Volume 45, Number 3, 2019.

Mobility & Vehicle Mechanics

International Journal for Vehicle Mechanics, Engines and Transportation Systems

ISSN 1450 - 5304

UDC 621 + 629(05)=802.0

UNIVERSITY OF KRAGUJEVAC, FACULTY OF ENGINEERING

SERBIAN SOCIETY OF AUTOMOTIVE ENGINEERS

Mobility & **V**ehicle **M**echanics

Volume 45
Number 3
2019.

Motorna **V**ozila i **M**otori

Mobility & **M**otorna

Vehicle **V**ozila i

Mechanics **M**otori

Volume 45
Number 3
2019.

M V M **M**obility **V**ehicle **M**echanics

For Publisher: Prof. dr Dobrica Milovanović, dean, University of Kragujevac, Faculty of Engineering

Publishing of this Journal is financially supported from:
Ministry of Education, Science and Technological Development, Republic Serbia

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MOBILITY & VEHICLE MECHANICS

DOI: 10.24874/mvm.2019.45.03.01
UDC: 519.857:656.1

MULTI-CRITERIA OPTIMIZATION OF SINGLE INTERSECTION UNDER OVER-SATURATED CONDITIONS

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Received in August 2019 Accepted in September 2019

RESEARCH ARTICLE

ABSTRACT: Intersections are junctions where at least two roads or streets meet or cross. Consequently, they represent the most critical spots in the city traffic network, in terms of traffic safety. When determining the Level of Service at signalized intersections, the Highway Capacity Manual (HCM) does not take into account the traffic safety factors. In order to overcome this shortcoming, we propose in this paper the multi-criteria approach to the single intersection traffic control problem. The first objective function to be minimized is the average control delay experienced by all vehicles that arrive at the intersection. The second objective function to be minimized is the traffic safety risk index on intersection. These two criteria are in conflict, and the task is to find a good compromise between them. The analysed problem is solved by the combination of dynamic programming, and compromise programming. The proposed approach was tested in the case of the intersection that is controlled with two phases, under over-saturated traffic flows.

KEY WORDS: single signalized intersections, vehicles control delay, traffic safety risk index, dynamic programming, compromise programming

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VIŠEKRITERIJUMSKA OPTIMIZACIJA IZOLOVANE PREZASIĆENE RASKRSNICE

REZIME: Raskrsnice su mesta na uličnoj mreži gde su ukrštaju dva ili više saobraćajnih tokova. Kao posledica toga, one predstavljaju kritična mesta po pitanju bezbednosti saobraćaja. Kada se utvrđuje Nivo Usluge na signalisanim raskrsnicama, po HCMu (međunarodnom priručniku za ovu oblast), u obzir se ne uzimaju faktori bezbednosti saobraćaja. U ovom radu autori predlažu višekriterijumski pristup za rešavanje problema upravljanja izolovanom signalisanom raskrsnicom. Prvu kriterijumsku funkciju, koju treba minimizovati, predstavljaju ukupni prosečni vremenski gubici svih vozila koji prođu raskrsnicom u određenom periodu vremena. Druga kriterijumska funkcija, koju treba minimizovati, se odnosi na indeks rizika bezbednosti na raskrsnici. Kada su dve kriterijumske funkcije u konfliktu cilj je pronaći dobar kompromis između njih. Postavljeni problem je rešavan kombinacijom dinamičkog programiranja i kompromisnog programiranja. Predloženi pristup je testiran na primeru prezasićene raskrsnice kojom se upravlja pomoću dve faze.

KLJUČNE REČI: izolovana signalisana raskrsnica, vremenski gubici vozila, indeks bezbednosti, dinamičko programiranje, kompromisno programiranje

MULTI-CRITERIA OPTIMIZATION OF SINGLE INTERSECTION UNDER OVER-SATURATED CONDITIONS

Aleksandar Jovanović, Dušan Teodorović

1. INTRODUCTION

An intersection represents the junction where at least two roads or streets meet or cross. There are different types of conflict points at traffic intersections. According to the number of traffic crashes occurring at intersections, it can be concluded that intersections are the most critical element at the street network. When determining signal plans (cycle and splits) engineers most frequently do not include the safety factor into account. Every traffic crash at the intersection results in a significant drop of capacity (up to 50% [9]). This percentage varies depending on the severity of the crash and the intersection clearance time after the crash. Additional consequences of reducing intersection capacity may be an increase in the congestion level in the network, an increase in the emission of harmful gases, an additional delay of vehicles, etc. For that reason, to efficiently control the signalized intersection, it is necessary to consider traffic safety factors.

In this paper, a mathematical model that optimizes two objective functions: the average control delay per vehicle and traffic safety risk index, is developed. The proposed mathematical model aims to provide such signal plans (cycle and splits) that control traffic demand in an efficient and safe manner.

Controlling the single intersection was an area of interest for many authors in the last few decades. The most common objective functions used in various models are the total vehicle delays, the total number of stops, or some of the economic and environmental criteria. The author [2] proposes one of the first models for controlling a single signalized intersection. Webster's model determines the cycle time and the split of green time for under-saturated traffic demands without phases overlap. Some of the most important works are as follows: ([1, 2, 3, 6, 8, 12, 13, 15, 17]).

The problems of controlling an over-saturated single intersection were analyzed, among others, by the following authors ([4, 18]).

Analysis of the traffic control problems, taking into account traffic safety factors, can be found in the following papers ([9, 16, 19]). Authors [16] developed a unique fuzzy logic model for controlling traffic flows in specific situations at the intersections, such as traffic crash, construction zone at the intersection and so on. Authors [9] proposed a new methodology for determining the Level of Service at a signalized intersection taking into account the traffic safety risk index. The methodology assumes that the safety risk index is in the function of the control parameters (cycle and splits) at the intersection. Authors [19] developed a multi-criteria model based on genetic algorithms. The aim of the author was to optimize two objective functions at the same time: vehicle control delay and safety of vehicles and pedestrians at the intersections. Other researches that treat the traffic control problems from the aspect of traffic safety can be found in the following papers ([5, 14, 22, 24]).

2. FORMULATION OF THE PROBLEM

The problem that we study in this paper could be formulated in the following way: For the given number of phases, determine cycle length, and splits in such a way to minimize the two objective functions at the same time: average control delay experienced by all vehicles that arrive at the intersection within given time period, and the traffic safety index under over-saturated conditions.

Let us first analyze the formulas to calculate the average vehicle control delay in oversaturated conditions, as well as the traffic safety indexes at a single signalized intersection. In the next step, we propose the mathematical formulation of the problem.

2.1 Vehicle control delay under over-saturated conditions

Let us suppose that we have parameters of the signal plan: cycle (C) and the green time of the i-th line or i-th group of lines (g_i). The average control delay per vehicle on the i-th line or the i-th group of lines at the signalized intersection (d_i) are calculated as (HCM 2010):

$$d_i = \frac{0.5 \cdot C \cdot \left(1 - \frac{g_i}{C}\right)^2}{1 - \left[min(1, X_i) \cdot \frac{g_i}{C}\right]} + 900T\left[(X_i - 1) + \sqrt{(X_i - 1)^2 + \frac{4 \cdot X_i}{c_i T}}\right] + d_{3i} \tag{1}$$

where:

X_i - degree of saturation on i-th line or i-th group of lines,

c_i - capacity of i-th line or i-th group of lines (veh/h),

T - duration of analysis period (h),

d_{3i} - additional delay, per vehicle, on i-th line or i-th group of lines (s/veh).

The relation between traffic demand (q_i) and capacity (c_i), on i-th line or i-th group of lines, present degree of saturation (X_i), i.e. (HCM 2010):

$$X_i = \frac{q_i}{c_i} = \frac{q_i}{s_i \frac{g_i}{C}} = \frac{q_i/s_i}{g_i/C} \tag{2}$$

where s_i represent saturation flow for i-th line or i-th group of lines.

The additional delay d_{3i} equals (HCM 2010):

$$d_{3i} = \frac{1800 \cdot Q_{bi} \cdot (1 + u_i) \cdot t_i}{c_i \cdot T} \tag{3}$$

where Q_{bi} is initial queue (veh) on the i-th lane or i-th group of lines; c_i is capacity of the i-th lane (veh/h) or i-th group of lines; t_i is duration of unmet demand of the i-th lane or i-th group of lines; u_i is delay parameter of the i-th lane or i-th group of lines.

The duration of unmet demand, t_i, and delay parameter, u_i, equals:

$$t_i = min\left\{T, \frac{Q_{bi}}{c_i \cdot [1 - min(1, X_i)]}\right\} \tag{4}$$

$$if\ t_i < T\ then\ u_i = 0; else\ u_i = 1 - \frac{c_i \cdot T \cdot [1 - min(1, X_i)]}{Q_{bi}} \tag{5}$$

2.2 Traffic safety risk index

Traffic safety risk index on intersection during the j-th phase (RI_j) is calculates as [9]:

$$RI_j = \frac{g_j + y_j}{C} \cdot \sum_k NCV_k \cdot SCP_k \quad (6)$$

where:

k - index of conflict type at intersection,

g_j - green time of j-th phase,

y_j - yellow time of j-th phase (3 second),

NCV_k - number of vehicles in conflict for k-th type,

SCP_k - degree of "severity" for k-th type.

At a single intersection, exist three types of vehicle-to-vehicle traffic conflicts: 1. Crossing (k=1); 2. Merging (k=2); 3. Diverging (k=3). We assume that for different types of conflict, degree of "severity" have the following values: SCP_1=3; SCP_2=1.5; SCP_3=1.

2.2.1 Mathematical formulation of the problem

The mathematical formulation of the traffic signal timing problem in the case of over-saturated flows reads:

$$Minimize \quad d = \frac{\sum_i q_i \cdot d_i}{\sum_i q_i} \quad (7)$$

$$Minimize \quad RI = \sum_j RI_j \quad (8)$$

$$Subject\ to: \quad C_{min} \leq C \leq C_{max} \quad (9)$$

$$g_{jmin} \leq g_j \leq g_{jmax}, \qquad \forall\, j \in F \quad (10)$$

$$\sum_j g_j = C - L \quad (11)$$

where:

d – average control delay at the intersection (s/veh),

RI - traffic safety risk index at the intersection,

w_1, w_2 – objective function weights,

F - total number of phases,

L - Cycle lost time (seconds),

C_{min}, C_{max} - minimal and maximum values for cycle (seconds),

g_{jmin}, g_{jmax} - minimal and maximum green times for j-th phase (seconds).

Criteria function (7), to be minimized, presents the average control delay experienced by all vehicles that arrive at the intersection within a given time period under over-saturated conditions. Criteria function (8), to be minimized, presents and traffic safety risk index at the intersection. The constraint (9) defines the interval of the feasible cycle length values. The constraint (10) defines the interval of the feasible green time length values. The relationship between cycle length, green time lengths and the lost time is described by the constraint (11).

3. THE PROPOSED SOLUTION OF THE PROBLEM BY COMPROMISE PROGRAMMING AND DYNAMIC PROGRAMMING

The chosen objective functions are mutually in conflict. There is usually no solution that at the same time minimizes both criteria. For this reason, the solution of the considered problem usually comprises a Pareto-optimal solution. This is the solution where no criterion can be improved without simultaneously worsening at least one of the other criteria.

The x^* is the Pareto optimal solution for problem if there is no other $x \in X$ such that:

$$f_i(x) \leq f_i(x^*), \qquad \forall\, i = 1, 2, \dots, r \tag{12}$$

The index i is the index of the objective functions and goes to r (in our case, $r = 2$).

In order to solve the multi-criteria optimization problem, we use the Compromise Programming. By using the Compromise Programming we try to obtain a solution that is as close as possible to the ideal solution in terms of distance. We try to minimize the L_p distance (Duckstein 1984) that is defined in the following way:

$$L_p = \left[\sum_{i=1}^{r} {w_i}^p \cdot \left|\frac{f_i(\vec{x}) - f_i^o}{f_{imax} - f_i^o}\right|\right]^{\frac{1}{p}} \tag{13}$$

where:

-$f_i(\vec{x})$ -i-th objective function value that is the result of implementing decision $\vec{x}$,

f_i^o - the optimum value of the i-th objective function,

f_{imax} - the worst value obtainable for the i-th objective function,

w_i - i-th objective function's weight,

p - the value that shows distance type.

For $p = 1$, all deviations from the optimal solutions are in direct proportion to their magnitude, while when $2 \leq p \leq \infty$, a bigger deviation carries a larger weight in the L_p metric. In the our case, we calculate the L_p in the following way:

$$L_p = \sqrt{w_1^2 \cdot \left|\frac{d - d_{opt}}{d_{worst} - d_{opt}}\right| + w_2^2 \cdot \left|\frac{RI - RI_{opt}}{RI_{worst} - RI_{opt}}\right|} \tag{14}$$

where w_1 is the weight of the first criteria and w_2 is the weight of the second criteria. The optimal values for the first and the second criteria are denoted by d_{opt} and RI_{opt}, respectively.

In order to obtain the optimal values, as well as the worst values we perform the single-objective optimization. We obtain the solution that produces the optimal delay value by solving the problem (7) - (11) and by ignoring the objective function (8). This optimal solution generates simultaneously the worst traffic safety risk index. The optimal traffic safety risk index and the worst delay could be obtained by solving the problem (7) – (11) and by ignoring the objective function (7).

We perform the single-objective optimization, as well as the minimization of the L_p metric, by using the Dynamic Programming technique. The Dynamic Programming splits the problem into several, simpler, sub-problems. Dynamic Programming is a mathematical procedure that solves problem in stages. The computations at the various stages are linked in such a way, that the optimal solution of the considered problem is obtained when the final stage is reached. The basic concept of the Dynamic Programming is most easily explained by the network created of stages and states. A network suited for traffic control on a signalized isolated intersection is shown in the Figure 1. Let us introduce the following notation:

- g_1 - green time allocated to phase 1,
- g_2 - green time allocated to phases 1 and 2,
- g_n - green time allocated to phases 1, 2,.. and n-th.

Any of the stages can be found in some of the states. Stages in this network model, except the first one, represent the signal phases. The first stage represents the cycle value reduced by all red time (L). States for the first stage take a value from range C_{min} to C_{max} with a 1-second increment. Other stages (g_1, g_2, to g_n) can be found in some of the states, from g_{min} to g_{max}, with a 1-second increment.

The network is created only by those branches that connect compatible nodes. Compatible nodes are those which satisfy the constraints (11). The branches are weighted by appropriate metric. Finding the shortest path through the network gives us an optimal solution for the analyzed problem.

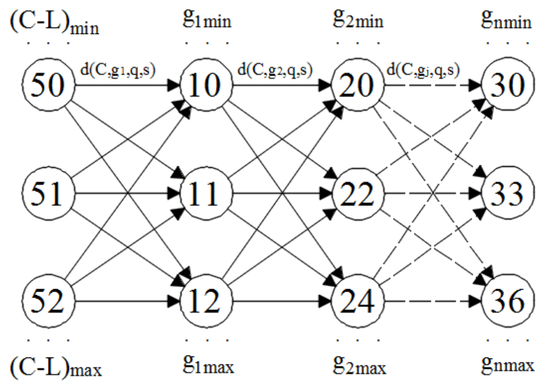

Figure 1. Dynamic programming network

The inefficiency of this algorithm is reflected in the long CPU time. Practically, it can only be applied up to signal plan with three phases [10].

4. NUMERICAL EXAMPLE

The proposed approach for solving the analyzed problem was tested on the hypothetical intersection shown in the Figure 2. We analyzed the over-saturated intersection controlled by two phases. The lane flows, for the considered intersection are indicated in Figure 2 (in veh/h). The analyzed period is equal to one hour (T = 1 hr). Cycle lost time L is equal to 12 (in seconds). Table 1 shows saturation flow values per line that were used in the calculation. The value of the initial queues of unserved vehicles, at the beginning of time period T, is also given in Table 1. Traffic lines are indicated with capital letters A, B, C and so on.

Table 1. Lane saturation flows and initial queues

Saturation flows (veh/h)											
A	B	C	D	E	F	G	H	L	M	R	T
1500	1600	870	451	1600	1500	456	1600	1500	1500	1600	613
Initial queues (veh)											
A	B	C	D	E	F	G	H	L	M	R	T
21	10	17	0	12	5	0	4	7	14	8	2

The minimum allowed cycle length C_{min} and the maximum allowed cycle length C_{max} were respectively equal to 60 seconds and 120 seconds, while the minimum value of the green time g_{min} and the maximum value of the green time g_{max} were respectively equal to 7 seconds and 80 seconds.

These input data are taken from the paper of [11].

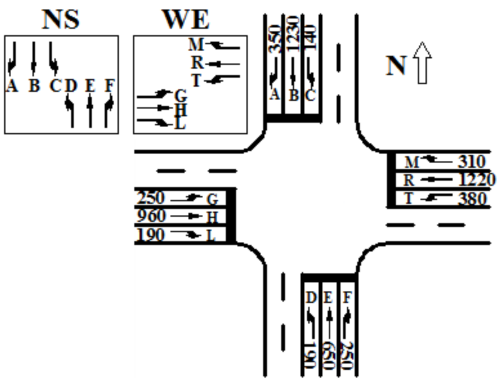

Figure 2. Test intersection with phase plan and traffic demands

The obtained results are shown in the Table 2. We presented the obtained solutions as the following sequence: $C, g_1, g_2, \ldots, g_n$. For example, the solution 120, 50, 58 represents the case when the cycle length equals 120 seconds. There are two phases in this case. The green light lengths are respectively equal 50 seconds and 58 seconds.

Table 2. Solutions

w		Solution	d (s/veh)	RI	L_p
w_1	w_2				
1	0	120;50,58	697.42	8691.25	0
0	1	60;41,7	4137.95	7572.50	0
0,9	0,1	80;34,34	829.08	8394.38	0.087
0,8	0,2	60;25,23	983.26	8132.50	0.127
0,7	0,3	60;28,20	1120.42	8027.50	0.155
0,6	0,4	60;30,18	1264.94	7957.50	0.175
0,5	0,5	60;32,16	1462.23	7887.50	0.184

0,4	0,6	60;34,14	1731.93	7817.50	0.182
0,3	0,7	60;36,12	2116.10	7747.50	0.168
0,2	0,8	60;38,10	2669.10	7677.50	0.139
0,1	0,9	60;40,8	3519.24	7607.50	0.088

Like in other practical multicriteria decision-making problems, a solution must be found that is frequently called the "implementation" solution. In order for a solution to be accepted as the best from the users' viewpoint, the decision maker must have other solutions for comparison.

In our case, because of the over-saturated conditions, the "implementation" solution could be the solution where *w* is (0.9, 0.1).

5. CONCLUSION

The mathematical model presented in this paper tries to optimize the control parameters of the single signalized intersection: cycles and splits, under over-saturated conditions. A multi-criteria approach has been proposed based on the delays of vehicles and traffic safety indexes at the intersection. Dynamic programming is applied as a method for finding optimal solutions in the case of single objective function. Compromise programming was used as a method for solving the multi-criteria optimization problem. The model was tested on a hypothetical intersection that is controlled by two phases. In the case where an intersection is controlled with more than three phases, this algorithm becomes ineffective. In cases with more than three phases some of the metaheuristics algorithms should be used instead Dynamic Programming. The numerical example shows the applicability of the proposed approach.

ACKNOWLEDGMENT

This research was partially supported by the Ministry of Education, Science and the Technological Development Republic of Serbia, through the project TR36002 for the period 2011– 2014.

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MOBILITY & VEHICLE MECHANICS

DOI: 10.24874/mvm.2019.45.03.02
UDC: 629.3.027.5:620.9

LIFE CYCLE ASSESSMENT OF THE CAR TIRE WITH ECO INDICATOR 99 METHODOLOGY

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Received in September 2019, Accepted in October 2019

RESEARCH ARTICLE

ABSTRACT: Today automotive industry is a driving force for development of national economics so number of vehicle increases expeditiously. As an integral part of the vehicle, tires are generated annually in large amount all over the world. Growth of the car tires production affect environment and also the growth of non-degradable waste which has a large energetic potential but which currently is not fully used. The aim of this study is to evaluate the environmental impact of car tire during its whole life cycle and to identify activities in life-cycle phases that can be improved. That analysis can be achieved throughout its service life, from the acquisition of the raw materials through to the recycling of the worn tire, because the tire constantly interacts with the environment. Approaches to effectively reducing the negative environmental impact can be demonstrated only on the basis of detailed knowledge of this interaction.

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This is why a life cycle assessment quantifies the material and energy flows in the different stages of a tire's life cycle (life cycle inventory analysis) and describes the interaction with the environment (impact assessment and interpretation). In this study, environmental impact is evaluated by using methodology Eco Indicator 99, which is one of the most widely used impact assessment methods in Life Cycle Analysis (LCA).

KEY WORDS: LCA, Eco-indicator 99, product, tire

ANALIZA ŽIVOTNOG CIKLUSA AUTOMOBILSKE GUME POMOĆU METODOLOGIJE – EKO INDIKATOR 99

REZIME: Danas se automobilska industrija smatra pokretačkom snagom razvoja nacionalnih ekonomija, pa se iz tog razloga broj proizvedenih vozila u svetu ekspeditivno povećava. Takođe, kao sastavni deo jednog automobila, broj proizvedenih autombilskih guma u svetu se povećava. Rast proizvodnje automobilskih guma ima negativan uticaj na životnu sredinu, što se može objasniti i povećanom količinom generisanog gumenog otpada. Cilj ove studije je proceniti uticaj automobilskih guma na životnu sredinu tokom čitavog životnog ciklusa, ali i identifikovati aktivnosti u životnom siklusu automobilske gume koje je moguće poboljšati, a u svrhu smanjenja negativnog pritiska na okolinu. Naime, automobilska guma nakon faze upotrebe ima veliki energetski potencijal, koji se trenutno ne koristi u potpunosti. Spomenuta analiza se sprovodi tokom celog životnog ciklusa gume, od procesa nabavke sirovina za proizvodnju, pa do procesa tretiranja/odlaganja istrošene gume. Mere efikasnog smanjenja negativnog uticaja na životnu sredinu, mogu se definisati samo na osnovu detaljne analize interakcije automobilske gume i okoline tokom njenog životnog veka. Zbog toga se procenom životnog ciklusa pneumatika kvantitativno određuju materijalni i energetski tokovi u različitim fazama životnog ciklusa (analiza inventara životnog ciklusa) i opisuje interakcija sa okolinom (procena uticaja i interpretacija). U ovom radu uticaj na životnu sredinu se procenjuje korišćenjem metodologije Eko Indikator 99, koja predstavlja jednu od najrazvijenijih metoda za ocenjivanje uticaja životnog ciklusa proizvoda na okolinu.

KLJUČNE REČI: analiza životnog ciklusa, Eko indikator 99, proizvod, guma

LIFE CYCLE ASSESSMENT OF THE CAR TIRE WITH ECO INDICATOR 99 METHODOLOGY

Angelina Pavlović, Danijela Nikolić, Saša Jovanović, Goran Bošković, Jasmina Skerlić

1. INTRODUCTION

The automotive industry is one of the most developed industries in the world. That can be explained by the fact that the number of a vehicle increases expeditiously. In 2018, the international automotive industry produced an estimated 70.5 million passenger cars. Worldwide, passenger car sales are expected to continue to grow to about 80 million units in 2019 [1]. The vehicles were manufactured using a wide range of different types of materials in order to meet the highest needs of customers. End-of-life tires are one of the main sources of waste in end-of-life vehicles. At the end of the product lifecycle, complex multi-component materials cannot be directly reused, such as the car tire. The number of vehicles on the market is growing as well as the number of tires that constantly interact with the environment. The car tire has a negative effect on the environment. Each year, more than half a million tons of worn tires are removed and replaced by a corresponding number of a new tires. In designing, construction and production of tires, care should be taken of energy efficiency and environmental protection so the aim of this study is to evaluate the impact of the car tire on the environment during its life cycle.

The concept of the product life cycle (PLC) was introduced in the fifties of the last century in the scientific researches. The existence of the biological life cycle is implemented on the products [2]. Namely, the PLC represents one cycle or the process from birth to death. The product life cycle is an important phenomenon because it describes all the phases through which it passes. In each phase, the product is interdependent with the society, economy and environment, and it encounters a number of limitations. From the view point of the environment, the current economic model is based on the transformation of resources into ready to use products and their disposal. This economic model, i.e. the product life cycle is not eco-friendly.

The previously mentioned fact can be proved by certain analyses, such as life-cycle assessment (LCA). The LCA is a technique to evaluate environmental impacts related to all the phases of a product's life cycle.

2. LIFE-CYCLE ASSESSMENT METHOD

As it is already mentioned, the LCA is a way for rating the environmental impacts of one product from raw material extraction through to its disposal. All stages in the life cycle of the product are considered in an LCA.

Namely, this assessment includes the entire life-cycle of a product and takes into account numerous activities: the extraction and processing of raw materials; manufacturing; transportation and distribution; use; reuse; maintenance; recycling; and final disposal [3]. LCA, as one environmental technique, has worldwide usage. The main reason for that can be explained by the fact that LCA represents an environmental tool that can help to identify opportunities for product improvement. Strengthened awareness that resources are limited as well as an increasing environmental pressure, were the motive for creating LCA concept. Usage of life-cycle assessment concept begun in the 1960s in different ways and under a variety of names [4]. Today there are many different definitions of LCA.

The principles and framework of the LCA methodology are regulated in the International Standards Organization (ISO) documents 14040 and 14044. ISO 14040 and ISO 14044 define four phases of an LCA as shown in figure 1.

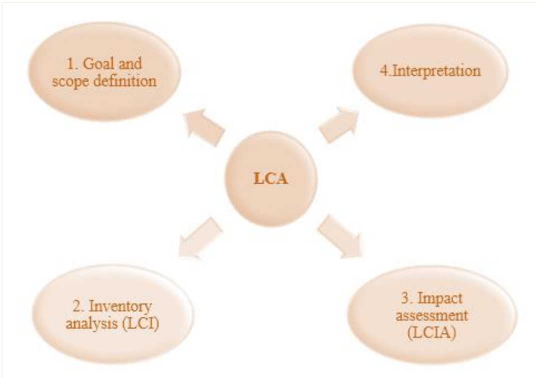

Figure 1. Phases of an LCA

According to ISO 14040, LCA is a technique for assessing the environmental aspects and potential impacts related with a product, by:

- compiling an inventory of relevant inputs and outputs of a product system
- evaluating the potential environmental impacts associated with those inputs and outputs by certain methodologies
- interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study [5].

Life-cycle assessment of products enable a reliably decision-making regarding a specific phase of the life cycle. With iterative approach such as LCA, it is possible to measure products environmental impacts, and thus select the strategies and measures for improving specific phases that are analyzed during the assessment of the product.

Due to its universality, LCA is used in almost all industry branches, in particular in machine building, construction, electronics, traditional and alternative energy, production of polymers, food products, product design and waste disposal.

3. OBJECT OF ASSESSMENT

Rubber is a natural or synthetic macromolecular substance which is converted by chemical reactions into a networked structure, which creates the new product - a tire or elastomer. The tire is an extremely tough material that can be reversibly elastic in a wide temperature range.

Today, more than fifty thousand types of rubber products are produced, which can be grouped into several groups. One of those groups is pneumatics or tires.

The pneumatic is the only point of contact between the road and the vehicle. From the aspect of steering and maneuvering with the vehicle, the wheel and the tires are in the group of the most important vehicle assemblies, both for function and safety. Apart from transferring the entire mass of the vehicle to the ground, enabling the movement and maneuvering of vehicles, wheels with tires also attenuate the impact caused by uneven pavements, which are transmitted to all vehicle systems.

The characteristics of the tire, in addition to the construction, also depend on the materials used for their manufacture. Since the beginning of the automotive industry, the design of a car tire has changed over time. In fact, modern tires have over two hundred components. These components are divided into a few groups such as natural rubber, synthetic rubber, carbon and silicon, metallic and textile reinforcement cables, numerous chemical agents, etc [6]. Production of car tires requires a lot of raw materials, but bigger problem related to environmental arises when tires become waste. As a large number of worn tires are generated every year, it is very difficult to handle this much waste. Tires in the form of waste can be major environmental concern. The generation of waste tires can cause numerous problems such as fire hazards, environmental hazards and land usage [7].

Because of the above-mentioned problems, the life cycle assessment of a car tire has to be detailed done, from its cradle to its grave. The focus of this study is the environmental impact of the passenger car tire. The analyzed material composition of the tire corresponds to a summer tire that is produced by Continental [8]. In this research data for 175/70 R-13 tire is used.

4. LIFE-CYCLE ASSESSMENT OF THE CAR TIRE

In this research life-cycle assessment of the car tire is done by using the main methodological phases. Those phases are developed from the side ISO and they are already shown on figure 1.

When the life-cycle analysis of the car tire is performing, all phases must be involved: from the stage of excavation, production and supply of raw materials for manufacturing of tires till stage of disposal of worn tires. Therefore, method of analyzing the life cycle of the car tire is divided into several phases:

- The production phase - includes the production of raw materials, their transport to production section, production of tires and packaging
- The distribution phase - involves the transport of the final product and the installation process on the car.
- The phase of use - includes using process scenarios and process such as maintenance or cleaning of the tires.
- The final phases – includes process of collecting the worn tires as well as different end-of-life scenarios (recycling, recover, reuse) of worn tires.

These phases are illustratively shown on figure 2.

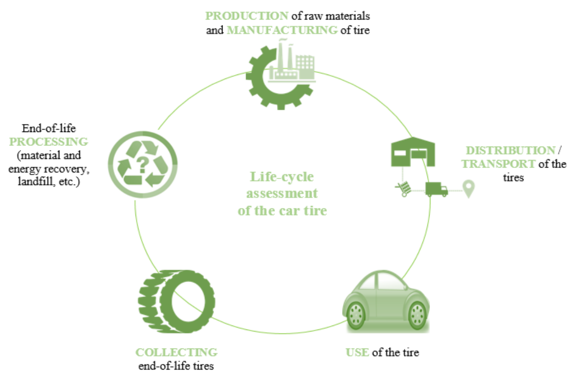

Figure 2. Life-cycle of the car tire

According to ISO documents life cycle assessment includes four steps that are analysed in next subsections for this case study.

4.1 Goal and scope of case study

Goal definition and scope are crucial for all the other phases of LCA [9]. Definition of goal and scope of one case study includes the reason and the motive for performing a life-cycle analysis. Besides the reason and the motive of an LCA, this step must involve the description of the functional unit and the analyzed system boundaries.

The goal of an LCA study shall unambiguously state the intended application, the reasons for carrying out the study and the intended audience, i.e. to whom the results of the study are intended to be published [10].

The goal of this study is to analyze the environmental impacts of 175/70 R-13 car tire. This product is selected because the modern tire in operation (use phase) usually exceeds 60.000 to 130.000 km. The duration of use mostly depends on the conditions of use. The problem occurs when for the safety reasons the tire must be replaced with a new one. According to the estimation, the natural process of decomposition of disposed tires lasts about 150 years [11]. The worn car tire has a negative impact on the environment so, in order to reduce that impact, it is necessary to do an LCA.

The goals of the conducted life-cycle assessment are the following:

- Analysis and explanation of the material and energy flows in the different phases in life-cycle of one tire
- Estimation of emissions and waste that go into the environment and that are considered like export flows.
- Recognition of the principal effect on the environment during the life-cycle of one tire.
- Identified opportunities to improve the environmental performance of the car tire during its life-cycle.
- Definition of measures for reducing the negative impact of worn tires on the environment.
- Evolution of one methodology for assessing tires, i.e. in general - rubber products.

During the life-cycle analyses of one product, the definition of the functional unit (FU) is required. The functional unit represents a measure of functional outputs and it complies with the requirements of the LCA study.

The basic purpose of the functional unit is to provide a reference level for normalization of input and output data, in order to further making comparisons based on LCA results [12].

In this research, it is assuming that the functional unit is one car tire with an average service life of 50.000 km over a four-year period. The weight of the analyzed tire is assumed approximately 6.5 kg. The next important assignment in the phase of definition the goal and scope is to establish the system boundaries. The system boundaries determine which unit processes shall be included within the LCA [5]. The precise LCA considers the impact of all life-cycle of tires on the environment starting from obtaining the raw material till the end of the production process. Due to lack of available data, next processes are involved in the analysis: production of the tire, use the tire and transport of the tire.

4.2 Life-cycle inventory analysis

Life Cycle Inventory (LCI) analysis is the second phase of life-cycle assessment. This phase includes creating an inventory of flows from and to nature for a product system [13].

Namely, during this phase all the material flows, the energy flows as well as all the waste streams deliver to the environment over the whole life cycle of the analyzed product are identified and, when it is possible - are quantified.

Based on the functional unit and initial resources quantification, as well as on the processes description presented above, it is feasible to create simple life-cycle “process tree”, which will present the inventory analysis of the given product.

The process tree system includes only processes and transportation directly involved in the production, use and disposal of the analyzed product, the ancillary materials and the equipment [14]. The process tree of the car tire is shown on figure 3. The software STAN 2.6 was used to create model that represents process tree of the analysed car tire. Red arrows refer to flows that are considered as input flows. Blue arrows indicate the output flows which are almost always observed as harmful flows to the environment. The output flows of the life cycle inventory analysis are made up of the atmospheric emissions, emissions into water and waste stream.

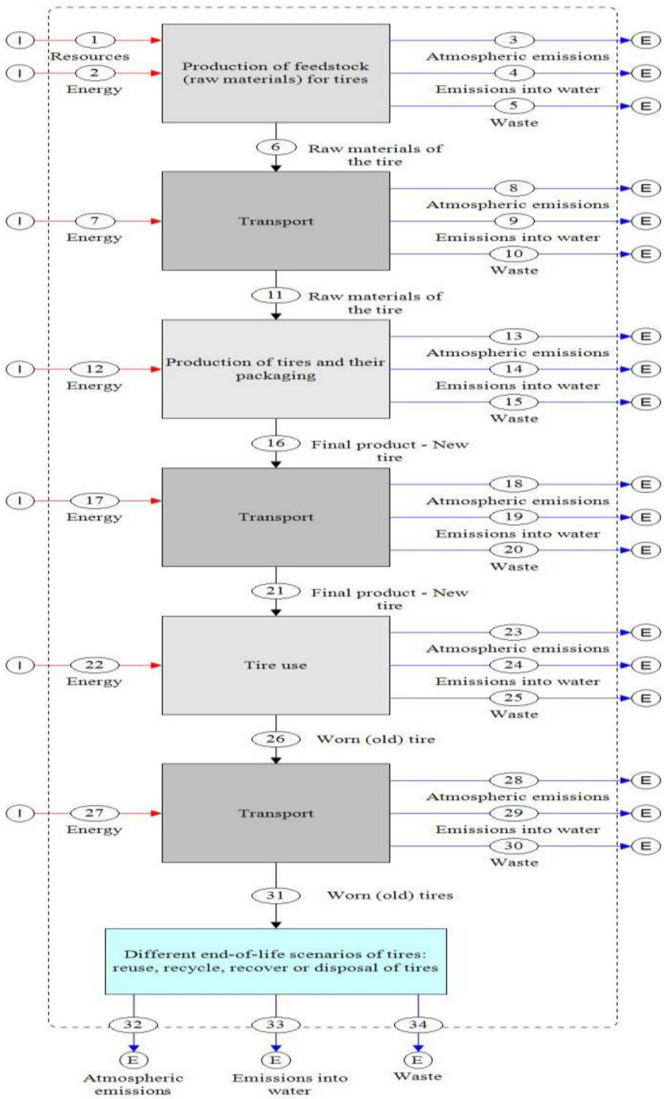

Figure 3. Process tree of the car tire (inventory analysis)

4.3 Life-cycle impact analysis

Inventory analysis is followed by a life-cycle impact assessment (LCIA). This phase of LCA is aimed at evaluating the significance of potential environmental impacts based on the LCI flow results. The impact assessment framework is a multi-step process, starting by selecting and defining impact categories, which are relevant to the analyzed product. This is followed by a classification step, which assigns LCI results to the impact categories [3]. The objective of LCIA is to further process and interpret the results of LCI in terms of their potential impact on the environment and society [15]. Also, the LCIA gives all necessary data and information for the succeeding phase of LCA.

Life-cycle impact analysis is an important stage of LCA because according to results which are got from analysis, it can be defined strategy for reducing the impact of one product on the environmental.

The core principles of the LCIA phase are based on a methodology that is used for its performing. The essential step in this phase is a selection of methodology.

So far, a number of methodologies for assessing environmental impact have been developed and all of those are adapted to assessing impacts in different areas of LCA application.

In this case study, methodology Eco-Indicator 1999 (EI 99) is used because it is the only methodology that is possible to use with collected data.

4.3.1 Methodology ECO-INDICATOR 99 and its implementation

Eco-indicator 99 is one of the most widely used impact assessment methods in LCA. It is the successor of Eco-indicator 95 which allowed that an environmental load of a product is expressed in a single score [16, 17]. The Eco-Indicator 99 methodology is one of the most developed methodologies for assessing the impact of the product life-cycle on the environment. The result of this method is called an eco-indicator that is expressed in points. The EI shows the overall estimated impact of a process or product on human health, the quality of ecosystems and the impoverishment of natural resources [18].

The standard Eco-indicator values can be regarded as dimensionless figures. All obtained values are expressed as the Eco-indicator point (Pt). In this research work, milli-point (mPt) is used as a unit of Eco-indicator. Following the Eco-Indicator 99 methodology, tables 1, 2 and 3 were filled up. These tables are related to impacts at each stage with their quantification in eco-points. The EI 99 includes weighting factors which represents a weight given to a data point (material or process)to assign it a lighter, or heavier, importance in one phase. According to the life-cycle inventory analysis and the assumed values of input flows, life-cycle impact analysis was done.

As already mentioned, more than two hundred raw materials are needed for the production of a single tire, therefore, in analyzing the environmental impact, only those that are most important was taken into the assessment. The amount of specific material or process is defined in accordance with the data from the company Continental [8].

The following tables show the final environmental impacts in specific phases of the car tire.

Table 1. Eco-indicator of production phase

Material or process	Amount	Indicator	Result
Rubber	4.51 kg	360	1,623.6
Silica	1.3 kg	60	78
Carbon black	2.8 kg	180	504

Steel	0.98 kg	86	84.28
Coal	1.4 kg	4.2	5.88
Air	N/A	N/A	N/A
Water	N/A	N/A	N/A
Gas-fired heat (forming)	13 MJ	5.3	68.9
Total [mPt]	**2,364.66**		

Table 2. Eco-indicator of transportation phase

Material or process	**Amount**	**Indicator**	**Result**
Petroleum	0.5	210	105
Total [mPt]	**105**		

Table 3. Eco-indicator of use phase

Material or process	**Amount**	**Indicator**	**Result**
Petroleum	0.97	210	**203.7**
Air	N/A	N/A	**N/A**
Total [mPt]	**204**		

Due to insufficient data, the eco-indicator was not calculated for the end-of-life phases but according to literature, it can be concluded that the car tire has a big negative impact on the environment in this phases.

4.4 Life-cycle interpretation

The interpretation is the final phase of an LCA where the results of the other phases are considered together and analyzed in the light of the uncertainties of the applied data and the assumptions that have been made and documented throughout the study [19].

The results that are got are fairly clear – it is obvious, that the production phase implies the biggest environmental impact.

It must keep in mind, that for completion of the work, some strong assumptions are made, such as the amounts of materials and also, excluded some highly influential materials that could add significantly to that phase of PLC. Likewise, the end-of-life phase of the car tire was not considered as well as the different end-of-life scenarios of tires, such as reuse, recycling or disposal of tires. Taking into consideration the determined goal of this research, its clarity and simplicity as well as the constraint of data, it can be said, that the performed analysis is reasonable. The conducted analysis is not entirely accurate, because most of the used data in assessment is assumed. The quantities and environmental impact of the individual components in the input-output flows vary. To allow for a comparison of the individual phases in the life of a tire, it is a good idea to define a common reference size for all stages.

Besides the analyzed phases, LCA must take into account: cumulative energy input, global warming effect, acidification and nitrification.

5. CONCLUSION AND FURTHER RESEARCH

Summarizing this work, it can be said that the life-cycle assessment is a very useful and undoubtedly necessary environmental procedure, which earned its place among the popular modern environmental management and performance tools.

The purpose of the LCA of one car tire is getting the results of its environmental impact during all life-cycle. Using this analysis, it is possible to monitor all phases of the tire's life cycle and take appropriate steps in the design phase of the car tire in order to minimize those impacts. The assessment of the impact of the car tire on the environment is a very complex task because a lot of data is taken into account and many situations are assumed.

On the basis of the conducted analysis, the most critical phase is the phase of production during the entire life-cycle of the car tire. Life-cycle assessment of the car tire is very important because this product has a big number of different raw materials that after the use phase, it has a potential and it can become one valuable resource in some other process of production. Changes in the process of production as well as in the end-of-life scenarios are necessary, i.e. transit from a linear model of production to a circular economic model is necessary. Exactly in that way, it is possible to reduce the footprint of the production phase of the car tire on the environment. That can be explained by the fact that in the process of production will not be used new raw materials because the already worn materials will be reused or recovered. In further research, this assessment will improve significantly through the constant development and modernization as well as updating of the database.

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MOBILITY & VEHICLE MECHANICS

DOI: 10.24874/mvm.2019.45.03.03
UDC: 519.718

FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS OF MECHANICAL SYSTEMS' ELEMENTS

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Received in August 2019 Accepted in September 2019

RESEARCH ARTICLE

ABSTRACT: Basic concepts and a brief history of the development of Failure Modes, Effects and Criticality Analysis - FMECA are given in the introductory part of the paper. In the present considerations, the quantitative FMECA is based on the assumption that the intensity of the element's failure is constant and is mainly applied in electronic systems. Based on the current procedure, taking into account the specificity of the mechanical system's elements in terms of the intensity of the failure, the proposal of the quantitative FMECA of these elements is given. The procedure has been expanded with a step of determining the absolute criticality of the elements from the aspect of reliability and functional safety. The application of the procedure is illustrated through the case of determining the criticality of the elements of the light commercial vehicle's steering system based on exploitation data.

KEY WORDS: reliability, quantitative FMECA, steering system, commercial vehicle

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ANALIZA VRSTE OTKAZA, EFEKATA I KRITIČNOSTI ELEMENATA MEHANIČKIH SISTEMA

REZIME: U uvodnom delu rada je prikazan osnovni koncept i kratak istorijski razvoj analize vrste otkaza, efekata i kritičnosti (eng. Failure Modes, Effects and Criticality Analysis) – FMECA. U dosadašnjim razmatranjima, kvantitativna FMECA zasniva se na pretpostavci da je intenzitet otkaza elemenata konstantan i uglavnom se primenjuje kod elektronskih sistema. Na osnovu postojećeg postupka, uzimajući u obzir specifičnosti elemenata mašinskih sistema u pogledu intenziteta otkaza, dat je predlog kvantitativne FMECA ovih elemenata. Postupak je proširen korakom za određivanje apsolutne kritičnosti elemenata sa aspekta pouzdanosti i sigurnosti funkcionisanja. Primena postupka je ilustrovana na primeru određivanja kritičnosti elemenata sistema za upravljanje lakih teretnih vozila na osnovu podataka iz eksploatacije.

KLJUČNE REČI: pouzdanost, kvantitativna FMECA, sistem za upravljanje, teretno vozilo

FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS OF MECHANICAL SYSTEMS' ELEMENTS

Dobrivoje Ćatić, Jasna Glišović

1. INTRODUCTION

Failure Modes and Effects Analysis (FMEA) is one of the basic and the most used method for analysing the safety and reliability of technical systems [1, 2, 3]. Efficiency of FMEA method application is the greatest if used in the phase of design by multi-disciplinary team of experts. FMEA is generally an inductive (bottom – up) method. It is based on consideration of all potential failures of constitutive parts of the system and effects they have on the system. Criticality Analysis (CA) is a procedure for evaluation of criticality rating for all constitutive parts, where, by criticality, a relative measure of item's failure modes influence on reliable and safe operation of the system is meant. Joint FMEA and CA analysis are called Failure modes, effects and criticality analysis – FMECA [4].

FMECA was developed for USA military purposes as a technique for assessment of reliability through determination of effects of different failure modes of technical systems [3]. This method dates from November 9th, 1949, as an official document in a form of an American military standard, denoted as MIL-P-1629 [5], titled 'Procedures for Performing a Failure Mode, Effects and Criticality Analysis'. Outside the military, FMEA began to be used in the aircraft and space industry. During the fifties and sixties, airline company Boeing has developed FMEA method and became one of its creators. NASA in 1966 had published its procedure for FMEA, which was used in the Apollo program [6].

Although FMEA is considered an useful tool for improving product quality, this method is beginning to be used in the automotive industry only in the early seventies. In 1971 Ford Motor Company introduces an internal standard that refers to the FMEA method. The Automotive Industry Action Group (AIAG) and the American Society for Quality Control (ASQC) copyrighted industry wide FMEA Manuel in February of 1993 [7].

Considering the content of publications that were developed later and related to the FMEA method, it can be concluded that the MIL-P-1629 standard and its revised version MIL-STD-1629A from 1980 [8], represent the basis for the part referring to the quantitative FMECA. Motor vehicle's steering system is a mechanical system that has to meet high demands regarding reliability [9, 10]. Importance of the motor vehicle's steering system for human safety requires a detailed analysis of structural components in view of occurrence of their failure during exploitation. For the failure analysis of the considered device, it is necessary to know the structure, way of operating, working conditions and all factors that have a greater or less influence on its reliability.

2. QUANTITATIVE FMECA

Analysis of the modes, effects and criticality of failures of technical systems' elements can be done qualitatively or quantitatively, depending on whether the data on failure intensity of elements are known [5, 8]. FMECA quantitative procedure is based on exploitation data (mostly electronic elements), if the intensity of failures is known or can be assessed, is implemented in three steps [1, 8, 11, 12, 17]:

1. Determination of criticality C_{ij}^k of failure mode j of element i is to be done by categories of failure effects k (k = 1, 2, 3, 4), using [1, 8, 12, 18]:

$$C_{ij}^{(k)} = \alpha_{ij} \cdot \beta_{ij}^{k} \cdot \lambda_i \cdot t_i \tag{1}$$

where:

α_{ij} - relative rate (frequency measure) of failure mode j of element i, ($0 \leq \alpha_{ij} \leq 1$, $\sum_j \alpha_{ij} = 1$)

β_{ij}^{k} - conditional probability that failure mode j of element i will cause category k failure effect according to the adopted classification (values are taken orientationaly from Table 1, according to recommendations from [1, 8, 11, 17, 18],

$\lambda_i = \sum_j \lambda_{ij}$- failure rate of element i (primary source of failure rate data for electronic part and values of influencing factors is MIL-HDBK-217F [19],

λ_{ij}- part failure rate of mode j of element i, and

t_i - operating time of element i.

Table 1. Guideline values failure effect probability

Failure effect description	Probability value of $\beta_{ij}^{(k)}$ [-]
Actual loss	1.00
Probable loss	0.10 < < 1.00
Possible loss	0 < ≤ 0.10
No effect	0

Calculated values of C_{ij}^{k} apart from being the starting point for determination of other quantitative properties of element's criticality, they make it possible to rank the element's failure modes according to effects in order to evaluate the most critical system's failure modes from the aspect of reliability and safety.

2. Determination of failure criticality of element i, which causes the k-th category of failure effects [1, 8, 17]:

$$C_{i}^{(k)} = \sum_{j} C_{ij}^{(k)} \tag{2}$$

Calculation of $C_{i}^{(k)}$ enables the isolation of the most important elements whose failures lead to certain categories of effects.

3. Determination of criticality of the k-th category of the system's effects, by summation of criticalities of all elements failure modes for the specified effect category [17]:

$$C_k = \sum_{i} \sum_{j} C_{ij}^{(k)} \tag{3}$$

Calculated values of C_k are statistical indicators of the representation rating of the individual category of effects.

According to standard of International Electromechanical Commission IEC 60812 [12], 'the major deficiencies of this approach are the implicit assumption of constant failure rate and that many of the factors are predictions or best guesses only. This is especially the case when the system components cannot have an associated failure rate, just the calculated failure probability for the specific application, its duration, and associated stresses, such as mechanical components and systems'.

3. QUANTITATIVE FMECA PROCEDURE FOR MECHANICAL SYSTEMS' ELEMENTS

Depending on the behavior of intensity of failure function *h(t),* the entire exploitation life of mechanical parts can be divided into three periods (Figure 1) [13]: the initial period (high intensity of failure with a tendency to sudden decrease), the period of normal operation (intensity of failure is approximately constant) and aging period (intensity of failure is an increasing function of time).

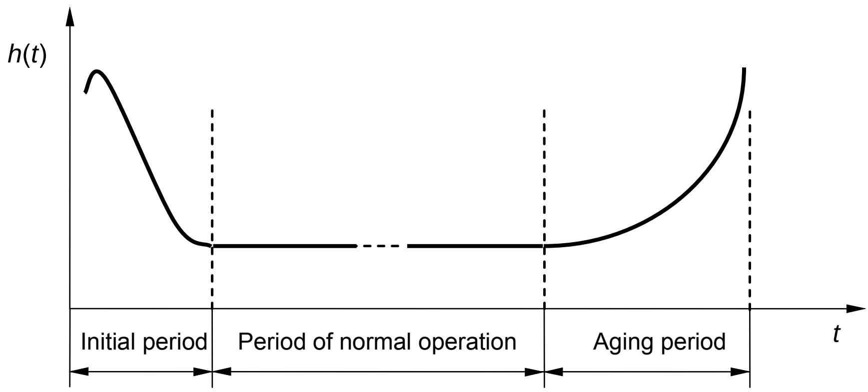

Figure 1. The intensity of failure of mechanical systems' elements as a function of operating time

The question is: What value of intensity of failures and from which the period of operation should be taken to determine the criticality of elements that will equally represent all modes of failure of elements in the entire service life? This dilemma is particularly evident if one considers that there are elements with the failure modes are characteristic only for certain periods of operation. In addition, unlike the exponential distribution for other distributions of intensity's failure is a complex function of time, which depends on several parameters (e.g., the Weibull distribution, depending on the model, there are two or three parameters). Determination of functional dependence and the parameters of the distribution require a detailed examination of elements for the assessment of reliability.

Ultimately, if you know the functional dependence of $h(t)$, then the criticality of an element must be the same function of time. In this way, you would get the criticality as a variable in time. This approach (if there is an objective feature), is interesting for ranking the criticality level of elements in different periods of operation.

Due to the unrealistic images of the degree of criticality, given by the assumption that the intensity of failure of mechanical systems' elements is constant and because of the objective impossibility of determining the intensity of failure as a function of time for every failure mode for each element of the mechanical system, it is established that the intensity of failure of machine elements can't be taken as a failure parameter for calculating the criticality.

Mean time of operation until the failure of an element is an indication of durability, which is relatively easy to determine. It is logical that the criticality of an element is less as time of operation until failure is larger and vice versa. On this basis, we can conclude that the criticality of an element is inversely proportional to the mean operation time until the failure of that element.

Based on the existing methodology for the quantitative FMECA, and taking into account the previous remarks, we developed a quantitative procedure FMECA for elements of mechanical systems consisting of four steps [14, 15, 16, 20]:

1. Determination of criticality of failure mode *j* of element *i* is to be done by categories of failure effects *k* (*k* = 1, 2, 3, 4), using [21]:

$$C_{ij}^{(k)} = \frac{\alpha_{ij} \cdot \beta_{ij}^{(k)} \cdot t_i}{t_{sr_{ij}}} \tag{4}$$

Unlike the meaning of α_{ij} in expression (1), there are many elements of mechanical systems in which failure occurs only in a relatively small number of systems throughout the entire service life. Therefore, in order to have a realistic criticality assessment, in this case α_{ij} represents a relative share of the failure mode of an element in all systems.

Tags $\beta_{ij}^{(k)}$ and t_i have the same meaning as in equation (1), and $t_{sr_{ij}}$ is mean operating time to failure of mode *j* of element *i*.

$t_{sr_{ij}}$ represents the average working time until the failure mode *j* of element *i* occurs.

In general, mean operation time to failure of element is the mathematical expectation of random variable of operation time to failure. For a set of measured values of a random variable, the mean operation time to failure is equally arithmetic average of the obtained results:

$$t_{sr} = \frac{1}{n} \cdot \sum_{i=1}^{n} t_i \tag{5}$$

where:

n - total number of results, and

t_i - time until the failure of the element *i*.

2. Determination of failure criticality of element i, which causes the k-th category of failure effects, according to expression (2).

3. Determination of 'absolute criticality' of element *i* according to [15, 16, 20]:

$$C_i = a_1 C_i^{(1)} + a_2 C_i^{(2)} + a_3 C_i^{(3)} + a_4 C_i^{(4)} \tag{6}$$

where:

a_k- 'weight' of the *k*-th (*k* = 1, 2, 3, 4) category of effects (values may be determined using subjective evaluation of effect's 'weight' for each case, from the interval between 0 and 1) and

$C_i^{(k)}$- the *i*-th element criticality for the *k*-th category of effects.

This step is an extension compared to the starting method FMECA. The idea is to assign each category of effects corresponding 'weight' in proportion to the importance of effects. For example, the system that would have four categories of effects, which are defined so that the effects of category one are most serious, and the effects of category four are easiest, the 'weight' factors of category of effects can be adopted as follows:

$a_1 = 1.00; a_2 = 0.75;\ a_3 = 0.40\ and\ a_4 = 0.20.$

4. Determination of criticality category *k* of the system's effects, by summation of criticality of all elements' failure modes for the specified effect category according to expression (3).

Due to the large amounts of data, a quantitative FMECA of elements of mechanical systems is difficult without the use of computers and related software. Therefore, it was established the computer program. By using the program it was performed a quantitative analysis of the criticality's level of steering system's elements for light commercial vehicles.

4. QUANTITATIVE FMECA OF STEERING SYSTEM'S ELEMENTS OF LIGHT COMMERCIAL VEHICLES

Steering system is one of the vital parts of the complex mechanical system called 'motor vehicle' [9]. Together with the braking system and the tires, it has crucial significance for safety of motor vehicles and people in traffic. Thus, great attention is given to demands that are set before the steering system regarding reliability.

In order to determine the critical elements of the restrictive effect on a reliable and safe operation of steering system of commercial vehicles, based on data from exploitation, the quantitative analysis of modes, effects and criticality of failure of this system's elements is performed. Basis for this analysis was a complex data structure in the form of a table data sheet. Procedure for data acquisition needed for quantitative FMECA of the light commercial vehicle's steering system consisted of the following steps [14]:

1. Structural system division, identification and coding of constitutive elements of the light commercial vehicle's steering system was carried out on the basis of the technical documentation of the vehicle's manufacturer by forming a structural block diagram [22];

2. The adoption of structural level for conduction of analysis of criticality (It is accepted that the quantitative method FMECA should be conducted at the lowest level of replaceable units in the steering system);

3. Identification and recording of the most failure modes of steering system's elements were done by forming the fault tree [23];

4. Determination of relative participation of individual element failure modes;

5. Category definition of final failure effects. All failure mode effects of the steering system's elements are classified in four categories:

k.1 - effects which threatened the safety of people and vehicles due to the immediate termination of performing the functions of the system

k.2 - there is the possibility of performing an interruption of steering system's function after a while, if the failures are not eliminated

k.3 - output and input parameters of the system are beyond the permissible limits (the appearance of increased clearance, required torque on the steering wheel is larger than normal or abnormal geometry of the wheels due to deformation of a lever mechanism of steering system) and

k.4 - changes to the system's elements that do not significantly influence the functioning and can have serious effects, and changes that, if not remedied, may lead to the emergence of modes of failure with the effects *k*.3.).

6. Categorization of element's failure modes according to effects and determination of conditional probabilities of final effects occurrence was done with the help of technical personnel services for the maintenance of the considered type of vehicle (Conditional

probability of occurrence of final effects of element's failure modes are determined by subjective evaluation based on Table 1)

7. Determination of mean operating time until element failure occurs (Systems and elements of motor vehicle are loaded with variable loads in the course of time. The total number of load variation cycles is proportional to distance passed. Thus, time until failure of the most elements of motor vehicles occurs is measured in kilometres of distance passed.) and

8. Calculation of the total operation time of elements. Operation time of steering system's elements of motor vehicles t_i is the same for all elements and has no effect on the relative criticality of failure modes of elements. Therefore, when calculating the criticality it was taken as unit of time.

Forming of input files for the program of quantitative FMECA of mechanical systems' elements was performed based on the data, which one part is shown in Table 2. To calculate the elements absolute criticality in accordance with (6), the following weighting factors of effect categories are adopted: $a_1 = 1;\ a_2 = 0.5;\ a_3 = 0.3\ and\ a_4 = 0.2$. Weighting factors were adopted by subjective assessment of the experts from the subject area.

Designation Q in Table 2 is for quantity or number of identical elements within the scope of discussed object of analysis.

By processing of the acquired data given in Table 2, by using the computer program for quantitative FMECA of mechanical system's elements, the results are obtained for:

- criticality of the steering system elements' failure modes without taking into account the effects (Table 3)
- criticality of the steering system elements' with taking into account the effects (Table 4)
- absolute criticality of the steering system elements' (Table 5) and
- criticality of final failure effects of the steering system elements' (Table 6).

Table 3 contains the initial part of the output results of the program obtained by criticality ranking of a total of 49 different steering system elements' failure modes regardless of the result. Based on Table 3, the top two places by criticality occupy increased clearances in a tie-rod's ball joints. Criticality of the longitudinal tie-rod with ball joint is determined by the criticality of the tie-rod's ball joint. Thus was obtained about the same level of criticality of both the assembly. Increased clearance in tie-rod joints most frequently occurs in aging period, due to wear of sliding surfaces of the ball pin and the cup. An influence may be exerted on the increase of mean operating time until the increased clearance in the joint occurs or on reduction of a tie-rod joint's criticality by the increase of material's or surface layer's resistance to wear, by better lubrication and by better protection from the influence of the environment.

On the third and fifth place by the criticality are failure modes of steering shaft's bushings. Increased clearance and cracking of bushes occur during aging period due to wear. The failure of bush is primarily reflecting the occurrence of vibration on the steering wheel. In fourth place by the criticality is cracking the rubber insert of coupling. The failure occurs due to aging and loss of elasticity of rubber. It is manifested in the appearance of the visible clearance in coupling and delay of output effects of systems on steering wheels with respect to the input effect on the steering wheel.

Table 2. Part of the base of the FMECA procedure for elements of the steering system of light commercial vehicles

Element's name	Elem. code	Q [-]	Failure mode	Failure mode code	Rel. rate α_{ij} [-]	Loss prob. $\beta_{ij}^{(k)}$ [-]	Final effect	$t_{sr_{ij}}$ [km] x103
Steering wheel	61001	1	Damage Insufficient tightening of screws	N.06 N.31	0.002 0.001	1.0 0.1	k.4 k.2	20 3
Steering shaft	61002	1	Radially throw Damage of the groove for connection	N.02 N.07	0.0002 0.03	1.0 0.4	k.4 k.3	3 200
Steering shaft bracket	61004	1	Insufficient tightening of screws Cracking at weld	N.31 N.69	0.0002 0.0005	1.0 0.8	k.3 k.3	30 100
Steering shaft bushing	61005	1	Cracked bushes Increased clearance	N.06 N.35	0.3 0.7	1.0 1.0	k.3 k.3	200 100
Steering head support	61006	1	Cracking Insufficient tightening of screws	N.06 N.31	0.0005 0.0002	0.8 1.0	k.1 k.3	300 30
Rubber insert	61011	1	Cracking	N.06	1	1.0	k.3	200
Housing of the steering head	61101	1	Damage of the cover sealer Porosity of the case	N.37 N.81	0.01 0.008	0.7 0.3	k.4 k.4	200 15
Worm shaft	61103	1	Damage of the teeth Cracking - fracture Damage of grooves	N.05 N.06 N.07	0.006 0.0005 0.001	1.0 1.0 0.8	k.3 k.1 k.3	300 350 200
Roller bearing of the steering head	61104 61105	1 1	Bearing damage No adjustment of the clearance	N.11 N.62	0.006 0.003	1.0 0.7	k.3 k.3	350 400
Shaft with segment	61110	1	Damage of the teeth Cracking - fracture Damage of grooves No adjustment	N.05 N.06 N.07 N.62	0.006 0.0005 0.001 0.005	1.0 1.0 0.6 1.0	k.3 k.1 k.3 k.3	300 350 200 30
Sliding bearing of the output shaft	61107	2	Bearing damage	N.11	0.01	1.0	k.3	350
The lever of the longitudinal tie-rod with ball joint	62110	1	The deformation of the lever Cracking - fracture Damage of the thread Loose connections Increased clearance	N.02 N.06 N.07 N.31 N.35	0.0005 0.0007 0.003 0.001 0.9948	0.6 1.0 0.8 1.0 1.0	k.3 k.1 k.2 k.2 k.3	30 100 100 15 100
Tube of the transverse tie-rod	62201	1	Damage of the thread Insufficient tightening of the clamping ring	N.07 N.31	0.0001 0.0003	0.8 1.0	k.2 k.2	10 15

Tie-rod's ball joint	62120	1	Body joint deformation	N.02	0.0002	0.3	*k*.3	40
	62210	1	Fracture of the eyeball or the ball joint's body	N.06	0.0007	1.0	*k*.1	100
	62230	1	Damage of the thread	N.07	0.003	0.8	*k*.2	100
			Loose connections	N.31	0.001	1.0	*k*.2	15
			Increased clearance	N.35	0.9951	1.0	*k*.3	100

Table 3. Criticality of the steering system elements' failure modes without taking into account the effects

No.	Code	Element's name	Failure mode	Eff. name	α_{ij} [-]	$\beta_{ij}^{(k)}$ [-]	$t_{sr_{ij}}$ [km] x103	t_i [km]	Criticality $C_{ij}^{(k)}$[-]
1	62210	Tie-rod ball joint	Increased clearance	*k*.3	0.9951	1.0	100	1	0.9951E-05
2	62110	The lever of the longitudinal tie-rod with ball joint	Increased clearance	*k*.3	0.9948	1.0	100	1	0.9948E-05
3	61005	Steering shaft bushing	Increased clearance	*k*.3	0.7000	1.0	100	1	0.7000E-05
4	61011	Rubber insert	Cracking	*k*.3	1.0000	1.0	200	1	0.5000E-05
5	61005	Steering shaft bushing	Cracking of bushes	*k*.3	0.3000	1.0	200	1	0.1500E-05
6	61003	Sealer of steering shaft	No hermetic	*k*.4	0.1200	0.4	150	1	0.3200E-06
7	61110	Shaft with segment	No adjustment	*k*.3	0.0050	1.0	30	1	0.1667E-06
8	61101	Housing of the steering head	Porosity of the case	*k*.4	0.0080	0.3	15	1	0.1600E-06
9	61003	Shaft seal	Insufficient tightening of the bolts	*k*.4	0.0030	0.1	3	1	0.1000E-06
10	61001	Steering wheel	Damage	*k*.4	0.0020	1.0	20	1	0.1000E-06
11	61002	Steering shaft	Radially throw	*k*.4	0.0002	1.0	3	1	0.6667E-07
12	62002	Lever on wheels	Loose connection with sleeves	*k*.2	0.0010	1.0	15	1	0.6667E-07
13	62110	The lever of the longitudinal tie-rod with ball joint	Loose connections	*k*.2	0.0010	1.0	15	1	0.6667E-07
14	62210	Tie-rod's ball joint	Loose connections	*k*.2	0.0010	1.0	15	1	0.6667E-07
15	61002	Steering shaft	Damage of the groove for connection	*k*.3	0.0300	0.4	200	1	0.6000E-07
16	61109	Sealing ring	No hermetic	*k*.4	0.0200	0.7	350	1	0.4000E-07
17	61101	Housing of the steering head	Damage of the cover sealer	*k*.4	0.0100	0.7	200	1	0.3500E-07
18	61101	Steering wheel	Insufficient tightening of screws	*k*.2	0.0010	0.1	3	1	0.3333E-07
19	61107	Sliding bearing of the output shaft	Bearing damage	*k*.3	0.0100	1.0	350	1	0.2857E-07
20	62110	The lever of the longitudinal tie-	Damage of the thread	*k*.2	0.0030	0.8	100	1	0.2402E-07

		rod with ball joint							

Table 4. Criticality of the steering system elements' with taking into account the effects

a) Criticality by effects k.1			
No.	Code	Element's name	$C_i^{(2)}$ [-]
1	62210	The lever of the longitudinal tie-rod with ball joint	0.7000E-08
2	62110	Tie-rod ball joint	0.7000E-08
3	61110	Shaft with segment	0.1429E-08
4	61103	Worm shaft	0.1428E-08
5	61006	Steering head support	0.1333E-08
6	62001	Lever on the steering head	0.1333E-08
7	62002	Levers on wheels	0.1143E-08
b) Criticality by effects k.2			
No.	Code	Element's name	$C_i^{(2)}$ [-]
1	62210	The lever of the longitudinal tie-rod with ball joint	0.9067E-07
2	62110	Tie-rod ball joint	0.9067E-07
3	62002	Lever on wheels	0.6667E-07
4	61001	Steering wheel	0.3333E-07
5	62201	Tube of the transverse tie-rod	0.2800E-07
6	62001	Lever on the steering head	0.1667E-07
c) Criticality by effects k.3			
No.	Code	Element's name	$C_i^{(3)}$[-]
1	62110	The lever of the longitudinal tie-rod with ball joint	0.9958E-05
2	62210	Tie-rod ball joint	0.9953E-05
3	61005	Steering shaft bushing	0.8500E-05
4	61011	Rubber insert	0.5000E-05
5	61110	Shaft with segment	0.1667E-06
6	61002	Steering shaft	0.6000E-07
7	61107	Slide bearing of output shaft	0.2857E-07
8	61012	Flange on the worm shaft	0.2567E-07
9	61103	Worm shaft	0.2400E-07
10	61104	Roller bearing of the steering head	0.2239E-07
11	61004	Steering shaft bracket	0.1667E-07
d) Criticality by effects k.4			
No.	Code	Element's name	$C_i^{(4)}$ [-]
1	61003	Sealer of steering shaft	0.4200E-06
2	61108	Housing of the steering head	0.1950E-06
3	61001	Steering wheel	0.1000E-06
4	61002	Steering shaft	0.6667E-07
5	61108	Sealing rings	0.4000E-07
6	61102	Steering head's cork	0.6666E-08

Based on a criticality degree of steering system's elements with taking into account the effects (Table 4), it may be seen that, in severe categories of effects the dominant position occupies failure modes of the lever of the longitudinal tie-rod with ball joint and the tie-rod ball joint, but with relatively small values of criticality. For effect *k*.1, criticality of elements is the order of magnitude of 10^{-8}, and for effect *k*.2, the order of magnitude is 10^{-7}. For effect *k*.3, the top two places are tie-rod ball joints which together with steering shaft bushing and a rubber insert of coupling have the criticality degree of order 10^{-5}. Shaft with segment has a criticality of the order 10^{-6}, while the criticality of other elements is the order of magnitude of 10^{-7}. The degree of critical elements resulted from *k*.4, due to an effect, is not relevant for the determination of critical elements in the system.

By the most critical elements of steering systems can be reached directly, based on the degree of absolute criticality of elements. Table 5 shows the results of the ranking of all 20 elements of the considered steering system according to the degree of absolute criticality. Based on these results, the most critical elements of the steering system, according to the sequence, are the lever of the longitudinal tie-rod with ball joint, the tie-rod's ball joint, steering shaft bushing, etc.

Table 5. Absolute criticality of the steering system elements

No.	Code	Element’s name	C_i [-]
1	62110	The lever of the longitudinal tie-rod with ball joint	0.3040E-05
2	62210	Tie-rod ball joint	0.2988E-05
3	61005	Steering shaft bushing	0.2550E-05
4	61011	Rubber insert	0.1500E-05
5	61003	Sealer of steering shaft	0.8400E-07
6	61110	Shaft with segment	0.5144E-07
7	61002	Steering shaft	0.3900E-07
8	61108	Sealing rings	0.3665E-07
9	62201	Tube of the transverse tie-rod	0.3448E-07
10	61012	Flange on the worm shaft	0.3133E-07
11	61101	Housing of the steering head	0.1917E-07
12	62002	Lever on wheels	0.1400E-07
13	61004	Steering shaft bracket	0.9330E-08
14	61001	Steering wheel	0.8628E-08
15	61104	Roller bearing of the steering head	0.8571E-08
16	61006	Steering head support	0.7701E-08
17	61107	Slide bearing of output shaft	0.6717E-08
18	62001	Lever on the steering head	0.5001E-08
19	61103	Worm shaft	0.3333E-09
20	61102	Steering head's cork	0.1333E-10

The other way of determination of the most critical elements of the steering system is a comparative analysis of Table 4 and Table 6. In Table 6, there is an obvious predominant occurrence of elements’ failure modes with category of effect equal to three. 96.62% of a total sum of elements 'criticality are elements' failure modes with third category of effects. Table 4 contains the elements ranked by criticality and by category of effects.

Table 6. Criticality of final failure effects

No.	Final effect	C_k [-]	Rel. crit. %
1	*k*.3	0.3363E-04	96.62
2	*k*.4	0.8284E-06	2.38
3	*k*.2	0.3260E-06	0.94
4	*k*.1	0.2067E-07	0.06

Figure 2 shows Pareto analysis of elements' criticality rate of light commercial vehicles' steering system elements with failure modes that have a third category of effects is given. Since the representation of failure modes of elements for the remaining categories of effects is negligible, Figure 2 illustrates also the overall criticality of the elements.

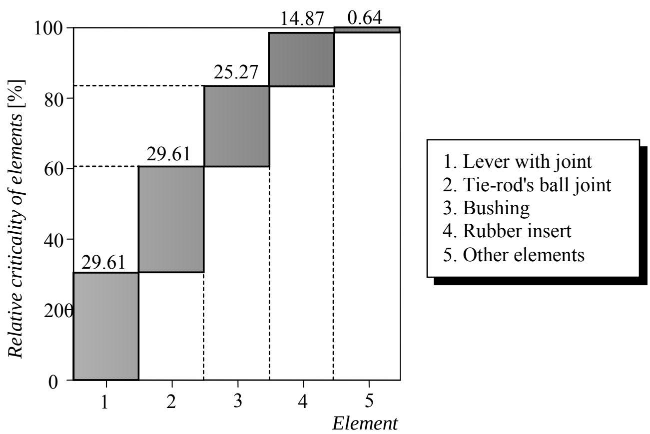

Figure 2. Pareto analysis of criticality rate of elements for category of effects k.3

Based on the results of the program for a quantitative analysis of the degree of criticality and Figure 2, it can be concluded that the most critical elements of steering system in terms of durability and safety are: the lever of the longitudinal tie-rod with ball joint, tie-rod ball joint, steering shaft bushing and rubber insert of coupling. All other elements are within 0.64% of criticality. In this case, Pareto analysis of absolute criticality of steering system elements gives similar results.

5. CONCLUSIONS

The procedure of quantitative FMECA, which is defined by existing standards, can be applied without reservation when the intensity of all modes of failure of elements is constant, i.e. when it is not the function of time, and therefore, characterizes the reliability of elements for the entire period of operation (for example, at electronic elements). However, application of this methodology, in cases_where the intensity of failure as a function of time, (for example, at mechanical elements), can lead to major errors and distortions of real images of criticality of elements. Therefore, a modification of the existing procedure of quantitative FMECA is made in the sense of creating the possibility of applying the method to the mechanical systems. The intensity of the failure, as a functional reliability indication, common to all the failure modes of the element, is replaced by the reciprocal value of the mean time to failure of individual failure modes. In addition, the relative frequency of the failure mode is defined as a part of failure mode for all machine system elements during the service life. This means that in most cases, the sum of relative frequencies is significantly lower than one. By introducing the aforementioned changes, the criticality of the failure mode of elements, which significantly reflects the real state, is obtained.

The procedure of quantitative FMECA of mechanical system's elements contains a step for determining the absolute criticality of the elements. By ranking the obtained values of the absolute criticality, the degree of criticality of system's elements can be directly assessed from the aspect of durability and safety without additional complicated analysis. Calculation of the absolute criticality especially comes to the fore in cases where the relative criticality of failure modes of elements by categories of effects is uniform.

Calculation of criticality failure modes of elements of mechanical systems and their ranking by degree of criticality is important because it points to the elements and their failure modes in which a criticality is the greatest. Analysis of the causes of critical failure modes of elements can be determined directions of undertaking concrete measures to minimize or completely eliminate the causes of failure, or lower the effects of failure. Thus increases the reliability of critical elements, and thus the reliability, dependability and quality of the entire system. Generally, machine system's level of reliability can be increased by increasing the reliability of constitutive components or by introducing the parallel connections. Due to space limitations in motor vehicles steering systems, it is not possible to introduce parallel connections, so the only possibility to increase the system's reliability is through the increase of each component's reliability.

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MOBILITY & VEHICLE MECHANICS

DOI: 10.24874/mvm.2019.45.03.04
UDC: 62.585.3:62

CONTROL STRATEGY FOR AFTERMARKET ELECTRONIC THROTTLE CONTROL

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Received in September 2019, Accepted in October 2019

RESEARCH ARTICLE

ABSTRACT: This paper presents the development of electronic throttle control, provided for use in an experimental light hybrid-electric vehicle that was a final product of ongoing student project. Originally, the IC-engine throttle system was operated using mechanical linkages and cable, which was enhanced by developing a new system containing sensors and actuators. Therefore prototype of such a system had to enable the possibility of exerting control of both IC engine, powering the rear axle, and two electric hub motors, powering the front axle, by using the single accelerator pedal. This way full exploitation of hybrid drive potentials can be enabled.

KEY WORDS: throttle-by-wire, electric drive, hybrid drive, project-based learning, student project

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STRATEGIJA UPRAVLJANJA SISTEMOM ELEKTRONSKE KOMANDE GASA ZA NAKNADNU UGRADNJU

REZIME: U ovom radu dat je prikaz mehatronskog pristupa rešavanju zadatka koji je obuhvatao elektrifikaciju komande gasa električno-hibridnog vozila Hermes, nastalog iz studentskog projekta na Fakultetu Tehničkih Nauka u Novom Sadu. Hibridno vozilo prednji pogon dobija od SUS motora, dok zadnji dobija od dva elektromotora, koji se nalaze u točkovima. U cilju poboljšanja efikasnosti ovog paralelnog hibrida, kao i redukcije broja pedala gasa predložen je sistem senzora, aktuatora i mikrokontrolera koji bi bili upravljani u povratnoj sprezi, dok je, kao potencijalno rešenje, izrađen model prototipa mehanizma, koji bi u potpunosti zamenio uže, odnosno mehaničku vezu između pedale gasa i karburatora hibridnog vozila..

KLJUČNE REČI: elektrifikacija, hibridno-električno vozilo, projektno-orijentisano učenje, studentski projekat

CONTROL STRATEGY FOR AFTERMARKET ELECTRONIC THROTTLE CONTROL

Jelena Prodanović, Boris Stojić

1. INTRODUCTION

Electronic vehicles are frequently mentioned lately, but it is not widely known that first vehicles with electronics power-train date from the late 19th century. Their development was left aside because IC engines were widely used and improved constantly. Unlike the electrical industry that was struggling to develop batteries with prolonged working hours, desired sustainability, efficiency, and capacity, the fuel industry was a step ahead by producing fuel and making it's supplying affordable and simple. But technology of today allows the electrical industry to quickly evolve and offer many new possibilities such as a modern hybrid-electric vehicles. A vehicle of that type was made by students at the Faculty of Technical Sciences on a Mechanisation and Construction Engineering Department ([1], [2]). The vehicle was named Hermes and was designed as a hybrid with parallel configuration meaning it has two different power sources (two hub motors for powering the front axle and an IC engine for powering the rear axle). This hybrid has full driveability but needs further improvement, such as reducing the number of acceleration pedals since it has two, each one for different power supply and implementing the so-called drive-by-wire (or drive-by-throttle) system as a part of hybrid's electrification. Purpose of this paper came from the desire of making such a system (or at least the prototype) that would make a better outcome in comparison with the previous, mechanical one, by achieving better engine efficiency, improving torque delivery from the engine, increasing fuel consumption, reducing environmental pollution, but at the same time maintaining similar driving experience as it was with the previous mechanical configuration.

2. ELECTRONIC THROTTLE CONTROL

Basic considerations were taken into account like:

- Which type of carburettor is implemented in the vehicle?
- Which microcontroller should be used along with the appropriate sensor(s) and actuator(s)?
- What mechanism is already within the acceleration pedal's box, whether it already has a potentiometer?
- How much space is left on the vehicle for implementing such a system?
- Are there any parts on the vehicle that are protected from vibrations and humidity that can handle parts with sensitive properties?
- What are other limitations?

Drive-by-wire throttle bodies date from the beginning of the 20th century but this vehicle's carburettor doesn't have the conventional throttle body with the butterfly, but with the needle valve.

Aftermarket ECUs with the throttle body are widely utilised systems, most commonly containing two sensors at the accelerator pedal and two sensors on the throttle body. DC motor is directly connected to the throttle body and a PID controller is used for fast, yet accurate control of drive-by-wire throttle body [3]. Three main PID parameters are its gains: proportional, integral and the derivative gain. The values of these gains are highly important since they are directly responsible for the system behavior as well as system safety. The way for getting these values accurately is by doing various tests and experiments which is done by the ECU manufacturers. Since this paper deals with a control strategy for aftermarket electronic throttle control that should be implemented in a student-made vehicle which contains rather rare type of carburettor new approaches needs to be made.

Figure 1. Hermes, hybrid-electrical vehicle [1]

Student-made electric vehicle (Figure 1) is named H.E.R.M.E.S. which is an acronym of the Hybrid Educational Recuperative Moto-Electrical Special vehicle. Its rear-drive axles are powered by a gasoline engine that was taken from the quad vehicle (named Loncin) with the cylinder capacity of approximately 220 cm3, containing one four-stroke cylinder that is fed by the carburetor. The maximum power it can achieve is 11 kW with a 17 Nm torque and has a 4-speed gearbox with the reverse gear. Additional chain transmission was made for connection of both rear axle and redesigned differential that was taken from the Yugo vehicle. Front axles are powered by two DC hub-motors with the power of approximately 1 kW per each, which was controlled by the suitable controllers. Nominal hub-motor voltage is 48 V with the power supply made out of 4 serial 12 V semi-traction batteries. Currently, Hermes'es gasoline and electrical power drives are not able to work simultaneously but this problem can be overcome by implementing control strategy that will involve appropriate microcontroller and electrification of the acceleration pedal (so-called drive-by-wire system) and automatization of both the clutch and the gearbox. Additional criteria should be taken into account like noise reduction, economic aspects (like vehicle's efficiency and environmental performance), etc.

Estimated vehicle's properties are

- Maximal velocity: 100 km/h
- Rise time: 10s (0-60 km/h)
- The maximum distance achieved by driving in the electrical regime: 20 km.

Properties of vehicle's chassis

Frame is made out of three modular segments (front, middle and rear) connected with screws so that further modifications are enabled if needed. For frame design seamless steel pipes segments Ø 21,3 mm, with a wall thickness of 2,6 mm are used.

The front axle is McPherson's type, based on the front axle Yugo's elements.

The braking system is containing two front and rare disc brakes with the main brake cylinder also from the Yugo vehicle.

Mass and dimensions

- Mass: 500 kg
- Weight distribution: approximately ’’50/50’’
- Wheelbase: 2500 mm.

3. ACCELERATION PEDAL CONFUGIRATION

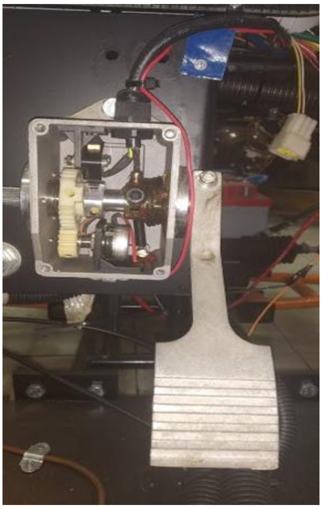

Figure 2. Acceleration pedal and it’s mechanism

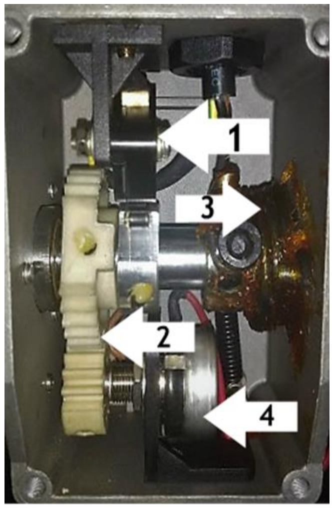

Figure 3. Main parts of acceleration pedal’s mechanism

Acceleration pedal (Figure 2) that is already implemented in the vehicle was made by the unknown manufacturer from China. Based on Figure 3 given acceleration pedal consists of:

1. Limit switch
2. Gear pair
3. Spring
4. Potentiometer.

Since all acceleration pedals used in the drive-by-wire systems have, at least two potentiometer sensors for the purpose of improving the safety strategy, those two sensors should correlate which results with the decreasing potential errors that can occur during the drive. For making the prototype of such a system one potentiometer was used, since it imitates the present state of the Hermes vehicle, although this should be improved by replacing current acceleration pedal with the more advanced one.

4. CARBURETTOR AND THE NEEDLE THROTTLE VALVE

Alike butterfly throttle, needle valve consists of a spring which is responsible for opening/closing carburettor airflow tunnel, depending on whether or not acceleration pedal is pressed. By this we want to point out the great importance of the type of the desired material needed for producing such a spring, meaning that its properties such are quality, durability and most importantly reliability is a matter of concern.

According to [8] and [9], one of the most suitable simulation methods used for design procedures, saving experimental test resources and reducing potential mistakes that could be made during diagnostics of a product is FEM (Finite element method). This method along with the theoretical an experimental approach given in [7] could be used as a model for further work on designing the most durable spring for aftermarket electronic throttle given in this paper.

Figure 4. Throttle valve inside of the carburettor

Figure 5. Complete appearance of the needle throttle valve

As it's seen from both Figures 4 and 5 needle valve motion inside of the carburetor is linear and that motion is achieved by stepping on the acceleration pedal and when the pedal is released, spring inside the valve pushes it back to the original (''natural'') position. Cable throttle system produces lagging due to inherent amount of flex [4]. This problem has been solved by implementing the drive-by-wire system, meaning that replacing throttle cable with the ECU system and tuning such a system to achieve desired goals mentioned in the introduction part of this paper.

5. DC SERVO MOTOR

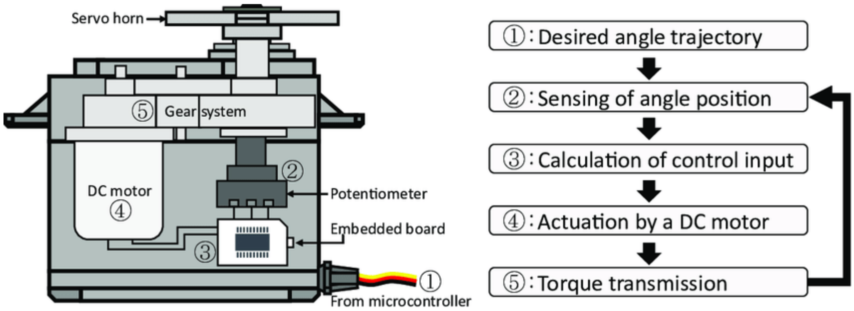

Figure 6. Basic working principle of a DC servo motor [5]

DC servo motor (Figure 6) was chosen among the diversity of potentially suitable electromotor, because of advantages it produces on the system.

Main advantages are:

- It's quick response to the given input signal (input signal is acceleration pedal position)
- Built-in potentiometer with output signal that acts as a feedback signal meaning that signal directly corresponds to the current position of a servo's shaft or in other words potentiometer acts as a servo shaft's encoder.
- Small dimensions, which make this servo motor compact and easy to install
- Compatibility with the microcontroller such as Arduino, Raspberry Pi…
- Scotch yoke mechanism (Figures 7 and 8) was considered as the best option because:
- It was easy to print (by using 3D printing technique and ABS as a filament)
- Has few moving parts
- Directly converts rotary to linear motion
- Servo motor shaft is directly connected to the mechanism, which reduces the number of additional sensors and actuators (like in a regular, throttle valve).

It produces pure sinusoidal output signal, which allows smoother operation and tuning, since the relationship between throttle position and the air flow is nonlinear.

6. 3D PRINTED SCOTCH YOKE MECHANISM

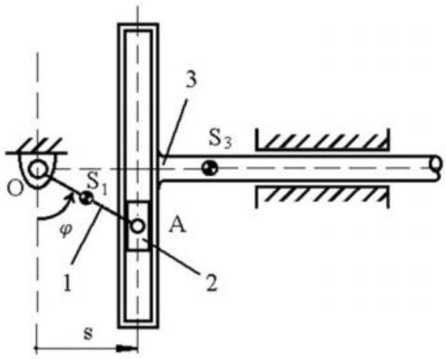

Figure 7. Working principle of a Scotch yoke mechanism [6]

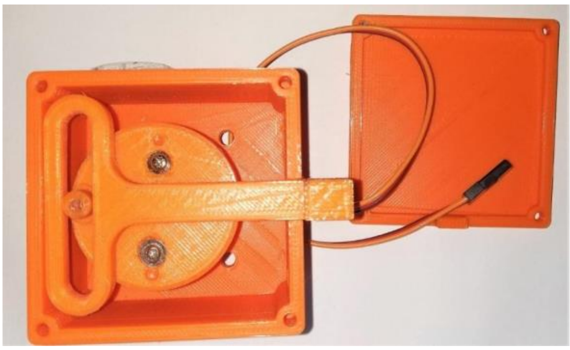

Figure 8. Servo motor and the Scotch yoke 3D printed mechanism

7. HARDWARE DESCRIPTION

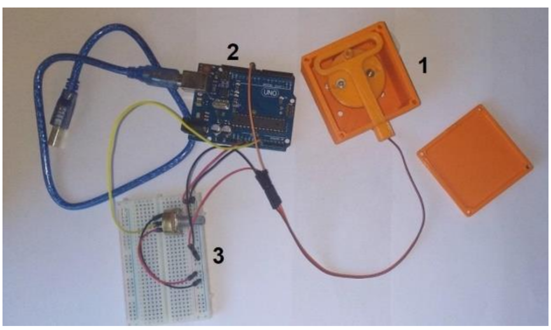

Figure 9. Prototype

Prototype (Figure 9) consists of:

1. Scotch yoke mechanism with the servo motor inside

2. Uno R3 microcontroller
3. Breadboard with the potentiometer.

8. CONCLUSION

This paper presents a mechatronics approach through developing regulation for electronic throttle control device needed for the improvement of the student-made hybrid vehicle. The vehicle is configured as a parallel hybrid with IC engine power at the rear axle and two electric hub-motors at the front axle. Originally, the IC engine throttle system was operated using mechanical linkages and cable, which is not appropriate for optimal control of the simultaneous operation of both the IC engine and electric motors. Therefore prototype of new electronic throttle control system had to be developed, exerting control of both IC engine and electric hub motors by using the single accelerator pedal. This way full exploitation of hybrid drive potentials can be enabled. Appropriate sensors, actuators, mechanisms, control algorithms and microcontroller were chosen, to achieve the first steps for desired, adequate control strategy for aftermarket electronic throttle control or so-called drive-by-wire control. The new control system also has to use a controller with the appropriate software for conversion of the control signal to the actuator displacement.

Further improvements that could be made are:

- Creating throttle maps for different working regimes, which can be implemented together with the ECU system meaning that the ECU system will switch from one map to the other according to the tuning parameters
- Additional potentiometers for gaining more accurate signals and reducing errors
- Adding more input signals like signals from the engine sensor(s) and signals with the information about vehicle velocity
- Testing prototype in various working conditions such as vibrations and higher/lower temperatures.

ACKNOWLEDGMENTS

This paper was done as a part of the researches on the project TR35041 – "Investigation of the safety of the vehicle as part of cybernetic system: Driver-Vehicle-Environment" and the project TR31046 " Improvement of the quality of tractors and mobile systems with the aim of increasing competitiveness and preserving soil and environment", supported by Serbian Ministry of Education, Science and Technological Development.

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MOBILITY & VEHICLE MECHANICS

DOI: 10.24874/mvm.2019.45.03.05
UDC: 66.017:629:02

APPLICATION OF NANOCOMPOSITES IN THE AUTOMOTIVE INDUSTRY

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Received in September 2019, Accepted in October 2019

RESEARCH ARTICLE

ABSTRACT: The development of new lightweight and strong materials and the design of new products are among the key elements for the development of new advanced construction and vehicle parts for the automotive industry. The use of composite materials in the automotive industry has been popular in recent decades due to the need to reduce vehicle weight, which directly affects fuel consumption and exhaust gases emission. In this way, the development of improved new materials with improved performance is accomplished. Nanocomposites represent a new class of materials that has excellent thermal and mechanical properties. The application of nanocomposites for development of automotive components is reflected in the improvement of the production rate, environmental and thermal stability, and the reduction in weight in the automotive industry, less wear parts, and indirectly to reduce CO_2 emissions and environmental pollution. This research paper presents a review of the application of nanocomposites (metal, ceramic and polymeric) in the automotive industry.

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KEY WORDS: application, ceramic matrix nanocomposites, metal matrix nanocomposites, polymer matrix nanocomposites, vehicles

PRIMENA NANOKOMPOZITA U AUTOMOBILSKOJ INDUSTRIJI

REZIME: Razvoj novih laganih i jakih materijala i dizajn novih proizvoda su jedan od ključnih elemenata za razvoj nove napredne konstrukcije i delova vozila za automobilsku industriju. Upotreba kompozitnih materijala u automobilskoj industriji popularna je poslednjih decenija zbog potrebe za smanjenjem težine vozila, što direktno utiče na potrošnju goriva i emisiju izduvnih gasova. Na ovaj način se postiže razvoj poboljšanih novih materijala sa poboljšanim performansama. Nanokompoziti predstavljaju novu klasu materijala koji imaju odlična termička i mehanička svojstva. Primena nanokompozita za razvoj automobilskih komponenti ogleda se u poboljšanju brzine proizvodne, životne sredine i termičke stabilnosti i smanjenju težine u industriji vozila, smanjenju habanja delova i indirektno na smanjenje emisije CO_2 i zagađenja životne sredine. Ovaj istraživački rad predstavlja pregled primene nanokompozita (metala, keramike i polimera) u industriji vozial.

KLJUČNE REČI: primena, keramička matrica nanokompozita, metalna matrica nanokompozita, polimerna matrica nanokompoziti, vozila

APPLICATION OF NANOCOMPOSITES IN THE AUTOMOTIVE INDUSTRY

Sandra Veličković, Blaža Stojanović, Lozica Ivanović, Slavica Miladinović, Saša Milojević

1. INTRODUCTION

Automotive industry is constantly making efforts to the development and application parts that are light weight, and which at the same time possess excellent mechanical and tribological properties. Today, the automotive industry must meet certain requirements in terms of reducing fuel consumption and at the same time to maintain adequate comfort and safety of the vehicle. Another important factor is the weight of the vehicle, which has a direct impact on fuel consumption and thus the emission of toxic and harmful products of combustion [1–3].

The hardest part of the vehicle is the body shell, which makes 40% of its total weight. Therefore, the most common approach to lightweight design integrated within the structure of the vehicle which uses a combination of different materials, depending on their engineering properties and functional characteristics. In recent years increased use of high-strength steel, which in compact European cars makes 50 to 60% of the body. In addition to the use of steel, has increased the use of thermoplastics and thermoset composites used for coating bodywork, bonnet, roof components and other components of the body. The main materials used in the automotive industry are composites which are made of high-strength steel, aluminum, and composites of carbon fiber and plastic. Applying high-strength steel is achieved by lessening the weight by 20% compared to the conventional steel constructions, use of aluminum of 40% and 50% at the application of composites of carbon fiber. Therefore, by using light materials, reduces the weight of the vehicle, for example, the weight of aluminum ties in the suspension is smaller by 15% than the conventional, hollow composite shaft is 18% lighter than the conventional, and the application of forged aluminum rim saves up to 36% when compared to steel wheels [4].

Aluminum as a very light material is used as the main matrix element in the production of composite materials referred to as aluminum metal matrix composites (AMCs). Application of aluminum composite is widespread, from the military, automotive, flights until the space industry. AMCs compared with primary aluminum alloy have a good combination of mechanical and tribological properties. In addition, these properties can be tailored to the specific requests [1,2]. AMCs possess improved physical and mechanical properties such as strength to weight ratio, a good ductility, a high strength and a high modulus of elasticity, low thermal expansion coefficient, good wear resistance, good corrosion resistance, high temperature creep resistance, and better fatigue [5]. The use of lightweight materials for the production of automotive components also contributed to the reduction of air pollution.

Nanocomposites represent a new class of materials that exhibit excellent thermal and mechanical properties. Due to the high performance are suitable for use in aerospace, automobile, chemical and transport industry [2]. The first industrial production of nanocomposites in the automotive industry occurred in 1991 with the production of timing belt covers as part of the engine for Toyota Camry cars [6].

Most research and development based on nanotechnology is being implemented in the automotive sector. Nanotechnology is applied to parts of the body, chassis and tires, automotive interiors, electrical and electronics, IC engines and drive systems [7]. In recent years, remarkable progress has been made in various industries which motivated researchers to work on new structural materials for better performance in engineering applications.

Tiruvenkadam N. et al have made investigations of the use of the aluminum hybrid nanocomposite for the IC engine cylinder liner (NL) analyzing the performance, combustion and emission characteristics of the engine and others. The aim was to replace the piston cast-steel composite material with the base of Al 6061 and Nano reinforcement zirconium dioxide (ZrO_2), silicon carbide (SiC) and Solid lubricant graphite (Gr) to the size of reinforcement 100 nm, 220 µm and 100 microns, respectively. The mass fraction of each reinforcement amounted to 2.25 wt. %. They concluded that the combination of the selected matrix with reinforcement suitable for NL based on the density, mechanical and thermal properties and of a homogeneous mixture is carried out based on SEM analysis. They also found that the application of NL can achieve greater in−cylinder pressure and higher efficiency. Applying NL is reduced emissions of CO, HC and smoke quantity output, but the increased NOx emission [8].

Carvalho O. et al have applied a hybrid nanocomposite with an aluminum base for making the piston ring [9]. The material that was used is a hybrid nanocomposite with aluminum base reinforced with SiC particles, and nano MWCNT's of the order of 50 nm, produced by hot−pressing technique in order to evaluate the different fraction of CNTs. The best results have shown abrasion in case of the 6 wt. % CNTs, however, because the best ratio between mechanical and tribological properties of a piston rings are selected from the 2 wt. % of CNTs.

Testing of mechanical and tribological characteristics of the nanocomposite is executive for the production of connecting rods are Ramachandra M. et al [10]. The application of aluminum alloys with 99% of purity and reinforcement n−ZrO_2 25 nm in size were made using the nanocomposite powder metallurgy technique for the production of connecting rods. Testing of wear is made to pin on disc wear testing machine. The study came to the conclusion that the nanocomposite has a higher value than the hardness of the material base, and also reduces wear nanocomposites.

The application of the nanocomposite with a base of aluminum A356-reinforced nano−particles of the CNT is used for making disc brakes and the drum [11]. Sundaram M. and Mahamane U. produced nanocomposite by the method of casting with mixing. Tests have shown that an increase in the mass fraction of nano reinforcement CNT based on the A356 leads to an increase in hardness, while reducing wear, and friction coefficient. Increasing the hardness of the nanocomposite with an increase in the value of reinforcement in the aluminum base and have found Ranaa R. et al [12]. They interrogators aluminum nanocomposite reinforcement with SiC is used for the preparation of camshafts. Stir the nanocomposite is produced casting method with the percentages by weight of reinforcement of SiC of 1 to 4 wt. % And a particle size of 40 nm in the Al base. To improve the mechanical and tribological characteristics of aluminum nanocomposite came Asmatulu R. et al [13]. LM6 alloy strengthened reinforcement nano SiC and Al_2O_3 in the relationship 0.5, 1.0, 1.5 and 2 wt. % of a styrene casting method. Based on the results concluded that as such, the composite can be used in the automotive industry for the production of brake discs.

Summarizes the application of a hybrid nanocomposite with aluminum base Al 356 and Al 7075 in the automotive industry have made Dhanabal S. et al. [14]. As reinforcement nano size is used various kinds of materials and by methods of making nanocomposites discussed with stirring casting and pressure casting. The study characterization of nanocomposites came to the result that the piston for making the best show nanocomposites with reinforcement SiC−Al_2O_3, Al_2O_3−MoS_2, TiC, Gr, for the piston ring are nanocomposites reinforced with Al_2O_3−graphite, drum brakes for the reinforcement TiB_2−SiC, the shaft reinforcement is SiC, for camshaft reinforcement SiC−CNT, Al_2O_3−TiC and Al_2O_3 for valves.

The aim of this research is reflected in the review of the application of nanocomposites with metal, polymer and ceramic base in the automotive industry, and anticipates further growth in the use of these composites. The increase in the use of nanocomposites for automotive components is expected from year to year because the use of these composites impact on reducing the weight of vehicles, environmental and thermal stability and promoting environmental actions.

2. COMPOSITE MATERIALS

Composite materials are produced by adding basic material of the reinforcement in order to improve certain characteristics, depending on the purpose of the selected base material and the reinforcement. The composites are used as a basic structural material in the aerospace and automotive industry is comprised of deformable metal base and the rigid ceramic as reinforcement. These compositions are known as a composite with a metal base (MMC−Metal Matrix Composite). The first level of classification of composite materials depending on the base material, in addition to existing MMC polymer matrix composites (PMC−Polymer Matrix Composite), a ceramic matrix when it is about composites with ceramic matrix (CMC−Ceramic Matrix Composite) [15, 16].

The second level of classification of composites relates to the shape of reinforcement - the particles, short fibers, laminar composites with continuous fibers and woven composites. In this category are braided and knitted fiber bundles (short fibers, continuous fiber laminated composites) and woven composites (braided and knitted fiber architectures are included in this category) [17]. When the composite material has reinforcement in which at least one dimension in the nanometer scale or less than 100 nm, then the case of nanocomposites [16]. Therefore, the nanocomposites are composites that consist of the base material and the nano size of the reinforcement which do not dissolve in one another.

Nanocomposites reinforced particles are largely used in the automotive industry due to their ability to withstand high temperatures and pressures. Several manufacturing methods used to produce them. The main disadvantage of these materials is a lack of homogeneity in the dispersion of the particles as and weak links between the matrix and the particles. However, research and testing of nanocomposites are still underway about the process of obtaining and variations of certain parameters in order to overcome the aforementioned shortcomings.

2.1 Metal Matrix Nanocomposites

Nanocomposites reinforced particles are largely used in the automotive industry due to their ability to withstand high temperatures and pressures. Several manufacturing methods used to produce them. The main disadvantage of these materials is a lack of homogeneity in the dispersion of the particles as and weak links between the matrix and the particles. However, research and testing of nanocomposites are still underway about the process of obtaining and variations of certain parameters in order to overcome the aforementioned shortcomings.

Metal Matrix Nanocomposites (MMNC's) use ductile metallic matrix in which the ceramic reinforcement adds. Various properties of these composites is improved, including the density, the hardness, abrasion, deformation and corrosion resistance depending upon the reinforcement (type, type and content) and the matrix as a manufacturing process. MMNC's become important because composites are used in the industry [19]. Nano−particles as a reinforcement in metal matrix composites have been progressively replaced other types of reinforcement such as nano−fibers, nano−whiskers or nano−platelets. The main division is reinforcing the oxides, carbides, nitrides and borides. The most commonly used types of nanoparticles are: SiC, TiC, WC, TaC, TiB_2, AlN, and Al_2O_3 [18, 20]. For an easy and high–quality use in automobile components as a template for the production of MMNCs used low density metals such as aluminum (Al), magnesium (Mg), and titanium (Ti) [20]. Aluminum and aluminum alloys have found many applications in addition to the automotive and aerospace industry in conjunction with carbon–reinforced composites, and silicon carbide. Use of aluminum alloy (such as Al–Si alloy) for a matrix is preferred because of its advantages, including low cost and easy workability [17].

The most important production methods that are used for aluminum composites are: stir casting, squeeze casting, compo casting and infiltration, spray deposition and powder metallurgy [17]. Stir casting ranks first among all the available techniques because of the low cost, the possibility of using a wide range of materials as well as on processing conditions, where they can be made with compositions up to 30% in the volume fraction of reinforcement [18].

Basic classification process for obtaining nanocomposites can be classified into three groups:

1. Solid state processes include different powder metallurgy techniques with modifications in the processing steps such as, high–energy ball mill, hot pressing, hot isostatic pressing, cold pressing followed by sintering treatment and extrusion
2. Liquid state processes include different processes such as casting, stir casting and squeeze casting list and
3. Semi–solid processes include recasting technique with its variants such as compo casting or in combination with squeeze casting list.

Figure 1 presents the predictions of application of aluminum in different types of vehicles.

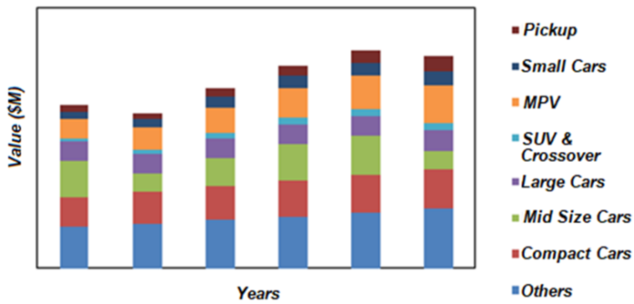

Figure 1. Application of aluminum from 2017 to 2022 [22]

Typical automotive parts which are made of a composite based aluminum alloys as a cylinder head (cylinder head), the pistons, the wheels, crankcase, cylinder head cover, intake manifold, the intake system and the drive means such as fork for a change–speed, drive shaft, gears, gear housing and so on. Application of aluminum castings in the field of automobile industry followed the development of the casting process, the melt treatment and thermal treatment. Great efforts have been made with the aim of improving mechanical and tribological characteristics, by controlling the microstructure that is by improving the processes for preparation, treatment of the metal melt and the heat treatment [15, 16]. Research of composite materials precisely nanocomposites is still in progress. Researchers have been testing the nanocomposite concluded that they can be applied for the production of the respective parts of cars, such as the piston rings [8], the pistons [9], the connecting rods [10], the disc brakes and the drum brake [11], the camshaft [13], the shafts and the valves [14]. Nanoparticles are common by–products of combustion of oil and other hydrocarbon compounds, combustion and exhaust gases. As stated above, in the automotive industry uses a lot of materials with nanoparticles, and in recent years studies have shown that these nanoparticles can be found in water, air, soil, and therefore in the bodies of animals and humans. These results have led to a debate about toxicity and impact on the environment nanocomposites. Method maturities of nanoparticles in the human body by inhalation, absorption through the skin and if swallowed. Diseases that occur accumulation of nanoparticles in the body of the inflammatory airway disease, bronchitis, asthma, lung cancer, neurodegenerative diseases, cardiovascular disease, liver cancer, Parkinson's disease, Alzheimer's disease, Crohn's disease, and others. Because of these dangers should be given a lot of attention to protecting people during manufacture, transport, handling, use, disposal and recycling of parts and machines which in themselves have nanocomposites [13].

2.2 Polymer Matrix Nanocomposites

The polymers are excellent in terms of low density, ease of machining and the corrosion resistance, however, their rigidity and strength are much less than is required for structural applications. The polymers are considered to be suitable for structural applications matrices, due to their light weight, light processing and long−term stability [23].

Traditional micro reinforcement shall be replaced by nano−reinforcement in a polymer matrix, making a polymeric nanocomposite. These reinforcement leads to a significant improvement of certain structural and functional features of the polymer in relation to the polymer micro−reinforced reinforcement [4].

Polymer matrix nanocomposites (PMNCs) are a combination of materials wherein one dimension of the reinforcement is less than 100 nm. The main conditions for the development are the low density PMNCs, ecological and high mechanical properties with a high production speed, good surface finish and with improved corrosion resistance, as well as better operating temperatures [18]. The preparation of nanocomposites uses a wide range of polymers, of which the most commonly used elastomers, thermoplastics and thermosets [23]. With the development of nanotechnology, various types of nano−reinforcement such as silicate nanoparticles are produced and used in the polymer materials to create so−called nanocomposites of polymer matrix (PMNCs). Uniform dispersion of nanoparticles in the polymer matrix leads to a significant improvement of the properties of the nanocomposites as compared to those of conventional reinforced composites micro particles [23, 24]. When the polymer matrix is added a small amount of the nanoparticles leads to improve the mechanical properties, the increase in resistance to cracking and propagation, as well as reducing the coefficient of thermal expansion (CTE) of the PMNCs. As reinforcement in polymeric materials for making these PMNCs, silica nanoparticles are used due to relatively high elastic modulus, low density, and good abrasion resistance, low coefficient of thermal expansion, high thermal stability, and low running costs [24]. There are different processes for the preparation of polymer nanocomposites and each of them has its advantages and disadvantages. As well as in the manufacture of nanocomposite of metal and this must be taken into account for selecting the appropriate method, which corresponds to the target application of the material, as well as the material properties, the ratio of the base and reinforcement, as well as the dispersion of the target performance. Solvent mixing, melt mixing, and in situ polymerization are some of the most common routes for nanocomposite synthesis [23, 25]. Automotive market has the largest market share of the polymeric nanocomposites thanks to widespread use such as a drive mechanism, the inner and outer power train, suspension and braking systems, exhaust systems and catalytic converters, lubrication, tires and body parts [4, 26]. On the basis of more stringent legal regulations regarding standards of reducing emissions of cars is expected that the market of polymer nanocomposites recorded a significant increase in applications in the automotive and defense industries, as well as in aerospace engineering. It is expected that the production of nanocomposites result in reducing carbon dioxide emissions from cars. In addition to the automotive industry, the use of polymer composites is increased and the airline industry due to increased production of laminates, sandwich structure, lightning rods and anti-radar protection. Besides the already mentioned application of polymer composites are also used in bio–medicine at the recording of biological, cell tracking, the magnetic separation of biological, nanomedicine [26].

Other potential applications PMNCs in the automotive industry are as follows [18]: the cap of belt gear unit, the bonnet, fuel hoses, fuel valves, door frames, backrests, fuel hoses, and fuel valves, door frames, seat backs, step assists, heavy duty electrical enclosures, sail panel, box rails, fascia, grills, hood louvers, instrument panels, side trims, body panels, and fenders, sensors, fuel cells. Figure 2 shows the application of polymer nanocomposites with the parts of the car.

The automotive industry in Europe invests more than 5% of annual turnover in research and development, and the main focus is on the development of better coatings and paints and stronger, more robust parts for end use. Therefore it is expected that the use of polymeric nanocomposites car market growth over the next ten years [6]. Overall, the use of plastics in the global market is promising for passenger cars, light commercial vehicles and heavy commercial vehicles. It is anticipated that the global plastics market by 2023 jump to 25.2 billion, and is predicted also a growth of 2.6% in the period from 2018 to 2023.

Figure 2. Illustration of the usage of polymer nanocomposites parts [6]

New trends have directly influence the dynamics of the plastic industry, including the development of technologies for recycling of plastic, and replace PA 66 with cheaper and more advanced PA 6. The diagrams, Figure 3 shows the prediction of application of polymeric materials from 2018 to 2023.

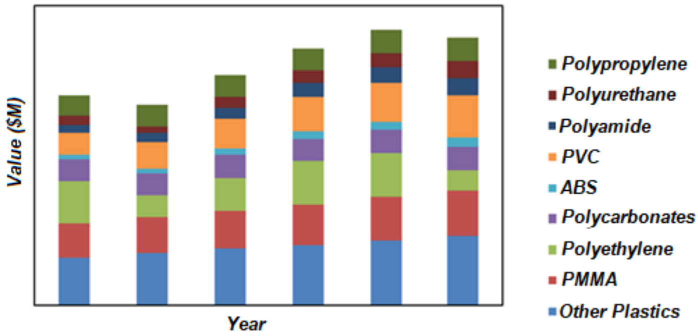

Figure 3. Histogram display forecasting application of polymeric materials in cars from 2018 to 2023 [22]

Trends, opportunities and market forecasts in the automotive industry until 2023, Figure 4 by type of vehicle: passenger cars, light-duty commercial vehicles and heavy-duty commercial vehicles. Based on the diagram in Figure 4 can be concluded that in the next five years, provides for reducing the use of heavy vehicles, indicating an increase in the application of new materials, i.e. nanocomposites.

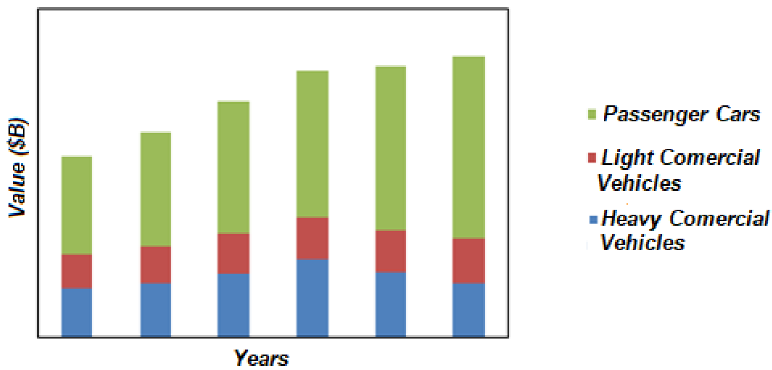

Figure 4. Histogram display forecasts car market in the world [6]

2.3 Ceramic Matrix Nanocomposites

Ceramic composites with dispersed metal particles represent a class of promising material for high performance applications in harsh environments, such as high temperature. These materials offer the possibility of combining a resistance to heat, resistance to degradation, and the abrasion resistance of the ceramic phase having a high mechanical strength and thermal conductivity is provided with metal phase. Ceramic matrix nanocomposites (CMNCs) is used for making nozzle assemblies, materials stoves, systems for converting energy, gas turbines, thermal engines, etc. [27]. The ceramic materials are insensitive to extremes of temperature as opposed to the steel at a high temperature changes the mechanical properties. In particular, they showed good composite materials reinforced with carbon fibers, which are very durable at high temperatures, have a high wear resistance, and have substantially lower specific weight compared with steel and aluminum. Carbon fiber reinforced composites are increasingly being used for car parts that are exposed to high loads, such as e.g. brake disks, valves, cylinder liners, spark plugs, sensors, isolators, filters, piston and others. Safe driving is achieved by applying the brake discs made of ceramic composites, because the discs have a great resistance to deformation and wear, thereby enabling a great savings in weight. Advantages of using the ceramic composite material in the automotive industry are: the ability to create very complex shapes, reduce the cost of after-treatment of parts, the possibility of connecting the parts during the manufacturing process, dimensional stability in extreme working conditions, corrosion resistance, ease of maintenance, longer life time, possibility to work-up and recyclability [28]. Disadvantages application of ceramic composite materials in the automotive industry are: the high cost of production, no serial production, the potential for products that are not in use, lack of skilled labor, cruelty (no deformability), sensitivity to moisture and temperature, inability to repair, toxicity, flammability, etc. Another downside application of ceramic materials is the tendency to fracture, expensive process of production and insufficient research [28].

The aforementioned disadvantages are the reason of low presence of micro and nano-ceramic materials in the automotive industry which can be seen in the diagram in Figure 5.

Compared to conventional CMCs ceramic nanocomposites have improved hardness, high strength, toughness and creep resistance, thermal shock resistance, flame retardancy, magnetic and optical properties, chemical inertness, wear resistance and low density. In addition to automotive applications because of their thermal shock resistance and flame retardancy are used for high-temperature thermal shock zones, such as the fusion energy applications, in gas turbines, aerospace applications, cutting tools, rock drill tips, tools and dies as well as general wear parts, and many others [29]. The interest of science in recent decades toward the magnetic nanocomposites because of their functional properties for which are widely used starting from the field of magnetic fluid catalysis and adsorption, biotechnology, biomedicine, magnetic resonance imaging, data storage, electronics, magneto-optic and photo catalysis to supercapacitors, hyperthermia, drug shipments, remediation of water, collecting energy. When environmental and biomedical and catalytic apply magnetic metal–ceramic nanocomposites because of its porous structure. These composites are composed of a dispersion of nano–particulate Fe^0, CO^0, or Ni^0 nanoparticles usually in amorphous silica or alumina ceramic matrix [30, 31].

3. STATUS OF APPLICATION OF NANOCOMPOSITES IN THE WORLD IN THE AUTOMOTIVE INDUSTRIES

Improving the performance of vehicles in terms of quality elements as well as the reduction of greenhouse gas emissions is the constant tendency of the automotive industry. The main driver of the motor vehicle industry is to increase fuel efficiency and reducing vehicle weight. The application of composites in cars is affected by high production as well as stringent market regulations. According to the International Organization of Motor Vehicle Manufacturers, in 2016, total production of 95 million cars and commercial vehicles. In the following chart according to research [26] provides an overview of the car market in the US with revenues by products in recent years and forecasting to 2025, Figure 5.

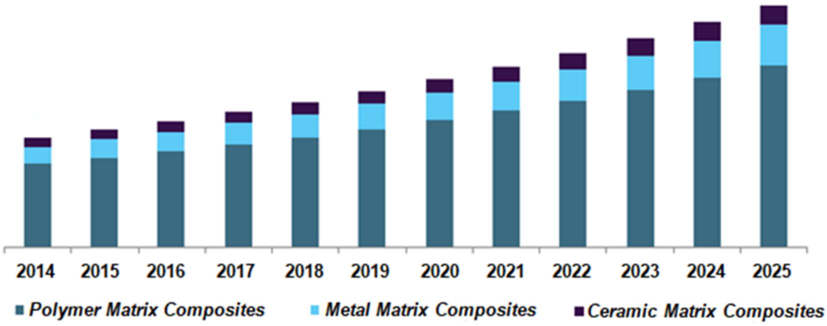

Figure 5. The car market in the US revenue by product, 2014 – 2025 (USD Million) [26]

Growing of carbon emissions due to increased number of vehicles in recent years in the world, launched by governments around the world to react and reconsider the emissions from vehicles. Countries such as China, Japan, Vietnam and Indonesia have implemented various policies in terms of emission standards.

Car manufacturers and composites are well acquainted with the regulations of the countries and producing products that meet specified standards. Automakers believe that reducing vehicle weight is one of the most effective solutions for ensuring compliance and reducing emissions. For every 100 pounds per 45 kg (from 2 to 3%), results in low emissions [26].

According to studies [22] of the global vehicle market is projected to grow by 5.3% in the period from 2018 to 2023 with great possibilities in the areas of passenger cars, commercial vehicles and heavy commercial vehicles segment. The main growth drivers for this market are increasing production of the vehicle, increasing the need to improve the ride quality and the growing need for advanced systems of safety and comfort [22].

According to reports and prognosis [32] of the European market of automotive composites there is a possibility of growth in a variety of applications, exterior, interior, chassis systems, body and others. It is anticipated that the European market of automotive composites by 2021 will reach $ 4.1 billion and is projected to grow by 5.8% from 2016 to 2021. The main growth drivers for this market are increasing car production and increasing demand for lightweight materials. The European Union has set new standards require that passenger cars must meet CO_2 emission target of 95 $g \cdot km^{-1}$ (equivalent to 57.9 mpg) by 2021, and for the production of light vehicles is 147 $g \cdot km^{-1}$ (equivalent to 43.3 mpg) by 2020 years. The European Commission proposes to improve European standards of fuel economy.

New trends that influence the dynamics of the industry include increasing penetration of thermoplastic and carbon composites. Another emerging trend is in the formation of strategic alliances between the OEMs and the supplier of carbon fiber and the resin in the automotive industry.

4. CONCLUSIONS

The following generalized conclusions can be written from the study performed during presented research:

- The main initiators of growth in demand nanocomposites are increasing car production and increasing demand for lightweight materials. It is expected that the implementation of the structural and operating parts increase the rate because composites act as an excellent substitute for metal parts
- Increasing importance is attached to reducing the weight of vehicles because of improving fuel economy, then to improve vehicle performance and reduce emissions. Based on the review of literature predicts an increase in demand for nanocomposites in the automotive industry in the coming years
- It is expected that the increase in research and development activities nanocomposites lead to an increase in their application in structural and operating parts and thus stimulate the growth of the market. The advantage of using nanocomposites in external components and drive luxury cars have a positive impact on demand in the market. Nanocomposites based on a variety of materials of metal or plastic reinforced with metal or ceramic nanoparticles can significantly improve the strength of parts. Different requirements of the automotive industry, such as improved mechanical, electrical, thermal, corrosion, self-cleaning and antiwear properties, and sensing abilities correspond nanocomposites reinforced with nanoparticles, nanofilms, nanoflakes, nanotubes, nanofibers and
- In the future, attention should be paid, in addition to developing lighter materials, the protection of the environment through increased recycling rates of the vehicle at end of life. Based on the examination papers noted that talking about the difficulties in the recycling of composites and can not give up on their application in the automotive industry, it is necessary to find a proper recycling methods.

ACKNOWLEDGMENTS

This paper presents the research results obtained within the framework of the projects TR35021, TR35033 and TR35041 financially supported by the Ministry of Education, Science and Technological development of the Republic of Serbia.

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ili poštom na adresu Časopisa
Redakcija časopisa M V M
Fakultet inženjerskih nauka
Sestre Janjić 6, 34000 Kragujevac, Srbija

Po objavljivanju rada, Redakcija časopisa šalje prvom autoru jedan primerak časopisa.

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