (well-trained staff and equipment).

Respecting to its position in SFRS, the SFS is responsible for the intervention documentation. This task is operationalized by implementation of the decision support system with statistics module (SWD-ST). The system archives all information structurally collected by SFRS commanders at the emergency operation scene. The information statement is accessible from the SFS Main Headquarters website [20].

The structure of the database considers a causes-based division of all the accidents, respecting two fundamental (from fire services point of view) kinds of negatively-perceived events - fires (F) and local hazards (LH).

Fire formally means uncontrolled combustion process in undesirable place. As far as events documentation is concerned, fires are divided into four categories [19, 21]:

- Small Fire (F/S) characterized by burning area of 70 $m^2$ or volume of 350 $m^3$ or forests, fields, peat bogs and wasteland at area lower than 1 ha or events which require maximum 4 extinguishing jets;
- Medium Fire (F/M) characterized by burning area from 71 $m^2$ to 300 $m^2$ or volume of 351 $m^3$ to 1500 $m^3$ or forests, fields, peat bogs and wasteland at area from 1 ha to 10 ha or events which require from 5 to 12 extinguishing jets;
- Big Fire (F/B) characterized by burning area from 301 $m^2$ to 1000 $m^2$ or volume of 1501 $m^3$ to 5000 $m^3$ or forests, fields, peat bogs and wasteland at area from 10 ha to 100 ha or events which require from 13 to 36 extinguishing jets;
- Very Big Fire (F/VB) characterized by parameters that exceed values for F/B.

Local hazard (LH) is understood as any kind of negative phenomena that is not fire – event, which states danger to people, property or environment and is a consequence of civilization development, people operation or natural disaster. LH categories are compiled below:

- Small Local Hazard (LH/S) related to scope-limited events, conducting without the use of specialized equipment (except measurement instruments, which identify no agents);
- Locally-limited Local Hazard (LH/L) corresponding to urgent failures of machines, instruments, vehicles and other object, when maximum 1 victim is dead or maximum 3 victims are supported by medical rescue teams (from outside the SFRS) or maximum 4 fire service teams (12-24 firefighters) participate in the action;
- Medium Local Hazard (LH/M) corresponding to urgent failures of machines, instruments, vehicles and other object, when 2-3 victims are dead or 4-10 victims are supported by medical rescue teams (from outside SFRS) or maximum 5-12 fire service teams (15-72 firefighters) participate in the action or 1 special rescue unit supports the primary rescue resources;
- Big Local Hazard (LH/B), that means urgent, unforeseen event, which refers to mass danger to people life, health, property or environment, exceeds quantitative values of LH/M and requires the SFRS resources in strength of 1 battalion (to 480 firefighters);
- Catastrophic Local Hazard (LH/C) related to urgent, unforeseen event, which refers to mass danger to people life, health, property or environment and

***Table 2** Detailed equations for elementary road risk assessment*

| $C_i$ | Class of consequences (i) | Category of transportation mean (j) | | | |
|---|---|---|---|---|---|
| | | T1 - motorcycles, bikes | T2 - buses, trolley buses | T3 - lorries, heavy traffic machines, tanks, lorry trailers | T4 - cars, light traffic machines, car trailers |
| 1 | F/S | $R_{F/S,T1} = P_{F/S,T1} \cdot 1$ | $R_{F/S,T2} = P_{F/S,T2} \cdot 1$ | $R_{F/S,T3} = P_{F/S,T3} \cdot 1$ | $R_{F/S,T4} = P_{F/S,T4} \cdot 1$ |
| 2 | F/M | $R_{F/M,T1} = P_{F/M,T1} \cdot 2$ | $R_{F/M,T2} = P_{F/M,T2} \cdot 2$ | $R_{F/M,T3} = P_{F/M,T3} \cdot 2$ | $R_{F/M,T4} = P_{F/M,T4} \cdot 2$ |
| 3 | F/B | $R_{F/B,T1} = P_{F/B,T1} \cdot 3$ | $R_{F/B,T2} = P_{F/B,T2} \cdot 3$ | $R_{F/B,T3} = P_{F/B,T3} \cdot 3$ | $R_{F/B,T4} = P_{F/B,T4} \cdot 3$ |
| 4 | F/VB | $R_{F/VB,T1} = P_{F/VB,T1} \cdot 4$ | $R_{F/VB,T2} = P_{F/VB,T2} \cdot 4$ | $R_{F/VB,T3} = P_{F/VB,T3} \cdot 4$ | $R_{F/VB,T4} = P_{F/VB,T4} \cdot 4$ |
| 1 | LH/S | $R_{LH/S,T1} = P_{LH/S,T1} \cdot 1$ | $R_{LH/S,T2} = P_{LH/S,T2} \cdot 1$ | $R_{LH/S,T3} = P_{LH/S,T3} \cdot 1$ | $R_{LH/S,T4} = P_{LH/S,T4} \cdot 1$ |
| 2 | LH/L | $R_{LH/M,T1} = P_{LH/M,T1} \cdot 2$ | $R_{LH/M,T2} = P_{LH/M,T2} \cdot 2$ | $R_{LH/M,T3} = P_{LH/M,T3} \cdot 2$ | $R_{LH/M,T4} = P_{LH/M,T4} \cdot 2$ |
| 3 | LH/M | $R_{LH/B,T1} = P_{LH/B,T1} \cdot 3$ | $R_{LH/B,T2} = P_{LH/B,T2} \cdot 3$ | $R_{LH/B,T3} = P_{LH/B,T3} \cdot 3$ | $R_{LH/B,T4} = P_{LH/B,T4} \cdot 3$ |
| 4 | LH/B | $R_{LH/VB,T1} = P_{LH/VB,T1} \cdot 4$ | $R_{LH/VB,T2} = P_{LH/VB,T2} \cdot 4$ | $R_{LH/VB,T3} = P_{LH/VB,T3} \cdot 4$ | $R_{LH/VB,T4} = P_{LH/VB,T4} \cdot 4$ |
| 5 | LH/C | $R_{LH/VB,T1} = P_{LH/C,T1} \cdot 5$ | $R_{LH/VB,T2} = P_{LH/C,T2} \cdot 5$ | $R_{LH/VB,T3} = P_{LH/C,T3} \cdot 5$ | $R_{LH/VB,T4} = P_{LH/C,T4} \cdot 5$ |

requires the SFRS resources in strength of at least of 1 battalion (at least 480 firefighters).

Table 1 presents a statement of information about road events when the SFRS entities operated in 2019, [20].

Above-presented order highlights a possibility of use the database in risk assessment processes as direct numbers of events at particular levels of consequences are noticed. This increases a cognitive potential of the database and allows for its relatively easy use in road risk assessment method.

### 2.2 Road risk assessment method

At the highest level of generality, "(…) risk is the possibility of an event causing negative consequences (…)" [14]. Thus, a road risk ($R$) can be named as a possibility of road events (collisions, accidents) causing negative consequences. From practical point of view, it can be expressed by a relation between the possibility measure ($P$) and the consequence measure ($C$), as it is presented in equation (1):

$$R = P \cdot C\,. \tag{1}$$

Operationalizing the road risk assessment, particular kinds of measures depend on accessible information sources, which characterize the road safety in analyzed context. Due to SWD-ST database structure, $P$ is explicated by the events' frequency and $C$ considers classes of the consequences [22-23]. From this point, the database allows to elaborate a qualitative-quantitative road risk assessment method, in accordance with the following equation:

$$R_{i,j} = P_{i,j} \cdot C_i\,, \tag{2}$$

where:

$R_{i,j}$ - road risk index for $i$-th class of consequences and $j$-th category of transportation mean,

$P_{i,j}$ - frequency of events in $i$-th class of consequences and $j$-th category of transportation mean,

$C_i$ - consequence measure which refers to $i$ -th class of consequences.

Table 2 shows 36 detailed equations that describe different approaches for the road risk assessment, respecting events' categories ($F$ and $LH$), multiple $C$ in particular events' categories, as well as different categories of transportation means. The table deals with elementary road risk index for $i$-th class of consequences and $j$-th category of the transportation means.

Equations from Table 2 make possible to implement data directly from the database and assess the road risk indexes. The total number of risk indexes, which are possible to be calculated from the elementary road risk assessment equations, is difficult to unambiguously estimate. However, respecting operational, resource allocation and training perspectives, for further analysis it is crucial to define:

- **average road risk index** for particular transportation means at particular classes of consequences:

$$\overline{R_{i,j}} = \frac{\sum_{m=1}^{n} R_{i,j,m}}{m}\,, \tag{3}$$

where: $m$ = {2015,2016,2017,2018,2019} in analyzed period of time,

- **total road risk index** for particular transportation means (in terms of all the classes of consequences) in analyzed year:

$$R_{total} = \sum_i \sum_j R_{i,j}\,, \tag{4}$$

- **cumulated road risk index** covering all transportation means (in terms of all classes of consequences) in analyzed year

$$R_{cum} = \sum_j R_{total}\,. \tag{5}$$

Presented road risk assessment method allows to create the road safety picture due to the most serious events on Polish roads. This gives an additional value for further analysis on operational means connected to the non-system and system dimensions of the SFRS interventions.

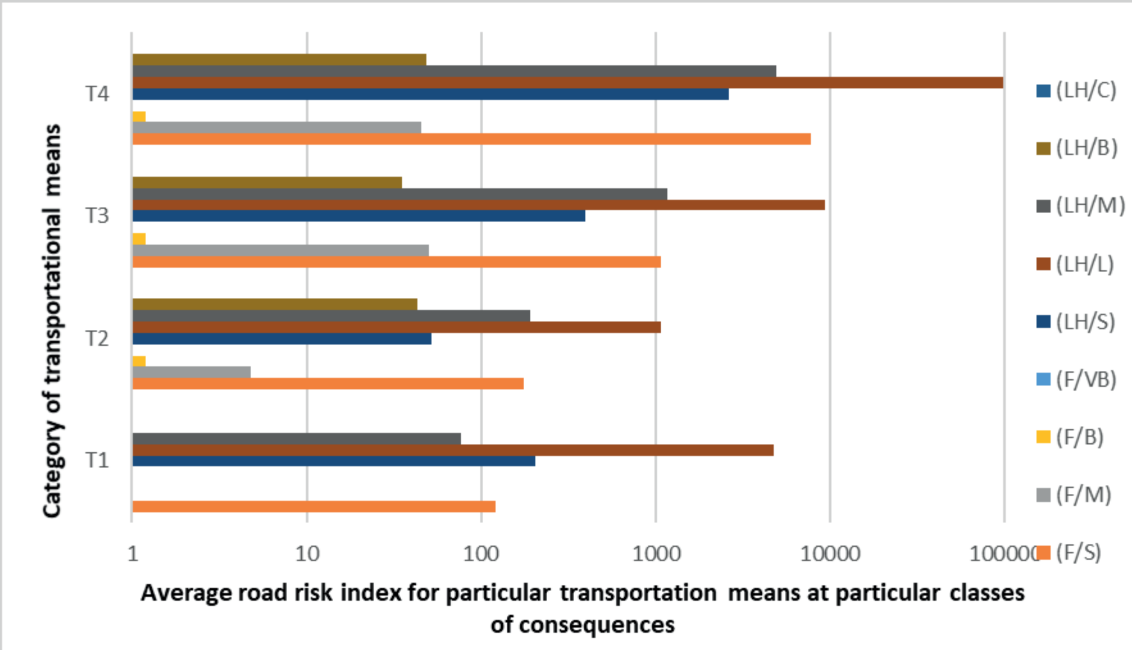


***Figure 1*** *Average road risk index for particular transportation means at particular classes of consequences* $(\overline{R_{i,j}})$

## 3 Results and Discussion

### 3.1 Road risk assessment and non-system dimension of the SFRS interventions

As the non-system dimension of the SFRS interventions patterns the micro scale of road risk assessment, the assessment results can be interesting for the fire rescue unit commanders, local SFS headquarters and local administration decision makers (mayors, starosts).

Use of Equation (2) gives elementary results of road risk assessment that are compiled in Annex 1 to this paper. In addition, practical implementation of Equation (3) allows to visualize differences in average risk indexes for particular transportation means at particular levels of consequences. They are presented in Figure 1.

Referring to particular classes of consequences is useful from practitioners' point of view, as it reflects total spectrum of road events characteristics (initiating factors, hazard development and firefighting rescue action effectiveness). Preliminary analysis of Figure 1 shows that the highest levels of the road risk concern LH/L and F/S events for T4 (cars, light traffic machines and car trailers), as well as LH/L events for T3 (lorries, heavy traffic machines, tanks and lorry trailers) and T1 (motorcycles and bikes). Relevant indexes cover approximately 90% of the total average road risk index value. Thus, the LH/L and F/S should have the strongest influence on operational procedures, tactics and strategies directed on technical (corresponding to LH specification) cooperation with medical rescue teams, other fire service teams (totally 15-72 rescuers) and 1 special rescue unit participation in the action. Consequently, such a perspective should be used when training scenarios are formulated. Relatively small number of victims is noticed, so the main attention should be put to strictly technical activities. Especially when the medical support is assumed. Quite interesting are results for average risk indexes for fires. Only one distinctive value is noticed for F/S. This proves that firefighting protection for the road event should be generally ensured at the basic scope (1-2 engines to build maximum 4 extinguishing jets). Previous conclusions shed a light into resources allocation. As firefighting protection resources means mostly 1-2 engines with 6-8 firemen, the rest of human resources and equipment need to be technically-related. This can be dealt with as a suggestion for the road emergency standard, as well.

Certainly, other kinds of circumstances should be also mentioned when operational, resources location and training issues are analyzed. Nevertheless, the results highlight main, risk-based determinants of the issues beyond doubt. Rationally, determination of information about other classes of consequences and categories of transportation means should be limited to additional training scenarios, continuity operational plans and resources allocation for the special rescue unit for road emergencies.

### 3.2 Road risk assessment and system dimension of the SFRS interventions

System dimension of the SFRS interventions respects the macro scale of the road risk assessment. Thus, relevant results should give a valuable information for prime commanders of the SFS (main headquarters, province headquarters) and decision makers at a strategic level of public administration (ministers, head of the central entities).

Figure 2 presents values of cumulated road risk index for particular transportation means in terms of all the types

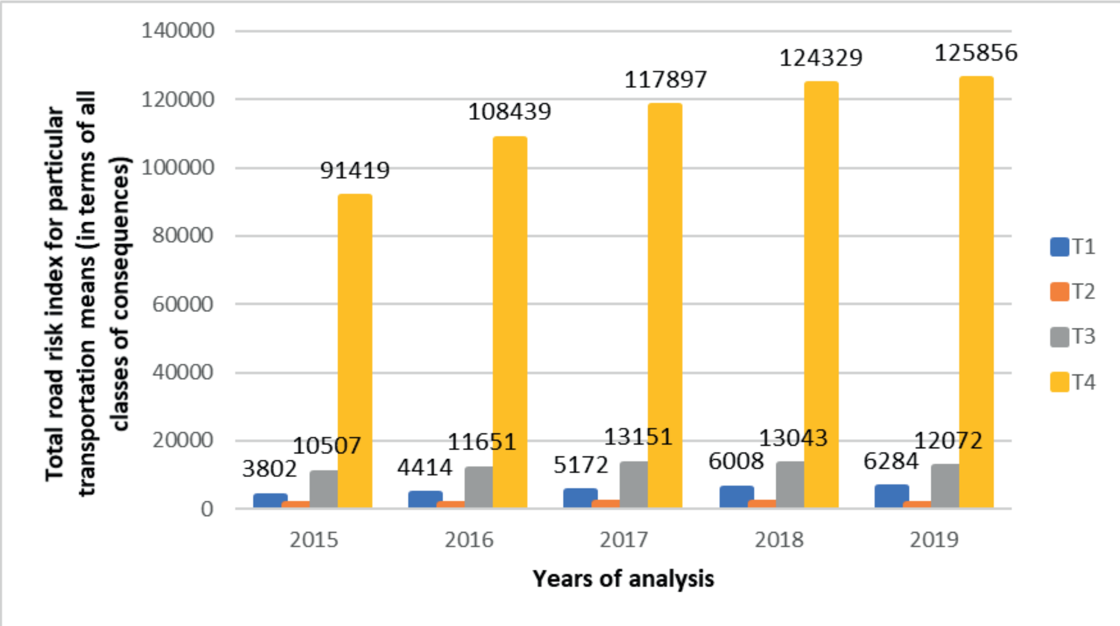


***Figure 2*** *Total road risk index for particular transportation means (in terms of all the classes of consequences) in analyzed year.*

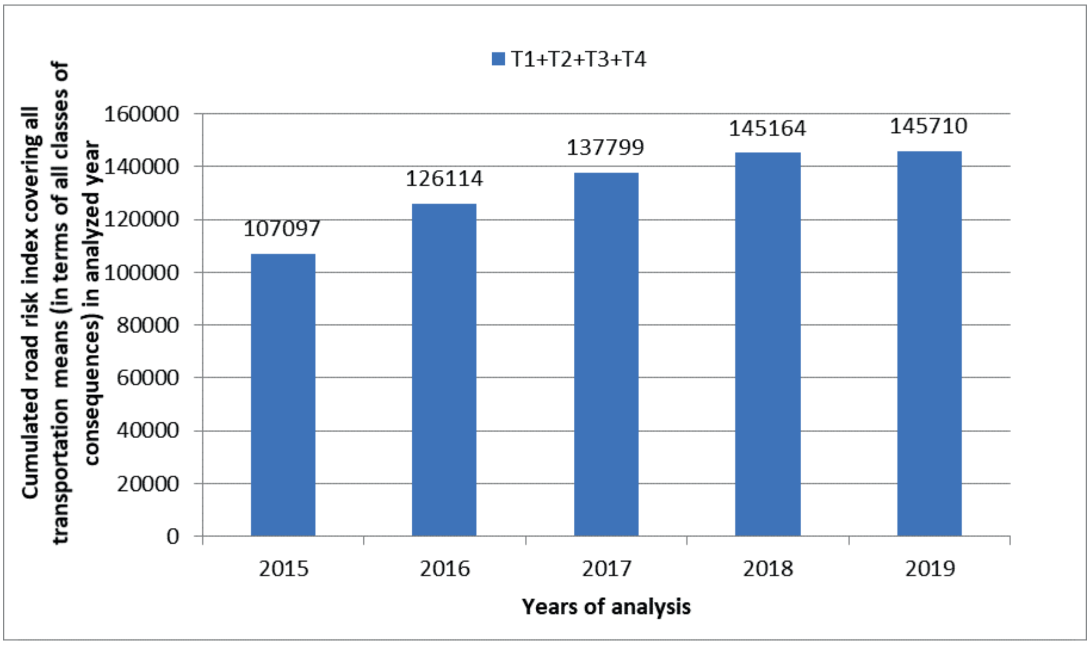


***Figure 3*** *Cumulated road risk index covering all the transportation means (in terms of all the classes of consequences) in analyzed year*

of events for the last five years in Poland. The time-related distribution of values shows crucial points for macro scale analysis.

Analysis of the total road risk index in terms of all the classes of consequences in particular years gives information indicating general road safety situation in Poland, where T1 - motorcycles, bikes, T2 - buses, trolley buses, T3 - lorries, heavy traffic machines, tanks, lorry trailers and T4 - cars, light traffic machines, car trailers. The results confirm a core location of the T4 values in an entire road risk picture. The total road risk index for cars, light traffic machines and car trailers clearly exceeds other indexes. It emphasizes that object circumstances should be taken into account in emergency system design above all. In this way, additional emergency units may be investigated to build new system development opportunities in the nearest future (new institutional and non-institutional partners). Furthermore, the system needs to be prepared especially for the T4 event conditions on a mass scale of the events occurrence (many accidents at the same time in the same administration zone). Information concerning rescue from cars, light traffic machines and car trailers should be an element of current, emergency state-of-the-art, widely implemented in all the fire service units. Object procedures should be thoroughly exercised and state a training framework for all the road emergency scenarios. In addition, central-planned equipment procurements need to stem from the highest road risk level in described context. Respecting the micro scale analysis, the procurements and the system development direction should ensure a relatively quick build of potential for the riskiest events (they must ensure that the first echelon of emergency resources will meet the LH/L and F/S requirements).

Knowledge of the total road risk index for particular transportation means (in terms of all the classes of consequences) in analyzed year enables to calculate cumulated road risk index covering all the transportation means (in terms of all classes of consequences) in this year - to calculate it, total road risk values obtained in each year for particular category of transport means should be summed.

Figure 3 indicates a steady increase in value in each sequential year for all the categories of transportation means (where T1 - motorcycles, bikes, T2 - buses, trolley buses, T3 - lorries, heavy traffic machines, tanks, lorry trailers and T4 - cars, light traffic machines, car trailers). However, a significant difference should be noted. The increase in the value of risk in a given year in relation to the value of risk from the previous year, expressed as a percentage differed significantly in subsequent years and amounted to:

- in 2016 – 17.76% (compared to 2015);
- in 2017 – 9.27% (compared to 2016);
- in 2018 – 5.34% (compared to 2017);
- in 2019 – 0.38% (compared to 2018).

This means that cumulated road risk index covering all transportation means (in terms of all the classes of consequences) permanently increases and expresses a decrease of road safety in Poland.

## 4 Conclusion

Risk assessment can be executed in many ways. Generally, it is a derivative of a simple correlation between probability and consequences. Practically, it requires access to realistic data. Especially, when the qualitative-quantitative or quantitative methods are desired.

The road risk assessment definitely requires a strong relation to real data, giving realistic reasons for decision makers to create operational procedures, resource allocation and training processes, referring to micro scale and macro scale of an analysis.

Even if the results do not surprise (T4 seems to be quite typical group of vehicles which participate in collisions and road accidents, in general), the methodology of the road risk assessment states framework for detailed analysis of the road risk determinants and their hazards-, type of consequences- and time-related divisions. The natural next step seems to be the risk mapping, which makes possible to analyze road risks in particular administration zones with deepen research of relevant differences and reasons. Moreover, different groups of transportation means can be scientifically explored (rail, inland etc.). In addition, the road risk assessment is based on direct number of road incidents. It is justified by the research objective, when operational perspective of the fire service states the research framework. For the fire service point of view, it is crucial to be aware of the number of events and their operational consequences (thus relation to number of extinguishing jets, area or volume of hazard, number of victims, number of rescuers, support from other emergency entities etc.). Classes of consequences in the SFS data base match these issue. Thus, the data base allows for the risk assessment in its emergency operational realm. However, in the future research additional risk measures can be considered. Respecting number of vehicles, number of drivers, number of vehicle kilometers per year would increase the risk assessment potentials for other road safety perspectives and make closer to its objective value.

Concluding, the total picture of the road safety is very complex and determined by many different factors. Presented method makes a first step to do this with focus on events with the highest influence on safety, when emergency services are involved to rescue peoples' lives and health.

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## Annex

***Table 3** Results of the elementary road risk assessment for T1 (motorcycles, bikes), [20]*

| Category of consequences ($i$) | Year | | | | |
|---|---|---|---|---|---|
| | 2015 | 2016 | 2017 | 2018 | 2019 |
| F/S | 105 | 109 | 112 | 146 | 132 |
| F/M | 0 | 0 | 2 | 0 | 2 |
| F/B | 0 | 0 | 0 | 0 | 0 |
| F/VB | 0 | 0 | 0 | 0 | 0 |
| LH/S | 181 | 180 | 209 | 256 | 204 |
| LH/L | 3470 | 4174 | 4798 | 5522 | 5796 |
| LH/M | 42 | 60 | 51 | 84 | 150 |
| LH/B | 4 | 0 | 0 | 0 | 0 |
| LH/C | 0 | 0 | 0 | 0 | 0 |

***Table 4** Results of the elementary road risk assessment for T2 (buses, trolley buses), [20]*

| Category of consequences ($i$) | Year | | | | |
|---|---|---|---|---|---|
| | 2015 | 2016 | 2017 | 2018 | 2019 |
| F/S | 176 | 165 | 174 | 176 | 185 |
| F/M | 2 | 0 | 6 | 10 | 6 |
| F/B | 3 | 0 | 0 | 0 | 3 |
| F/VB | 0 | 0 | 0 | 0 | 0 |
| LH/S | 43 | 42 | 59 | 61 | 57 |
| LH/L | 932 | 1056 | 1106 | 1276 | 1014 |
| LH/M | 165 | 198 | 198 | 201 | 201 |
| LH/B | 48 | 40 | 36 | 60 | 32 |
| LH/C | 0 | 0 | 0 | 0 | 0 |

***Table 5** Results of the elementary road risk assessment for T3 (lorries, heavy traffic machines, tanks, lorry trailers), [20]*

| Category of consequences ($i$) | Year | | | | |
|---|---|---|---|---|---|
| | 2015 | 2016 | 2017 | 2018 | 2019 |
| F/S | 1038 | 1031 | 1069 | 1151 | 1091 |
| F/M | 54 | 54 | 36 | 56 | 50 |
| F/B | 0 | 0 | 0 | 6 | 0 |
| F/VB | 0 | 0 | 0 | 0 | 0 |
| LH/S | 333 | 361 | 433 | 452 | 393 |
| LH/L | 8244 | 9276 | 10320 | 9960 | 9014 |
| LH/M | 810 | 897 | 1245 | 1362 | 1512 |
| LH/B | 28 | 32 | 48 | 56 | 12 |
| LH/C | 0 | 0 | 0 | 0 | 0 |

***Table 6*** *Results of the elementary road risk assessment for T4 (cars, light traffic machines, car trailers), [20]*

| Category of consequences ($i$) | Year | | | | |
|---|---|---|---|---|---|
| | 2015 | 2016 | 2017 | 2018 | 2019 |
| F/S | 6948 | 7511 | 7888 | 8479 | 8306 |
| F/M | 64 | 28 | 30 | 40 | 64 |
| F/B | 0 | 0 | 3 | 3 | 0 |
| F/VB | 0 | 0 | 0 | 0 | 0 |
| LH/S | 2310 | 2353 | 2777 | 2915 | 2806 |
| LH/L | 78700 | 94434 | 102286 | 107384 | 107884 |
| LH/M | 3345 | 4077 | 4833 | 5472 | 6756 |
| LH/B | 52 | 36 | 80 | 36 | 40 |
| LH/C | 0 | 0 | 0 | 0 | 0 |

Nadiia Kulbashna - Iryna Lynnyk - Andrii Galkin - Oleksii Prasolenko - Sergii Dulfan

# SAFETY ASSESSMENT OF ADJACENT ROADS SECTIONS VIA MAXIMUM ENTROPY DRIVER'S PERCEPTION FIELD

*Characteristics have been developed, by which the boundaries of coherence of adjacent road sections are established in accordance with requirements for the traffic safety. The coordination of adjacent sections of the road is carried out taking into account the driver's behavior program, which is presented in the work as a value of the maximum entropy of his perception field. The choice of this criterion is determined by the possibility of a comprehensive assessment of many road environment factors that influence the driver. The boundaries of coordination of the maximum entropy values of adjacent road sections with use of the accident rate are established.*

***Keywords:*** *adjacent road sections, maximum entropy, matching characteristics, accident rate*

## 1 Introduction

At the present stage of development of transport engineering, the system arrangement of the road environment is the main means of ensuring the traffic safety. Approaches to reducing accidents, due to technical means of organizing the traffic, have practically exhausted themselves [1]. At the same time, existing approaches can be improved and supplemented, taking into consideration the human factor in assessing their safety [2]. The movement of the driver is carried out in the road environment, which includes various elements of engineering and technical support [3]. A drastic change in traffic conditions, when moving from one section of the road to another, can negatively affect the functioning of the driver [4-6]. Constant adaptation of the driver to changing conditions contributes to development of fatigue, causes his erroneous actions and as a result, leads to the creation of emergency situations. Therefore, it is necessary to organize such traffic conditions that, on the one hand, would not create undesirable transient phenomena in the driver's body and provide all the necessary information to select the right actions as a result of driving. This requires a comprehensive assessment of factors of the road environment acting on the driver and the development of a method for coordinating traffic conditions on adjacent sections of roads (Human-Surrounding interface).

The article consists of the following sections: the first section provides an analysis of the literature and identifies major shortcomings of existing approaches to infrastructure design; in the second section is presented an analysis of scientific researches is revealed, which revealed shortcomings of certain methods of the traffic safety assessment; in the third section, for designing the infrastructure of the road environment, taking into account the human factor, a method is proposed consisting in assessing traffic safety by the consistency of adjacent sections of roads. Maximum entropy is chosen as the criterion. An accident rate was used to assess the danger of the road infrastructure, which was determined on the basis of statistics on road accidents over 5 years and the volume and composition of traffic flow; in the fourth section experimental studies were conducted to determine the values of the maximum entropy, on three roads with a length of 45 kilometers with participation of 26 drivers. During the movement of cars, traffic factors and speed were recorded. During the processing of the survey results, the length of the driver's perception field was calculated according to the empirical formula, depending on the speed of movement. Within each field of perception, the number of factors of the road environment was determined by which the value of the maximum entropy was calculated.

According to dependence of the maximum entropy on the accident rate, an information content of the maximum entropy has been proved in terms of traffic safety. To coordinate adjacent sections of roads, the ratio of values of the maximum entropy of the previous and subsequent sections is applied. Dependence of these relations on the accident rate and application of the hazard limits of the accident rate, established by the regulatory document of Ukraine, allowed to establish the limits of the maximum entropy changes that characterize sections of the road as safe, low-risk, dangerous or very dangerous.

## 2 Analysis and statement of the research problem

When examining the road environment, scientists usually consider the safe combination of the individual

**Nadiia Kulbashna[1], Iryna Lynnyk[2], Andrii Galkin[3,*], Oleksii Prasolenko[3], Sergii Dulfan[3,4]**
[1]Departament of Electric Transport, O. M. Beketov National University of Urban Economy in Kharkiv, Ukraine
[2]Department of Urban Construction, O. M. Beketov National University of Urban Economy in Kharkiv, Ukraine
[3]Department of Transport System and Logistics, O. M. Beketov National University of Urban Economy in Kharkiv, Ukraine
[4]Department for Infrastructure of Kharkiv City Council, Ukraine
*E-mail of corresponding author: galkin.tsl@gmail.com

elements of the plan and profile of the road. Thus, in [7] the distribution of the roads, according to homogeneous geometric characteristics and the mandatory reduction of the deviations of the speeds in the adjacent sections, is proposed. In [8] is proposed to use the length of the driver's perception field as sections of the road, taking into account variables and constant factors of the road environment. IInfluence of road gradients on other traffic parameters is studied in [4]. It is indicated that the value of the vehicle's initial speed of entry to an adjacent section of the road is a significant parameter, changes of which may be a criterion for the consistency of structures on road sections. The methods proposed in the works [4, 7-8], despite their simplicity and practicality, are limited by the number of criteria and do not contain a systematic assessment.

In [1] the condition of the roadway is taken as a characteristics that affects the accident rate. A systematic approach was used, consisting in study of relationship of the four elements: driver's behavior, vehicle conditions, roadway bed and environment. In particular, in [9] is indicated that a modern approach to ensure the road safety and reduce the risks of traffic participants getting into the road transport aaccident, is a reconstruction of the road environment. However, the issue of the traffic safety, which was considered, does not concern individual sections, but the road as a whole.

The cluster analysis was used to investigate the traffic conditions in road sections in [10]. The sections of roads with similar characteristics were determined and the speed was used as a criterion. Despite the need to harmonize adjacent sections of roads, the method has not been developed.

The closest to solving the problem of ensuring the traffic safety on adjacent sections of roads is the work by Babkov [11]. It uses the method of plotting speeds and defines the requirements for divergence of the safe speeds on adjacent sections of roads. The criterion is the value of the safety factor, which is the ratio of the speeds of traffic in adjacent areas.

A similar approach was considered in [2], where a speed that correlates well with the driver's heart rate variability is selected as an indicator of the driving safety. An assessment of the conditions is proposed: good consistency, which does not require reconstruction of the road sections; average consistency requiring minor adjustments to conditions; poor consistency with poor road safety, requiring the road section reconstruction.

In [5] is proved that unsatisfactory traffic conditions on the road sections cause an increase in the emotional tension of the driver, which affects the reduction of the speed of movement.

Based on the principle of interaction between the driver and the road environment, intelligent systems are developed to help the driver to ensure the safety of the vehicle. Thus, the problems associated with implementation of autonomous vehicles are discussed in [12]. Accounting for interaction of the driver with the road environment in the case of vehicle automation was also considered in [13]. A number of key problems are described that arise due to the fact that automated systems are not always reliable and the process of error management in the context of human interaction and automation is not well understood. Author of [3] proposes implementation and analysis of algorithms to identify static and dynamic objects of the road environment using the visual perception module, which relates to the driver's assistance system.

Therefore, despite the benefits of the latest means of driving safety, the task of organizing a human-centered road environment cannot be overlooked. Orientation to ergonomic design and reconstruction of the road environment allows to take into account the psycho-physiology of the driver and create a comfortable movement on the road, which, like the vehicle, is the place of his work.

Research presented in [6] showed that result of the directional control of the driving conditions is the speed adjustment, which provides drivers with an opportunity to choose easier and more convenient driving modes during driving. The algorithm of regulation of functional norms of speed of movement by means of the directed influence on the conditions of movement within each field of perception of the driver is developed. However, this work does not consider a modal assessment of changes in these indicators along the road.

Despite the fact that the speed is a result of the purposeful activity of the driver in the road environment, it cannot be considered as a complex criterion. The need for a systematic assessment arises because it is necessary to take into account many factors of the road environment acting on the driver.

The choice of a complex criterion at the present stage of the study of interaction of the system «driver - vehicle - road environment» components should be based on systems theory and theory of information [14]. With the aim of purposeful optimal control of the complex dynamic systems, which include, in particular, the road environment, methods of the system theory evaluate the fundamental relationships between individual elements and the whole system, as a whole [15]. This provides an opportunity to evaluate results of the complex impact of the traffic environment on the driver of a vehicle.

Thus, in the work [16], on predictability of driver's behavior in certain road conditions, forecast models for reducing congestion in urban roads were developed. The speed of movement on individual sections of roads is also used as a criterion and information entropy, which characterizes the time series of speeds on each section of the road, was used to quantify the speed uncertainty. To determine the state of traffic, it is proposed to use the random entropy, which takes into account the number of speed states [15], temporary entropy to estimate the probability of not exceeding the speed and the actual entropy that establishes the sequence of states of the road section [17]. In [18] are evaluated regularities of the influence of the information flow on the driver's work in the " «driver - vehicle - road environment»» system. However,

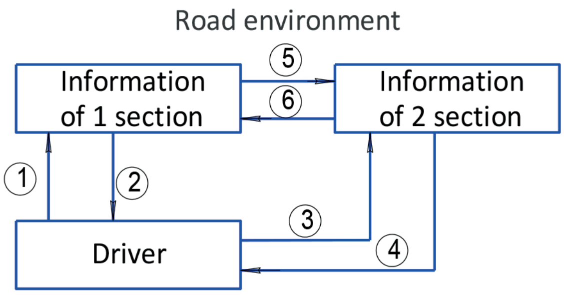


***Figure 1** Scheme of coordination of the traffic conditions on adjacent sections of roads*

studies do not address the issue of consistency of the entropy parameters in adjacent sections of roads.

The most productive for harmonizing the parameters of adjacent sections of the road is the concept presented in [19]. The concept is based on coordination of the drivers behavior programs, which are carried out by selecting values of the next section's setting. Coordination of programs' means that it is necessary to select such elements of the traffic environment in another section, which, at the moment of transition from section to section, will not lead to undesirable transients. According to the proposed concept, in [20] the behavior programs on adjacent sections of the road were presented in the form of harmonization of entropy parameters. This approach makes it possible to take into account the states and components of the «driver - vehicle - road environment». But the proposed concept does not have a developed method, so it needs further study.

Thus, research has shown that the available methods of assessing the road safety do not sufficiently take into account influence of all the factors of the road environment on the driver. A systematic approach to determining the driver's interaction with the road environment has not been developed and, therefore, they may not be basic to ensure the road safety.

Therefore, there is a need, on one hand, to evaluate the influence of road factors of road sections on the driver by complex indicators. On the other hand, according to the indicators obtained, it is necessary to resolve the issues of coordination of sections of the road environment when moving a vehicle from one section of the road to another.

The purpose of this article is to develop an assessment of the safety of adjacent road sections by the maximum entropy of the driver's perception field.

To achieve this goal it is necessary to solve the following problems:

- draw up a coordination plan for adjacent sections of roads on the information links of the driver's interaction with the road environment;
- to offer the criterion of complex information influence of the road environment on the driver;
- based on the experimental studies to determine dependence of the accident rate on the maximum entropy of the field of perception of the driver;
- to develop an assessment of the coordination of traffic conditions on adjacent road sections by the maximum entropy of the driver's perception field.

## 3 Materials and methods

### 3.1 The coordination scheme of adjacent sections of the road

The harmonization process of adjacent sections of roads is performed according to connections, which are schematically shown in Figure 1. Considering the subsystem «driver - road environment» in the general system «driver - vehicle - road environment», it is necessary to ensure coordination, which is in accordance with the information characteristics of the driver's perception field to his requirements of comfort and safety. For this purpose, connections 1 and 2 must be realized (Figure 1). That is, through these connections, the driver's activities are consistent with the road environment of a certain section of the road. Moving to the next section, the driver interacts with another road environment (connections 3 and 4, Figure 1), which has a new information load. These new informational impacts should also be consistent with the driver's activities. To coordinate conditions of the road environment in adjacent areas, connections 5 and 6 are used (Figure 1). Based on these connections, information parameters of adjacent sections are brought into correspondence; they were previously aligned with the requirements of the driver.

Therefore, in order to coordinate adjacent sections of roads, it is first necessary to select the parameter according to which the activity of the driver is consistent with the road environment and then proceed to the coordination of this parameter in the adjacent sections.

It is proposed to use the maximum entropy of the driver's perception field as a criterion for providing the necessary conditions for the traffic on the road sections [19]. The driver's behavior program on adjacent sections of the road is considered while driving in a column when the driver's coordinates are unchanged and can be expressed as:

$$V^{(1)} - V_{\Sigma H}^{(1)} = 0; \quad V^{(2)} - V_{\Sigma H}^{(2)} = 0, \tag{1}$$

and in free mode (overtaking) when the driver's coordinates change. Then the behavior programs can be expressed as follows:

$$X^{(1)} - X^{(1)}_{\Sigma H} = 0; \quad X^{(2)} - X^{(2)}_{\Sigma H} = 0, \tag{2}$$

where:
$X^{(1)}$, $X^{(2)}$ - the actual distances from the vehicle to the edge of the roadway in the cross section of the road in the first and second sections, respectively;
$V^{(1)}$, $V^{(2)}$ - the actual vehicle speeds in the first and second sections, respectively;
$X^{(1)}_{\Sigma H}, X^{(2)}_{\Sigma H}$ - individual norms of the provisions of vehicles in the cross section of the road of the first and second sections, respectively;
$V^{(1)}_{\Sigma H}, V^{(2)}_{\Sigma H}$ - individual norms of speeds of movement of the first and second sections, respectively.

It was proved in the work [20] that individual rate norms can be expressed in terms of the maximum entropy $H_m$, then for matching the adjacent sections it is necessary to satisfy the condition of equality of the maximum entropies of the first and second sections. In 20] was also indicated that for coordination of the adjacent sections it is not necessary to provide the same road parameters. It is enough that their total informational impact on the driver in the second section is equal to the informational impact in the first section.

Therefore, harmonization of adjacent road sections implies that the maximum entropy of the next section $H_{m(n+1)}$ and the previous $H_{m(n)}$ is minimized.

### 3.2 Estimation of the consistency of adjacent sections of the road

The length of the field of perception was determined by the empirical formula in different sections [21]:

$$L = 15 + 4.3 \cdot V, \tag{3}$$

where: $L$ - length of the driver's perception field, m; $V$ - car speed (actual entry speed), km/h.

During the processing of the experimental data, the maximum entropy of the driver's perception field was estimated by formula [22]:

$$H_{m\Pi C} = n^2. \tag{4}$$

where:
$H_{m\Pi C}$ - maximum entropy of the field of perception;
$n$ - the number of objects in the field of perception.

When processing the experimental data, it was also necessary to estimate the maximum entropy in terms of the traffic safety. For this purpose, the influence of accident rate on maximum entropy was estimated.

It is a common method of estimating the risk of a section of a road by the number of traffic accidents (road accidents), so during the data processing of the experiment the data on road accidents that happened over five years were used.

Based on the number of accidents, the aaccident rate was calculated according to the following formula [23]:

$$K_{np} = \frac{10^6 \cdot Z}{365 \cdot L_y \cdot I}, \tag{5}$$

where:
$K_{np}$ - accident rate coefficient, accidents/1 million auto/km mileage;
$Z$ - number of accidents during the year;
$I$ - average annual daily traffic volume in both directions, auto/day;
$L_y$ - length of the road section, km.

The volume and composition of the movement were estimated using the moving observer method [23]. According to this method:

$$I = \frac{n_\varepsilon + (n_\delta - n_M)}{t_n + t_o}, \tag{6}$$

where:
$I$ - traffic volume, auto/h; $n_\varepsilon$ - number of oncoming cars;
$n_\delta$ - the number of cars overtaking the experimental vehicle;
$n_M$ - the number of cars overtaken by the experimental vehicle;
$t_n$ - travel time in the forward direction, hrs;
$t_o$ - travel time in the opposite direction, hrs.

The obtained values of the accident rate with use of Equations (5), (6) were used during the processing of the experimental data.

## 4 Results

### 4.1 Results of experimental research

The experimental races were carried out in the field conditions on three roads with length of 20, 15, 10 kilometers, respectively:

- Road 1. The width of the roadway ranges from 7.0 to 10.5 m, the road has two or three lanes, axial marking is applied. The coefficient of adhesion of the car wheel with road surface is 0.39-0.41, the volume factor is 1.03-1.27;
- Roads 2 and 3. The width of the roadway is 7.0 m, the width of the roadbed is 12.0 m, the height of the embankments and the depth of the notches do not exceed 1.0 m; there are two lanes, there is an axial marking.

Experimental studies in the field conditions were conducted in the summer in the same weather conditions (dry, sunny, air temperature in the cab - 22-26 $^0$C).

The studies used passenger cars. Test drivers with 3-7 years of experience and aged from 25 to 45 years were involved in the field experiments. In the course of the experimental races, the actual speed of movement, the

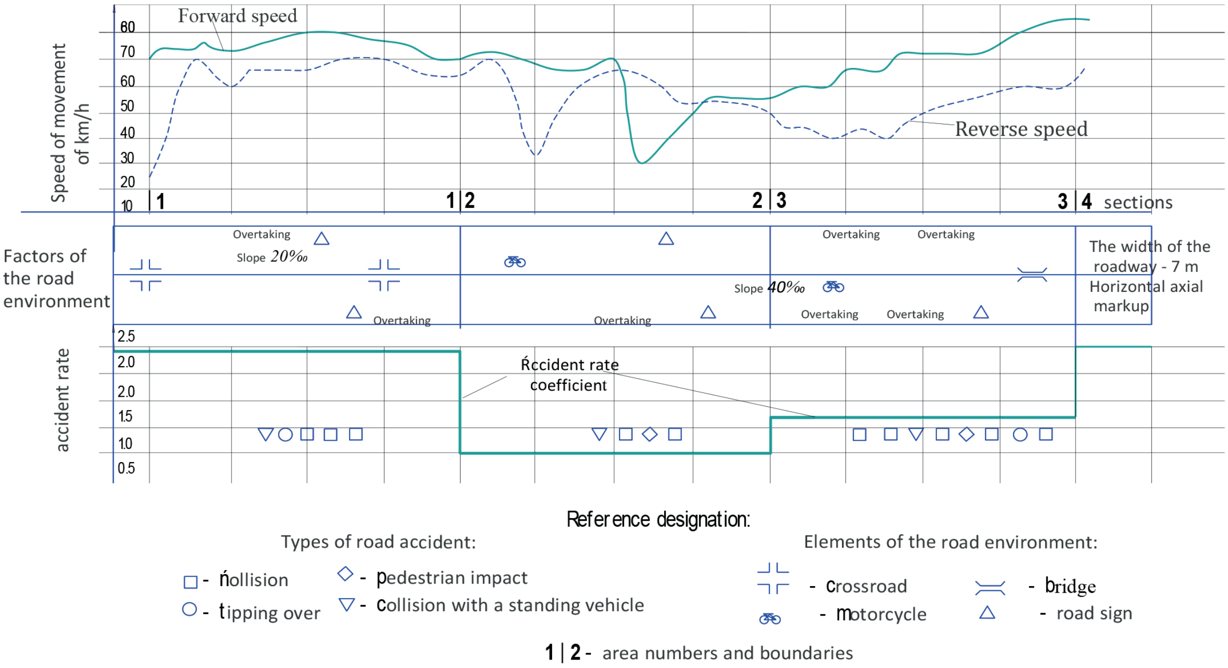


***Figure 2** Fragment of a linear graph of the road 1*

***Table 1** Assessment of experimental data on the road 1*

| Section | The length of the field of perception, m | $V$, km/hrs | $n$ | $H_{m\Pi C}$ | $H_m$ | Volume of daily traffic, aut/h; | Number of road accidents for 5 years | $K_{\Pi p}$ |
|---|---|---|---|---|---|---|---|---|
| | 325 | 72 | 6 | 36 | | | | |
| 1 | 344 | 76.5 | 7 | 49 | 44.67 | 2107 | 5 | 1.3 |
| | 331 | 73.5 | 7 | 49 | | | | |
| | 316 | 70 | 10 | 100 | | | | |
| | 221 | 48 | 5 | 25 | | | | |
| 2 | 230 | 50 | 7 | 49 | 52.5 | 1154 | 4 | 1.9 |
| | 258 | 56.5 | 6 | 36 | | | | |
| | 303 | 67 | 7 | 49 | | | | |
| 3 | 325 | 72 | 11 | 121 | 73 | 548 | 8 | 2 |
| | 350 | 78 | 7 | 49 | | | | |
| | 368 | 82 | 6 | 36 | | | | |
| 4 | 288 | 63.5 | 5 | 25 | 41.67 | 884 | 3 | 1.86 |
| | 273 | 60 | 8 | 64 | | | | |
| … | … | … | … | … | … | … | … | … |
| | 252 | 55 | 7 | 49 | | | | |
| 20 | 252 | 55 | 9 | 81 | 48.7 | 945 | 3 | 1.74 |
| | 253 | 55 | 4 | 16 | | | | |

travel time of the sections and their length, as well as the factors of the road environment, were recorded.

The data of the experiment were analyzed and processed in acomplex on the linear graphs of the investigated roads. A fragment of the linear graph of the road 1 is shown in Figure 2.

While processing the experimental results, the road was divided into sections that were equal to the length of the driver's perception field.

Due to the fact that for an assessment of each driver's perception field $H_m$ there are insufficient statistical data on road accidents, 3-4 perception fields were combined so as to obtain sections of the same length (approximately one kilometer), and the maximum entropy of the driver's perception field was taken as the average of the totality of these values on the site $H_{m\Pi C}$. Assessment of the road sections 1 is presented in Table 1.

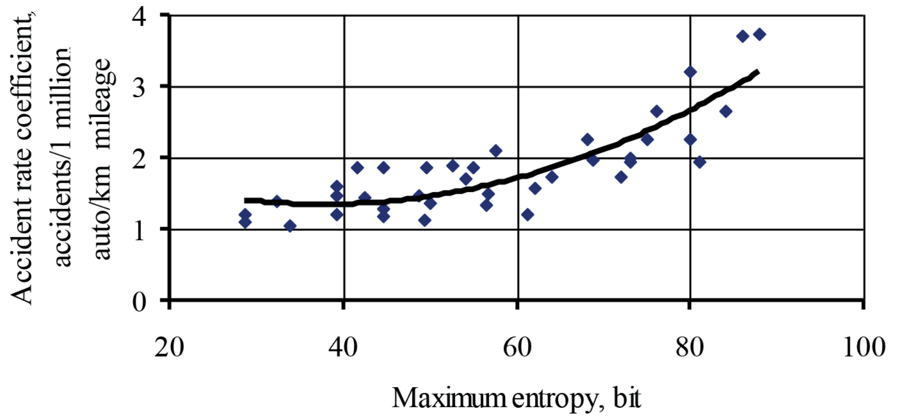


***Figure 3** Dependence of the accident rate on the maximum entropy of the driver's field of perception.*

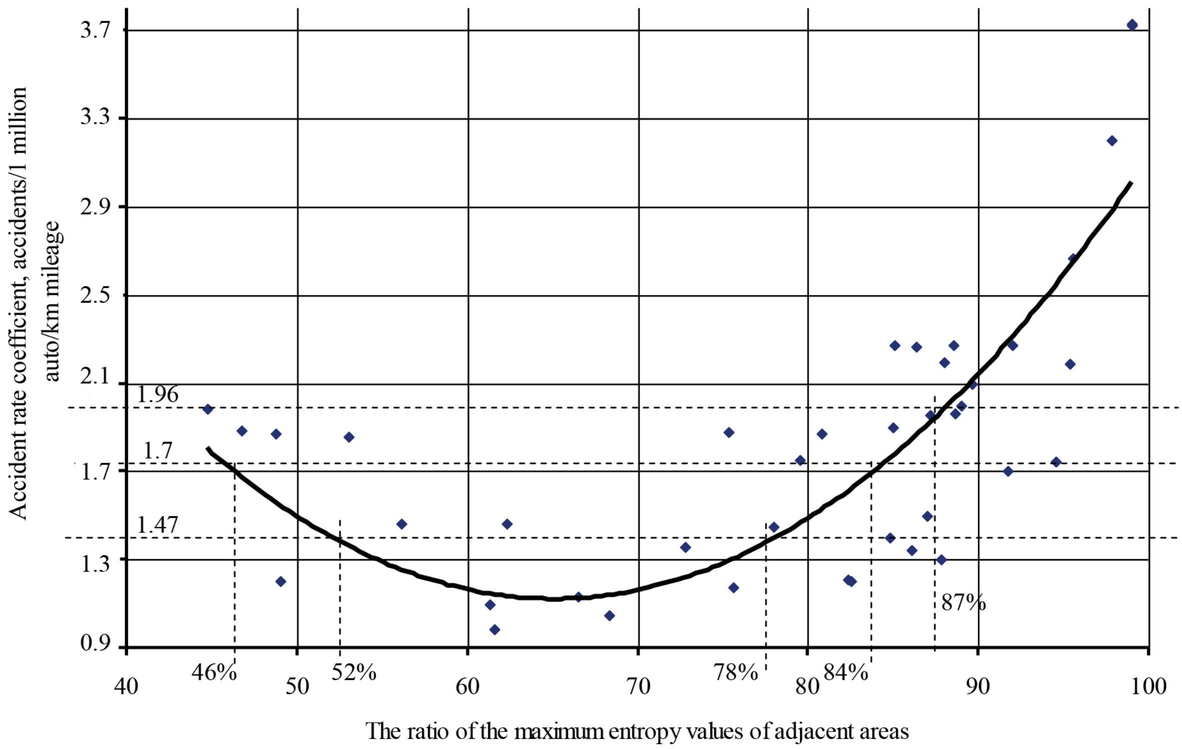


***Figure 4** Dependence of the accident rate coefficient on the ratio of values of the maximum entropy of adjacent areas*

**4.2 Processing the data**

According to results of Table 1, as well as results of evaluation of roads 2 and 3 (which are not presented), dependence of the accident rate $K_{np}$ on the maximum entropy of the field of perception of the driver $H_m$ (Figure 3) is estimated, which estimates the degree of danger of the conditions of road sections.

Analysis of the empirical data proved the curvature of the nature of the relation $K_{np} = f(H_m)$ (Figure 3). The following regression equation was obtained by processing the experimental data using the method of least squares:

$$K_{np} = 0.0007H_m^2 - 0.056H_m + 2.4\,. \tag{7}$$

A correlation index of $r' = 0.851$ indicates a high bond density, the probability of which was estimated by the Student's t-test. The quadratic error $m_\eta = 0.085$, the reliability criterion $t_T = 10.01$ is greater than the tabular $t_p = 2.7$ for 0.01% coverage, which indicates the reliability of the correlation index. Thus, the maximum entropy of the driver's perception field is an indicator of the traffic safety on adjacent road sections.

The relation $(H_{m(n)}/H_{m(n+1)})$, where $H_{m(n)}$ and $H_{m(n+1)}$ are values of the maximum entropy of the field of perception of the previous and next sections, respectively, was used to harmonize adjacent road sections in the free mode. This ratio is in line with the accident rate. Analysis of the empirical data proved the curvature of the bond $K_{np} = f(H_{m(n)}/H_{m(n+1)})$, which is presented in Figure 4.

***Table 2*** *Estimation of indicators of the traffic conditions consistency on adjacent sections of roads by the driver's perception field maximum entropy*

| Section safety assessment | Value of the accident rate, according to [24] | Ratio of the maximum entropy values | Assessment of sections consistency |
|---|---|---|---|
| Dangerous | 1.71…1.96 | Less than 46% | Aligned |
| Low-risk | 1.45…1.71 | 46 … 52% | Aligned |
| Safe | Less than 1.45 | 52 … 78% | Aligned |
| Low-risk | 1.45…1.71 | 78 … 84% | Aligned |
| Dangerous | 1.71…1.96 | 84 … 87% | Not aligned |
| Very dangerous | More than 1.96 | More than 87.0% | Not aligned |

Processing the experimental data using the least squares method allowed us to obtain the following regression equation:

$$K_{np} = 0.0016(H_{m(n)}/H_{m(n+1)})^2 - \\ - 0.214(H_{m(n)}/H_{m(n+1)}) + 8.081. \quad (8)$$

The density of the relationship between the accident rate and the ratio $H_{m(n)}/H_{m(n+1)}$, was estimated by the correlation index $r' = 0.785$. Since the value of $r'$ is large, the hypothesis that there is a close bond $K_{np} = f\ (H_{m(n)}/H_{m(n+1)})$ is confirmed. The reliability of the correlation index was evaluated by the Student's t-test. Quadratic error was $m_\eta = 0.103$, with the reliability criterion $t_p = 7.62$. Since the calculated values of $t_p$ are larger than the table values $t_p = 3.55$ for 0.001% coverage, it can be considered that the calculated correlation index is quite reliable.

It is clear from Figure 4 that with increase in difference of values of the maximum entropy of adjacent areas, the accident rate decreases, but only to a certain limit. This is due to the fact that the accident rate is defined in the areas where the driver is in adaptation state and the road environment is considered comfortable. The subsequent increase in the entropy divergence in adjacent sections (Figure 4) leads to an increase in the relative accident rate on the road.

### 4.3 Safety assessment of the motion conditions by maximum entropy

Using values of the accident rate (represented by certain intervals) and the corresponding safety assessment of the section, established by the normative document [24], taking into account all the accidents (with victims and material losses), on the basis of dependence (Figure 4), estimation of change in the maximum entropy of the driver's perception field in adjacent sections of roads is proposed. The assessment of the sections' safety is given in Table 2.

Analysis of the output data of Table 1 and developed estimation of indicators of consistency of traffic conditions on adjacent sections (Table 2) shows that out of 45 kilometers 10 sections are safe, which is 22.2% of the total number of considered sections, 9 sections (20%) belong to the unsafe, dangerous - 11 (24.4%) and very dangerous 15 (33.4%).

Assessment of the traffic conditions by the maximum entropy of the perception field allows to characterize the consistency of adjacent sections of roads based on indicators that guarantee the safe working conditions for the driver. Conditions on adjacent sections of roads are considered aligned if the maximum entropy values vary from 46% to 84%, which when moving to the next section creates safe or low-risk driving modes. Adjacent sections, where the maximum entropy value changes by less than 46%, are considered as consistent, as well, if they contain the number of road objects that are optimal for the driver to perceive. If the value of the maximum entropy is more than 84%, the movement is considered dangerous or very dangerous, which indicates the inconsistency of the traffic conditions in the sections.

At the same time, results of the study are valid for drivers who have undergone measurements (26 people), an increase in the number of drivers with different psychological types [6, 8] can refine the results obtained and take into account their peculiarities when assessing the safety of adjacent road sections. The study used passenger cars for research purposes. Under these conditions, the factors characterizing «vehicles» and «drivers» in the " driver - vehicle - road environment» system remained unchanged or less changed. At the same time, additional experiments on trucks, buses, special vehicles will expand the data obtained and adjust the results of the study. In general, these refinements do not affect use of the developed method and evaluation of the road characteristics and will further diversify the road infrastructure for different users.

The obtained modal evaluation of the characteristics of traffic conditions allows to conclude on the safety of passage of adjacent sections. From a practical point of view, the characteristics presented make it possible to determine road safety during their design and operation.

## 5 Conclusions

The paper proposes a method for improving the traffic safety on adjacent sections of roads, which takes into account the human factor when assessing the environment.

The maximum entropy of the field of perception is chosen as a criterion of the complex information influence of the road environment on the driver. The dependence of the aaccident rate on the maximum entropy of the driver's perception field is established. It is proved that the maximum entropy of the driver's perception field is an indicator of the of traffic conditions' safety on adjacent sections of roads.

The coordination scheme of adjacent sections of roads on the information links of the driver's interaction with the road environment is presented. For the first time, an estimate relate traffic conditions on adjacent sections of suburban roads by the maximum entropy of the driver's perception field was obtained. It is established that the conditions of motion in adjacent sections are considered consistent if the maximum entropy values differ by no more than 84%. The practical value of the obtained modal assessment of the traffic conditions is that it allows to conclude that the passage of adjacent sections of roads is safe during their design and operation. In the case of discrepancy with the characteristics proposed in the work, in practice, the design of the road environment should be changed or its reconstruction made by reducing or increasing the number of elements on the road, combining them, reinstalling them and the like.

Results presented in thise paper can be used in the field of traffic organization and safety, namely in design of the road infrastructure, taking into account the human factor with which the driver perceives the environment (external environment).

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Daniel Ondrusik - Dalibor Balner - Adam Thomitzek

# EXTINGUISHING OF POOL FIRES USING THE WATER MIST

*Currently, there is progressive use of fire protection systems that use the high-pressure water mist. The extinguishing effect of water mist on flammable liquids is not sufficiently elucidated. Therefore, experiments were designed to gain new knowledge about the mechanism of the high-pressure water mist extinguishing.*

*As a source of the pool fire, gasoline, kerosene, diesel and ethanol were used. Flammable liquids were stored in a circular steel container with a diameter of 165 mm and a depth of 12 mm. The container was placed in an enclosed room of 2.7 x 2.7 m x 3 m. In the experiment, the time to extinguish flammable liquids was measured using nozzles of different spray characteristics of the water mist. The nozzles with orifice 400 μm, 800 μm and 1000 μm were used at a constant pressure of 70 bar.*

***Keywords:*** *water mist, pool fire, extinguishing time, flammable liquid, nozzle*

## 1 Introduction

Many types of transport use automatic fire protection systems (e.g. locomotives, aircrafts etc.). Currently, the trend is to move from chemical extinguishing agents (pure extinguishing agents alternatives replacing halons) to the use of the high-pressure water mist. The great advantage of water mist is easy availability and minimum damage level of devices in the case of fire. Vehicles use flammable liquids as fuel, lubrication and energy transfer (hydraulics) for their function. The mechanism of extinguishing the burning vapours of flammable liquids by means of water mist is not sufficiently described. Experiments presented in this article were designed to explain the effect of nozzle diameter on extinguishing of various types of flammable liquids. The penetration of water mist particles into the flame is influenced by the content of carbon soot particles. The content of soot particles in the flame varies for different liquids.

In extinguishing the pool fires using a water mist it is necessary to define parameters of the water mist. The main parameters of the water mist are size and velocity of droplets, which have an impact on their overall kinetic energy and mass loading of the droplets. Additionally, extinguishing is determined by the type of nozzle, i.e. the geometry of the ejected water mist [1]. It is possible to come across similar water mist parameters in attenuation of heat radiation, where water mist curtains are used [2-4]. To increase the extinguishing effectivity, it is necessary to optimally design parameters of the water mist for various types of flammable liquids. In reference to parameters of the water mist during the termination of a fire, the main extinguishing mechanisms are the cooling effect, oxygen isolation effect and attenuation of the heat radiation towards the surface of a liquid. The cooling effect has the two phases - the gas phase cooling (reduces the energy necessary for a fire chain reaction) and the liquid phase cooling (reduces the heat from the surface of the fuel) [1, 5]. Another scientific paper describes the overall extinguishing effects of the water mist: „*The main effects usually observed in water mist action are gas phase cooling, oxygen displacement, fuel vapor dilution, wetting and cooling of the fuel surface. Two secondary mechanisms have also been identified: radiative transfer attenuation and kinetic effects*", [6]. Extinguishing of pool fires by a water mist is a subject that many authors address, where the aim should be the finding and unification of suitable parameters of the water mist for a defined flammable liquid.

Source [5] is an experimental study dealing with interaction of the water mist with pool fires contained in a stainless steel pan. The experiment was performed on a small scale in a stainless steel container with an inner diameter of 150 mm and a height of 10 mm. The container was placed 600 mm above the ground. A nozzle with a working pressure of 0.5 MPa a jet angle of 60° and flow rate of approximately 1.0 $ml.s^{-1}$, was placed at a height of 300 mm above the container. The water tank is under pressure by nitrogen at the required level and the nozzle creates the water mist. The Volume Mean Diameter of the mist was about 80 μm. The radiation spectra of the flames were measured by a monochromator and the radiant heat flux was obtained by a heat flux sensor before and after application of the water mist. Thermography was used to visualize the thermal field of the flame. These characteristics were measured for the liquid pool fires of kerosene, heptane and ethanol. The obtained results showed that in the case of heptane and ethanol it was easy to extinguish the fire using the main extinguishing effects

**Daniel Ondrusik[1], Dalibor Balner[1,*], Adam Thomitzek[2]**
[1]Department of Security Services, Faculty of Safety Engineering, VSB -Technical University of Ostrava, Czech Republic
[2]Department of Fire Protection, Faculty of Safety Engineering, VSB -Technical University of Ostrava, Czech Republic
*E-mail of corresponding author: dalibor.balner@vsb.cz

of the water mist. In the case of kerosene, the extinguishing was a lot more difficult. The authors of the study assume, that this can be explained by a greater production of soot, which prevented penetration by the mist through the buoyancy effect of the burning gases and onto the surface of the flammable liquid. Due to this, the necessary amount of water does not reach the surface of the liquid, leading to an increase in the fire intensity due to expansion of the water mist during the evaporation. A higher amount of evaporated water also further propagates the mixing of flammable vapors with an oxidative element and changes chain reactions. A sufficient mass loading of the mist jet is an important parameter in extinguishing kerosene with a water mist. As can be concluded from article [5], the process of extinguishing, just like the temporary increase of the intensity of the fire, is a key part of the interaction of the flammable liquid with the water mist. Which process prevails will depend on the type of fuel, the characteristics of the water mist (size of the droplets, concentration) and the pressure used. As is mentioned below, the source, which describes the extinguishing effect of the water mist with additives also mentions the increasing and diminishing intensity during the pool fires and divides this effect into four phases (details in source [7]). Source [1] dealt with the effectivity of extinguishing pool fires with a single-jet nozzle mist apparatus in an open space. The experiment was done using the steel containers, with diameters of 130 and 200 mm, with ethanol and kerosene as a fuel. In measuring the heat flux and temperature, authors were set to calculate the effectivity of extinguishing with reference to various working pressures (4-10 bars) on the mist system and various distances of the nozzle from the test container. They concluded from the results obtained, that the greater the distance of the nozzle from the fuel, the harder it is to extinguish the fire (especially during the pressure being below 6 bars). They also found out that extinguishing kerosene could be easier than extinguishing ethanol, under the condition that the water mist has a greater mass loading and a higher momentum of droplets. With extinguishing, it also depends on the type of the nozzle - full cone spray pattern, hollow cone nozzle. The article also mentions the oxygen isolation effect of the smoke containing soot, which can, with help of the mist, reach the fire zone and keep the oxygen out, especially in the case of kerosene. This phenomenon works with the opposite effect than the described in article [5]. The time it takes to extinguish ethanol and kerosene is also influenced by their flash points. An interesting fact is that the pulse jets of water mist can increase the effectivity of extinguishing. [1]

The research also focused on possibility of boosting the extinguishing by the water mist with additives. Article [8] focuses on differences in extinguishing the pool fires (diesel, gasoline and ethanol) with and without additives. The experiment took place in a well-ventilated room of 3 x 3 x 3 m, using a square container of 15 x 15 cm placed at a distance of 65 cm from the floor and 1 m from the nozzle. The additives used were film-forming agent AFFF, $NaHCO_3$, a representative sample of the metal compounds and multi-component agent (MC additive). The gathered results showed, that in adding the respective additives, it is possible to increase the extinguishing effectivity of the water mist. However, it is necessary to mention that effectiveness of the additive greatly depends on the type of the fuel used [8].

The increased extinguishing effectivity of the water mist with additives is also confirmed by article [7]. The process of extinguishing pool fires with water mists with additives can be divided into four parts - flame early growth stage (flame development stage), preliminary inhibition stage, again flame growth stage and again inhibition stage. In using the water mist with additives, the extinguishing effect of the mist has the added benefit of terminating chemical reactions by pairing with free radicals, decreasing the surface tension of the water or creating a film on the surface of the fuel (depending on the type of additive) [7, 9].

The aim of experiment, presented in this article, was to determine the extinguishing time of ethanol, kerosene, gasoline and diesel using water mist.

## 2 Creation of a water mist

In cooperation with the company PKS Servis spol. s.r.o, a system for creating a water mist by the brand TechnoMIST was used. The system for creating a water mist consists of a high-pressure water pump with a filter, armature, a pipe system and a nozzle with different orifice. A diagram of the system for creating a water mist is shown in Figure 1.

### 2.1 High-pressure water pump with a filter

A pump from the brand Tecnocooling type PREMIUM was used in the system for creating a water mist (Figure 2). It is a plunger high pressure pump, which consists of a brass head and three ceramic pistons. A single-phase electric motor with 1450 (RPM) is the source of power, enabling a 70 bar working pressure of the pump. The electric motor is air-cooled and connected to the standard electric outlet 230V/50 Hz. At operating pressure, the flow of the water at ejection point from the pump is, with regards to the quality of water, around 2 $1.min^{-1}$. A water filter made from a plastic body with cellulose lining is placed at the water inlet point into the pump (Figure 2). The filter is capable of capturing mechanical impurities above 5 µm [9].

### 2.2 Pipe system

The pipe system is made up of a resistant black nylon hose with a thickness of 3/8” (the outer diameter 10 mm, the inner 5 mm, thickness of the wall 2.5 mm) [9]. This hose is adapted to usage at high pressures.

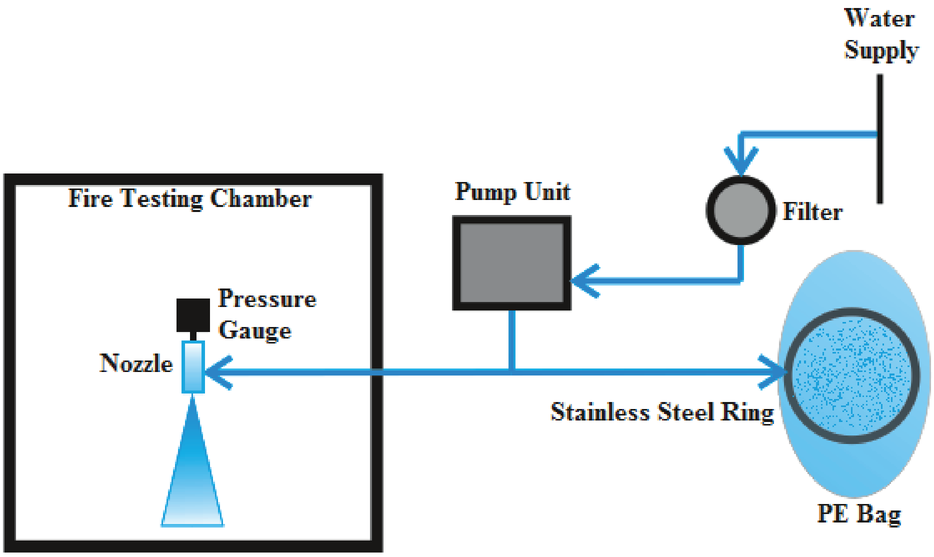


***Figure 1*** *System for creating a water mist*


***Figure 2*** *High-pressure pump and filter at the supply line*

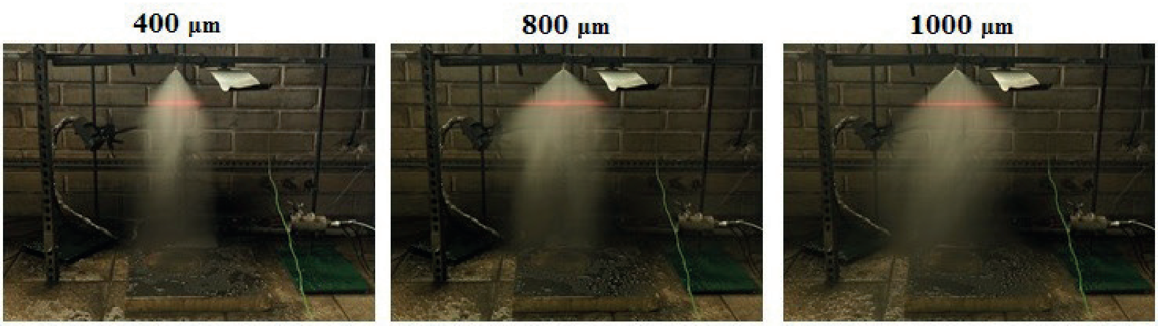


***Figure 3*** *The spraying characteristics of the tested nozzles*

## 2.3 Armatures

The hose is divided into two branches by a T-piece. The first branch leads to a stainless steel ring with a diameter of 400 mm with 5 openings for the mist nozzles. There were 3 nozzles 800 µm and 2 nozzles 1000 µm placed on the ring, enabling, together with a measured nozzle, the defined pump flow of 2 1.min$^{-1}$. The ring is placed in a PE bag, so that the mist would not escape into the surrounding and cause higher humidity in the area of the experiment. The second branch leads to another T piece, which enables the connection of the pressure sensor and the end holder of the nozzle, where it is possible to change the tested nozzles. The pressure sensor is connected to a connector and allows monitoring the pressure on the tested nozzle.

## 2.4 Nozzles

Change of the water mist parameters was achieved by nozzles with orifice diameters of 400 µm, 800 µm and 1000 µm. The nozzles created water mists of a various mass loading, size of droplets, flowrate of water and geometry of the spray cone. The shape of the spray cone of the individual nozzles used is in Figures 3 and 4 (thermogram).

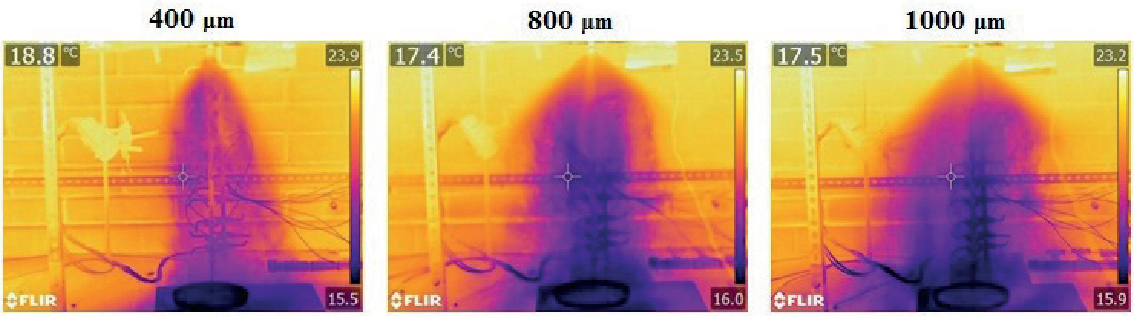


***Figure 4** The spraying characteristics of the tested nozzles (thermogram)*

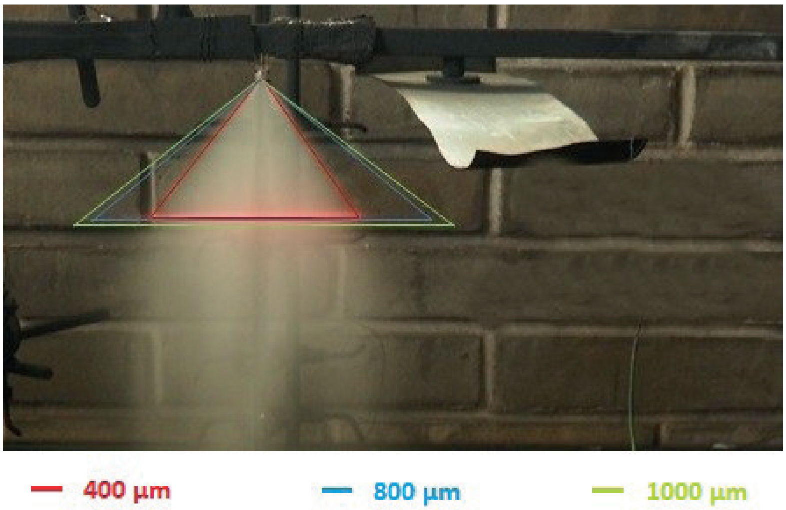


***Figure 5** Comparing the spray cones widths*

***Table 1** Measured water flowrate for individual nozzles*

| Nozzle | 400 µm | 800 µm | 1000 µm |
|---|---|---|---|
| $Q_v$ (ml.min$^{-1}$) | 145.21 ± 0.21 | 343.56 ± 0.99 | 417.29 ± 3.08 |
| δ (%) | 0.17 | 0.31 | 0.84 |

From the taken images, it is evident that the spray cone of the water mist is influenced by the flow of air, which is present despite the space being enclosed. This phenomenon cannot be completely ruled out. The way in which the water mist is distributed into this space is influenced, apart from the parameters of the nozzles, by the geometry of the room and flow of air inside it and the slight fluctuations of pressure on the nozzle, as well. It is also evident, that the width of the spray cone is almost the same in nozzles 800 µm and 1000 µm, whereas in nozzle 400 µm, it is noticeably narrower. The visual comparison of the widths of the spray cone is shown in Figure 5.

For each nozzle, a measurement of the water flowrate was executed in five independent measurings. Results of the flow $Q_v$ is represented with the standard uncertainty type A and a relative deviation δ (Table 1).

## 2.5 Pressure sensor

The pressure sensor was connected to the system for creating a water mist just before the nozzle in order to measure the water pressure in real time. The pressure sensor DMP_333G-01, by the company BD SENSORS s.r.o., with a range of 0-600 bars and a 0.25% accuracy, was used for measurement. Display and logging of the pressure was done by the multi-channel logger ALMEMO 5690-2 from the German manufacturer AHLBORN.

## 2.6 Measuring apparatus

The laboratory where the experiment was conducted was designed for performing tests, which are on the border between laboratory and large-scale tests. The room is equipped with a fire testing chamber of dimensions 2.7 x 2.7 x 3m (length x width x height, respectively), which is separately ventilated from above the roof of the premises. It is possible to measure the fire parameters with a small heat output and to try various fire safety equipment [10]. The measuring equipment (Figure 6), placed in the laboratory, consists of the following:

- A steel container with a flammable liquid placed on a concrete plate,

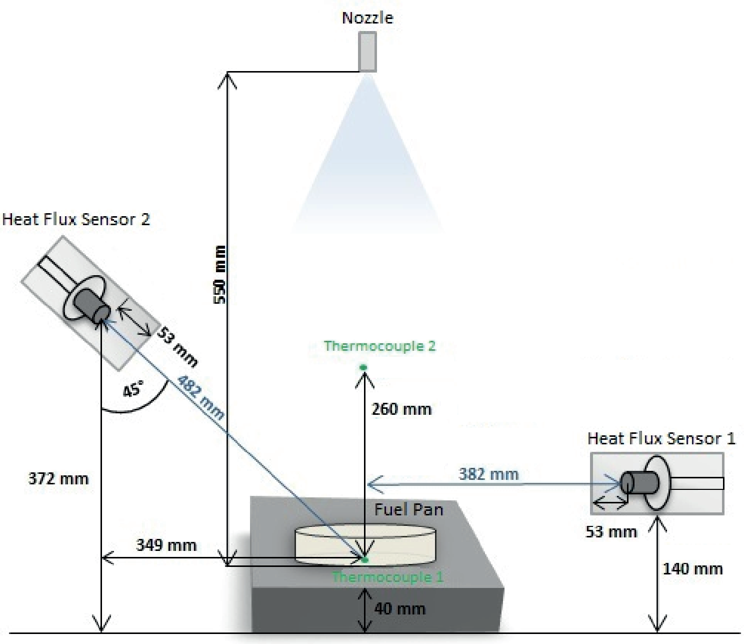


***Figure 6*** *Diagram of the measuring equipment*

- Two heat flux sensors Hukseflux SBG01 with measuring range of 0-10 kW.m$^{-2}$,
- Two thermocouples for measuring temperature,
- Nozzles with orifice 400 µm, 800 µm, 1000 µm,
- Pressure sensor DMP_333G-01 (BD Sensors), range 0-600 bars, accuracy 0.25%.

The logger ALMEMO 5690-2 by AHLBORN was used for logging the measured values, to which a pressure sensor was connected along with two heat flux sensors and two thermocouples. The logger therefore noted the heat flux in one second intervals on two heat flux sensors, the pressure of the water on the nozzle and the temperature on the two thermocouples. The data was then saved onto a SD card for further processing.

The steel container of a diameter 165 mm and a depth of 12 mm was placed onto a cement pad of a height of 40 mm. The steel can was placed always at the same place during the experiment and was placed on the pad in such a way that the center of the container was on the vertical axis in reference to the nozzle. In addition, the placement of the concrete pad itself was always the same during the measuring.

The second measured parameter was the heat flux on the two sensors. Values of the heat flux especially helped to determine the optimal time for finding the constant intensity of burning the tested liquids (to define pre-burn time), based on the referenced measurements without application of the water mist. Observations of behaviour began after extinguishing with the water mist has started. The first sensor was placed at a height of 140 mm above the ground of the room, with which it was in a parallel position. The distance from the center of the container to the first heat flux sensor was 382 mm, where the sensor was, due to protection from flames and decrease of the angle of detection, inserted into an aluminium pipe to a depth 53 mm (see Figure 6). The same method of protection was used for the second heat flux sensor, as well. This particular sensor was placed 349 mm from the center of the container at a height of 372 mm. The sensor was aimed to the center of the container, where it formed an angle of 45° with the floor. The distance from the front of the sensor to the center of the steel container was 482 mm. The power supply cabling and water cooling for the heat flux sensor were further protected from heat by aluminium foils.

The next parameter measured was temperature by way of the two thermocouples. The first thermocouple was placed at the bottom of the steel container, and therefore only recorded the temperature of the flammable liquid during the experiment. The second thermocouple was placed on the center axis of the stainless steel container at a height of 260 mm above its bottom and recorded temperature of flames during the experiment. The measuring apparatus placement is shown in Figure 6.

The pipe system itself was also protected from heat by an aluminium foil. The tested nozzle was, before the start of the extinguishing process, protected from heat by an aluminium plate, which was mechanically controlled with a stretched wire. For the exact setting of the beginning of the water mist application, a switch was placed on the logger, which logged the data from this event in real-time. The switch was always manned by another person, who reacted to voice prompts. This person was also responsible for the turning on/off the pump at the required moment.

## 3 The course and results of the measuring

There were four standardly used flammable liquids with various physical and chemical properties used for the experiment: diesel, gasoline, kerosene and ethanol. After setting up the system for creating the water mist and the measuring equipment, it was necessary

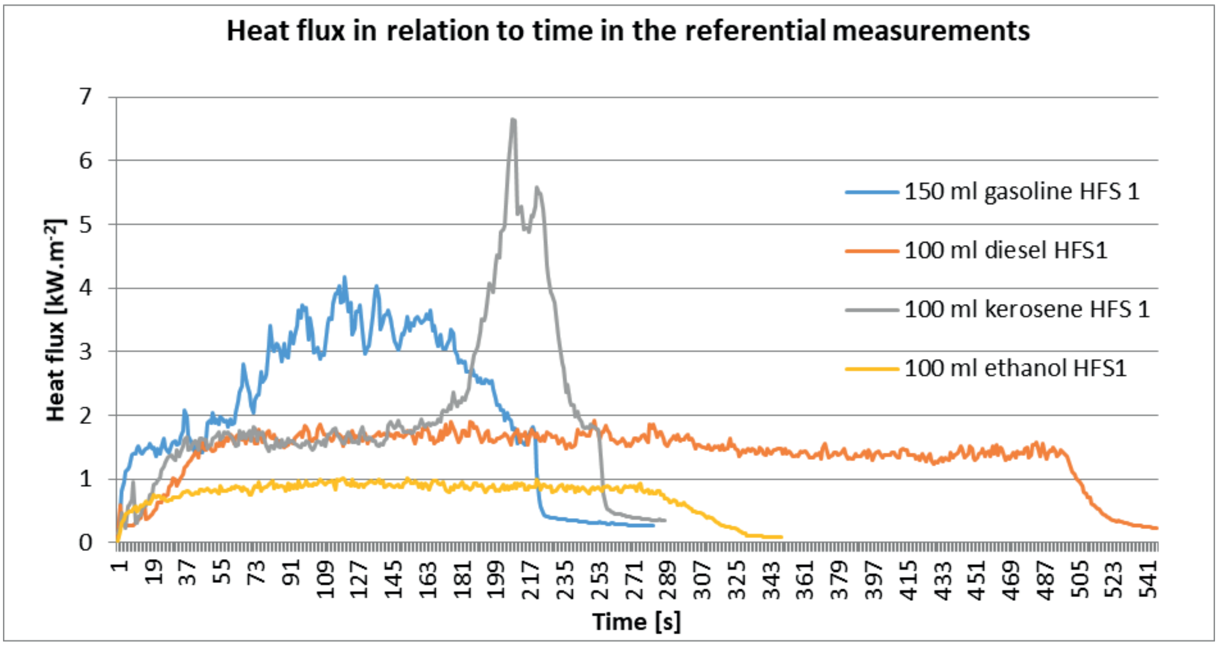


***Figure 7*** *Heat flux in terms of time in the referential measurements of the liquids used*

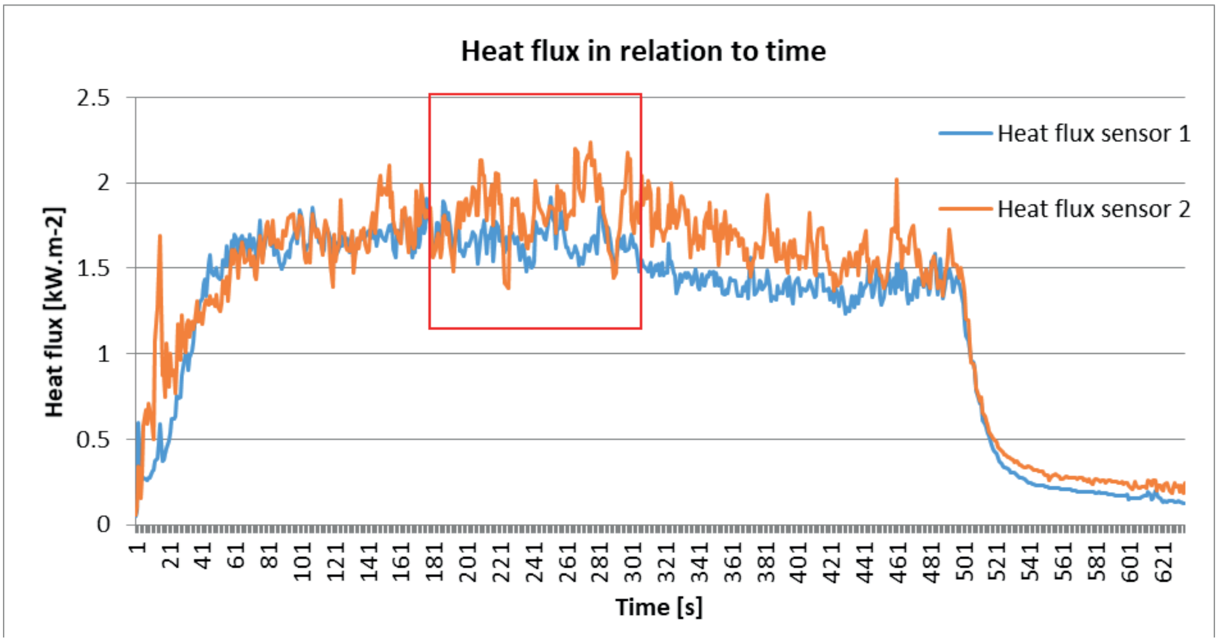


***Figure 8*** *Heat flux in terms of time during referential measuring of 100 ml of diesel*

to determine the method of measuring, which would provide consistent conditions for the duration of the whole experiment. The first task was to always properly prepare the equipment for measuring. Then it was necessary to set the amount of flammable liquid that would be used for burning. Each flammable liquid was set on fire for testing without application of the water mist. This test served as a reference for setting the measuring of the total burning time of the flammable liquid and setting the heat flux during the course of burning. The goal was to find the amount of flammable liquid that burned long enough to have a steady intensity and to note the time interval, when this steady burning takes place. This information was obtained from data of the heat flux sensors. Figure 7 shows the heat flux in relation to time (measured by sensor 1), in the referential measurements of the liquids used.

Figure 8 shows the measurements of diesel together with a highlighted area of consistent burning and time.

Before measuring the time to extinguish the flammable liquids, measurements were taken of the environment in the fire testing chamber by way of a pressure, temperature and relative humidity gauge of the brand Lutron, type MHB-382SD. There were relatively stable conditions in the laboratory, which should not noticeably affect the experiment; that is why the data is not provided here. For the better understanding of mechanisms during the extinguishing with the water mist, individual experiments were recorded/photographed on the digital cameras

***Table 2** Extinguishing time of flammable liquids using various nozzles*

| Time (s) | Gasoline | Diesel | Kerosene | Ethanol |
|---|---|---|---|---|
| Nozzle 400 μm | 66.99 s | 51.44 s | 9.09 s | 2.09 s |
| Nozzle 800 μm | 77.37 s | 49.90 s | 9.64 s | 3.67 s |
| Nozzle 1000 μm | 20.74 s | 45.26 s | 5.77 s | 4.11 s |

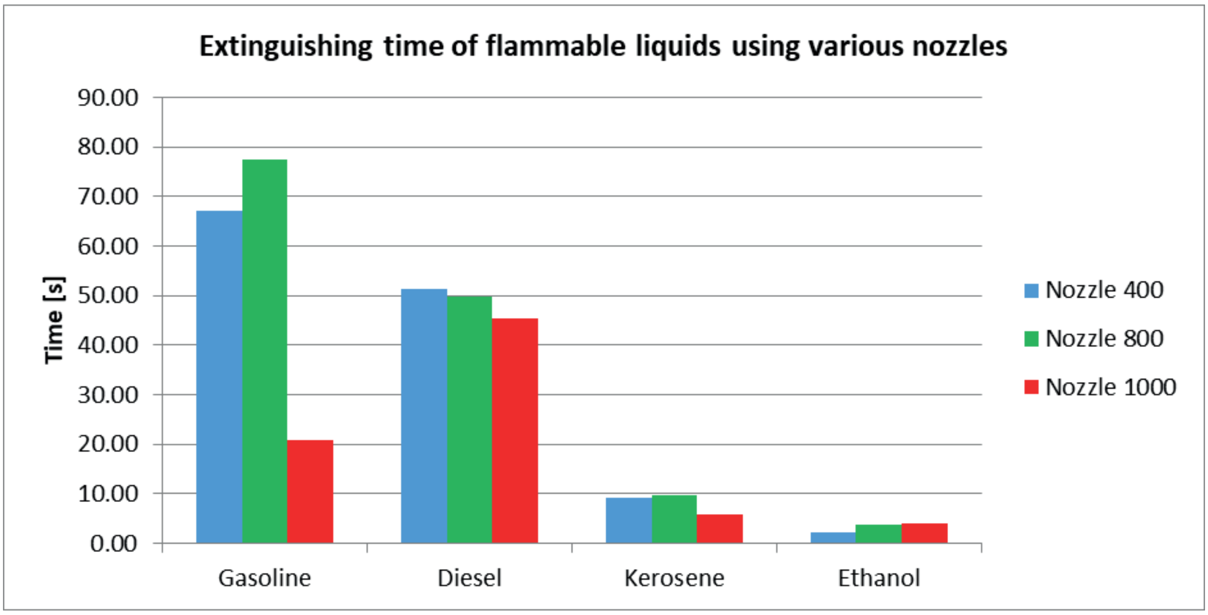


***Figure 9** Extinguishing time of flammable liquids using various nozzles*

(Panasonic HC-V500, Canon EOS 600D, Panasonic DMC-FZ20, Huawei Nova 3) and some on the thermo-camera FLIR T640.

## 4 Results and evaluation

Water mist extinguishing is a very complicated process, which has many variables. For that reason, the experiment focused on determining the time to extinguish the flammable liquids with water mist using various kinds of nozzles. Table 2 shows the extinguishing time of flammable liquids using various nozzles. The extinguishing time began to be measured always after the steady intensity burning phase and application of the water mist.

The extinguishing time is shown graphically in Figure 9, as well. From Figure 9 and Table 2 it is evident that the 1000 μm nozzle extinguished the fastest and did so in the case of gasoline, diesel and kerosene. On the contrary, it was the slowest in the case of ethanol; however, the extinguishing times were very short and all the three nozzles showed to be very effective here. The 1000 μm nozzle however, had the greatest flowrate, as well and that is 417.29 $ml.min^{-1}$. The 800 μm nozzle demonstrated the longest time to extinguish in the cases of gasoline and kerosene. The time, which a burning liquid takes to be extinguished, is, apart from the water mist characteristics, influenced by the flammable liquid. None of the used nozzles appeared to be the fastest in extinguishing of all of the used liquids.

Figure 10 compares the total volume of water needed for extinguishing the flammable liquids with the use of various nozzles. The required amounts of water measured in volume were calculated from the flowrate of the individual nozzles multiplied by the time needed for extinguishing the flammable liquids. The 1000 μm nozzle used the least amount of water in case of gasoline extinguishing, despite having the greatest flowrate. On the other hand, it used the most water in the case of diesel. The 400 μm nozzle showed the highest effectivity in terms of used water in the case of ethanol, kerosene and diesel, where it used the least amount of water. Here it is necessary to mention that due to the shape of the spray cone, not all of the water that flowed through the nozzle may have been used for extinguishing. In 800 μm and 1000 μm nozzles, which had a wider spray cone, the water mist could have had a greater oxygen isolating effect. However, due to droplets, which did not get into the zone of the fire, the entire potential of cooling was not taken advantage of. Those effects, however, were not discussed further, it would be necessary to determine the overall heat balance of the burning, in relation to effects of the water mist in using the individual nozzles, which was not the aim of the study.

The heat flux strongly correlates with the intensity of burning and, therefore, with the buoyancy of flammable gases, which has a negative effect on small water droplets. If the water droplets do not have the necessary kinetic energy, they are not able to permeate the zone of the fire and terminate it. The highest values of the heat flux were shown by gasoline (can be seen in Figure 7), which also

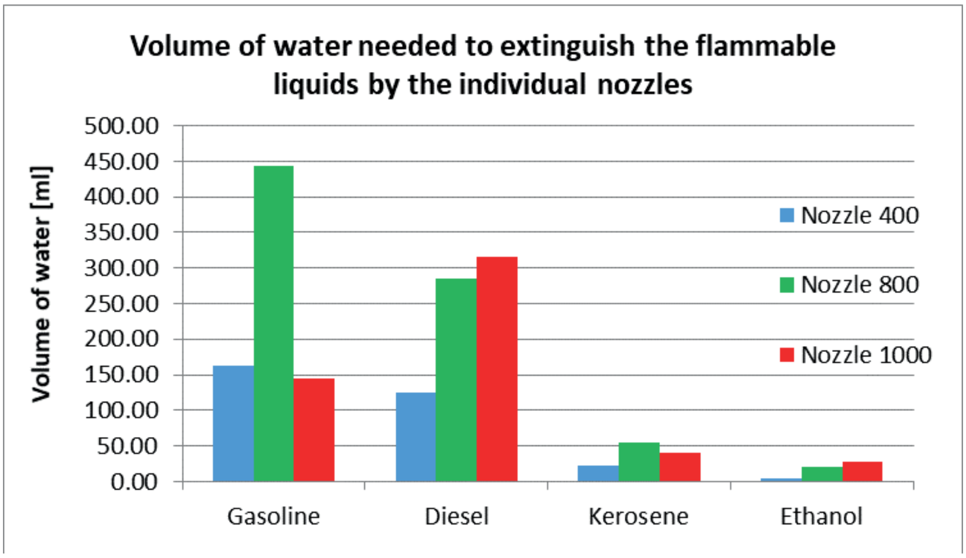


***Figure 10*** *Volume of water needed to extinguish the flammable liquids by the individual nozzles*


***Figure 11*** *The comparison of gasoline pool fire intensity at the time of 40 s and 85 s from the ignition*


***Figure 12*** *The comparison of diesel pool fire intensity at the time of 75 s and 175 s from the ignition*

took the longest time to extinguish. An exception was the 1000 μm nozzle, which most likely had the necessary mass loading and kinetic energy of water droplets for a rapid extinguishing of the fire. Similar values of the heat flux on sensor 1 (Figure 7) were measured in the case of kerosene and diesel. The peak of the curve of kerosene is caused by the boiling of the liquid out of the steel container and did not have an effect on the extinguishing time. Nevertheless, the times of extinguishing of both of these liquids varied noticeably. In the conditions of this experiment, the times for extinguishing kerosene were noticeably lower than the times to extinguish diesel or gasoline. The smallest values of the heat flux on sensor 1 (Figure 7) were measured in the case of ethanol, which also had the shortest extinguishing time.

Scientific papers claims of the longer time for extinguishing kerosene (in comparison to heptane or ethanol) can be attributed to a high production of soot, which prevents the water mist from penetrating through the buoyancy of the flammable gases [5]. However, another view exists, which states there is a shorter extinguishing time of kerosene (in relation to ethanol) due to the oxygen isolating effect of the smoke containing soot. Smoke can be pushed by the water mist into the fire zone and keep oxygen out, especially when the water mist consists of the high mass loading and large droplet momentum [1].

The oxygen isolating effect of smoke could have a general impact on the shorter extinguishing time of kerosene (in some references there are claims that there could be a shorter extinguishing time in the case of kerosene than ethanol due to this effect). Due to the fact that diesel also produces the large amount of soot; the soot impact on penetration of the water mist could have manifested itself here and prolonged the extinguishing time. The time to extinguish the pool fires is necessary to be considered in relation to the flash point [1].

From results of the experiment, it is evident that during the extinguishing of the flammable liquids with the water mist, it is necessary to consider parameters of the created water mist, as well as the type of the flammable liquid itself. Further, it is important to consider the space where the extinguishing takes place and many other parameters. The easiest solution, therefore, is to carry out a practical experiment. In the case of design of systems for extinguishing the pool fires on a small scale that would be, for the timely extinguishing of flames, to investigate the kinetic energy of the droplets, which is important for penetration of the mist through the buoyancy of the flammable gases. The kinetic energy of these droplets should be high enough to overcome this buoyancy of the gases, but it should also not splash the fuel on impact. Further, it would be suitable to use the higher mass loading of the droplets.

The experiment was conceived to extinguish the steadily burning pool fires and therefore it was important first to find out the time it took to reach this value in the used liquids. Authors of [8] state that in their experimental conditions the time it took to reach the steady burning for gasoline and ethanol was 40 s. In conditions of the present experiment, it is observed, however, that such a time was not enough to reach this steadily burning phase. According to these measurements, it is concluded that the time for steady burning for ethanol and gasoline has to be 90 s. In the above-mentioned literature it is also stated that the time for steady burning of diesel was 75 s [8]. In the present measurement conditions it is observed, again, that this number does not match the time it took for the steady burning, which was reached in 180 s. Figures 11 and 12 compare the intensity of burning in times given by [8] and in times right before initiation of the extinguishing.

## 5 Conclusion

A pump with a working pressure of 70 bars, the pipe system and various nozzles were used for creating the water mist. For the purposes of this measurement the nozzles with orifice 400 μm, 800 μm and 1000 μm were used, which enabled creation of the water mist of various parameters. The basic parameters of the water mist are mass loading, shape of the spray cone, size and velocity of droplets, which, at a defined pressure, have an impact on their kinetic energy. The nozzles used had, during the same operating pressure, various flowrates and shapes of the spray cone. The water mist varied in the mentioned parameters.

In the experiment, the extinguishing time for the chosen flammable liquids, heat flux recorded by two sensors and the temperature, were measured. For the better understanding of the interaction of the water mist with the pool fires, the experiments were recorded on a camera and some on the thermo-camera, as well.

From the obtained data, it was evident that the 1000 μm nozzle was the fastest at extinguishing pool fires in the case of gasoline, diesel and kerosene. On the contrary, it was the slowest in the case of ethanol; however, times for the fire extinguishing were very low and all the three tested nozzles showed to be very effective. The 1000 μm nozzle, however, also had the greatest flowrate. The 800 μm nozzle took the longest time to extinguish gasoline and kerosene. The 400 μm nozzle then managed to extinguish ethanol in the shortest time. None of the used nozzles appeared to be the fastest in extinguishing of all the used liquids. From the perspective of amount of the used water, the most effective was the 400 μm nozzle, which used the least amount of water to extinguish diesel, ethanol and kerosene pool fires.

These results showed that a sufficient kinetic energy of droplets in the water mist to penetrate the buoyancy of the flammable gases is a key parameter. The better results could also have been achieved if there was a greater mass loading of the water mist. An important factor influencing the effectiveness of the fire extinguishing by the water mist is also the type of the flammable liquid. This is also confirmed by literary sources, which state that parameters of the water mist are defined for the concrete type of the flammable liquid.

In the cited sources, it is written that extinguishing by the water mist is affected by the soot production, which affects penetration of the water mist through the buoyancy of the flammable gases of the liquid. This phenomenon probably took place in the case of the diesel extinguishing, which was not possible to execute in a short time. However, kerosene, which also produces a large amount of soot and is mentioned in literature, as well, was possible to be extinguished quickly. That could be due to the opposite effect of soot, which exists as mentioned in the text. Influence of the soot particles would be worth exploring further for finding the importance of the mentioned effects. That work could also help in the understanding the complex extinguishing mechanisms in extinguishing by the water mist.

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Andrzej Szymanek

# SYSTEM APPROACH IN ROAD SAFETY STUDIES

*The road safety management methodology should be based on a system approach. This means that the road transport must be formalized as a complex system (CS), and then safety can be interpreted as an emergent feature of such a system. Road accidents should be interpreted as "organizational accidents". They should be studied using concepts such as "normal accident theory" (NAT) and "highly reliable organization" (HRO). The main purpose of the article is to show the usefulness of these concepts for the road safety and risk management, especially in Polish conditions. The system approach to road safety research (and transport safety) will allow for the better safety results.*

***Keywords:*** *road safety, road risk management, system approach, complex systems*

## 1 Introduction

Road transport generates the highest social costs, including the costs of: road accidents, environmental degradation, congestion. Among them, the costs of road accidents are the highest. Therefore, one of the four main objectives of the road transport management is to minimize the number of road accidents, as well as reduction of fatal and serious accidents.

Paradoxically, a coherent safety management methodology does not yet exist. Road transport must be described as a complex system and it follows that there is the need for a systemic approach to road safety management.

Effective transport safety management is management according to the objectives set out for the transport system under consideration.

The road safety management is a system management, whereby an acceptable risk of traffic accidents and/or risks of other road incidents over a specific period and in a specific area is managed.

## 2 Road transport is a system with the greatest potential for the risk reduction

This system, which generates higher costs, also has greater potential to reduce them. The road transport generates the highest costs and therefore through effective risk management a relatively greater reduction of losses could be achieved, thus reducing costs.

The primacy of the road transport in generating external costs is confirmed by various indicators. These relate primarily to the risk of fatal and serious accidents, as well as the costs of environmental degradation. Below there are two indicators that show that the road transport is the most dangerous and socially expensive, Table 1 [1], Table 2 [2].

Here are some of the more important characteristics of road accidents [3]:

1. The road safety is a major public health concern; in 2016, around 1.35 million people died in road accidents worldwide;
2. Today, it is estimated that macroeconomic losses due to road accidents will cost the world economy almost USD 1.8 trillion between 2015 and 2030. This number is higher than the total GDP of Canada in 2017 (the tenth largest world economy) [4];
3. Macroeconomic costs of road accidents vary in different regions of the world. The highest aggregate economic burden is in the USA (USD 487 billion) and in China (USD 364 billion). For Poland, this burden is estimated at USD 15.7 billion. On the other hand, average costs of road accidents, calculated (in USD) per capita, are the highest in Luxembourg (1465). For Poland this indicator has a value of 417 USD. It is estimated that the average annual economic burden of the road accidents will amount to 0.12% of the world GDP in the coming decade, with the average burden per capita amounting to 231 USD [4].

The 2018 WHO report describes the level of the road safety and the costs of road transport [3]:

1. Road accidents are the 8th cause of death worldwide for all the age groups and the main cause of death for children and young people aged 5-29 years;
2. More than half of all the road fatalities involve unprotected road users;
3. Road accident mortality rates are more than three times higher in the low-income countries than in the high-income countries.

In 2018, 25100 fatalities were recorded on the roads of the European Union, meaning a decrease of 21% compared to 2010. The average road mortality rate in 2018 in the EU was 49 deaths per 1 million inhabitants. Nevertheless, it is doubtful that the planned 50% reduction in the number

**Andrzej Szymanek**
Faculty of Transport and Electrical Engineering, Kazimierz Pulaski University of Technology and Humanities in Radom, Poland
E-mail of corresponding author: a.szymanek@uthrad.pl

***Table 1*** *Annual Average Probability of Fatal Transport Accident (AAPFTA) [1]*

| Transport type | AAPFTA | Transport type | AAPFTA |
|---|---|---|---|
| Road transport | $2.25 \bullet 10^{-4}$ | Rail transport | $75 \bullet 10^{-7}$ *[30 times smaller]* |
| Sea transport | $5 \bullet 10^{-5}$ *[4.5 times smaller]* | Air transport | $17 \bullet 10^{-7}$ *[132 times smaller]* |

***Table 2*** *Average costs of transport accidents, (2000) [2]*

| Transport | | | | | | |
|---|---|---|---|---|---|---|
| Road | Rail | Air | Road | Rail | Air | Water |
| Passenger transport [euro/$10^3$ vehicle-km] | | | Freight transport [euro/$10^3$tons-km] | | | |
| 32.4 | 0.8 | 0.4 | 7.6 | 0.0 | 0.0 | 0.0 |

of fatal accidents will be achieved in the ending decade 2010-2020.

In the *Europe on the Move* package from May 2018, the European Commission proposed a new approach to road safety policy for 2021-2030. The long-term goal is to bring the number of fatalities and serious injuries in road transport closer to zero by 2050. The closest new intermediate target is to reduce the number of road fatalities by 50% by 2030 [5-6].

## 3 Road safety as a research problem

One of the many effects of traffic intensification was an increase of number of road accidents. The reaction to this phenomenon was planning various road safety strategies. The historical order and context of these strategies is discussed by Lu at works [7-8].

The reports of the *Organization for Economic Co-operation and Development*, *(OECD)* highlighted several major aspects of the road safety issues that have gained particular importance in theoretical work and road safety research at the beginning of the 21st century.

Among other things, a great need to build the road safety theories and models was pointed out [9]: *"Unfortunately, the lack of theoretical basis is more common in road safety research than in many other research fields. (...) There is a lack of new research hypotheses and formulation of general principles of counteracting"*.

**Safety defined in terms of accepted losses**. As a scientific concept or construct - "road safety" is usually interpreted by political decision-makers, traffic experts, the media and the public opinion - as a category representing the total number of road accidents and their results (fatalities and injuries of different severity) in a given time period.

A different - according to the author, more creative - is interpretation of "road safety" given by N.G. Levenson [10]: *Freedom from accidents or losses. (...) safety should be defined in terms of acceptable losses"*. Levenson adds*: Deciding on the level of acceptable losses is obviously not a trivial issue and contains complex and ethically contentious forms of socioeconomic evaluation at the political level*. This was already a definition that announced the need to handle and manage risk. The key issue here is decision making - determining the level of acceptable losses. And that is the problem of the risk assessment.

## 4 Three important elements for systemic road transport safety studies

Safety studiesas a **"tied discipline".** One form of discipline integration is clustering, when a single idea becomes an axis of interest for several disciplines. This idea can be a phenomenon, a problem, a person, a geographical area, or other. Specialists from different disciplines study a common theme from the perspective of their own disciplines. This is how a "bonded discipline" arises. It seems that such a knotty idea may be the "transport safety". A thesis can be formulated, [11]: "transport safety" is a nodal idea that binds research on different branches of transport. It is an interdisciplinary research".

OECD experts for a long time have stressed the need for a multidisciplinary approach to road safety research [9].

Geysen's thesis as a tool for a broad view understanding of safety issues

W. Geysen in his work [12] formulated as obvious as inspiring thesis: "(...) *safety problems in different areas are very often of the same nature and can be formalized in the same way*". This thesis allows to search for principles and methods of effective road transport safety management in other systems.

Geysen's thesis allows the use of: reasonable analogies, recognized theoretical concepts and some safety models for safety transport studies. Among other things, the aim is to critically review the known safety principles and implement them in the field of transport. However, when seeking reasonable analogies, it is important to keep in mind the characteristics of transport and road transport particularly. Geysen's thesis provides a methodological basis for research of the road transport safety, based on the philosophical and methodological canons of Safety Science.

Safety in any system can be considered on four levels [12]:

1. level of the " safety philosophy" - setting safety criteria and expected losses;

2. the level of investigation of ways and methods, which may be useful in improving safety;
3. the level of "safety technology" - implementation of safety improvement techniques;
4. level of "safety policy" - compilation of knowledge and practice of levels 1-2-3.

**Haddon's idea.** The system approach to road safety research was applied by Haddon, which in the model "3 phases of accident - 3 groups of risk factors" showed the idea of systematic "safety intervention management" in the road traffic. He spoke about the need for "comprehensive systemic treatment". In his model he presented an epidemiological approach to road accidents as a "disease"; he distinguished three phases of the disease and a triad of general causative factors: man, vehicle, environment. Treatment of such a disease would consist of interventions in each of these phases and in each group of risk factors, thus in each of the nine "Haddon's cells" [13].

Haddon's model can be interpreted - this is the author's view - as a variant of the principle of defense in depth; it also resembles the "blunt-sharp-end" model. And no wonder - both of these tools, although formally different from the point of view of safety philosophy, are similar and describe well the essence of systemic approach to safety in general.

## 5 General system theory in the description of road safety

Since the 1960s of the 20th century, attention was drawn to usefulness of the systemic approach, introduced into the scientific circulation by von Bertalanffy [14]. Among other things, it was postulated that the road transport should be interpreted as a complex and open system, which allows to explain its inherent properties, hierarchical structure and interactive processes. Road accidents are the result of a failure to adapt the "structure" of this system to the cognitive abilities of road users. Eliminating some of the road accidents is possible by "matching" the traffic to road users. This can be achieved by systemically improving all the elements in the road traffic, i.e. by analyzing the effects of the whole. The lack of this methodology results, for example, in the "risk transfer" effect, which is the result of risk compensation by road users.

The basic argument for applying the systemic approach to transport safety issues is that the traditional, reductionist approach has serious limitations that can be forced through a holistic view of transport safety issues [15]. The reductionist approach does not primarily take into account the dynamic and blurred interactions between the transport participant, mode of transport and transport infrastructure [16].

The Skyttner's thesis that the system approach to road transport safety can play an important role: safety is emergent property of the road transport [17]. Thus, it is a system property that reveals itself when elements of the transport system cease to be independent and interact with each other. Emergency is the appearance of a new system property, as if from nowhere and unexpectedly. Of course not out of nowhere, but as a result of unobservable complex interactions on different levels of the system structure. Adopting the thesis about emergence means that it is the interactions between the elements of the transport system that are decisive in the occurrence of transport accidents - especially in road transport [18-19]. The issue of emergencies in general systems has a rich literature, see e.g. [20].

Levenson's observation is interesting in relation to "safety optimization" [19]. Well, the optimization of safety of particular elements or subsystems does not have to lead to the optimization of the whole system (for example, transport) due to complex and non-linear interactions between these elements.

If a systemic approach is adapted to the road safety testing, the complexity and dynamics of its processes can be explained by interactions between traffic participants, vehicles and road elements. Road safety, as well as other measures of "performance" of the traffic system, can be seen as properties resulting from incorrect interactions between the traffic system components. The systemic nature of the road safety problem is also referred to by W. Haddon, who over 40 years ago gave an inspiring definition of road transport as: "*an ill-designed "man-machine" system that requires comprehensive systemic treatment*"; [13].

The emphasis on the need for a research approach based on "systems-oriented approach" appeared in OECD expert opinions [9, 21]. Systemic analysis is mentioned here as one of the disciplines belonging to the fourth paradigm of the road safety research, while the "system-oriented approach" should characterize the fifth research paradigm.

## 6 Road transport as a complex system

The transport system, which is analyzed over a large area and in the long term, can be interpreted as a complex system; it is justified here the definition of such systems [22]: *A complex system is one of which development is very sensitive to initial conditions or small disruptions, where the number of independent interacting elements is large, or where there are many possible paths of development for the system.*

Large transport systems have both known forms of complexity: 1. chaotic complexity; 2. organized complexity.

The first is the result of a very large number of elements (infrastructure elements, means of transport, human factor involved in implementation and participation in transport). The second one results from the course of transport working processes, mainly traffic processes. Safety depends on the strength of the functional links present in such systems. There are a tight and coupling connections. The former is characteristic of a decentralized and the latter of a centralized (hierarchical) management structure. This leads to a paradox that characterized C. Perrow: the system should be both centralized and decentralized.

Large transport systems are complex systems, as they have the following features:

1. they have difficult to define boundaries; they are ultimately determined by the purpose and scope of the study;
2. they are open systems, according to the cybernetic approach;
3. they are memory-based systems; they are dynamic systems;
4. they are "embedded" systems, i.e. their subsystems are also complex systems in themselves;
5. they can "produce" emergencies (the emergence of new features);
6. the interactions between the elements of these systems are non-linear, which means that initially small transport incidents can have large effects;
7. there are feedback loops in the interactions between the elements, which means that there are both negative and positive (amplifying) feedback.

Transport systems also meet other criteria for complex systems:

8. they are intrinsically hazardous systems;
9. they contain mixtures of "hidden failures" (e.g. incorrect design conditions);
10. the changes made generate new forms of damage (failures);
11. safety is a system characteristics, not an individual component.

In transport systems comes to huge numbers of interactions between elements of transport infrastructure, means of transport and the activities of the human factor. The products of these interactions are sometimes hard to predictable behaviors, systems, in particular, human behavior in the areas of decision-making and action. The ultimate product are transport accidents and congestion - the main negative effects of transport /NET/ [23].

The work on road accident investigation methodologies often considers that the underlying causes of traffic accidents are mainly due to external (exogenous) rather than internal (endogenous) sources. This leads to the conclusion that the complexity of the road environment may in certain situations exceed the adaptability of road users, resulting in the generation of behavioral errors. From a sociotechnical point of view, 'complexity' of the system means that the road system is not properly designed for road users. This is confirmed: adapting the traffic system to the expectations of the road users is an important issue in the Swedish study "*Vision Zero*" (*SVZ*).

D. Woods identified complexity factors in those systems where the capabilities and skills of the human factor are important, i.e. in sociotechnical systems, which also include any transport system. In particular, he identified four "dimensions" with which he defined "cognitive requirements" to solve complexity problems in any field [24]:

1. Dynamism - the property of a system to generate events that cause changes;
2. Number of subsystems and the extent (extensiveness) of links between them;
3. Uncertainty - which refers to information about the investigated problem (phenomenon); this information may be ambiguous, imprecise, erroneous, incomplete;
4. Risk - which refers to the "nature" of different system results and their relative frequency.

These dimensions are also characterized by the complexity of transport systems, in particular traffic systems. The degree of system complexity depends on these dimensions. It is believed that the increase in complexity of any particular situation in the system under analysis increases the potential for cognitive and perception errors. Therefore, the greater the complexity of the situation, the greater the temporary instability of the system, which may increase the risk of accident. This thesis is consistent with results of general systems theory and can be fully applied in road safety research.

## 7 Perrow's theory of "normal accidents". Transport accidents as system accidents

Charles Perrow's main thesis of the "Normal Accident Theory" (NAT) reads [25]: Accidents in complex organizations ... are inevitable. This is exactly how road accidents must be understood globally: they are inevitable. Therefore, there remains only one rational strategy to improve the road safety - to eliminate fatal and serious accidents. Of course, this is known (*SVZ*), but 35 years ago the creator of NAT stated this, only in a general perspective.

What Perrow described as normal accidents or ordinary accidents, he also called, and later on others: *systemic accidents or organizational accidents*. According to Perrow, these are: *unexpected interactions with many failures in a complex system*. From more recent work on NAT, one can list [26-27].

The rather pessimistic Perrow's thesis about inevitable accidents in complex systems has its alternative; supporters of the "high reliability point of view" claim that good design and effective management in such systems can significantly reduce the probability of accidents [28-29].

It divides systems into simple and complex ones, depending on the type of interaction in these systems. Simple systems are those where simple interactions - i.e. predictable - such as those in the domino sets prevail. Systems are complex if complex interactions are predominant - i.e. unpredictable, coming from an accumulation of factors or aspects that, taken separately, appear to be without risk. The occurring complex interactions in the system are accompanied by an emergence that initiates unpredictable system behaviors that develop so quickly that the system operator no longer understands the resulting situation, making it irreversible and leading to a system accident. It is this aspect of safety that Perrow emphasizes when he says that "accidents in a complex system are inevitable". System accidents are the effects of an accumulation of the so-called "common-mode failure", which are created in the system by unknown feedback between system components.

An extensive definition of a systemic accident is given by Llory (1999); I quote de Almeida [30]: *"The accident is organizational to the extent that it is, primarily, the product of a socio-technical organization. It is no longer only the result of an "unfortunate" combination of passive and latent failures with active and direct failures, no longer only the result of a specific combination of human errors and material failures".* And on: The accident is *"… rooted in the history of the organization: a series of decisions, or the absence of decisions; the evolution of the organizational, institutional and cultural context that interferes in the future of the system; the progressive evolution (deterioration) of conditions or factors that are inside the organization; some particular events that have a notable impact on the life and functioning of the socio-technical system, creating an unfavorable situation: territory into which the accident (or incident) may intrude and develop. […] the accident incubates. The incubation period may be long…"*

The frequency of occurrence of systemic accidents depends on many aspects of the functioning of a complex system, but most of all it depends on:

- the degree of "interactive complexity";
- the degree of "strong links" between system interactions.

The latter feature makes the system highly interdependent, i.e. changing one part of it can quickly affect the state of other parts and the whole system.

It would be interesting to verify the hypothesis on the frequency of system accidents in the road transport. It would need to be examined whether this frequency depends on the interactive complexity and strong links in large road transport systems, as well as in integrated transport systems. Possible "transport interpretations" of system accidents, known from other technical areas, would be of a great importance [19].

For a large road transport system to meet the criterion of "strong links" it would have to have the following characteristics [30]:

- most of the work processes are time dependent, i.e. the system cannot be stopped while waiting for corrective interactions to appear;
- specific and unchangeable sequences prevail, such that event A always leads to event B;
- the system is inflexible, i.e. planned in such a way that there is only one way to achieve the final goal.

Only the first criterion seems to be met by any road transport system. By contrast, the dangerous goods transport system would mostly meet these criteria.

## 8 High reliability organizations (HRO) and transport safety management

In 1984, a group of researchers from the University of California at Berkeley initiated research on complex systems, which was named *High Reliability Organizations (HRO)*. The point is that there are systems whose integral parts are the highly dangerous technologies, and yet serious accidents hardly ever happen there. Those are systems in which errors and failures can have disastrous consequences for people and the environment. The matter of talking are the nuclear power, chemical industry, management systems in passenger aviation, maritime industry. So, the *HRO*s are systems where disasters are avoided and where the so-called "normal accidents" are expected (a concept Perrow) due to the many risk factors and complexity of such systems.

How can one define the *HRO* in the easiest way? According to K. Roberts, this can be done by answering the following question: how many times could such an organization fail without producing disastrous results? If the answer is: tens of thousands of times, it means that one is dealing with the *HRO* [31]; quoted after: [32]. The key term "fail" here refers to the errors and malfunctions that may occur in such a system, and yet, there will be little consequence.

One may ask: are the large transport systems - which are, after all, complex systems - also the *HRO* type systems? So, can safety management in the road transport systems be implemented using the philosophy and methodology used in *High Reliability Organizations*? Large transport systems may sometimes be the *HRO* systems' exemplifications; it is primarily about functioning of transport in the crisis management conditions, as well as the transport of hazardous materials. In general, however, road transport could not be classified as the *HRO* systems, because [23]:

1) The potential consequences of individual road transport incidents are hardly ever catastrophic; of course, the extent of losses when dealing with road accidents over longer periods of time is catastrophic;
2) Road accidents are not rare events (in the probabilistic sense).

A review of the subject literature is contained in the paper [33].

## 9 A new paradigm of systemic understanding of road safety

Since 2000, when it was shown how a systemic approach to road safety management could be used, global, national and regional variants of this approach have begun to emerge. In the WHO report of 2004 [13] and the *Auckland Regional Road Safety Plan* 2009/12 - a characteristic of the "new" paradigm of understanding road safety can be found [34]:

1. Traffic injuries are highly predictable and can be prevented by a rational analysis of possible remedies.
2. Road safety is a multi-sectoral social health problem and it is impossible to achieve success in reducing road accidents without the full involvement of all actors (including other road risk "owners").

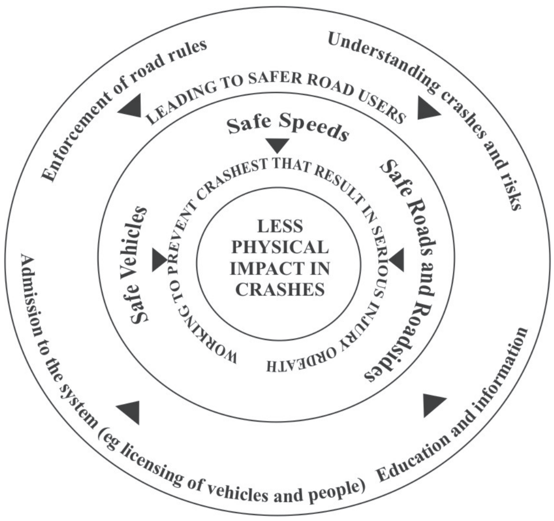


***Figure 1*** *Systemic approach to road safety [35]*

3. Any behavior of road users should not lead to death and serious injury; a traffic safety system should help all of them to cope with increasingly demanding conditions.
4. The sensitivity of the human body should be a control parameter (constraint) in the design for traffic and speed management systems.
5. Technology transfer should be in line with local conditions and the need to know how to implement local road safety solutions.
6. Injuries in road accidents can be interpreted as lost social capital and therefore all the road users should be equally protected, keeping in mind, however, that unprotected road users are subject to disproportionate risks and injuries in road accidents.

It is worth recalling here the definition of "human capital" [13]: this concept covers both direct costs and indirect costs for individuals and society as a result of road accidents; these costs include, among others: medical costs (initial, ad-hoc, rehabilitation), insurance costs, all the administrative costs related to the accident, occupational costs.

The ARRSP 2009/12 Regional Road Safety Programme contains an early version of the systemic approach to road safety management [34]. Hence, several conclusions, which are worth promoting:

1. There must be complementarity of roles and actions at all the levels of governance and social stakeholders in order to achieve the overarching objective of keeping the risk of the road accidents in the area to a minimum;
2. Road authorities, planners, investors must make efforts to plan, design and build sustainable and safe transport;
3. The necessary actions include
   a) increasing safe access to all the modes of transport;
   b) building "forgiving" transport infrastructure;
   c) recognizing that vehicle speed management is at the heart of this approach.

This is the quintessence of the system approach - expressed in a somewhat advertising form: "*Safer road users using safe vehicles, travelling at safe speeds, on safe roads, will reduce the impact of sudden collision forces, which will cause less injury to people*" [34].

A graphical interpretation of the systemic approach to road safety is shown in Figure 1.

Such a "road system" allows for human error, not leading to death or serious injury and responsibility for the risk reduction is shared between the road users and system managers.

## 10 Road transport safety system (RTSS)

The researcher's object of interest is "road transport", i.e. a certain real object in which one identifies entrances, exits, surroundings and various types of exchange that take place between the "transport-round" pair. Here, of course, it is possible to describe in detail such an object as the road transport considered in a certain area and at a certain time. It can be defined by describing the transport structure, means of transport and four main work processes:

1. initial and final processes (loading);
2. traffic processes;
3. traffic control processes;
4. disruptive processes - among other groups of transport system processes.

Different systems can be defined for such an object and each of them will describe specific properties of the analyzed object - that is the road transport. The property one is interested in is "safety" - therefore, the "road transport safety system" is defined, which must meet the following rigorous system method:

1. Accuracy: the system should be strictly defined so that it is clear what belongs and what does not belong;
2. Invariability: the definition of the system should be unchangeable; it is not acceptable that some elements of the system sometimes belong to the system and sometimes not to it;
3. Comprehensive: the division of the system into subsystems should be complete, which means that

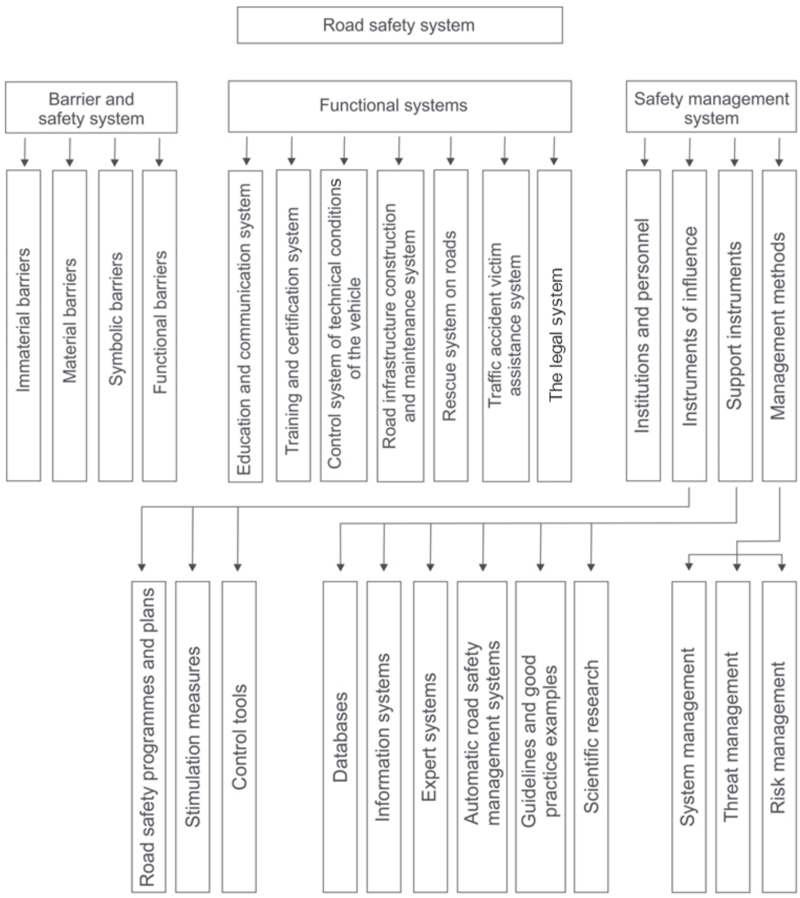


***Figure 2*** *The road transport safety system [36]*

the system must not contain elements, which do not belong to any of the subsystems;

4. Disconnection: the division of the system into subsystems should be separable. This means that a system must not contain elements belonging to several subsystems simultaneously;
5. Functionality: the system shall be kept separate according to the specific function performed.

The concept of the RTSS should be considered as a convenient conceptual abbreviation for everything that concerns the road transport safety, considered in a specific area and at a specific time. Thus, the RTSS is defined by the three components:

1) The purpose of the system - to reduce individual and social risks in different areas of transport operation;
2) A set of system components:
   - The human factor in road transport;
   - Technology (means of transport, road infrastructure, rescue and medical technology);
   - Environmental factors;
   - Four working processes: motion, control; initial and final, disruptive;
   - Intangible components (standards, bans, procedures, etc.);
3) The system's relational structure, i.e. a set of relations (interactions) between elements of the system - important for achieving the system's goal.

The RTSS defined in this way is a useful abstract and can be used to model various safety and road risk issues. Such a system can be described by the scheme shown in Figure 2.

## 11 Conclusions

Any road safety improvement programme requires the implementation of the 5E methodology *(Education - Engineering- Enforcement - Encouragement - Evaluation)*. These are components of the system approach. The construction of the road safety improvement programmes in Poland must be supported by scientific research - also those less known in Poland. This is research based on a systemic approach to road safety. In particular, several topics should be addressed:

1. Develop "transport interpretations" of system accidents known from the Perrow's theory of normal accidents [25].
2. Develop a Polish methodology for identifying gaps in the road traffic management system. It is primarily to identify the so-called hidden conditions of management failures and active management errors; the basis is the theory of J. Reason [37] and the works of Rassmussen, e.g. [38]. A little on this subject is also presented in the paper [39].

3. Develop methods for analyzing the road risk reduction potentials.
4. Continue work on the selection of criteria and methods of the risk analysis, which are the most useful for road transport systems [40].
5. Expand the road safety research (and more broadly transport safety) to risk studies in supply chains in which the road transport plays an important role [41]. Interesting are those studies that use the concept of Human Reliability Organizations (HRO) to describe and analyze supply chain disruptions [42].

Among the various systemic approaches to the road safety research in the article, the author's research results are briefly shown. They concern the following issues:

- Integrated risk management in the road safety system [36].
- Potential safety concept in modeling risk and supply chain reliability [41].
- Use of complex systems theory and the HRO concept in modeling the transport safety [23].
- Use of the „Swiss cheese model" and the LTSA model to identify „management gaps" in the Polish road transport system [39].

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Achmad Teguh Wibowo - MY Teguh Sulistyono - Mochamad Hariadi

# CRYPTOSPATIAL COORDINATE USING THE RPCA BASED ON A POINT IN POLYGON TEST FOR CULTURAL HERITAGE TOURISM

*This research was aimed to enhance the cryptospatial with geospatial blockchain based on a point in polygon test. Ripple Protocol Consensus Algorithm (RPCA) was used for developing a blockchain. The steps taken include: (1) Data from the surveyors were entered using application connected to the transaction set; (2) The transaction set sent data to the transaction proposal; (3) The transaction proposal will distribute to every connected validating of nodes for executing the smart contract with the point in a polygon test method; (4) If the process succeeded with the maximum fault tolerance of 20%, then the node records a new chain to the ledger. This method is faster than Practical Byzantine Fault Tolerance (PBFT) blockchain for approximately 26% to add a new chain in the ledger and for 52% to decrypt the blockchain with a mobile device. The result of this process is a cryptospatial coordinate for the cultural heritage tourism.*

***Keywords:*** *cryptospatial coordinate, cultural heritage tourism, RPCA, point in polygon test*

## 1 Introduction

Blockchain has become a disruptive innovation for many aspects of technology, business and governance [1]. Nowadays, the government, companies, and organizations are started to develop this technology to be applied to the public [2]. How blockchain works are how many nodes connected in a distributed network could maintain consensus and this network to adopt of hash based Proof-of-Work (PoW) algorithm [3].

This technology combines the advantages of peer-to-peer networks and cryptography to ensure the data validity because an entity connected in a blockchain network cannot change the data that is approved unless it involves all connected in a blockchain [4]. Besides, blockchain can ensure the correctness of recorded transactions over time. This feature supports transaction security from all the entities that do not trust each other.

Besides used for cryptocurrency, the blockchain can be implemented in the tourism industry [5]. This industry has explored to offer more integrated services so that tourists get a holistic experience [6]. Combining the blockchain and geospatial retrieval could be used in the tourism sector because majority of information always contain the spatial data on earth that requires specific expertise to handle geospatial data [7]. This technology is called Crypto Spatial Coordinate (CSC), which is recorded of data entry within a particular time, validate related to location, and specific mapping objects in temporal sequences [8].

Data from The Ministry of Tourism of the Republic of Indonesia recorded tourist visits in 2019 reached 1,330,288, [9]. The City of Surabaya is one of the popular tourist destinations. This city has a long history so that many cultural heritages such as buildings, museums, hotels and others [10]. Nowadays, Surabaya has implemented the smart city technology. However, the tourism sector has not yet implemented that technology, such as providing route navigation to cultural heritage locations and utilizing the blockchain as a CSC for the smart city implementation.

Based on the previous explanation, this research discusses the CSC used SHA256 encryption for headers and AES encryption for content added to the blockchain network. The Ripple Protocol Consensus Algorithm (RPCA) used to provide maximum fault tolerance of 20% [11] using five computers. The fault tolerance, obtained from the polygon query algorithm process [12], is based on point in polygon test [13] to detect the validity of the data entered.

## 2 Cryptospatial coordinate

A good example of cryptospatial coordinate, using the blockchain, is a FOAM [14], because this product requires proof of location associated, an immutable geospatial context that regular blockchain lacks and many more, [8].

In this research, development of the geospatial blockchain used Google Maps Service [15]. This process produced data latitude and longitude coordinates based on location, address, photo, and detail information. This data would be processed, using the AES encryption, required a private key and public key to read the data. The header of

**Achmad Teguh Wibowo[1,2], MY Teguh Sulistyono[1,3], Mochamad Hariadi[1,*]**
[1]Department of Electrical Engineering, Faculty of Intelligent Electrical and Informatics Technology (ELECTICS), Sepuluh Nopember Institute of Technology, Surabaya, Indonesia
[2]Faculty of Science and Technology, UIN Sunan Ampel Surabaya, Indonesia
[3]Faculty of Computer Science, Dian Nuswantoro University, Semarang, Indonesia
*E-mail of corresponding author: mochar@ee.its.ac.id

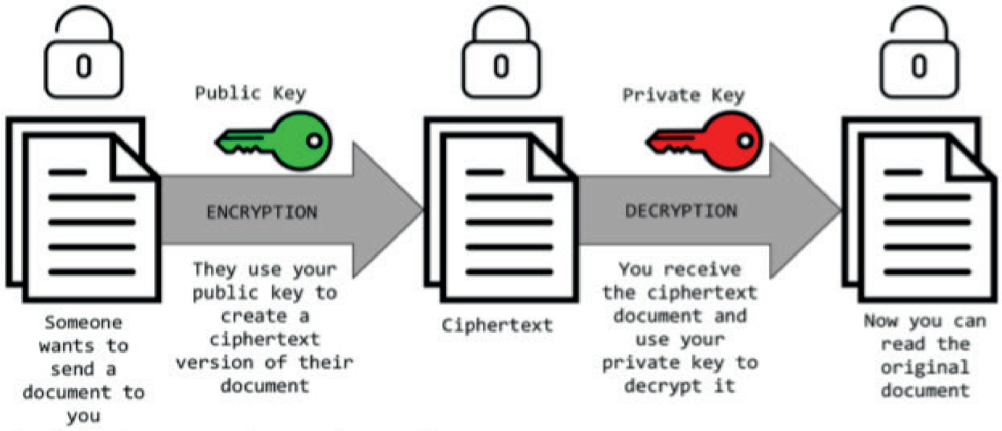


***Figure 1*** *Process encrypts the data using a private key [8]*

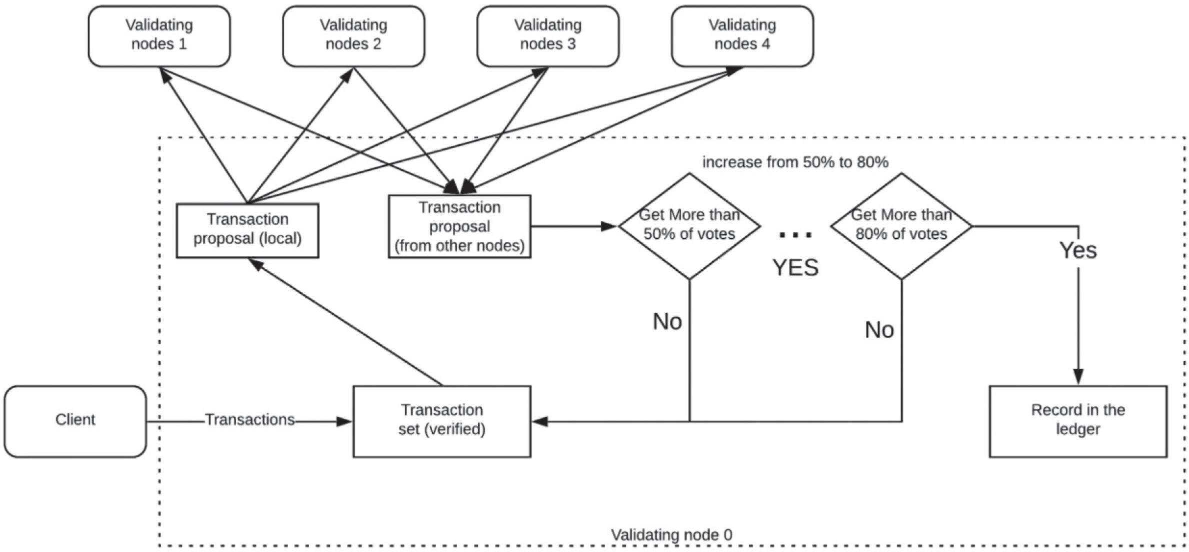


***Figure 2*** *Process of the consensus in the Ripple algorithm [16]*

***Table 1*** *Comparison of the main consensus permissioned blockchain*

| Property | RPCA | PBFT |
|---|---|---|
| Type | Absolute-finality | Absolute-finality |
| Fault Tolerance | 20% | 33% |
| Power Consumption | Negligible | Negligible |
| Scalability | Good | Bad |
| Application | Permissioned | Permissioned |

the blockchain was processed using SHA256 for validated data. Figure 1 explains encrypted data using a private key.

## 3 Ripple protocol consensus algorithm (RPCA)

Ripple does not use the PoW or Proof-of-Stake (PoS) mechanism to validate transactions because Ripple uses a consensus protocol with its specifications. This algorithm runs on per-missioned blockchain, unlike Bitcoin and Ethereum [16]. The RPCA algorithm is applied every few seconds by all the nodes to guarantee the transaction validity. The consensus process in Ripple validated by the node owned. This node called Unique Node List (UNL) [11]. Equation of the RPCA is:

$$F \leq (n-1)/5\,, \tag{1}$$

and the probability of correctness, given by $p^*$, is:

$$p^* = \sum_{i=0}^{\left(\frac{n-1}{5}\right)} \binom{n}{i} p_c^i (1-p_c)^{n-1}\,, \tag{2}$$

The pseudocode of the RPCA is shown:

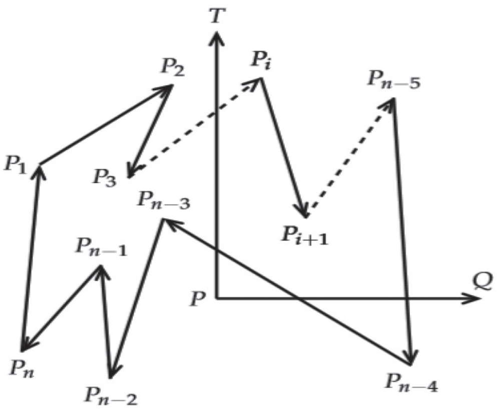


***Figure 3** Crossing Number Algorithm [19]*

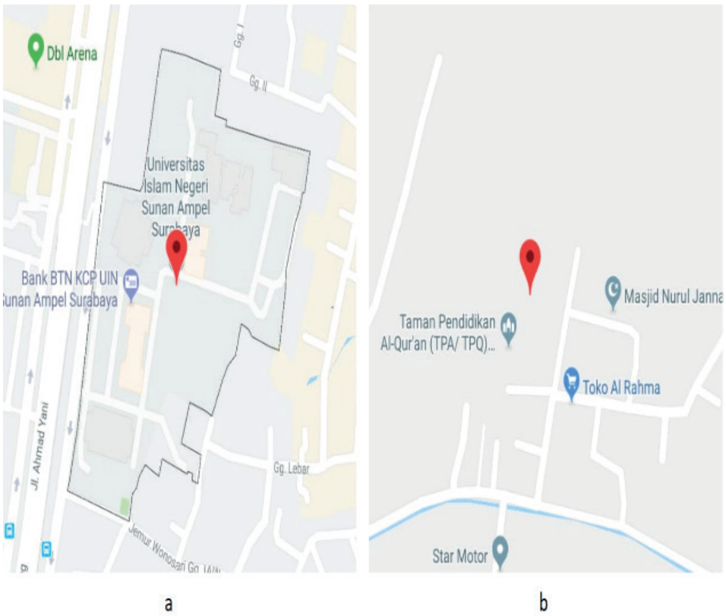


***Figure 4** (a) True condition while coordinate is inside the polygon area a predetermined, (b) False condition while coordinate is inside the polygon area a predetermined*

a) Each server processes a valid transaction and converts it to a transaction set;
b) The server sends a set of transactions to all the validation nodes to carry out a consensus process;
c) If the node produces true, then the transaction is delivered to the next transaction proposal, otherwise it will be discarded or inserted into the candidate ledger;
d) If the previous process gets a maximum error of 20%, then the transaction is
e) Recorded in a ledger, otherwise it will be discarded.

Figure 2 shows the process of the consensus in the Ripple algorithm and comparison of the main consensus protocol permissioned blockchain [16] is shown in Table 1.

## 4 Point in polygon test

The point in Polygon Test in this research uses the crossing number method. This method is a popular tool in drawing and visualization [17]. This research used the crossing number to calculate the ray line passing through the edge boundary polygon from point P. If the intersection number is even, then the point is outside the polygon area and vice versa, [18]. Figure 3 shows the crossing number algorithm.

This method is based on Jordan Curve Theorem [20]. This theorem explains a line repetition that does not intersect an object, separated into two components [21]. Equation of The Jordan Curve Theorem is:

$$C = \{(x, y); x^2 + y^2 = 1\}. \tag{3}$$

To enhance the crossing number the point in Polygon Test Test was used because this method runs a semi-infinite ray horizontal (increasing x, fixed y) from point P, and counting many boundary edges [18]. Equation of this method is:

$$f = \sum\nolimits_{x=0,\, y=0}^{n,m} (y - y_m)(x_n - x_m) > \\ > (y_n - y_m)(x - x_m). \tag{4}$$

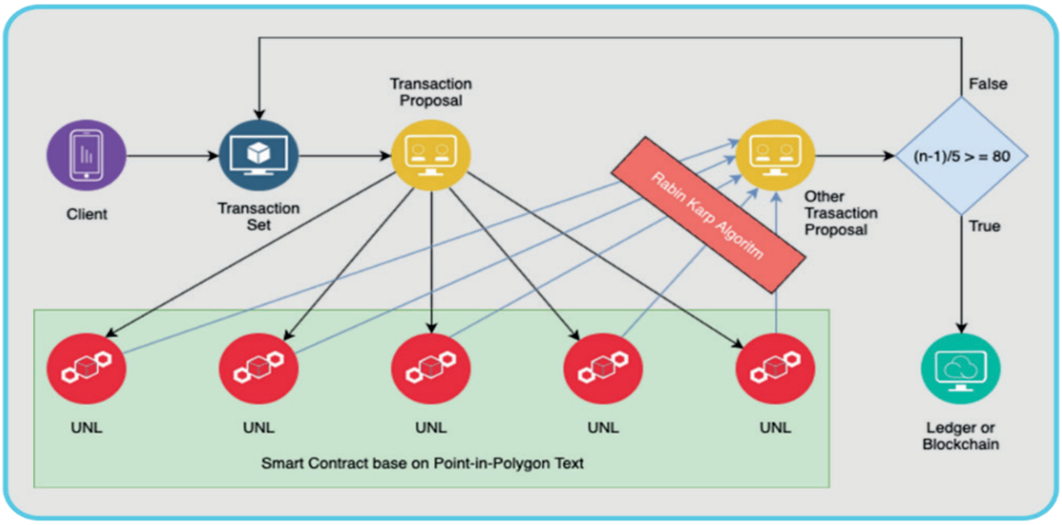


***Figure 5*** *Design of the RPCA in This Research*

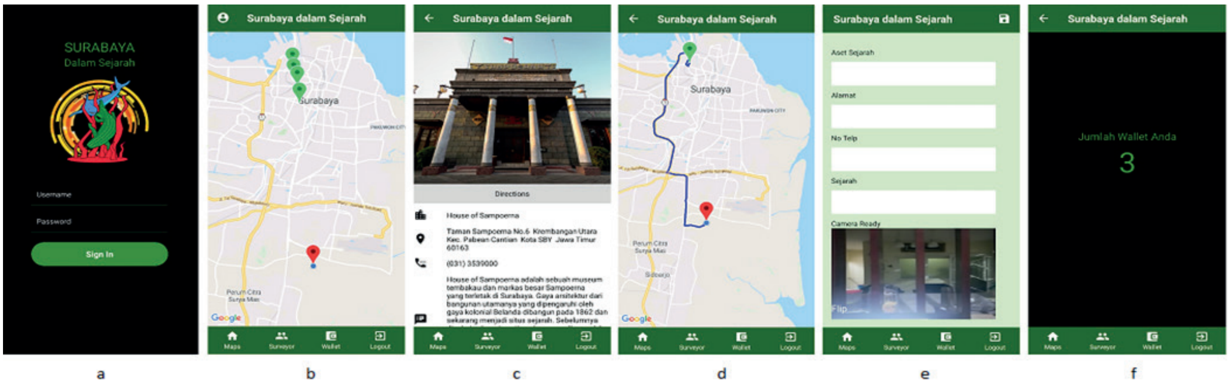


***Figure 6*** *(a) Login Form, (b) CSC of the decrypted blockchain, (c) The cultural heritage asset of the decrypted blockchain, (d) Form navigate to the cultural heritage asset, (e) Form input cultural heritage asset for encrypted to the blockchain, (f) Wallet balance for the surveyors*

An illustration of the point-in-polygon test method is shown in Figure 4.

## 5 Design

The experiment in a laboratory consisted of 9 computers and one mobile device. Specifications of 9 computers used consist of 4 GB of memory, I3-4150 CPU and Intel HD graphics card 4400. All the computers used Windows 10 platforms. Mobile devices used SOC Snapdragon 660, 4 GB of memory and Android 8 as the operating system. Figure 5 shows design of the RPCA for this research.

Figure 5 explains the process of this research. (1) Surveyor requests to send data of geospatial retrieval to be processed into a transaction set. (2) This server managed data and would it be sent to the transaction proposal. (3) This process would send data to the UNL that has been developed. (4) The UNL conducted a smart contract with the Point-in-Polygon Test method. The result of this process is true or false, if the result is right, then the Rabin Karp method validates the string with equation $f \leq (n-1)/5$. If the result of the vote UNL is $\geq 80\%$, then the system would create a new block into the ledger.

## 6 Implementation

The product of this research is an application based on mobile technology [22]. This product is shown in Figure 6.

Figure 6(a) shows the login form and a user must be registered in the whitelist account to add a new chain and view the total balance of their wallet. Figure 6(b) shows the marker of the assets a cultural heritage into the map. This marker is obtained from the decrypted data using the AES decryption. This data is CSC, which is obtained from the RPCA process.

Figure 6(c) shows the results of the decrypted method from the blockchain. This data includes photos, addresses, telephone numbers, and coordinates used to navigate to the cultural heritage location, selected in the previous process.

Navigate menu shown in Figure 6(d), where this menu can help the tourist to go in the direction of a cultural heritage location using the mobile devices.

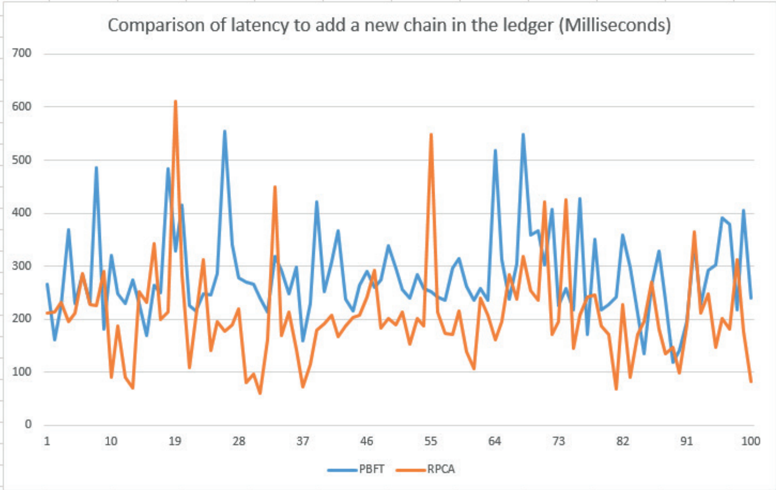


***Figure 7** Comparison of the latency RPCA and PBFT*

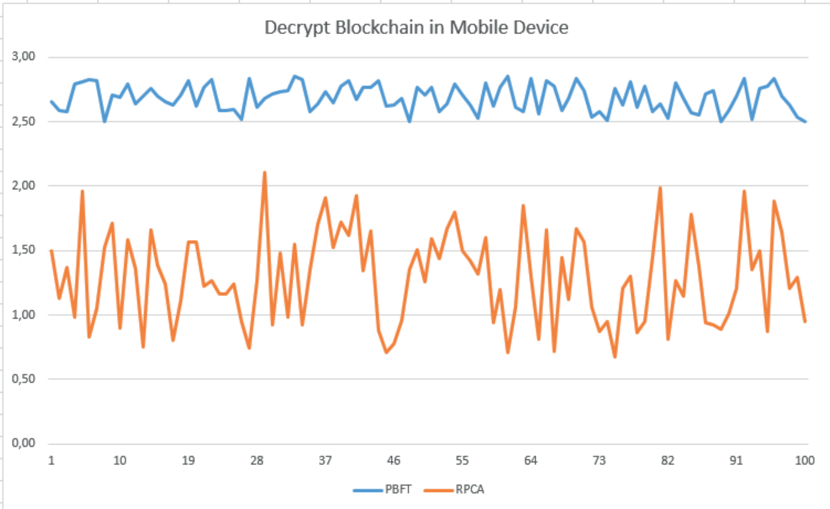


***Figure 8** Decrypt blockchain RPCA and PBFT in Mobile Device*

***Table 2** Average time in all evaluations*

| Evaluation | RPCA | PBFT |
|---|---|---|
| Comparison of latency to add new chain | 207.5626ms | 282.2318ms |
| Decrypt blockchain in mobile device | 1.29s | 2.69s |

Figure 6(e) shows the input form for the surveyor. This form consists of inputting a name, address, telephone and place description, photos and coordinates location of the cultural heritages. These coordinates are obtained by the location-based services from the surveyor's mobile device. Blockchain would validate coordinates sent by a surveyor, using a point-in-polygon test algorithm. If the coordinate is inside the polygon area, then value of the UNL server from consensus becomes true or vice versa. Figure 6(f) shows the wallet balance owned by the surveyor. This balance would be increased if input data by the surveyor is successfully validated by the UNL Server with a value ≥ 80% of fault tolerance, so that a new chain could be added to the ledger.

## 7 Evaluation

The first evaluation is presented in Figure 7. This evaluation shows the latency of the process to add a new chain in the ledger using the RPCA. This process output is compared to the PBFT method, using a similar specification computer. The PBFT method is used in a similar case. That research used five computers and one mobile device. One computer was used for the primary node and another computer was used for nodes to the smart contract process, the equation of this method is:

$$3f + 1\,, \tag{5}$$

where $f$ is the number of fault tolerance obtained from the consensus process.

Figure 7 shows that the RPCA is faster than the PBFT; this can occur because the PBFT method emphasizes the consistency of data in each node. However, the RPCA has advantages over the PBFT, especially related to speed for the consensus process. The next evaluation was performed to know the speed of the mobile device to the decrypt blockchain shown in Figure 8.

Figure 8 shows that the RPCA is faster than the PBFT method, because the PBFT sent replied messages to the client using all the nodes that have succeeded in the consensus process. The whole evaluation was carried out for 100 times to get the average time shown in Table 2.

## 8 Conclusions and future direction

This research was limited to the city of Surabaya and used the mobile application based on the React Native that has been tested, a mobile device with specifications: SOC Snapdragon 660, 4 GB of memory and Android 8 as the operating system. Implementation blockchain based on RPCA for CSC has been developed.

The allowed blockchain methods, especially the RPCA and PBFT, were compared. The result of evaluation is that the RPCA method is faster than the PBFT, approximately for 26% to add a new chain in the ledge, because the PBFT method emphasizes the consistency of data in each node.

The next experiment was testing the speed of the mobile device to decrypt blockchain. The evaluation result shows the time required for a mobile device to decrypt the blockchain; the RPCA method is faster for 52% than the PBFT, because the PBFT method runs by sent-replied messages to the client, using all the nodes that have succeeded in the consensus process.

This application has been presented at the Government Surabaya City Tourism Office. They are enthusiastic about developing the app and are willing to provide data on tourism destinations, especially cultural heritage tourism, to be implemented in it. Besides that, they have suggested a collaboration with Ministry of the Religion of Republic of Indonesia to use this application for the halal tourism, since the halal tourism sector has become a trend, especially in Indonesia.

It is suggested to consider the fault tolerance for the appropriate application scenario, because the design of the main consensus protocol, especially the RPCA and PBFT, has advantages and weaknesses to implement in any case and the RPCA method was proposed wince it could be applied for the CSC, not only cryptocurrency.

For the future directions, a novel algorithm was developed, to implement this application that is a combination blockchain of the RPCA and PBFT, which is currently still in the development phase. Implementation of this application is not only limited to the tourism sector, but it can be implemented for other areas, such as health, education, endowments, and many more.

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