Volume 41, Number 1, 2015.

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

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

Editors: Prof. dr ***Jovanka Lukić****; Prof. dr* ***Čedomir Duboka***

MVM *Editorial Board*
University of Kragujevac
Faculty of Engineering
Sestre Janjić 6, 34000 Kragujevac, Serbia
Tel.: +381/34/335990; Fax: + 381/34/333192

For Publisher: Prof. dr Miroslav Živković, dean, University of Kragujevac, Faculty of Engineering

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

Intentionally blank

NOTIFICATION TO AUTHORS

The Journal MVM publishes original papers which have not been previously published in other journals. This is responsibility of the author. The authors agree that the copyright for their article is transferred to the publisher when the article is accepted for publication.

The language of the Journal is English.

Journal ***Mobility & Vehicles Mechanics*** is at the SSCI list.

All submitted manuscripts will be reviewed. Entire correspondence will be performed with the first-named author.

Authors will be notified of acceptance of their manuscripts, if their manuscripts are adopted.

INSTRUCTIONS TO AUTHORS AS REGARDS THE TECHNICAL ARRANGEMENTS OF MANUSCRIPTS:

Abstract is a separate Word document, "*First author family name_ABSTRACT.doc*". Native authors should write the abstract in both languages (Serbian and English). The abstracts of foreign authors will be translated in Serbian.

This document should include the following: 1) author's name, affiliation and title, the first named author's address and e-mail – for correspondence, 2) working title of the paper, 3) abstract containing no more then 100 words, 4) abstract containing no more than 5 key words.

The manuscript is the separate file, „*First author family name_Paper.doc*" which includes appendices and figures involved within the text. At the end of the paper, a reference list and eventual acknowledgements should be given. References to published literature should be quoted in the text brackets and grouped together at the end of the paper in numerical order.

Paper size: Max 16 pages of B5 format, excluding abstract
Text processor: Microsoft Word
Margins: left/right: mirror margin, inside: 2.5 cm, outside: 2 cm, top: 2.5 cm, bottom: 2 cm
Font: Times New Roman, 10 pt
Paper title: Uppercase, bold, 11 pt
Chapter title: Uppercase, bold, 10 pt
Subchapter title: Lowercase, bold, 10 pt
Table and chart width: max 125 mm
Figure and table title: Figure _ (Table _): Times New Roman, italic 10 pt

Manuscript submission: application should be sent to the following e-mail:

mvm@kg.ac.rs ; lukicj@kg.ac.rs
or posted to address of the Journal:
University of Kragujevac – Faculty of Engineering
International Journal M V M
Sestre Janjić 6, 34000 Kragujevac, Serbia

The Journal editorial board will send to the first-named author a copy of the Journal offprint.

OBAVEŠTENJE AUTORIMA

Časopis MVM objavljuje orginalne radove koji nisu prethodno objavljivani u drugim časopisima, što je odgovornost autora. Za rad koji je prihvaćen za štampu, prava umnožavanja pripadaju izdavaču.

Časopis se izdaje na engleskom jeziku.

Časopis ***Mobility & Vehicles Mechanics*** se nalazi na SSCI listi.

Svi prispeli radovi se recenziraju. Sva komunikacija se obavlja sa prvim autorom.

UPUTSTVO AUTORIMA ZA TEHNIČKU PRIPREMU RADOVA

Rezime je poseban Word dokument, "*First author family name_ABSTRACT.doc*". Za domaće autore je dvojezičan (srpski i engleski). Inostranim autorima rezime se prevodi na srpski jezik. Ovaj dokument treba da sadrži: 1) ime autora, zanimanje i zvanje, adresu prvog autora preko koje se obavlja sva potrebna korespondencija; 2) naslov rada; 3) kratak sažetak, do 100 reči, 4) do 5 ključnih reči.

Rad je poseban fajl, „*First author family name_Paper.doc*" koji sadrži priloge i slike uključene u tekst. Na kraju rada nalazi se spisak literature i eventualno zahvalnost. Numeraciju korišćenih referenci treba navesti u srednjim zagradama i grupisati ih na kraju rada po rastućem redosledu.

Dužina rada: Najviše 16 stranica B5 formata, ne uključujući rezime
Tekst procesor: Microsoft Word
Margine: levo/desno: mirror margine; unurašnja: 2.5 cm; spoljna: 2 cm, gore: 2.5 cm, dole: 2 cm
Font: Times New Roman, 10 pt
Naslov rada: Velika slova, bold, 11 pt
Naslov poglavlja: Velika slova, bold, 10 pt
Naslov potpoglavlja: Mala slova, bold, 10 pt
Širina tabela,dijagrama: max 125 mm
Nazivi slika, tabela: Figure __ (Table _): Times New Roman, italic 10 pt

Dostavljanje rada elektronski na E-mail: **mvm@kg.ac.rs ; lukicj@kg.ac.rs**

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.

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

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

Volume 41
Number 1
2015.

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

Volume 41
Number 1
2015.

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

ANALYSIS AND COMPARISON OF MODERN IC ENGINES COMPARATIVE CYCLES BY USING A GENERAL THERMODYNAMIC CYCLE

Dragoljub Radonjić[1]

UDC: 621.43.018.4;536.8

ABSTRACT: Analysis and comparison of the comparative cycles is of great importance in assessing the effectiveness and efficiency of actual cycles of internal combustion engines. In conventional combustion engines are used the three main comparative cycles: otto, diesel and dual. The development of internal combustion engines, by applications: the new system of mixture formation (GDI, HCCI), variable valve timing, overboost system and aftertreatment of exhaust gases, bring to modification of the real working cycle, but also the need to introduce new comparative cycle such as Atkinson, Miller, Gruden and HEHC cycles.

Previous methods of analysis and comparison of the ideal cycle is reduced to the determination of the expression of specific work and thermal efficiency of each cycle as a function of the characteristic parameters, adopting the criteria of comparison and finally, comparison of the specific work and efficiency of the given cycle at different values of the selected parameter.

This paper presents a new method of comparison based on the application of the general thermodynamic cycle (GTC), introduced by the author. From the general thermodynamic cycle, in particular procedures can be carried out, all possible cycles for converting heat into work (total: 130), and by determining the expression of specific work and efficiency of this cycle and placing them in appropriate conditions can obtain expressions for the specific work and efficiency of each cycle. On the basis of these procedures has been developed a software package that provides graphical views of the following characteristics of the selected cycle: P-v and T-s diagrams, changes the specific work and thermal efficiency as a function of the desired dimensionless parameter, as well as the comparison of two or more cycles according to proposed criteria.

KEY WORDS: cycles comparison, the general thermodynamic cycle, specific work, the thermal efficiency

ANALIZA I POREĐENJE IDEALNIH CIKLUSA SAVREMENIH MOTORA SA UNUTRAŠNJIM SAGOREVANJEME PRIMENOM OPŠTEG TERMODINAMIČKOG CIKLUSA

REZIME: Analiza i poređenje idealnih ciklusa ima velikog značaja pri oceni efektivnosti i ekonomičnosti stvarnih radnih ciklusa motora SUS. Kod klasičnih motora SUS koriste se tri osnovna uporedna ciklusa: oto, dizel i kombinovani. Razvojem motora SUS, pre svega primenom: novih sistema za obrazovanje smeše (GDI, HCCI), promenljive šeme razvoda, nadpunjenja i sistema za naknadnu obradu izduvnih gasova, došlo je do modifikacije postojećih ciklusa, ali i do potrebe uvođenja novih uporednih ciklusa kao što su: Atkinson, Miler, Gruden i HEHC ciklusi. Dosadašnji metod analize i poređenja idealnih ciklusa se

[1] *Received: September 2014, Accepted October 2014, Available on line January 2015*

svodio na određivanje izraza za specifični rad i stepen iskorišćenja svakog pojedinačnog ciklusa u funkciji karakterističnih parametara, usvajanja kriterijuma poređenja i konačno, poređenja vrednosti specifičnog rada i stepena iskorišćenja datih ciklusa pri različitim vrednostima izabranog parametra.U radu je prikazan novi metod poređenja koji se zasniva na primeni opšteg termodinamičkog ciklusa (GTC), uvedenog od strane autora. Iz opšteg termodinamičkog ciklusa, po određenoj proceduri, mogu se izvesti svi mogući ciklusi za pretvaranje toplote u rad (ukupno: 130), pa se određivanjem izraza za specifični rad i stepen iskorišćenja ovog ciklusa i stavljanjem u njih odgovarajućih uslova mogu dobiti izrazi za specifični rad i stepen iskorišćenja svakog pojedinačnog ciklusa. Na bazi navedene procedure razvijen je softverski paket koji omogućava grafičke prikaze sledećih veličina izabranog ciklusa: pV i Ts dijagrama, promene specifičnog rada i stepena iskorišćenja u funkciji željenog bezdimenzionog parametra, kao i poređenje dva ili više ciklusa po zadatom kriterijumu.

KLJUČNE REČI: poređenje ciklusa, opšti tremodinamički ciklus, specifični rad, termodinamički stepen korisnosti

ANALYSIS AND COMPARISON OF MODERN IC ENGINES COMPARATIVE CYCLES BY USING A GENERAL THERMODYNAMIC CYCLE

Dragoljub Radonjić[1] PhD, Professor

UDC:621.43.018.4;536.8

INTRODUCTION

Describe the process of conversion heat into mechanical work in heat engines by a closed, thermodynamic cycle started Sadi Carnot (1796. ÷ 1832.), introducing the famous Carnot's cycle [8]. This cycle has the highest efficiency, but because of the wide changes interval of the characteristic state variables (pressure and volume) cannot be implemented in real heat engine.

With the advent of heat IC engines (Otto and Diesel), are introduced and the corresponding comparative cycles with isochoric (Otto) and isobaric heat addition (Diesel) cycle. The largest contribution to the development of Diesel engines represents, of course, the discovery of the fuel injection system under high pressure (James McKechnie, 1910).. This innovation led to the modification of the comparative Diesel engines cycle in which now used the combined method of the isochoric-isobaric heat addition in the literature known as: Sabathe's, Seiliger's or the combined cycle.

Regardless what is in the comparative cycle idealize the phases of the actual IC engines cycle (isochoric, isobaric and isochoric-isobaric heat addition, adiabatic compression and expansion and isochoric heat rejection), their study can define the basic relationship between the characteristic cycle parameters and efficiency, ie, the specific work that apply to the actual cycles. It is usual that this dependences is determined by the combined cycle, as well as the general, and from them, under pre-defined conditions, obtained expressions for the thermal efficiency and specific work of Otto and Diesel cycles.

Intensive development of Otto and Diesel engines for passenger cars, caused by strict regulations to improve the environmental characteristics and fuel consumption while preserving performance, influenced and the character of the cycles of modern engines. For this reason it was necessary to modify the existing comparative cycles and / or introduce new ones. Modern technologies that require or enable the implementation of new cycles are certainly GDI, HCCI engines, overboost, variable systems (VCR, VVT, VVL), EGR, fuel injection during the course of expansion, hybrid drive, etc.

Of the new comparative cycles which fullest characterize the actual working cycles of modern engines are certainly the most important: Atkinson's [2], Miller's [1], [4], [5] and HEHC [7] cycle, and cycles with isothermal expansion (Gruden [6]). Comparison of these cycles according to the criteria of economy (thermal efficiency) and effectiveness (specific work), involves the determination of the analytical expression of these values for each cycle individually, then assessment of the impact of cycle characteristic parameters on their values. In this paper just presents a method of using the general thermodynamic cycle (GTC) [3], for analysis and comparison of all existing comparative heat engine cycles.

In general thermodynamic cycle heat addition and rejection is isochoric-isobaric-isothermal (VPT) and the processes of compression and expansion are adiabatic, which allows to the appropriate combinations of these state changes derive all of the existing

[1] *Dragoljub Radonjić,Ph.D.,full.prof.,Faculty of Engineering in Kragujevac, S.Janjić 6, 34000 Kragujevac, drago@kg.ac.rs*

cycles (130). The formulas for the thermal efficiency, specific work and the values of the state variables (p, V, T, S) in the characteristic points of the general thermodynamic cycle are modeled by using Simulink program, so that the output can get graphical representations of state changes in the course of the cycle in the form of p-V and T-S diagrams, as well as diagrams depending on the thermal efficiency and specific work of any selected parameter. Setting a concrete cycle is carried out for selecting appropriate values of the input parameters in the model of the general thermodynamic cycle. Using this method can also be optimized values of the characteristic parameters of any cycle on the criterion of the thermal efficiency and specific work.

THE GENERAL THERMODYNAMIC CYCLE

The general thermodynamic cycle [1] is shown in p-V and T-s coordinate systems, Figure 1 and 2. As may bee seen from Figure 1 and 2, the general thermodynamic cycle (GTC) is obtained as a section of the cycle with maximal specific work (index "w") and cycle with maximal thermal efficiency (index "c" – Carnot cycle).

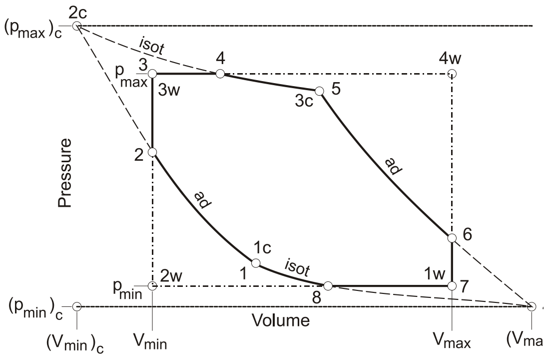


Figure 1 GTC cycle in p-V coordinates

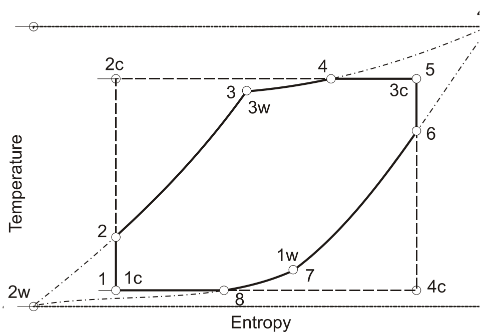


Figure 2 GTC cycle in T-s coordinates

This cycle is composed of the following processes:

- heat addition at constant volume (2 – 3), constant pressure (3 – 4) and constant temperature (4 – 5),
- compression (1 – 2) and expansion (5 – 6) without heat exchange with the surroundings (adiabatic processes),
- heat rejection at constant volume (6 – 7), constant pressure (7 – 8) and constant temperature (8 – 1).

The method of forming new cycle using the general thermodynamic cycle can be presented by schema in Figure 3

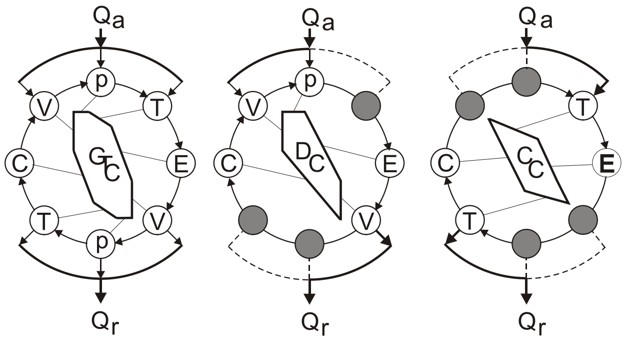


Figure 3 Schema of the new cycles formation from GTC cycle

The indices in Figure 3 have following meanings:

- Qa –total amount of heat added,
- QaV , Qap , QaT -amounts of heat added by constant volume, constant pressure and constant temperature, respectively,
- Qr –total amount of heat rejected,
- QrV , Qrp , QrT -amounts of heat rejected by constant volume, constant pressure and constant temperature, respectively,
- AC -adiabatic compression,
- AE -adiabatic expansion.

Combining the state changes in accordance with schema in Figure 3 it can obtain 130 new cycles. These cycles comprise all know cycles of the heat machines as well as cycles that up to now are not used. In Table 1, top 20 cycles in form of the excel table are presented.

For determination of the thermal efficiency and mean pressure (specific work) of the GTC, following dimensionless parameters are defined:

$\varepsilon = V_{max} / V_{min}$ (compression ratio), $V_{max} = V_6 = V_7$; $V_{min} = V_2 = V_3$
$x_p = p_{max} / p_{min}$, $p_{max} = p_3 = p_4$; $p_{min} = p_7 = p_8$
$x_T = T_{max} / T_{min}$, $T_{max} = T_4 = T_5$; $T_{min} = T_1 = T_8$
$\alpha_1 = p_3 / p_2$, $\alpha_2 = p_6 / p_7$
$\rho_1 = V_4 / V_3$, $\rho_2 = V_7 / V_8$
$\delta_1 = V_5 / V_4$, $\delta_2 = V_8 / V_1$

By using the relationships between these parameters it can write expression:

$$\frac{\alpha_1}{\alpha_2} = \left(\frac{\rho_2}{\rho_1}\right)^{\kappa} \left(\frac{\delta_2}{\delta_1}\right)^{\kappa - 1} \qquad (1)$$

Table 1 Excel table example of the heat machines cycles

Cycles designation	Cycle Nr.	Dimensionless input parameters						
		ε	α1	ρ1	ρ2	δ1	δ2	κ
V-p-T-AE-V-p-T-AC	1	10	3	1.3	1.3	1.5	1.5	1.4
V-p-T-V-p-T-AC	2	10	3	1.3	1.3	7.692308	1.5	1.4
V-p-T-AE-V-p-T	3	10	3	1.3	1.3	1.5	7.692308	1.4
V-p-T-V-p-T	4	10	3	1.3	1.3	7.692308	7.692308	1.4
V-p-T-AE-V-p-AC	5	10	3	1.3	1.3	1.5	1	1.4
V-p-T-V-p-AC	6	10	3	1.3	1.3	7.692308	1	1.4
V-p-T-AE-V-p	7	10	50	1.3	10	1.5	1	1.4
V-p-T-V-p	8	10	50	1.3	10	7.692308	1	1.4
V-p-T-AE-V-T-AC	9	10	3	1.3	1	1.5	1.5	1.4
V-p-T-V-T-AC	10	10	3	1.3	1	7.692308	1.5	1.4
V-p-T-AE-V-T	11	10	3	1.3	1	1.5	10	1.4
V-p-T-V-T	12	10	3	1.3	1	7.692308	10	1.4
V-p-T-AE-p-T-AC	13	10	3	1.3	1.3	1.5	1.5	1.4
V-p-T-p-T-AC	14	10	3	1.3	1.3	7.692308	1.5	1.4
V-p-T-AE-p-T	15	10	3	1.3	1.3	1.5	7.692308	1.4
V-p-T-p-T	16	10	3	1.3	1.3	7.692308	7.692308	1.4
V-p-T-AE-V-AC	17	10	3	1.3	1	1.5	1	1.4
V-p-T-V-AC	18	10	3	1.3	1	7.692308	1	1.4
V-p-T-AE-p-AC	19	10	3	1.3	1.3	1.5	1	1.4
V-p-T-p-AC	20	10	3	1.3	1.3	7.692308	1	1.4

THERMAL EFFICIENCY AND MEAN PRESSURE OF GTC

In accordance with the second law of thermodynamic, the thermal efficiency of the GTC is given by formula:

$$\eta_t = \frac{Q_a - Q_r}{Q_a} \tag{2}$$

where are:

$$Q_a = c_v T_{max} \left[\frac{1}{\alpha_1 \rho_1}(\alpha_1 - 1) + \frac{\kappa}{\rho_1}(\rho_1 - 1) + (\kappa - 1) ln\, \delta_1 \right] \tag{3}$$

$$Q_r = c_v T_{min} \left[\rho_2 (\alpha_2 - 1) + \kappa(\rho_2 - 1) + (\kappa - 1) ln\, \delta_2 \right] \tag{4}$$

In upper expressions c_v is specific heat at constant volume, $\kappa = c_p / c_v$ is adiabatic exponent and mater amount is 1 (ideal gas). The maximal and minimal temperature values are determined by expression:

$$T_{max} = T_{min} \alpha_1 \rho_1 \left(\frac{\varepsilon}{\rho_2 \delta_2} \right)^{(\kappa - 1)} \quad (5)$$

Substituting Q_a and Q_r into formula (2) we obtain the expression for η_t :

$$\eta_t = 1 - \frac{1}{x_T} \alpha_1 \rho_1 f(param) \quad (6)$$

where is:

$$f(param) = \frac{\rho_2(\alpha_2 - 1) + \kappa(\rho_2 - 1) + (\kappa - 1) ln \delta_2}{(\alpha_1 - 1) + \kappa \alpha_1 (\rho_1 - 1) + (\kappa - 1) \alpha_1 \rho_1 ln \delta_1}$$

By using the relation (1), the variables number in equation (6) can be reduced for one. Equation (6) may be rewritten as a follow:

$$\eta_t = 1 - \frac{1}{\varepsilon^{\kappa - 1}} (\rho_2 \delta_2)^{\kappa - 1} f(param) \quad (7)$$

and

$$\eta_t = 1 - \frac{1}{x_p^{\frac{\kappa - 1}{\kappa}}} (\alpha_1 \delta_2)^{\frac{\kappa - 1}{\kappa}} f(param) \quad (8)$$

The expressions for thermal efficiency η_t, (6), (7) and (8) as a function of x_T, ε and x_p are given respectively.

The cycle mean pressure (specific work), is determined by expression:

$$p_t = \frac{W_{cyc}}{V_{max} - V_{min}} \quad (9)$$

where is: W_{cyc} –cycle work which is determined in *p-V* coordinates by the area inside the contour describing the GTC.

Taking into account the know dependences for ideal (air) cycles:

$$W_{cyc} = Q_a - Q_r \quad (10)$$

and

$$V_{max} - V_{min} = \frac{(\varepsilon - 1)}{\varepsilon} V_{max} \quad (11)$$

the equation (7) may be rewritten in following form:

$$p_t = p_{max} \frac{\rho_1 A}{\varepsilon - 1} \left(1 - \frac{1}{x_p} \frac{\varepsilon}{\rho_1 \rho_2} \frac{B}{A} \right) \quad (12)$$

where are: $$A=\left(1-\frac{1}{\rho_1}\right)+\ln\delta_1+\frac{1}{\kappa-1}\left[1-\left(\frac{\rho_1\delta_1}{\varepsilon}\right)^{\kappa-1}\right]$$

$$B=\left(\rho_2-1\right)+\ln\delta_2+\frac{1}{\kappa-1}\left[1-\left(\frac{\varepsilon}{\rho_2\delta_2}\right)^{\kappa-1}\right]$$

$$p_{max}=p_{min}\,\alpha_1\left(\frac{\varepsilon}{\rho_2}\right)^{\kappa}\delta_2^{1-\kappa}$$

The equations (6),(7),(8) and (12), it can apply to all of the 131 cycles. The expressions for η_t and p_t , for a concrete cycle are obtained by inserting the corresponding values of the dimensionless parameters in these equations. In this manner it possible to estimate the influence of various parameters on the thermal efficiency and mean pressure for all cycles.

CYCLES COMPARISON

The comparison of heat-machine cycles is performed with purpose to choice an optimal cycle in consideration of the η_t and p_t values. By reason of larger parameters influence, the cycles comparison is performed for definite comparison cases. In literature following three comparison cases the most frequently are used:

p_{max}=const., Q_r=const., $\varepsilon \neq$ const., $Q_a \neq$ const.

p_{max}=const., Q_a=const., $\varepsilon \neq$ const., $Q_r \neq$ const.

ε = const., Q_a=const., $p_{max} \neq$ const., $Q_r \neq$ const.

FIRST COMPARISON CASE

In this case the temperature T_1 and pressure p_{min} are known. For adopted parameters values: x_p and Q_r it calculated:

$p_{max}=x_p\,p_{min}$=const.

$Q_{rc}=Q_r\,/c_v\,T_1$=const.

and from equation for Q_r the compression ratio ε:

$$\varepsilon=\left(\frac{x_p\rho_2\rho_1^{\kappa}\delta_1^{\kappa-1}}{Q_{rc}-\kappa\left(\rho_2-1\right)-\left(\kappa-1\right)\ln\delta_2+\rho_2}\right)^{\frac{1}{\kappa}} \tag{13}$$

Substituting the parameters values (ρ_1, ρ_2, δ_1, δ_2) for every cycles (Table 1), in expression (13), we obtain corresponding compression ratio value, and then the thermal efficiency and mean pressure of this cycle. By variation of the ρ_1, ρ_2, δ_1, δ_2 values it can estimate their influence on the η_t and p_t for this comparison case.

SECOND COMPARISON CASE

This comparison case is the same as preliminary besides: instead Q_r=const. it adopted Q_a=const., and then is calculated:

$Q_{ac}=Q_a/c_vT_1=const.$

From the equation for Q_a the compression ratio ε now is defined in form:

$$\varepsilon^{\kappa} + C_1\,\varepsilon + C_2 = 0 \quad (14)$$

$C_1=Q_{ac}\,(\rho_2\,\delta_2)^{\kappa-1}$

$$C_2 = x_p \rho_2^{\kappa} \delta_2^{\kappa-1}\left[\kappa(1-\rho_1)+(1-\kappa)\rho_1 \ln \delta_1 - 1\right]$$

By solution of the equation (14), are obtained the values for ε, and then the thermal efficiency η_t and cycle mean pressure p_t.

THIRD COMPARISON CASE

In this case for adopted parameters values:

$\varepsilon=const.$

$Q_a=const.$

it calculated:

$Q_{ac}=Q_a / c_vT_1=const.$

The equation for Q_a gives now the relationship between the others five parameters: α_1, ρ_1, ρ_2, δ_1, δ_2. This equation enables that for four adopted parameters values determines the fifth. Finally, as well as in preliminary cases, it determined the values η_t and p_t.

NEW METHOD FOR ANALYSIS AND COMPARISON OF THE COMPARATIVE IC ENGINES CYCLES

Based on the definition of the general thermodynamic cycle, the formula for calculating the state variables of the characteristic points of the cycle and the expression of the thermal efficiency and specifice work, developed a simulation model in Simulink which block diagram is shown in Figure 4.

Dimensionless values of input parameters (ε ... κ) may be constant (const.), or a variable in the range of its minimum (1.0) to the maximum value (max), where the selection of these variants is performed by using the switch S2. Constant values can be assigned discretely by input blocks or excel spreadsheets table (Table 1), wherein the choice of one or other variants perform with switch S1. The advantage of using excel tables is that at the input can be taken into account functional dependencies between different parameters. The output values are : added (Qa) and rejected (Qr) the amount of heat, thermal efficiency (ηt), cycle mean pressure (pt), p-V and T-S diagrams and depending on any two selected parameters, (eg. ηt = f (ε)). By setting the appropriate input values of dimensionless parameter (ε ... δ2), according to the described procedures of the individual cycles formation from the GTC , using this model it is possible for each of 130 cycles obtain the listed output parameters.

When analyzing the heat engines working cycles the special significance has their comparison by criteria of: economy (ηt) and effectiveness (pt), why is developed a simulation model for cycles comparison by foregoing criteria (three cases of comparison) shows by block diagram in Figure 4.

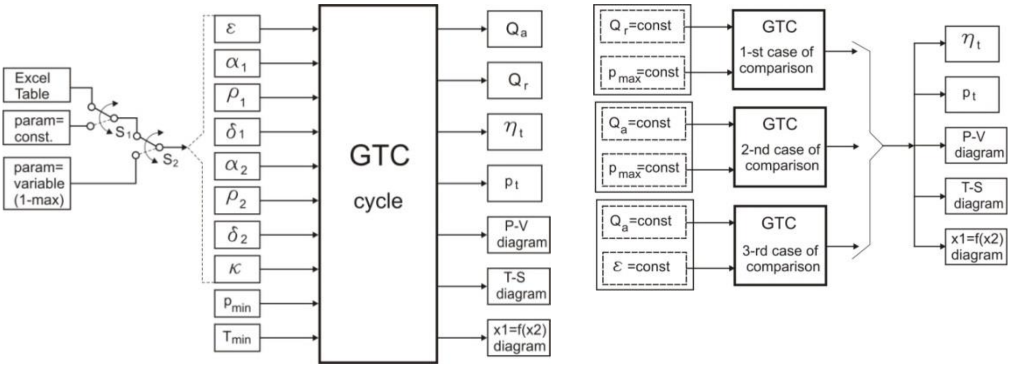


Figure 4 Simulation models for cycles analysis and comparison

In order to verify the developed model was compared to the three main IC engines comparative cycles (Otto, Diesel and Seiliger), and the results for the two comparison case ,(Qa = const., pmax = const), are shown by diagrams in the Figure 5 to 8 . The amount of heat Qa is determined by using a general thermodynamic cycle (the block diagram in Figure 4), for a combined cycle with the following values of dimensionless parameters: ε = 15, α1=2, ρ1 = 1.5 (δ1=1, ρ2 = 1, δ2 = 1) , κ = 1.4 and in dimensionless form is: Qa / Cv Tmin = 7.09 [-].

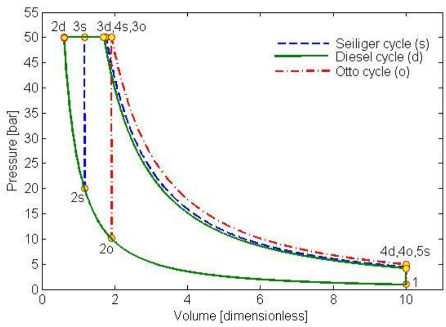


Figure 5 p-V diagram for 2- comparison case

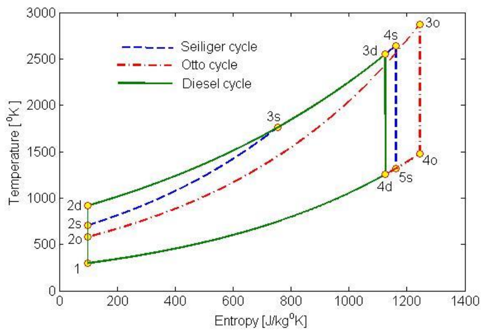


Figure 6 T-s diagram for 2- comparison case

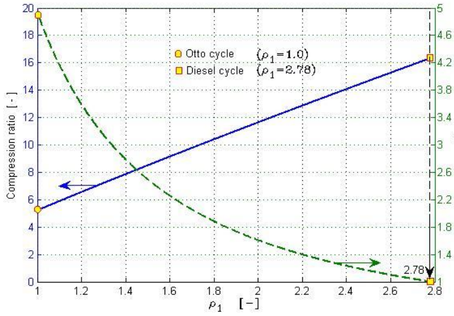


Figure 7 Diagrams depending on parameters ε, α1 and ρ1 for 2- comparison

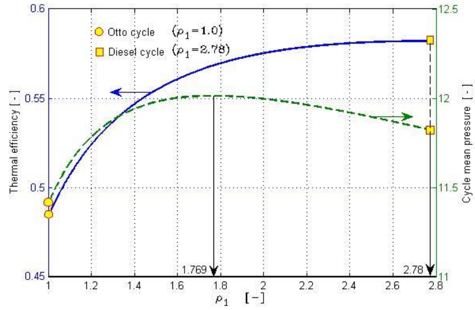


Figure 8 Diagrams depending on parameters ηt , pt and ρ1 for 2- comparison

case *case*

cP-V and T-s diagrams of basic comparative cycles obtained as graphical output of models in Figure 4, for second comparisons case are shown in Figure 5 and 6.

The diagrams in Figure 8 showing the influence of the previous expansion coefficient (ρ1) on the values of the thermal efficiency and mean cycle pressure all three cycles, wherein these values are obtained for the individual cycles by: ρ1 = 1.0 for Otto, ρ1 = 2.78 for Diesel and 1.0 <ρ1 <2.78 for Seiliger's cycle. These diagrams also confirm the known fact that the highest thermal efficiency in this case the comparison has diesel cycle (because of the highest value of compression ratio), while the maximum value of the mean cycle pressure occurs in Seiliger's cycle by the value of the previous expansion coefficient: ρ1 = 1.769.

COMPARATIVE CYCLES OF THE MODERN IC ENGINES

One of the well-known measure of improvement of efficiency, in particular Otto engines, is the use of the cycle with the extended expansion (the expansion stroke is larger than the compression stroke). Such a cycle was first introduced by James Atkinson in 1887, a patent registration of the engine with special piston mechanism that allows extended expansion (Figure 9). Modification of this cycle was made by Miller in 1957, who, instead of a special mechanism, the extended expansion realized by later or earlier closing of the intake valve which involves the use of the valve train with variable valve timing. In addition, this method of the compression stroke regulation leads to a decrease of the charging coefficient, which requires use of a supercharging system.

On Figure 9 are shown p-V diagrams: Atkinson's (1-2-3-4-1), Otto's (1-2-3-4"- 1) and Miller's cycle (1-2-4'-5 -1). Line 1'-2' and 1" - 2 ", corresponding to different lengths of compression stroke of Miller cycle and using them can determine the value of the required overboost pressure: pk1 and pk2.

HEHC cycle is a combination of the Atkinson, Otto and Diesel cycle (diagram in Figure10) and belongs to the group of cycles with a high fuel economy (High Efficiency Hybrid Cycle).

Application of catalyst systems for aftertreatment of exhaust gases in modern engines actualised the cycle with isothermal expansion because of the higher exhaust gases temperatures. P-V diagram of a such (Gruden's) cycle is shown in Figure10.

Using the general thermodynamic cycle and the above described procedure is carried out the comparison of specified cycles with the comparative cycles of the Otto and diesel engines. The comparison results are shown with diagrams in the following figures.

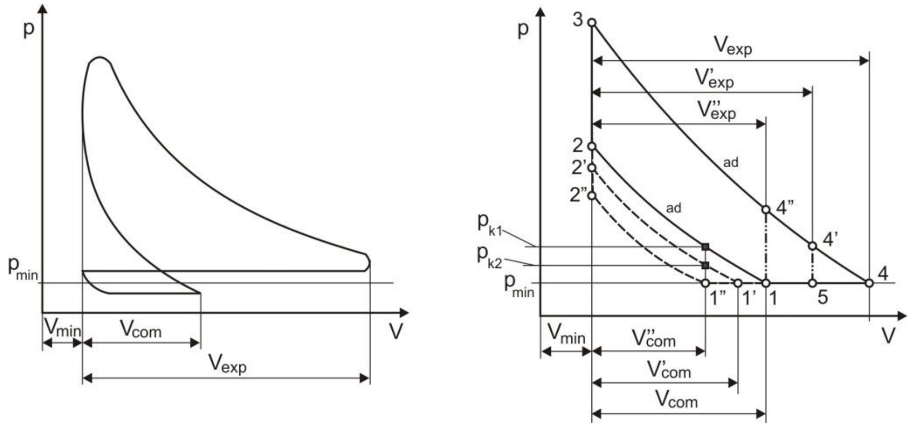


Figure 9 p-V diagrams of Atkinson (left) and Miller (right) cycles

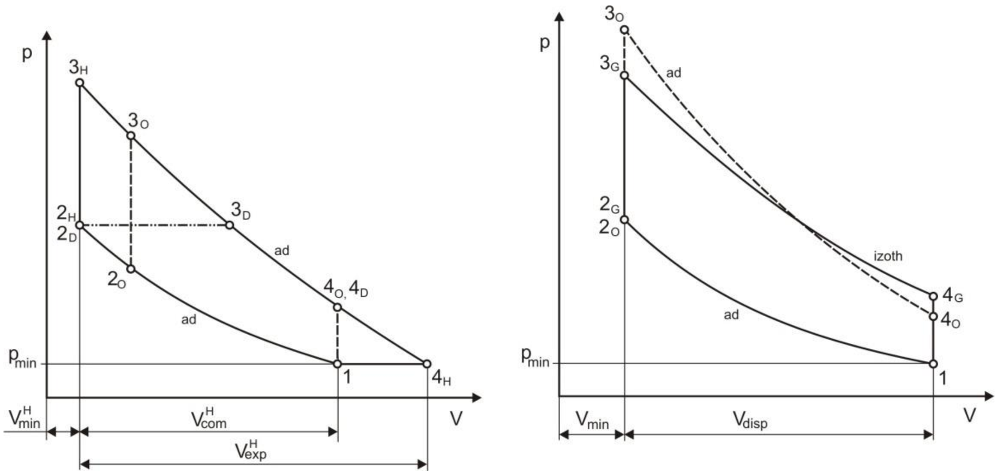


Figure 10 p-V diagrams HEHC (left) and Gruden (right) cycles

On Figure 9 are shown p-V diagrams: Atkinson’s (1-2-3-4-1), Otto’s (1-2-3-4”- 1) and Miller's cycle (1-2-4'-5 -1). Line 1'-2’ and 1” - 2 “, corresponding to different lengths of compression stroke of Miller cycle and using them can determine the value of the required overboost pressure: pk1 and pk2.

HEHC cycle is a combination of the Atkinson, Otto and Diesel cycle (diagram in Figure10) and belongs to the group of cycles with a high fuel economy (High Efficiency Hybrid Cycle).

Application of catalyst systems for aftertreatment of exhaust gases in modern engines actualised the cycle with isothermal expansion because of the higher exhaust gases temperatures. P-V diagram of a such (Gruden’s) cycle is shown in Figure10.

Using the general thermodynamic cycle and the above described procedure is carried out the comparison of specified cycles with the comparative cycles of the Otto and diesel engines. The comparison results are shown with diagrams in the following figures.

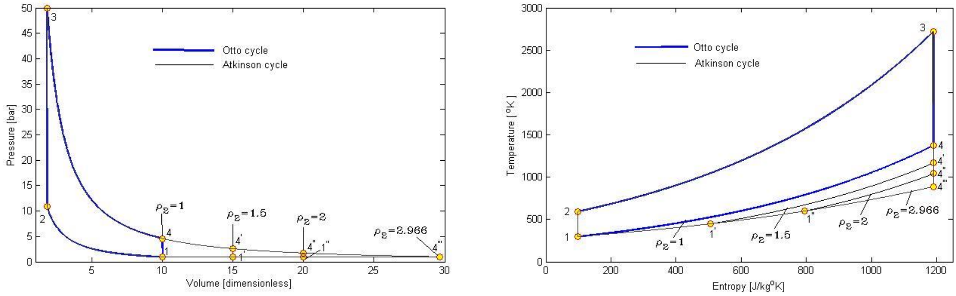


Figure 11 p-V and T-s diagrams of the otto and Atkinson cycles for 2-comparison case

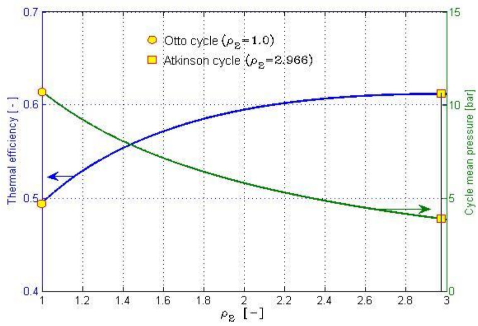


Figure 12 Diagrams depending on parameters: ηt , pt and ρ2 for 2- comparison case

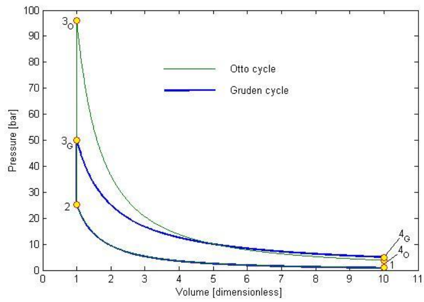


Figure 13 p-V diagrams of the otto and Gruden cycles for 3-comparison case

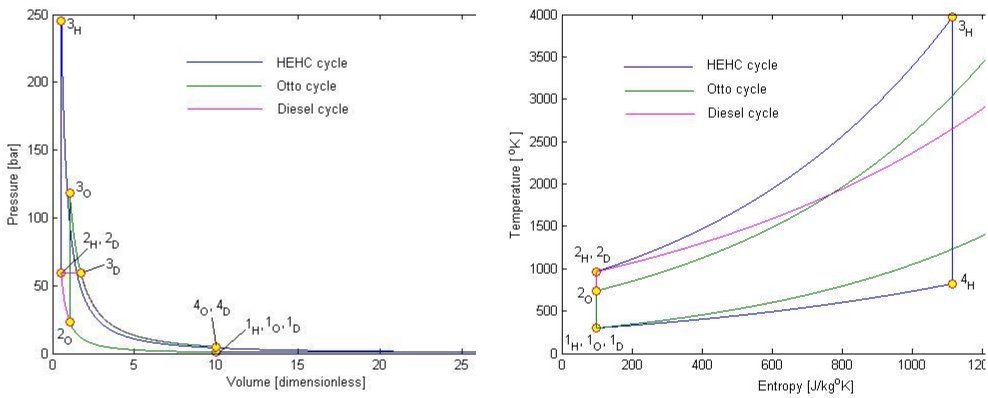


Figure 16 p-V and T-s diagrams of the otto diesel and HEHC cycles for 3-comparison case

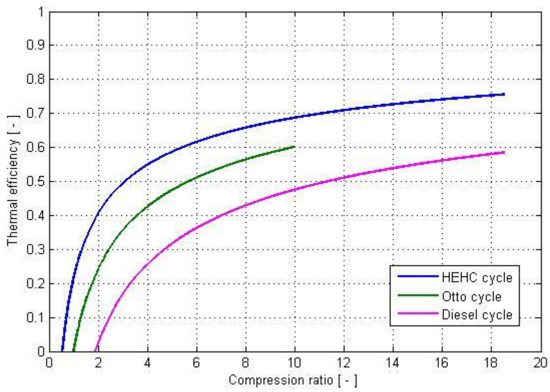


Figure 17 Thermal efficiency of the HEHC, otto and diesel cycle vs compression ratio for 3-comparison case

CONCLUSION

The method of analysis and comparison of the comparative IC engines cycles, based on a general thermodynamic cycle (GTC), provides the following benefits:

- Generate all the possible cycles of heat into work conversion (total: 130).
- Graphic presentation of each of the selected cycle in p-V and T-S coordinate systems.
- Graphic presentation of depending on two or more selected characteristic parameters of the cycle.
- Comparison of cycles per criteria set in advance with the graphical interpretation of the results of comparisons.

The above benefits are presented in the paper the examples of the analysis and comparison of the classic Otto, Diesel and combined cycles as well as cycles of modern combustion engines: Atkinson, Miller, Gruden, HEHC. The proposed method can be applied to all existing and new heat engines cycles..

REFERENCES

[1] Radonjić, D., Prilog izučavanju uporednih ciklusa toplotnih mašina, 20-ti jugoslovenski kongres Teorijska i primenjena mehanika, Kragujevac 1993, Zbornik radova str. 298-301,

[2] Ribeiro, B., Martins, J: Direct Comparison of an Engine Working under Otto, Miller and Diesel cycles: Thermodynamic Analysis and Real Engine Performance, 2007-01-0261, Copyright © 2006 SAE International,

[3] Ribeiro,B., Martins,J., Miller cycle analysis using EGM, Internal Combustion Engine Fall Technical Conference 2005, September 11-14, 2005, Ottawa, Canada, Proceedings of ICEF 2005, p. 1-6,

[4] Gruden, D., Combustion and Exhaust Emission of an Engine Using the Porsche-Stratified-Charge-Chamber System, Automobile Engineering Meeting Detroit, Michigen October 13-17, 1975, SAE 750888,

[5] Shkolnik, N., Shkolnik, A., High efficiency hybrid cycle engine, Proceedings of ICEF2005 ASME Internal Combustion Engine Division 2005 September 11-14, 2005, Ottawa, Canada,

[6] Gheorghiu, V., Enhancement potential of the thermal conversion efficiency of ICE cycles especially for use in hybrid vehicles, Hamburg University of Applied Sciences, Germany, p. 1-14,

[7] Dorić, J., Klinar, I., Realisation and analysis of a new thermodynamic cycle for internal combustion engine, Thermal Science, Year 2011, Vol. 15, No. 4, pp. 961-974,

[8] Carnot, S., Réflections sur la puissance motrice du feu et sur les machines propres a developper cette puisance, a Paris, chez Bachelier, libraire, Quai des Augustins, NO. 55. 1824.

Intentionally blank

STATE, DEVELOPMENT AND PERSPECTIVES OF USING LPG FOR MOTOR VEHICLES IN REPUBLIC OF SERBIA

Dejan Anđelković [1], Srđan Jović, Boris Antić

UDC:629.014.6

ABSTRACT: Lately, alternative fuels (liquefied petroleum gas-LPG, methane, biodiesel, hydrogen and others) are used as fuel sources. Special attention is given to LPG. Using LPG as a fuel source for motor vehicles in Serbia is gaining importance, especially when you take into consideration the safety of those motor vehicles. This paper shows current state, development possibilities and various perspectives for using LPG for motor vehicles in Republic of Serbia.

KEY WORDS: liquefied petroleum gas (LPG), consumption of LPG, motor vehicles, safety of motor vehicles that use LPG as fuel

STANJE, RAZVOJ I PERSPECTIVE PRIMENE TNG-A KOD MOTORNIH VOZILA U SRBJI

REZIME: U poslednje vreme, alternativna goriva (tečni naftni gas - TNG, metan, biodizel, vodonik i drugi) se koriste kao pogonska goriva. Posebna pažnja posvećena je TNG. Primena TNG – a kao pogonskog goriva motornih vozila u Srbiji dobija na sve većem značaju, naročito kada se uzme u obzir bezbednost motornih vozila. U ovom radu prikazano je trenutno stanje, razvojne mogućnosti i različite perspektive za primenu TNG-a kod motornih vozila u Republici Srbiji.

KLJUČNE REČI: tečni naftni gas (TNG), potrošnja TNG-a, motorna vozila, bezbednost motornih vozila sa TNG kao pogonskim gorivom

[1] *Received: September 2014, Accepted October 2014, Available on line January 2015*

Intentionally blank

STATE, DEVELOPMENT AND PERSPECTIVES OF USING LPG FOR MOTOR VEHICLES IN REPUBLIC OF SERBIA

Dejan Anđelković [1]Assistant, Srđan Jović [2], PhD, Assistant professor, Boris Antić[3], PhD, Assistant professor

UDC:629.014.6

INTRODUCTION

Total technological development in automobile industry in recent decades is directed toward solving two major, global problems: protection of the environment and preservation of natural resources. To a large degree this is reflected on the road traffic, that is, industry of motor vehicles. Ecology, however, is not only about preserving the environment, but also about rational usage of energy. In that framework, attention is given to using alternative fuel sources (liquid petroleum, methane, biodiesel, hydrogen, alcohol). Today, there is a global ecological movement in existence. It propagates the trend of ecologically acceptable ("environmentally friendly") vehicles in the world market.

Alternative fuels are a very current issue that keeps gaining more and more attention, mostly for two reasons. First is the knowledge that conventional fuels, fuels that are used the most for commercial and passenger vehicles, fall in the group of non-renewable natural resources, so in the near future their replacement with another fuel source should be considered. Second reason is of more ecological nature. Due to growing pollution of the planet and endangerment of people's health, plant and animal life, more and more stringent ecological conditions are set, that a vehicle needs to fulfil in order to be able to participate in traffic. [1] [6]

From the environmental aspect, considerable negative influence of road transport is air pollution. Every litre of spent fossil fuel when burned produces approximately 100g of carbon monoxide (CO), 20g of volatile organic compounds, 30g of nitrogen oxide (NOx), 2,5kg of carbon dioxide (CO2) and many other harmful and poisonous maters such as lead compounds, sulphur and solid particles. All these compounds, to a certain extent, lead to air pollution, whether by direct effect on health or globally, by causing greenhouse effects.

Emissions of CO2 in the world have increased by 45% between 1990 and 2010 and reached a record breaking 33 billion tons. Around 90% of global emissions of CO2 comes from burning fossil fuels. The biggest increase was recorded in countries whose economies developed suddenly, such as China and India, but also in already developed countries. The biggest increase of CO2 emissions was recorded in sector of manufacture and road traffic. In the sector of road traffic the increase of CO2 emissions was recorded in developed countries and countries in development, with the exception of 2008, when the increase of fuel prices and recession caused the decrease of emissions. [4]

Recently conducted study about climate changes caused by emission of gases from the economy sector showed that the biggest emitter of greenhouse gasses and air polluting gasses is road traffic. [14]

---

1 Dejan Anđelković, FTN Kos.Mitrovica, Kneza Miloša 7, dejan.andjelkovic@pr.ac.rs
2 Srđan Jović, FTN Kos. Mitrovica, Kneza Miloša 7, srdjan.jovic@pr.ac.rs
3 Boris Antić, Faculty of Transport and Traffic Engineering in Belgrade, Vojvode Stepe 305, b.antic@sf.bg.ac.rs

Experts, who are starting to work on energy efficiency in order to preserve and better use energy sources, are beginning to work on new projects that use alternative fuel sources and renewable energy sources [1]. Energy consumption is constantly growing. Prognoses indicate that in the following years, along with the further development of technologies and increase of population, the transport of people and goods will continue to grow. That will require more and more energy, that is, energy consumption will grow. According to some estimates by 2050, the needs for energy will more than double. Transport will use about 50% of the energy, mostly derived from oil [10]. According to that use of alternative fuel sources if more than justified, especially LPG as a fuel source for motor vehicles.

MOTOR VEHICLES AND LPG

LPG as fuel source for motor vehicles

First motor vehicle that used fuel in the form of a gas was constructed by a French engineer Etienne Lenaor in 1862 [8]. The vehicle used gas produced from coal, and the tank was located on the roof of the car or in the trailer. When a German engineer H. Blan managed to separate liquid gas (similar to LPG we use today) from petrol fumes, for the purpose of illuminating luxurious rail road cars, it was certain that liquid gas is an ideal fuel source for vehicles. During World War II, due to shortages of petrol, Germany recorded large consumption of LPG, to power trucks, busses and military vehicles. LPG in ex-Yugoslavia started to be used at the end of 1960, because of a price that was half of the price of petrol, and several years later due to shortages of petrol, when a state administration used driving system “odd-even”, limiting the sale of petrol and diesel by using coupons. [8]

The application of LPG in IC engines has a very long tradition. First IC engines used different kinds of gasses as fuel sources. LPG started to be used as fuel in 1912 in United States. Today, in United States, that is the third most often used fuel, right after petrol and diesel [3]. The number of vehicles that use LPG as a fuel source exceeds total number of vehicles that use other alternative fuel sources. LPG found its application in vehicles of all purposes and carrying capacity (busses, taxi vehicles, police cars, etc.)

Developed countries have been systematically working, for a long time, on massification of the LPG application as well power motor vehicles. In larger cities, with large volume of traffic, city busses and taxi vehicles use LPG. The longest tradition in that regard has Austria, where in Vienna almost all buses use LPG [3]. Buses that use LPG are the best recommendation and far cheaper solution with most favourable influence on the environment, regarding emission of harmful gasses. Today there are 13 million vehicles that use LPG in the world. [15]

Safety of vehicles that use LPG alternative fuel

Safety of using LPG on vehicles includes beliefs and prejudices that LPG is a very dangerous fuel. It is correct, that manipulation, distribution and storing of LPG are more risky in comparison to diesel and petrol. All that requires knowledge of basic characteristics about the mixture of propane and butane and strict application of safety measures. By applying those measures to their fullest extend the risk is removed, because the working pressure in the tank in normal conditions is slightly higher than the pressure in the boiler for hot water.

Tanks in vehicles are filled to 80% of full capacity, to leave room for expansion of fuel at higher temperatures [11]. All tanks that are installed in vehicles have a device (multi valve) that automatically stops refuelling. Vehicles that use LPG completely rely on this device that reduces the leakage of fuel during refuelling to a minimum. Refuelling time of LPG and petrol tanks is approximately the same.

Tanks for LPG are made from stainless steel, thick about 3-4 millimeters and have a very rigid construction, so they basically represent additional reinforcement during impact. In that regard, LPG tanks are considerably safer compared to standard petrol tanks. Although the gas pressure in the tank is 10 bars, all tanks are tested to a pressure of 30 bars. LPG tanks in vehicles must have an appropriate plate that confirms that testing was performed. On the tank, there must be a safety valve that releases the gas outside of the vehicle, when the pressure in the tank exceeds allowed level. In case of a fire, when a LPG tank is being heated, there will be no explosion, because the gas will gradually flow out, unlike a petrol tank that easily explodes at higher temperatures, due to presence of petrol fumes. When a LPG tank is emptied, certain amount of gas always remains in the tank and that is why the tank valve needs to be closed, so that there is no air diffusion into the tank and explosion. LPG explosion is possible only at gas concentration of 2-9% of relative volume of the container, which is practically impossible to achieve in open space when the car is in motion [7]. It should be mentioned that explosive mixture of LPG and air can be created in small closed space, where cars that use this space are being parked (especially in underground garages). This danger is successfully removed with only two openings for natural ventilation in underground garages or by installing an electrical valve that will prevent the loss of gas when the engine is shut down.

Installation of LPG system should be used by professional and certified services. Requirements that LPG systems need to fulfill, from a standpoint of traffic safety, can be found in ECE Rulebook No.67/01 and ECE Rulebook No. 115. The exact name of ECE Rulebook no.67/01 is uniform regulations about homologation of specific equipment for motor vehicles that use LPG and vehicles equipped with specific equipment for LPG regarding the installation of that equipment. ECE Rulebook no.115 provides uniform regulations about homologation of specific LPG replaceable systems that are installed in vehicles that use LPG as fuel source.

Safety of vehicles that use LPG in Serbia

Correct installation and reliability of LPG equipment that is being installed in vehicles in very important. In Serbia, there is more and more repairshops (mostly relying on world famous manufacturers of equipment for LPG installations) that with their evident quality of installation considerably contribute to elevation of reliability of vehicles that use LPG as a fuel source.

Practice showed that in Serbia there is no recorded rupture of LPG tank. Several accidents, where there was fire, were caused by human error, with the idea to save space in the trunk, so the LPG tank was not installed, but instead an ordinary LPG tank that is used in households. Poorly secured tank bounced around in the tank, damaged the pipes for LPG and lead to fire.

Guided by numerous prejudices about how safe it is to drive a car that uses LPG, AMSS (Center for motor vehicles) conducted a test in real fire conditions. Two cars were tested-one that used petrol and one that use LPG. In the first part of the test, vehicle with classic petrol engine was set on fire, with little over half a tank of petrol. The vehicle was set on fire simultaneously in several places and already after 5 minutes the flame started to engulf the interior of the vehicle, glass windows started to break, and paint melted. When the fire reached the back part of the vehicle, a faint pop was heard, because the pressure grew in the tank, due to rising temperature, and was released, and the fire continued to expand. That means, if the vehicle is fully functional, there is no danger from explosion.

Statistics show that there is a greater chance of explosion when the tank is emptier (a third or less), that is, when there is more air in it. Complete car burned down in less than 20 minutes. Second part of the test was setting a fire on the car with LPG, which had a completely new LPG device with complete installation, installed in the trunk, in accordance with current regulations and the tank was filled with 25 liter of gas. As in previous case, the fire was set simultaneously at several places, but mostly in the engine and passenger compartment. After only 5 minutes, sensor that were located 3 meter recorded a temperature over 105 degrees Celsius, and only after 8 minutes over 250 degrees. The next moment a huge flame appeared from the vehicle because the LPG started to burn and the gas was being released through a safety valve on the tank. Without this valve there would be an explosion, and this modern LPG device reduces the consequences, even in the case of fire. [5] [16]

If the car is functional and if the device is properly and professionally installed, even in the case of a major fire, there is no danger of explosion. The conclusion is that driving on LPG is equally safe as driving on petrol. In this case it was obvious that LPG tank did not rupture even in the case of fire. Only condition for a safe car that uses LPG is proper installation of LPG device with quality equipment elements. [2]

STATE IN SERBIA, DEVELOPMENT AND PERSPECTIVES OF USING LPG

Vehicles that use alternative fuel sources are extremely suitable for urban environments, where the pollution of man’s environment is greatest. These fuels are extremely well suited for city transportation, for powering agricultural machinery, city service vehicles, delivery vehicles, ambulance vehicles, taxi vehicles, indoor transport vehicles (for example, fork lifter), working vehicles (for example, loaders) and vehicles that are used for tourist purposes. Currently, poor economic cost effectiveness of using alternative fuels in road traffic in Serbia certainly plays an important part in its application. Regarding the criteria of cost effectiveness of using alternative fuels it should be pointed out that the fuel price, registration costs, taxes and other obligations that user of vehicle needs to pay come from global and fiscal politics of a country, especially from traffic development and energy politics. That means that the prices of alternative fuels, apart from manufacturing price, are also influenced directly by government with its decisions and measures. In this way the usage of one fuel is increased at the expense of another. The consumption of a fuel for which the government has the greatest interest, whose reserves are greatest and which does not pollute the environment can be supported.

It is very likely that in the following years three types of LPG will be present as alternative fuels in road traffic in Serbia: LPG-mostly from import, compressed natural gas (CNG)-mostly from import as a world trend, and biodiesel-manufacutred from raw materials found in Serbia (in the future).

Today, in technologically developed countries of the world, LPG has the most mass use out of all alternative fuels along with considerable increase of CNG. All in all, population and economy of Serbia are not sufficiently familiarized with alternative fuels, they don’t recognize the advantage of their use and there are no larger initiatives for expanding the awareness about positive effects of their manufacture and application.

The use of LPG in Republic of Serbia, as fuel source, started in the late sixties of the previous century. Back then the lack of LPG stations in the form they exist today, dictated the primitive way of pumping LPG from household tank, without fulfillment of basic safety measures. In the promotion of LPG and its mass use in the early eighties of the 20th century in Serbia, an important role was played by introduction of petrol coupons, so the LPG became a popular and acceptable fuel source, representing an alternative to other expensive energy sources. In Republic of Serbia today, LPG as a fuel source is gaining more and more users, which is also a result of relatively satisfactory network of LPG refueling stations.

Consumption of LPG in Republic of Serbia

In Republic of Serbia in 2004, 10.000 vehicles that used LPG were registered [13]. In only 5 years their number increased by 26 times, and according to data from [12], the number of registered vehicles that use LPG was 262.954, and in 2010 it continued to grow and was 302.090. Consumption of LPG in 2010 in Republic of Serbia is displayed in Table 1, by sectors. The biggest percentage of LPG is used in the area of traffic (81%), then in industrial sector (9%) and in the third place are household (7%).

Table 1 Energy balance of consumption of LPG in energetic purposes in 2010 in RS [13]

Sector	Amount (tons)	Amount (%)
Industry	31382	9
Construction	157	0
Traffic	298045	81
Households	27117	7
Agriculture	2439	1
Other	6410	2

Demand for LPG in the sector of road traffic continues to grow each year. In 2011, it is estimated that the consumption of LPG was over 400.000 tons (National LPG association). According to data from [13], the consumption of LPG in Republic of Serbia, in the road traffic sector, for the period from 2007 to 2010, is shown in the Table 2. In 2010 a drop in consumption is recorded, for about 50.000 tons in comparison to 2009, but the estimated consumption in 2011 was about 100.000 higher compared to 2010.

Table 2 Consuption of LPG in traffic sector in Republic of Serbia [13]

Year	**2007.**	**2008.**	**2009.**	**2010.**	**2011.***
Amount (tons)	247.508	300.925	347.856	298.045	400.000

The consumption of LPG is influenced by many factors, of which the most important are:

- The number of registered vehicles.
- Structure of vehicle fleet (the number of converted cars and the consumption of LPG)
- Price of LPG as a fuel source.
- Number of LPG refueling stations
- Awareness of the government and citizens about LPG as an ecologically cleaner fuel.
- The influence of the state on the promotion-use of LPG, by lowering of taxes and providing some form of benefits during regular annual vehicle registration.
- Conditions for procuring LPG device-possibility by credit.
- Removing eventual fear with potential users of LPG.

Number of registered vehicles

In Republic of Serbia, in 2010 1.565.550 passenger vehicles were registered, and in 2011 7.2% more, that is, 1.677.510 passenger vehicles [13]. According to information from RZS, the number of residents in Republic of Serbia in 2011 was 7.276.195. That means that in average 4 people go to one car. For comparison with neighbouring countries that entered in the whole deal with car LPG device much earlier, than it is the case with our country, Table 3. shows statistical information for them.

Table 3 The number of vehicles to 1000 residents

Country	The number of vehicels to 1000 residents
Serbia	230
Croatia	352
Slovenia	518

According to census from 2011, Republic of Croatia had 4.290.612 residents, and according to information MUP of Croatia, then number of registered passanger cars is 1.511.045 [18]. According to these data in Croatia, 3 people came to one vehicle or 352 vehicles to 1000 residents. [19]

According to information of Statistical office of Republic of Slovenia, the number of registered vehicles in 2011 was 1.061.646. In comparison to the number of residents, there are 518 vehicles to 1000 residents, that is, in average one vehicle to 2 people. Slovenia, according to number of vehicles in relation to the number of residents, is at the first place, before Serbia and Croatia.

In Serbia, according to data from RZS, out of all registered car, there are most cars made by Zastava, Volkswagen, Opel, Ford, Fiat, Renault, Mercedes, Pegout and Skoda. In percentages, the number of new Punto Classic vehicles with factory installed LPG system in total number of sold vehicles in Serbia is shown in Table 4. Sudden increase of these cars with LPG is recorded in 2009, when every fifth sold car had LPG system.

Table 4 Sales of new Punto Classic vehicles with LPG in Republic of Serbia in the period of 2009-2011. [17]

Year	2009.	2010.	2011.
Percentage in total sale	2.32%	19.45%	12.30%

Structure of vehicle fleet

In the process of analysis of consumption of LPG and the number of converted cars to LPG, one needs to start from a total number of registered passenger cars on the territory of Republic of Serbia, which amounts to around 1.7 million. Less than 6% of total number of registered passenger cars still use LPG as a fuel source. However, this number is higher, because in Serbia there is still a considerable number of vehicles that are converted to LPG in unauthorized mechanic shops, and a great number of vehicles that do not get tested after the installation of LPG system.

The trend of increase of consumption of LPG on the market of Serbia is mostly caused by the use of LPG as fuel source for motor vehicles. In 2011, the consumption of

LPG in the road traffic sector was increased by 33% in comparison to 2010. Dominant group of LPG users, as a fuel source, consists of taxi drivers, from which majority have LPG device installed in their cars. In Belgrade, according to information from MUP, there were 6.435 registered taxi drivers in 2011. In Serbia, large number of official vehicles is converted to LPG, and those are: part of vehicle fleet of Coca Cola, Pepsi, Grand Kafa, police vehicles, driving school vehicles.

In Serbia, devices for conversion of vehicles to LPG mostly have Italian origin, fairly high price and good quality. They are manufactured for old carburettor vehicles and new vehicles. While in the world, only the newest, sequential systems are installed, here in Serbia LPG is still being installed in carburettor vehicles, due to the vehicle structure. Sequential injection of gas is a mandatory instalment system in all EURO 3 and EURO 4 engines, and in engines with plastic intake manifold, from earlier generations. The most famous Italian manufacturer of installations for LPG is OMVL, LOVATO, LANDI and TOMASSETO. Polish manufacturers of LPG devices are also present in the market of Serbia, such as G.Z.W.M, Dutch PRINS, but also considerably cheaper equipment that comes from Bulgaria and Turkey.

The price of LPG as fuel source

Demand for LPG grows each years, so the expected demand in 2011 was around 400.000 tons. Manufacture in Serbia is nowhere near enough to satisfy the needs of growing number of vehicles that use LPG. Oil Industry of Serbia (NIS) manufactures LPG in its refineries in Pancevo and Novi Sad, and refines natural gas in Elemir. Apart from NIS, there is also a company called “Standard gas” that manufactures and distributes LPG in Serbia, who has is manufacturing plant in Odjaci in Vojvodina. Since the manufacturing capabilities in our country are limited, consumption of LPG in our market if supplemented by import. Table 5 shows the import of LPG in Republic of Serbia, which in 2009 and 2010 exceeded 250.000 tons. [13]

Government of Republic of Serbia, in amendment of the Law on excise taxes in June of 2011, abolished excise taxes for LPG. That freed LPG from excise taxes, unlike all types of petrol whose excise taxes is 48.12 din/l and diesel fuel whose excise tax is 35.57 din/l. Thus the state influenced on additional reduction of LPG price in comparison to other traditional fuels. Current information about excise taxes is not known.

Table 5 Import of LPG in Republic of Serbia in the period of 2008.-2010 [13]

Year	2008.	2009.	2010.
Import off LPG (tons)	241.444	257.458	254.856

The price of LPG is considerably lower in comparison to petrol and diesel fuels. Most experts for oil in the world estimate that the price, with temporary small price cuts, will continue to grow. The same will happen with the price of oil derivates, which means that the petrol and diesel will be more expensive. If that really happens, it can be concluded that the future, due to ecological consciousness and price, will belong to gas fuels.

The number of LPG refuelling stations and their distribution

One of more important elements that influence the usage of LPG as a motor fuel is distribution of stations in Serbia where LPG can be bought. At every major refuelling station in Serbia, apart from conventional fuels there is also LPG. The quality and the price are not the same at each station. There are many stations in Serbia that sell LPG. Exact number of station is not known, but the estimate is that there are over 400. Apart from NIS refuelling stations, there are a large number of private stations that sell LPG. NIS, as a domestic manufacturer of LPG, has six regional centers for LPG, which are located in Cacak, Elemir, Subotica, Nis, Novi Sad and Ovca. Table 6 shows the number of stations with LPG that are owned by Nis, AMSS and some private companies.

Table 6 The number of LPG stations in Republic of Serbia in 2012 in individual companies

Name of the station	Number of stations
NIS	87
“OMV”	61
“MOL”	31
“EKO”	44
“CryoGas”	8
“EuroPetrol”	15
“EuroLuxPetrol”	11
“Knez Petrol”	20
“AMSS”	9

Awareness of citizens and the state about LPG as an ecologically clean fuel

It is not likely that gaseous fuel will, in a sufficient extent, replace classic fuels without the support of the state. Gaseous fuels have numerous advantages over other types of fuel, above all, ecological suitability is most important for the state and that should be the first initiator for buying new vehicles that use LPG and converting used cars to use LPG.

Residents of Serbia does not have enough awareness about ecology, probably because of other long-term problems in the country, so the average consumer in Serbia takes into consideration the price of conversion and fuel price, when making the decision to take this step. If those facts are taken into consideration, a conclusion is reached that the state, aware of advantages that LPG brings, needs to adopt certain measures to make installation or gaseous fuels cheaper and thus make it sought after energy source. There several ways for the state to reduce the negative influence of traffic. One of those ways is a long-term plan of reduction of air pollution. It can be achieved by:

- Reducing the number of vehicles on the roads (for example, Belgrade, modelled after London, would have success using this politics, by limiting the access of vehicles to the center of the city)
- By reducing the emission of exhaust gasses from the vehicles, and that can be achieved in several ways: by improving the management of traffic flows; insisting on improving the state of vehicles; implementation of modern technologies for control of exhaust gases from vehicles; by supporting the population that uses clean fuels, such as LPG (an ideal solution from ecological and economic standpoint).

The use of LPG in the world rises with great speed, which is the best way to reduce air pollution. There is a huge potential for further development of LPG market in Serbia.

Influence of the state on improvement of LPG use through reduction of taxes and providing benefits

Increasing the use of LPG is possible to achieve if the state lowers taxes on vehicles that use LPG, provides benefits during regular registration of vehicles and similar. The problem comes down to the fact that the state first need to understand all these advantages of LPG, and then provide benefits to citizens that use LPG in their vehicles. The state needs to offer incentives so that the vehicles of public transport convert to LPG, like other countries do, and that vehicle fleets of major companies start using LPG.

Giving benefits to vehicles that use LPG should be seen in:

- Reducing taxes on gaseous fuels;
- Reducing custom taxes on the import of devices for vehicle conversion;
- Reducing taxes and providing benefits during regular vehicle registration;
- Campaigns that will raise awareness about the influence of vehicle emissions on health;
- Removing eventual fear with potential users of LPG;

Conditions for procuring LPG device

Manufacturers, importers, distributers and servicemen should take the initiative for massification LPG use in Serbia. Their actions on the state and marketing campaigns should persuade a potential buyer of the advantages of this fuel. That can be achieved through reduction of LPG price (margin is lowered, but turnaround is increased and also popularity of the fuel), by buying new vehicles that run on LPG in instalments or by interest-free credits, by more favourable prices for installing and procuring devices for conversion of vehicles to LPG. The state should also take part in there measures. The price of the device and installation of LPG in the car ranges from 250€ to 1200€, depending on the vehicle and the manufacturer of LPG equipment.

Existing fear of users from using LPG

One of often asked questions of citizens is the safety of alternative fuels. Car that run on LPG have safety elements that a cars that runs on conventional fuels do not have, which makes them safer, but public is still afraid. World standard for LPG equipment, installation and using are very high.

Each aspect of LPG industry is under the influence of state standardization in accordance to world regulations. Modern systems for LPG are designed in such a way to be safe in everyday exploitation, maintenance and safe in case of a traffic accident. All LPG tanks are tested according to much stricter criteria compared to classic tanks. In case of a traffic accident, they can withstand enormous forces and impacts without any deformations and fuel leakage.

The most common reason against installing LPG device in the vehicle is the fear of the unknown and prejudices. The fear from possible fire of LPG system in the car is real and that is the most often reason against installing LPG in the vehicle. So far, the experience shows that such fear is not founded, in fact petrol fumes are more dangerous and the risk of spontaneous combustion is higher.

CONCLUSIONS

The possibilities of replacing petrol and diesel with alternative fuels are high. The choice of most favorable alternatives is not simple. It depends on the number of facts, such as world reserves, accessibility, influence of the fuel on the environment, safety of fuel use, modifications on vehicles and the influence on the performance of the car, systems for supplying the vehicle with fuel, and others. Because of that, there should be and legal and fiscal regulation, which by system of taxes and other incentives should influence the use of alternative fuel sources. Gaseous alternative fuels, above all, the LPG, is the most acceptable alternative fuel in our country for the following reasons:

- LPG as fuel source does not contain lead and emits less CO2 (in comparison to petrol and diesel);
- Up to 50% saving in fuel costs;
- Engine works quieter and smoother;
- Life span of the engine is increased by about 30%;
- LPG device from one car can be transferred to another, under the condition that the cars have the same fuel supply system;
- There is no possibility of fuel leakage during refueling;
- Thanks to protection on multiple levels, the entire system is safe in comparison to forceful fuel unloading;
- LPG tanks, thanks to their constructive solution, quality of material and the way they are made and controlled, are far safer during impact from petrol tanks.

Apart from factors that influence the use of gaseous fuels in traffic, in order to intensify their use in our country, special attention needs to be directed to:

- Familiarizing all interested parties with the problem of securing energy sources for motor vehicles and reasons for application of alternative fuel sources;
- Determining global strategic orientation in order to define efficient energy and traffic politics, from a standpoint of fuel availability and environmental protection, and especially in order to gradually introduce LPG as a fuel source for motor vehicles.
- Wide familiarization of public with reasons and expected effects of using LPG, with safety properties of LPG and effects that are achieved in user and general level.

Consequences of traffic accidents of vehicles with LPG are the same as the consequences of traffic accidents of other vehicles, so this is one more indicator that vehicles with LPG are not less safe than vehicles that run on conventional fuels.

Activities for the protection of life environment, watched from the standpoint of emission of harmful ingredients of exhaust gasses, are seen in the intense development of engines with mandatory constant reduction of exhaust emission and fuel consumption [9]. With the increase of number of motor vehicles and with intensifying of road traffic the influence of exhaust gasses is increased on the environment.

Considering the average age of motor vehicles in Serbia, apart from applying stricter regulations, strategic and simulative state measures are needed, for purchasing modern vehicles that run on alternative fuels, whose use would influence the reduction of emission of exhaust gasses.

REFERENCES

[1] Anđelković, D., Antić, B., Vujanić, M., Subotić, M., Radovanović, LJ., “The perspectives of applying ethanol as an alternate fuel”, Energy Sources, Part B: Economics, Planning, and Policy, (201_) (In the press), Manuscript ID UESB-2012-0051.R3, (DOI 10.1080/15567249.2012.683930.).

[2] Buzanovskii, V., "Analysis of Applicability of Nanosensors in Explosion and Fire Safety Systems of Liquefied Petroleum Gas Production, Storage, and Utilization Facilities. Part 2", Chemical & Petroleum Engineering, Vol. 50 (3/4), 2014, pp. 201-205.

[3] California energy commission, ABCs of AFVs, “A guide to alternative fuel vehicles”, 1999, California.

[4] European Commission (EC) (2011), Joint Research Centre (JRC) - Netherlands Environmental Assessment Agency, ”Emission Database for Global Atmospheric Research (EDGAR)”, 2011, Netherlands.

[5] Ivanova, D., “LPG stations – conditions for contracting and construction, dangers that accompany machine equipment and their removal, equipment that manufactured in Serbia and Montenegro and Europe”, scientific symposium “Vehicles powered by gas“. 2005, Belgrade.

[6] Marjanović, Z., Brzaković, R., Joksimović, V., “Ethanol in IC engines – advantages and flaws of aplication”, Part of doctoral dissertation of the first author, 2009, Kragujevac.

[7] Marjanović, Z., Brzaković, R., “Safety of vehicles that use alternative fuels”, VI National conference about the quality of life, 2011, Kragujevac.

[8] Muštrović, F., “LPG (propane - butane) car gas”, 2008, Sarajevo.

[9] Pipitone, E., Genchi G., "Experimental Determination of Liquefied Petroleum Gas–Gasoline Mixtures Knock Resistance", Journal of Engineering for Gas Turbines and Power, Vol. 136(12), 2014, pp. 121502(1)-121502(7).

[10] Popović, V., “ECE regulations for vehicles powered by gas”, scientific symposium “Vehicles powered by gas“, 2005, Belgrade.

[11] Radonjić, B., Radojević, S., “Job safety and protection from fire when installing and maintaining the device and equipment for powering motor vehicles that use LPG as a fuel source”, scientific symposium “Vehicles powered by gas“, 2005, Belgrade.

[12] Republic institute for statistics (RIS), 2009, Republic of Serbia, Belgrade.

[13] Republic institute for statistics (RIS), 2012, Republic of Serbia, Belgrade.

[14] Unger, N., Bond, T.C., Wang, J.S., Koch, D.M., Menon, S., Shindell, D.T., Bauer, S., “Attribution of climate forcing to economic sectors”, Proceedings of the National Academy Sciences, Vol. 107 (8), 2010, New York pp. 3382–3387.

[15] World lpg gas (WLPGA), “Autogas Incentive policies”, A country by country analysis of why and how governments promote Autogas and what works, 2012, Siene.

[16] www.amss.org.rs/index.php?option=com_content&view=article&catid=42%3Ao-nama-razno&id=239%3Auporedni-test-koliko-smo-bezbedni-u-vozilima-na-teni-naftni-gas&Itemid=58

[17] www.fiatsrbija.rs

[18] www.mup.hr.

[19] www.stat.sl

Intentionally blank

STATE OF DEVELOPMENT AND PERSPECTIVE OF THE ELECTRIC VEHICLES

Zoran Nikolić [1], *Zlatomir Živanović*

UDC: 629.423.2-853

ABSTRACT: First Electric Vehicle (EV) has been made in in 1837. This type of motor vehicles has dominated throughout the whole 19th century. In the early 20th century the faster and more robust vehicles with Internal Combustion Engine (ICE) overcame them until late 20th century, when ecological and economic problems of further application of these vehicles have emerged. The interest in EV has risen sharply.

Researches are working in several directions in order to reduce the need for oil derivatives considering that the EV's are weak primarily due to inferior "reservoir of energy" to fully meet the current driving habits. Savings can be achieved in two ways, by making more economic motor vehicles or by the use of alternative fuels. Combining an electric propulsion and IC engine drives a hybrid vehicle is obtained, with a greater amount of batteries and "plug in" that is to some extent possible to reduce fossil fuel consumption and exhaust emissions. Intensive research work on exploring new battery is still to come. Today promising results with Li - air batteries, fuel cells and super capacitors, as well as the efforts of major car manufacturers indicate that the EV could soon appear massive in the streets of cities.

This paper deals with the development of EV, following the development of powertrain and can conclude the fact that in the near future this type of drive could return.

KEY WORDS: EV, EV development, Hybrid EV, EV History, EV perspective.

STANJE RAZVOJA I PERSPEKTIVA ELEKTRIČNIH VOZILA

REZIME: Prvo električno vozilo (EV) je proizvedeno je 1837. godine Ova vrsta motornih vozila je bila dominantna tokom celog 19. veka. Početkom 20. veka se brža i robusnija vozila sa motorima sa unutrašnjim sagorevanjem (ICE) su ih prevazišla sve do kraja 20. veka, a kada su se pojavili ekološki i ekonomskih problema primene ovih vrsta vozila. Interesovanje za EV je naglo porastao .

Istraživanja se realizuju u nekoliko pravaca kako bi se smanjila potreba za naftnim derivatima uzevši u obzir inferiornost „rezervoara za smeštaj energije“ EV da bi se u potpunosti zadovoljile trenutne vozačke navike. Uštede se mogu postići na dva načina, konstrukcijom ekonomičnog motornog vozila ili upotrebom alternativnih goriva. Kombinovanjem električnog pogona i IC motora dobijeno je hibridno vozilo, sa većim baterijama i "plug in" vozilo da bi se u izvesnoj meri smanjila potrošnja fosilnih goriva i emisija izduvnih gasova. Intenzivna istraživanja na razvoju novih baterija tek dolaze. Obećavajući rezultati danas sa Li - vazduh baterije , gorivo ćelije i super kondenzatori , kao i naporima velikih proizvođača automobila ukazao na EV To bi moglo uskoro pojaviti
 masovno na ulicama gradova .

Ovaj rad se bavi razvojem EV , Nakon razvoj pogonskih i može zaključiti ugled u bliskoj budućnosti ova vrsta diska mogao vratiti .U ovom radu prikazani su rezultati istraživanja u razvoju komponenata vozila od kompozitnih materijala, i neka novija dostignuća u primeni

[1] *Received: September 2014, Accepted October 2014, Available on line January 2015*

termo-plastičnih adhezivnih materijala, nano-modifikovanih fero-magnetnim česticama, osetljivim u elektromagnetnom polju kako bi se ubrzali procesi proizvodnje i rasklapanja.

KLJUČNE REČI: lightweight, composite material, CO2 emission reduction, adhesive joints, nanomodified adhesives

STATE OF DEVELOPMENT AND PERSPECTIVE OF THE ELECTRIC VEHICLES

Zoran Nikolić [1] PhD, BSc, Zlatomir Živanović [2], PhD, BSc

UDC:629.423.2-853

ABBREVIATIONS

AC	Alternating current
ACEA	European Automobile Manufacturer's Association
BEV	Battery electric vehicle
BP	British Petroleum
CNG	Compressed natural gas
DC	Direct current
EIA	Energy Information Administration
EU	European Union
EV	Electric vehicle
FCV	Fuel cell vehicle
GHG	Greenhouse gas
HEV	Hybrid electric vehicle
HV	Hybrid vehicle
IC	Internal combustion
ICE	Internal combustion engine
Li-air	Litium air
Li-ion	Litium ion
LNG	Liquefied natural gas
OICA	International Organization of Motor Vehicle Manufacturers
OPEC	*Organization of the Petroleum Exporting Countries*
PHV	Plug-in hybrid vehicle
UN	*United Nations*
ZEV	Zero-emissions vehicle

1 Zoran Nikolic PhD, BSc, Institute of Technical Sciences of the SASA, Belgrade, E-mail: zoran.nikolic@itn.sanu.ac.rs
2 Zlatomir Zivanovic, PhD, BSc,Universiy of Belgrade, Institute of Nuclear Sciences "VINČA", Department for I.C. Engines and Vehicles, 11001 Belgrade, PO Box 522, E-mail: zzivanovic@vinca.rs

INTRODUCTION

Usage and application of the electric motor vehicle started long before usage of motor vehicles with ICE and that marked the entire nineteenth century. Nevertheless, the EV could not withstand the competition with ICE vehicles, which were faster, stronger and more robust. The main reason for leaving the electric propulsion at the beginning of the twentieth century lies in the fact that the weight of 1 kg of batteries could accumulate around 25Wh of energy, and liquid fuels around 12.000Wh, and that meant that the reservoir of classic cars with ICE, which has weight about 50kg could store approximately 600kWh of energy, and a lead battery pack only about 2 - 10kWh [01] of electricity, which again in the early 20th century was much less.

In the seventies of last century, begins EV renaissance. Permanent increase in the price of oil, which reserves are dropping, and problems related to its production, transport and use, lead to renewed interest in EV. Simultaneously with the crisis and shortage of oil, ecology and environmental protection are gaining on importance. At that time, it seemed that the reserves of coal and oil wear out quickly, as predicted for the beginning of the third millennium, which lead people to start thinking about the "conservation of energy". Especially at the turn of this century, the need of making clean vehicles or vehicles of "zero emissions" was stressed. In addition, steady technical progress gave the quality and cost-effective solutions, speed control motors, lighter batteries and lighter materials for the body.

Large car manufacturers are starting to invest in the development of EV, as well as improving the components of the propulsion equipment. The decisive criterion for EV success is their price, a criterion that is still very vague. EV retails in small-series production between 30,000 and 75,000$, which mainly depends on the kind and type of battery. One cannot say how much EV will cost when mass produced. Historically, comparing the prices of other products, including classic cars, hinted that full production will significantly reduce their cost (expected even at half the current values).

As a transient solution to the pure EV, today HEV is intensively develop. In urban areas these vehicles operate as an EV with poorer performances and out of town they are using built-in IC engine power for drive or recharge the batteries. In this way, the HEV contribute greatly to the ecology, affecting the economy of operation, and at the same time intensively developing the fuel cell as a promising energy reservoir for use in EV. In terms of retail, they gained increasing popularity. They are made of ICE vehicles with an increasing degree of usefulness or with lower fuel consumption per unit of road. While modern materials are used, the resistance movement is reduced and vehicles are made to be more effective.

Even in HEV vehicles is being experimented with different types of plant, from the type of ICE plant to fuel cells. Prices of cars with these drives are still high because of two types of driving machines, but to create the habits of drivers, public authorities and institutions usually significantly stimulate sales by reducing taxes when selling these vehicles.

The fuel cell generates the least pollution from all sources of electricity made to run motor vehicles. Hydrogen is an ideal fuel for fuel cells, in the technical and environmental terms. Hydrogen can be produced in many ways, but when fossil fuels are becoming scarce and expensive, hydrogen will be the most likely to be produced of the water using the solar cells and renewable sources. In scenario where solar hydrogen will be widely used, the whole system energy transport will be almost perfect and the energy will be completely renewable.

It can be concluded that as the main means of mass transportation, a car with SUS drive marked the twentieth century. However, the consequences of this form of mass transportation are a large amount of exhaust of harmful substances that pollutes the environment. Finding alternative energy sources that would power the vehicle could solve this problem. One of the possible solutions is EV.

In addition to the level of efficiency of EV significantly higher than the corresponding motor vehicles with ICE, one can not ignore the fact that the cars with fossil fuel store over 44 times more energy than the EV battery pack. Until today, this is the main reason why there has been no large scale production and use of EV.

BRIEF HISTORY OF EV

First implemented electric motor drive was achieved by Moritz Jakobi [02], in 1838., when for a short time it propelled boat with 14 people on the River Neva in the presence of the Russian Emperor Nicholas I and his entourage. Still, the beginning of creation and use of EV can be marked with 1839. year when Robert Davidson [03] from Scotland made the first vehicle powered by electricity with the aim of replacing steam locomotives, which were noisy and dirty due to smoke and coal. That EV on the rails, that made trip from Edinburgh to Glasgow possible, which is about 130km with one wagon and with one more built-in primitive electric motor is used as the primary power source battery. The achieved speed was 6.5 km/h; and vehicle could not handle any kind of payload. Therefore, the use of this vehicle was very limited. Suitable battery pack was made by Plante in 1860. enabling the commercialization of EV.

The first small-scale production of EV began 1892. in Chicago. These vehicles were very clumsy but as such had very good sales. The vehicles had the appearance of carriages with large wheels, no roof, with a canopy that protected the passengers from rain and the sun. They were used for trips, to do a certain job, and even a taxi to transport more passengers. Passenger electric cars had engines up to several kilowatts which made it possible to develop a maximum speed of 20km/h while covering the distance over 100km on a single charge of the batteries. Usually EV used serial DC motors. Rechargeable batteries were with large capacity of up to 400Ah and voltage up to 100V. Share in battery weight, relative to the fully loaded vehicle with passengers, was over half, which enabled wide autonomous movement radius.

On the roads of America in 1900. were about 8,000 cars, and almost equally, one third of the total, at the time the vehicle was powered by electricity, steam vehicles and vehicles with ICE.

The fall of oil prices, discovery of oil wells had also impact on the wider application of EV. The invention of the muffler in the late 19th century reduced the noise of ICE vehicles and an electric starter at the beginning of the 20th century eliminated the need for manual operation. Further progress of the implementation of EV opposed by three obstacles: low top speed, limited radius of a single battery charge and the relatively high price compared to the mass production of Ford vehicles [04]. Car with a combustion engine was gaining increasing popularity due to their ease of refuelling, mobility, speed and autonomy, although the EV is still kept. EV are especially favoured by females, who considered gasoline-powered car dirty and difficult to drive, and in the same time those were the very characteristics that made it more preferred by men, driven by the passion of sports.

The main drawback of the EV back than was relatively short range between charging. At the end of the 19th century, the specific energy in the accumulator batteries was about 10Wh/kg. At the beginning of the 20th century, this value improved to the level of 18Wh/kg, that only a decade later stood at 25Wh/kg [05]. In addition, the charging stations were not enough branched, although the situation began to improve in the early 20th century. However, locating new sources of oil caused drop in price of gasoline and the advancement of technology in the production of ICE created the conditions for the rapid progress of these cars. Therefore, the development of EV,s remained on the side-lines.

Figure 1 The main reason for leaving the development of EV in the early twentieth century lies in the fact that the accumulator batteries could accumulate around 25Wh/kg energy, and oil derivatives around 12.000Wh/kg

FACTORS THAT CONTRIBUTE TO MORE INTENSIVE DEVELOPMENT OF EV

The growth of the gross national income of each nation, as well as general technical progress is determined by great needs for all types of energy. Annual percentage growth of energy need in the world is greater than the percentage of population growth.

Transport in cities today is based on oil derivatives. With the existing technical solutions EV today does not possess enough energy so that it can achieve performance and radius of competitive vehicles with combustion drive. On the other hand, the lack of emissions and low noise make the EV more attractive for some special purpose, such as short trips with frequent stops at which the vehicles with ICE,s have inefficient operation.

In addition to high economic dependence on oil and petroleum products, are a common problem and the problem of protecting the environment, reducing exhaust emissions and greenhouse gases. It is anticipated that, due to the development of technology, the energy consumption in the production systems and the addition of large-scale production in the coming years could largely stagnate.

There are several factors that influence the development of EV:

Population growth in the world

Population growth in the world had a constant value from the beginning of a new era to the 19th century, when the population was about 1 billion. The world population has grown to more than 6 billion people in the 20th century. Today there are over 7 billion people in the world. Although the assessment of the UN [06], contains three possible scenarios of population growth in this century, the most probable is one that predicts that the world population will increase in 2050. on about 8.9 billion, and will then come to a slowdown in growth to by the end of the 21st century, while stagnating in the following centuries.

Transportation needs

With the growth of population in the world there is a need to increase the transport of people, goods and raw materials as a prerequisite for the growth of production and consumption, including the standard of living. This steady growth is a natural and expected process of the development of civilization and one of the most important indicators of the development of society and humanity so that it is considered that the present life is unimaginable without road traffic.

In the world in 2012. according to OICA [07], was around 1143.231 million vehicles, of which 833.342 passenger cars and 309.888 commercial. That same year was produced a total of 87,249,845 new vehicles, an increase in respect to the previous year of 3.6%, of which 65,386,596 passenger cars and 21,863,249 commercial.

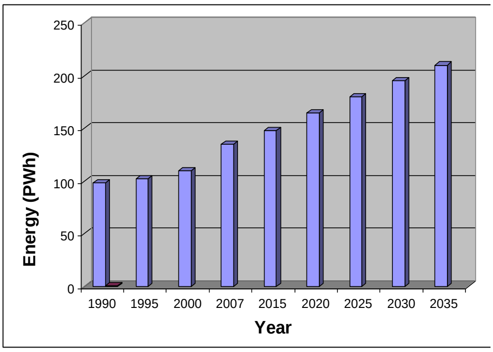


Figure 2 Consumption of total or primary energy in the world since 1990. year until now and forecast to 2035.

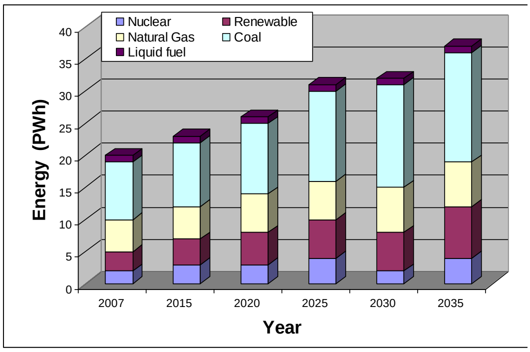


Figure 3 Share of energy sources in electricity generation in the world from 2007. until 2035. [09]

Energy needs

The growth of population in the world and the general technical progress conditioned the growing needs of all types of energy. Percentage growth of energy needs in the world is greater than the percentage of population growth.

Statistical summary of total consumption and primary energy in the world since 1990. until today, and forecast to 2035. [08] estimates that due to the increasing demands of consumer and especially due to the increasing demands for the transportation of goods and people, the demand for energy could increase by approximately 1,5 to 2% per year. It is believed that in the period from 2000. to 2050. year, energy need will be more than doubled.

Crude oil as an energy source

Although the share of oil in total production of primary energy percentually decreases, the production and consumption of oil is generally increasing. Efforts are made to find new sources and new evidence suggests that slowly this form of energy is reduced and scientists expect that for a certain time all sources of energy could dry up.

According to the BP Statistical Review (British Petroleum) [10], from 2011. Figure 04 shows the increase in prices of petroleum products in Rotterdam since 1993. expressed in U.S. $ per barrel.

Forecast of production of petroleum products in the world by 2035. according to the Energy Information Administration (EIA) [11], is shown in Figure 05. new oil fields are expected to be found, activation and depletion of existing ones, so that in the next 25 years, production of crude oil will retain most of the existing value. It is expected increase in natural gas consumption and non-conventional liquid fuels. At the same time this will make certain redistribution of consumption of liquid fuels. Increase in consumption of liquid fuels for transport is expected and to a lesser extent for other consumers.

Although people are still finding new sources of oil, the fact is that oil consumption is increasing and one day it will dry up so humanity will need to find other energy sources.

Figure 4 The prices of petroleum products on the market in Rotterdam from 1993. until 2010th year, expressed in U.S.$ per barrel

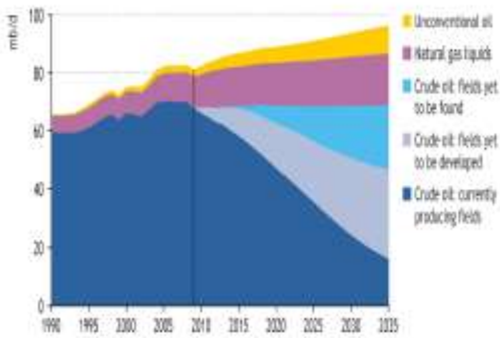


Figure 5 Forecast of the global production of liquid fuels by 2035.

Taking into account today discovered and researched fossil fuel reserves can be estimated that by mid-century, the transport sector and transport of energy resources could be generally supported, but certainly not after the 2050, if today's fuel reserves resulted in new energy crisis [12].

Environmental pollution and global warming

Pollution of air fuel combustion in motor vehicles is becoming the most important global problem, especially in urban areas around the world. The emission of pollutants originating from motor vehicles is caused by the level of traffic, the possibility of roads as well as meteorological conditions. Pollutants from the exhaust system of motor vehicles can reach the atmosphere and dependent on the composition, inflammability and fuel volatility. In contrast to the natural greenhouse effect, the additional effect caused by human activity contributes to global warming and may have serious consequences for humanity. The average surface temperature of Earth has increased by about $0{,}6^0$C [13], only in the twentieth century. In addition, if humanity do not take any steps towards limiting emissions of greenhouse gases in the atmosphere, it can be expected that the concentration of carbon dioxide by 2100. reaches between 540 and 970 million particles of the volume. This concentration of carbon dioxide would lead to a global temperature increase between 1.4 and $5{,}8^0$C by the end of this century.

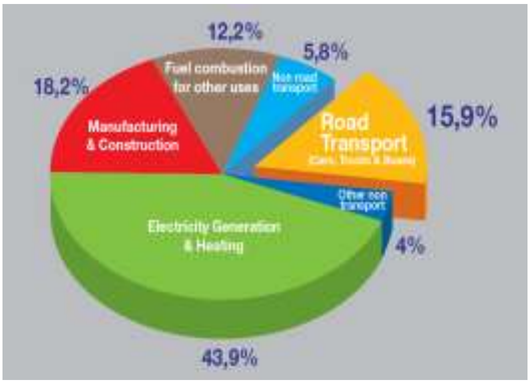


Figure 6 About 15.9% of global man-made CO2 emissions come from motor vehicles [14]. It is about 13% of total greenhouse gas

Temperature rise of this magnitude would also greatly affect the entire Earth's climate, and would be manifested as more frequent rainfall, more tropical cyclones and natural disasters every year in some regions, or on the other hand, in other regions such long periods of drought, which would have very bad effect on agriculture. Entire ecosystems could be seriously threatened with extinction species that could not quickly enough to adapt to climate change.

Production and consumption of electricity

An essential prerequisite for economic growth and development of each country and the region is a safe and reliable supply of electricity. Electricity consumption per capita is the highest in the Nordic countries (with a maximum value of 24.677kWh, Iceland) and in North America. Almost half of the EU countries have nuclear power plants so that in France and Lithuania almost 75% of electricity generation is from nuclear power plants. Primary energy demand increases by 41% between 2012 and 2035 [15], with growth averaging 1.5% per annum (pa). Growth slows, from 2.2% pa for 2005-15, to 1.7% pa 2015-25 and just 1.1% pa in the final decade.

Energy consumption grows less rapidly than the global economy, with GDP growth averaging 3.5% p.a. 2012-35. As a result energy intensity, the amount of energy required per unit of GDP, declines by 36% (1.9% p.a.) between 2012 and 2035th The decline in energy intensity accelerates; The expected rate of decline post 2020 is more than double the decline rate achieved from 2000 to 2010.

Electricity generation is mainly the combustion of solid fuels 40% and natural gas 20%. About 16% of electricity is obtained from hydropower and slightly less, 15% from nuclear power plants. Less than 10% is obtained from oil. It is believed that in the near future to reach a substantial increase in electricity would come from production from nuclear power plants, to a lesser extent from natural gas, and later from renewable sources.

High energy efficiency of electric drive

In order to analyse the energy level from the energy source to the wheels of the vehicle, it is necessary to bear in mind the following:

- The efficiency of operation of the mine of natural fuels (fossil fuels or nuclear energy),

- The production of electricity and
- The network transport.

Efficiency of electricity generation varies widely. According to European measurements, ranges from 39% for plants with coal production to 44% of power plants with natural gas, or the mean value of 42%. Power plants with combined cycle natural gas can reach the efficiency level of over 58%. If the mean value of 42% multiplied by the efficiency of the transfer of 92% efficiency from source to reservoir of 38% is obtained. Battery charger, battery recharging, transmission and losses in the electric motor give the utility of the reservoir energy to the wheels from 65-80%. In this way, the overall usefulness of the source to the wheels is from 25 to 30%.

Exploitation of natural fuel and transport network depend on the type of energy but have an average efficiency of about 92%. Together with losses in transport and processing receives the total level of efficiency from the source to the reservoir by about 83%. But the internal combustion engine is only 15-20% of the energy converted into useful work. In this way, the overall usefulness of the source to the wheel is 12 to 17%.

Table 1 Existing level of utility vehicles with ICE and EV [16-17]

	ICE	EV
From the source to the reservoir	83%	38%
From the reservoir of energy to the wheels	15–20%	65-80%
Total: From the source to the wheels	12–17%	25-30%

Energy efficiency is a very important data, and is expressed as the electric energy consumption from the electric distribution grid to one kilometre of road. It is obtained as the ratio of distance travelled per unit of electricity consumed. Measurements made in our country [18] showed that the specific energy efficiency of the flat road is about 5,1 km/kWh, while in the city's hilly operation is about 4,5 km/kWh. Specific energy consumption, defined as the ratio of electricity consumed from the electric distribution grid per unit of distance travelled, or the reciprocal value of energy efficiency, is on the straight road below 0.2 km / kWh and in the hilly city driving about 0.22 km / kWh.

FURTHER DEVELOPMENT EV

The main problem that follows the EV is connected to the "reservoir of accumulated energy." Existing battery, despite the fact that has been developed specifically for this application, has a lot of flaws in service. The efforts of scientists are focused precisely because of the finding of an entirely new principle for energy storage.

Hybrid vehicles

Not finding opportunities to the existing types of EV satisfy the habits of drivers of vehicles with conventional drive, as well as with vehicles with conventional drive meet certain environmental conditions, vehicle manufacturers have resorted to an interim solution, the so-called “hybrid power train”. As a combination of vehicles with ICEs and pure EV, hybrid vehicles reduce fossil fuel consumption by about 20% in the cities as well as emissions.

The general conclusion is that it performs a positive step towards the introduction of environmental drive vehicles. However, since there is no definite solution, experiments were conducted with pure electric and hybrid solutions, as well as various kinds of technical solutions drive. Despite the turbulent development of EV and HEV, some experts believe that vehicles with ICEs will dominate for another 15 years, but even after that, will not disappear [19]. Hybrid, a combination of electric motors and ICEs, is relatively simple and inexpensive solution that today meets the environmental requirements.

With the optimal allocation of functions between components of the hybrid drive can be achieved:

- Economical electric-powered cars, no combustion products and noise-free in city traffic;
- Cost-effective operation of ICEs with a nominal (generator) mode, high acceleration and high speed on the open road.

Due to the lack of rigid coupling ICE-drive wheels the transient regimes engine are eliminated and thus all the bad effects of these regimens on the increase in fuel consumption, emissions and noise. The ICE runs at a stationary regimes load and high efficiency of primary energy, just in time intervals when necessary to maintain the level of battery power within the given limits. With this variant of the HV performance are limited by the nominal capacity of the power plant and the radius of the reservoir tank of ICEs. Despite the turbulent development of EV and HV, some experts believe that vehicles with ICEs would dominate for another 15 years, but even after that will not disappear [20].

The main reason for the production and purchase of HVs is reduction in terms of the fuel economy in city driving, but commonly cited and displayed are information on saving energy and pollution reduction. Top selling hybrid Prius [21], has fuel-efficiency of 51mpg (21,7 km / l) in a city driving and 48mpg (20,4 km / l) on the open road. Typically in our presents data on consumption per 100km odometer, so that consumption in the city driving is 4,6 l/100km and on the open road is about 4,9 l/100km.

Plug in EV

If the HV possess a larger capacity battery that can be recharged via connection to an external source, i.e. the distribution network, then such vehicles we can call as "plug in" hybrid vehicle (PHV). Although PHV will never become a "zero emission vehicle" (ZEV) for their internal combustion engine, the first PHV which appeared on the market reduce emissions by one-third to half [22], and more modern models are expected to reduce emissions even more [23].

"Plug in" HV vehicles can cross a distance up to 120km with a charged battery and batteries, and then the batteries need to supplement from the power grid or by using the ICE. Often the on-board computer determines the most optimal conditions for recharging.

The primary difference between HV and "plug in" HV Prius becomes obvious if one looks at increasing the range or radius of the vehicle in electric mode, from about 2 km (Prius) to 23.4 km (PHV) [24]. In addition, specific fuel consumption in a hybrid mode is improved as well. Studies have shown that in Japan, 90% of drivers exceed the average daily distance below 50km, 60km and 75km in the EU and the U.S. respectively. In this case, the expected fuel economy greatly affects the price of electricity during the day, which in Japan is about 20 cents / kWh and late at night around 8 cents / kWh. It should be noted that the average price of electricity in Serbia is only about 5 EU cents / kWh.

The best-selling hybrid car in the U.S. "Toyota Prius", has the highest demand when the price of fuel rises. Country stimulates with $ 6.400 the cost of producers, so that the standard model sells for just U.S. $ 21.610. The fuel economy of this vehicle is 48mpg (4,9 l/100 km) in city driving and 45mpg (5,2 l/100km) on the open road. Compared to consumption of fuel per 100 km is 5,2 l/100km in city driving and 4.9 l/100km on the open road.

Large oil producers such as BP [25], are stipulating that in the next period until, 2030 PHV will dominate the market, mainly due to the reduction of fossil fuel consumption per kilometer distance.

EV fuel cell

The fuel cell is an electrochemical device that is used to convert chemical energy into DC power. The principle of operation of this device is the opposite of the operation of the electrolyser, and is composed of two electrodes between which is an electrolyte. The electrodes are separated by separators of the electrolyser, so in this space gasses are injected mainly hydrogen and oxygen. Oxidation takes place on anode and reduction of the fuel on cathode. Fuel cell system applied in autonomous electrical actuators is derived from the study of the space program [26].

The fuel cell has the potential to be more efficient than the engines for the following reasons [27]:

- fuel cell produces little amount of collateral products;
- has few moving parts (pumps for the chemical reaction and faucets);
- during this conversion process converts the energy of fuel into heat;
- the fuel is oxidized at a low temperature instead of burning in high temperature in the internal combustion engine;
- shows a small components as a result of oxidation at low temperature;
- In case of hydrogen (making the fluid), a side product is water.

Therefore, one can expect a wider application [28] of the "reservoir of energy" in the EV.

Based on the aforesaid, the following can be concluded - hydrogen plays a key role in the future clean energy, that is:

1. has the high energy content per unit weight of existing capacity;
2. when burned in the engine, hydrogen produces effectively zero emissions when powered by a fuel cell: only waste is water;
3. hydrogen can be produced from different national resources, including natural gas, coal, biomass, and even water;
4. Combined with other technologies such as carbon sequestration and storage, renewable energy and fusion energy, fuel cells can make future energy needs without harmful emissions.

   The great hope is to be taken in the development and deployment of fuel cells, so that some researchers [29] believe that fuel cells are the only way to achieve true zero-emission transport. Company Vice President *Ballard* - Research and Development division [30], which develops and manufactures fuel cells, said that by 2020 or 2025th year will be about one million vehicles with fuel cells.

It is interesting to note that FCEV has a disadvantage that their quick-change loads are low, so their work has to be combined with Supercapacitors. Supercapacitors are electrochemical systems that store energy in a polarized liquid layer, the intermediate layer between the ion conducting electrolyte and conductive electrodes. The possibility of storing the energy increases with the surface area of the intermediate layer. They have a higher specific energy and power of electrolytic capacitors - devices that store energy as an electrostatic charge [31]. They were developed as primary energy equipment for extra power during acceleration and inclined driving as well as for recharging during braking [32].

They can be used as a secondary energy source in HEV, accumulating energy while the vehicle is stationary or during braking. Ongoing research and development tend to form ultracapacitors with the possibility of $50 Wh/kg$ specific energy and specific power of 1,000 W/kg. However, ultracapacitors have certain disadvantages. The additional electronics needed to maintain certain parameters taking into account the characteristic of the capacitor to the voltage at the ends of the capacitor decreases linearly in accordance with the energy of the discharge.

Older solution for energy storage is the flywheel. A flywheel is a flat disk or cylinder that spins at very high speeds, storing kinetic (movement) energy. A flywheel can be combined with a device that operates either as an electric motor that accelerates the flywheel to store energy or as a generator that produces electricity from the energy stored in the flywheel. The faster the flywheel spins, the more energy it retains. Energy can be drawn off as needed by slowing the flywheel.

Modern flywheels use composite rotors made with carbon-fiber materials which have a very high strength-to-density ratio, and rotate in a vacuum chamber to minimize aerodynamic losses.

Flywheels can discharge their power either slowly or quickly, allowing them to serve as backup power systems for low-power applications or as short-term power quality support for high-power applications. They are little affected by temperature fluctuations, take up relatively little space, have lower maintenance requirements than batteries, and are very durable.

Battery-powered EV

Development of motor vehicles is going in the direction of renewable fuel and power, and there in the first place we see electrical energy that can be obtained from various sources. As previously noted [16-17], EV has higher degree of energy utilization and generally the existing solutions of sufficient quality except "reservoir of electricity." Existing batteries are not able to meet the habits of today's drivers of motor vehicles. Today, the most promising potential source of energy is the Li-air system.

The energy density of gasoline is 13,000 Wh/kg, which is shown as "a theoretical energy density" (Figure 07). The average utilization rate of passenger cars with IC engine, from the fuel tank to the wheels, is about 13% in US, so that "useful energy density" of gasoline for vehicles use is around 1.700 Wh/kg. It is shown as "practical" energy density of gasoline. The efficiency of autonomous electric propulsion system (battery-wheels) is about 85%.

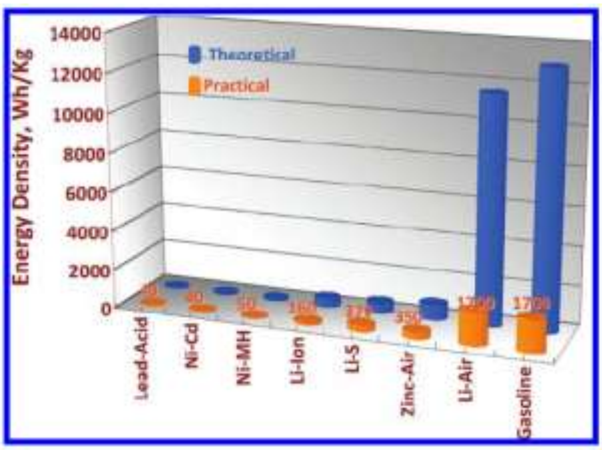


Figure 07. Image Energy density of different types of batteries and gasoline [33]

Significantly improvement of current Li-ion energy density of batteries is about 10 times, which today is between 100 and 200 Wh/kg (at the cellular level), could make that electric propulsion system be equated with a gasoline powered, at least, to specific useful energy. However, there is no expectation that the existing batteries, as Li-ion, have ever come close to the target of 1,700 Wh/kg.

The latest researches are conducted in the field of graphene [34]. Graphene's good electrical conductivity and large surface area per unit mass make it an exciting material for energy storage applications such as advanced batteries and supercapacitors.

Comparison of the main characteristics of EV

Comparison of basic characteristics of the EVs is shown in Table 2

CONCLUSION

Although the EV appeared before the IEC vehicles, they could not withstand the competition more robust and more powerful IEC vehicles, which have marked the entire 20th century. Beginning of the 21st century, noted that it was necessary to develop a vehicle with new properties to transport people. The vehicle must be powered by renewable energy and be environmentally friendly. Bearing in mind that there are still no quality solutions, today vehicles are developed in two directions, to save fossil or non-renewable energy sources and to be environmentally friendly.

Vehicles that use alternative fuels, as well HV, significantly reduce the need for petroleum products. In addition, motor vehicles are becoming faster, environmentally cleaner, safer and more energy efficient.

If renewable electricity gets developed significantly in the next period, it will allow the possibility of its cheap production. This means that, in addition to environmental, economic conditions will be met for the broader application of EV. Almost all the problems related to the technology of production EV are sufficiently well resolved, except for storage of energy. Fuel cells, electrochemical or new resources that could be made cheap enough and compact would allow in the near future, pass from the vehicles that use liquid fuel to EV. Price of the batteries today seems EV to be more expensive than buying appropriate vehicles with conventional drive. Accordingly, the price of EV, according to the mileage compared to cars with internal combustion-powered, would be the same. Fuel for EV's is cheap, maintenance is minimal, and the duration of the electric motor is significantly longer than the internal combustion engine. Taking into consideration the cost of air pollution, gas emissions that cause the effect of "greenhouse gases" and other market conditions, the factors that the company has to pay, it is believed that the golden era of EV is coming.

It is likely, however, there won't be a quick transition from internal combustion vehicles to EV. Still EV's are considered to be inferior and cannot meet the needs of potential buyers under all circumstances. The development of batteries has made great progress, but still not enough. In addition, if the battery problem is to be solved, there are still plenty of problems that need to be better addressed. Some of these problems will be solved on its own, such as drop in price of the components due to the increased production, but others, in support of the introduction of new vehicles in the traffic will be much harder to resolve spontaneously.

Set targets for electric-drive vehicle sales. To achieve the roadmap's vision, industry and government must work together to attain a combined EV / PHEV sales share of at least 50% of LDV sales worldwide by 2050th By 2020, global sales should achieve at least 5 million EVs and PHEVs (combined) per year [38]. Achieving these milestones will require that national governments lead strategic planning efforts by working with "early adopter" metropolitan areas, targeting fleet markets, and supporting education programs and demonstration projects via government-industry partnerships. Additionally, EV / PHEV sales and the development of supporting infrastructure should first occur in selected urban areas of regions with available, low GHG emission electricity generation.

Table 2. Major characteristics of HEV, PEV, FCEV and BEV [35].

Types of EVs	Hybrid EVs	PEVs	Fuel cell EVs	Battery EVs
Propulsion	Electric motor drives Internal combustion engine	Electric motor drives Internal combustion engine	Electric motor drives	Electric motor drives
Energy system	Battery Supercapacitor ICE generating unit Integrated starter generator	Battery Supercapacitor ICE generating unit Integrated starter generator	Fuel cells Need battery/ supercapacitor to enhance power density for starting	Battery Supercapacitor
Energy sources and infrastructure	Gasoline stations	Gasoline stations Electric grid charging facilities	Hydrogen Hydrogen production and transportation infrastructure	Electric grid charging facilities
Characteristics	Very low emission Long driving range Higher fuel economy as compared with ICE vehicles Dependence of crude oils Complex Commercially available	Very very low emission Long driving range Higher fuel economy as compared with ICE vehicles Dependence of crude oils Complex Commercially available	Zero emission or ultra-low emission High energy efficiency Independence on crude oils Satisfied driving range High cost Under development	Zero emission Independence on crude oils High energy efficiency High initial cost Commercially available Relatively short range
Major issues	Managing multiple energy sources Dependent on the driving cycle Battery sizing and management	Managing multiple energy sources Dependent on the driving cycle Battery sizing and management	Fuel cell cost Hydrogen infrastructure Fuelling system	Battery and battery management High performance propulsion Charging facilities

It is believed that the future and the past belong to the EV. This is a positive step towards the introduction of environmental drive vehicles. However, since there is no definitive solution, experiments are conducted with pure electric and hybrid solutions. Despite the turbulent development of EV and HV, some experts believe that vehicles with internal combustion engines will dominate for another 15 years, but even after that will not disappear [36-37], primarily due to a reduction in fuel consumption per kilometre of distance. At the meeting of the Competitiveness Council in San Sebastian, in 2010, ACEA President Dieter Zetsche [38] made clear statement: "The question is not whether the diesel and petrol will be replaced by electricity and hydrogen as the dominant means of tank cars. The only question is when? "

ACKNOWLEDGEMENT

This work was financially supported by the Ministry of Education, Science and Technological Developments Republic of Serbia (Projects No. TR 36035, TR 35041 and TR 35042).

REFERENCES

[1] Nikolić Z., Živanović Z., Kragić R., Development and prospects of electric vehicles in the country, Proceedings of the First Conference on OIEE, Belgrade, SMEITS 2011, p.177-190.

[2] Fredzon, I.R., Sudovbie elektromehanizmbi, Gosudarsvenoe soioznoe izdetelbstvo sudostroitelbnoi promibišlennosti, Leningrad, 1958, p. 5.

[3] Kordesch K., The electric automobile, Union Carbide Corporation Battery Product Division, Ohio, (1978).

[4] Chan C. C., The Rise & Fall Of Electric Vehicles In 1828–1930: Lessons Learned, Proceedings of the IEEE, Vol. 101, No. 1, January 2013, p.206-212.

[5] Larminie J, Lowry J., Electric Vehicle Technology Explained, John Wiley & Sons Ltd, England, 2003, p.4.

[6] -, World Population to 2300, UN Department of Economic and Social Affairs, New York, (2004), 240, ST/ESA/SER.A/236

[7] -, International Organization of Motor Vehicle Manufacturers. via NationMaster http://www.nationmaster.com/graph/ind_car_pro-industry-car-production

[8] -, World energy Outlook 2010, International Energy Agency, Key Graphs, OECD/IEA 2010, http://www.iea.org/statist/index.htm

[9] -, BP Statistical Review of World Energy, June 2011, http://www.bp.com/statisticalreview

[10] -, BP Energy Outlook 2030, London, January 2011, http://www.imf.org/external/np/res/commod/pdf/ppt/BP0113.pdf

[11] -, Annual Energy Outlook 2011 with projections to 2035, EIA, U.S. Energy Information Administration, DOE/EIA-0383 (2011)

[12] -, Medium-term markets 2011 Overview, International Energy Agency, OECD/IEA 2011, www.iea.org

[13] Metz B., Davidson O., Bosch P., Dave R., Meyer L., Climate Change 2007 Mitigation, Cambridge University Press, New York, USA

[14] CO2, International Organization of Motor Vehicle Manufacturers, OICA, World Resources Institute, Climate Analysis Indicators Tool, Transportation&stockbyte, p. 6.

[15] - , BP Energy Outlook 2035, January 2014, bp.com/energyoutlook, #BPstats

[16] -, International Organization of Motor Vehicle Manufacturers. via NationMaster http://www.nationmaster.com/graph/ind_car_pro-industry-car-production

[17] Bilen B., Nikolić Z., Mogućnosti i perspektive električnih vozila, Zbornik radova sa XVI međunarodnog skupa NMV 97, Beograd, (1997), p.49-52.

[18] Nikolić Z., Marjanović S., Dakić P., Neki rezultati ispitivanja električnog vozila YUGO-E, Zbornik radova sa XVI međunarodnog skupa NMV 97, Beograd, (1997), p.53-56.

[19] Higgins A., Profile of Ralf Schuermans, Electric & Hybrid Vehicle Technology International, July 2009, p.120.

[20] Akihira W., The Automobile of Tomorrow: Toyota,s Approach, A Toyota quaterly rewiew, No. 100, 1997, p.30-37.

[21] www.uscar.org/freedomcar

[22] -, Kampman B., Leguijt C., Bennink D., Wielders L., Rijkee X., De Buck A., Braat W., Green Power for Electric Cars, Development of policy recommendations to harvest the potential of electric vehicles, Delft, CE Delft, January 2010, page 20.

[23] Bagot N., It,s good, but is it enough?, Electric & Hybrid Vehicle Technology 97, 1997, p.22-23.

[24] Abe S., Development of Toyota Plug-in Hybrid Vehicle, Journal of Asian Electric Vehicles 2010; 8: p.1399-1404 . Journal of Asian Electric Vehicles, Volume 8, Number 2, December 2010, p.1399-1404.

[25] -, Annual Energy Outlook 2011 with projections to 2035, EIA, U.S. Energy Information Administration, DOE/EIA-0383 (2011)

[26] Panik F., Fuel cell for vehicle applications in cars - bringing in future, Journal of Power Sources 71 (1998), p.36-38.

[27] Frederick Veit R., Fuel of the future, Electric & Hybrid Vehicle Technology 98, 1998, p.124-127.

[28] Joon K., Fuel cells - a 21 st century power system, Journal of Power Sources 71 (1998), 12-18, Lamy C., Leger J.M., Fuell Cells - Aplication to Electric Vehicles, Journal de Physique IV, vol 4, 1994, p. 253 - 281,

[29] Nnji N., Fuel cells, Electric & Hybrid Vehicle Technology International, annual 2008, p.30-36.

[30] – Fuel cell future, Electric & Hybrid Vehicle Technology International, annual review 2005, p.96.

[31] Harrison R., Create a super car, Electric & Hybrid Vehicle Technology, annual review 2000, p.144-145.

[32] Baudry P., Marquet A., Application of Solid-State Electrolite Generators for Electric Utilities, Electrochemica Acta, vol 37, Iss. 9, 1992, p. 1627 – 1629.

[33] Girishkumar, L.G.G., McCloskey, B., Luntz, A. C., Swanson, S., and Wilcke, W., (2010), Lithium-Air Battery: Promise and Challenges, J. Phys. Chem. Lett. 2010, 1, 2193-2203, doi: 10.1021/jz1005384 |

[34] Jari Kinaret, Vladimir Falko, Andrea Ferrari, Jani Kivioja, Tomas Löfwander, Daniel Neumaier, Konstantin Novoselov, Vincenzo Palermo, Stephan Roche, GRAPHENE-CA, Coordination Action for Graphene-Driven Revolutions in ICT and Beyond Coordination and support action WP3 Defining the Research Agenda, Deliverable 3.2 “Research agenda for the GRAPHENE flagship”, Project funded by the European Commission under grant agreement n°284558

[35] Kamil Çag˘atay Bayindir, Mehmet Ali Gözüküçük, Ahmet Teke, A comprehensive overview of hybrid electric vehicle: Powertrain configurations, powertrain control techniques and electronic control units, Energy Conversion and Management 52 (2011) p.1305–1313.

[36] - International Energy Agency (IEA), Technology Roadmap, Electric and plug-in hybrid electric vehicles, June 2011, p.4.

[37] Higgins A., Profile of Ralf Schuermans, Electric & Hybrid Vehicle Technology International, July 2009, p.120.

[38] Dieter Zetsche, The Future of Electric Cars - The Automotive Industry Perspective, San Sebastian, 9 February 2010, http://www.acea.be/images/uploads/files/20100211_Speech_Dieter_Zetsche.pdf

RESEARCHING MOTORCYCLE’S STABILITY AT MOTION

Branislav Aleksandrović[1], Rajko Radonjić, Dragoljub Radonjić, Aleksandra Janković

UDC:629.016

ABSTRACT: The statistical analysis has shown that motorcycles are common cause of traffic accidents. Besides, in many cases it was confirmed that a driver, just before the traffic accidents occur fells from the motorcycle and therefore his injuries are more serious. In order to study influencing factors to this phenomenon, in this paper were established a simulation model in order to be able to analyse stability of the motorcycle in motion during braking process starting from high initial velocities. An experimental system for verification of simulation models has been developed and used. The obtained results regarding identification of the domain of stability of motorcycle’s movement at braking depending on weight status, weight distribution on wheels and used braking strategies, were presented and analysed.

KEY WORDS: motorcycle, breaking, stability, accident, simulation

ISTRAŽIVANJE STABILNOSTI KRETANJA MOTORCIKLA

REZIME: Statistička analiza je pokazala da su motorcikli čest uzrok saobraćajnih nezgoda. Osim toga, u mnogim slučajevima je potvrđeno da vozač, upravo pre nezgode padne i zato su njegove povrede su ozbiljnije. U cilju proučavanja uticajnih faktora na ovu pojavu, u ovom radu je formiran simulacioni model kako bi mogli da analiziraju stabilnost kretanja motocikla tokom procesa kočenja počevši od velikih brzina kretanja. Eksperimentalni sistem za verifikaciju simulacionog modela je razvijen i korišćen. Dobijeni rezultati koji se odnose na identifikaciju domena stabilnosti kretanja motorcikla u procesu kočenja u zavisnosti od masenog stanja, raspodele mase po točkovima i primenjene strategije kočenja analizirani su i prikazani u radu.

KLJUČNE REČI: motorcikl, kočenje, nezgoda, simulacija

[1] *Received: August 2014, Accepted September 2014, Available on line January 2015*

Intentionally blank

RESEARCHING MOTORCYCLE'S STABILITY AT MOTION

Branislav Aleksandrović [1]MSc, Teaching Assistant, Rajko Radonjić [2], PhD, Professor, Dragoljub Radonjić[3], PhD, Professor, Aleksandra Janković[4], PhD, Professor

UDC:629.016

INTRODUCTION

Dynamic characteristics of motorcycles, the conditions and the way of its usage, significantly effect on the behaviour of the driver - a motorcycle and traffic safety. Statistical analyses show that motorcycles are common cause of traffic accidents with severe consequences. The paper [1] presents the data analysed from statistical sample, showing that motorcyclists have 37 times greater probability to cause a traffic accident and 8 times greater probability that doing so he could be more injured compared to the injuries of the driver of passenger car. In paper [2] illustrative data are also presented, about percentage participation of victims in road traffic for two categories of participants, 52% cars, 24% single-track vehicles, of which, mopeds 5%, 6% bicycles, motorcycles 13%. Results of statistical analysis obtained for certain regions of the Republic of Serbia show an increasing number of traffic accidents in which motorcycles participated. [1].

In addition to statistics data regarding on road accidents involving motorcycles, in numerous paper works and studies in this field, the factors that have led to accidents were analysed, as well as the preventive measures for consequence reduction or their exclusion [3], [4], [5]. The specification of these factors is in relation to the goal of this research and in certain way it points out interactive conjunction system; the driver - a motorcycle - the road - the environment, therefore, the distribution of their functions and responsibilities on provoked traffic accidents in all three phases of the relevant events.

In our previous works we have analyzed some of impacting factors as the consequence of motorcycle's potential adverse properties compared to two trace vehicles, [3]. Following impacts are highlighted as dominant: 1 / motorcycle's open support structure that does not provide an integrated protective space for the driver and passenger, with unfavourable conditions of contact seats, supporting structure, brackets, controls, 2 / significant impact of driver's and passenger's body mass on dynamic characteristics of the motorcycle, 3 / the absence of its own stability in vertical position and at movement, which significantly complicates the steering function and increase the level of mental and physical stress. In this sense, numerous conducted expertises also show that the integrity and stability of the motion system, motorcycle - the driver - (co-driver), has a crucial influence on the number of traffic accidents and their consequences [5].

Bearing in mind the above presented approaches on current issues regarding motorcycle's safety, in subsequent chapters of this work are presented an approach of

1 Branislav Aleksandrović, Technical College of Appiied Studies Kragujevac, Kosovska 8, Kragujevac, Serbia, banealeksandrovic@gmail.com
2 Rajko Radonjić, Ph.D.,full prof., University of Kragujevac, Faculty of Engineering, Sestre Janjić 6, Kragujevac, Serbia, rradonjic@kg.ac.rs
[3] Dragoljub Radonjić, Ph.D.,full prof., University of Kragujevac, Faculty of Engineering, Sestre Janjić 6, Kragujevac, Serbia, drago@kg.ac.rs
[4] Aleksandra Janković, Ph.D.,full prof., University of Kragujevac, Faculty of Engineering, Sestre Janjić 6, Kragujevac, Serbia, alex@kg.ac.rs

theoretical - experimental research of motorcycle's stability at characteristic modes of motion.

The body of the paper is written using the Text body style. The first line of the paragraph is not indented. Live a blank line between the paragraphs. Do not leave a line of space above and below the headings.

OBJECTIVE

During planning of the research within this paper work, the following goals were settled:

1. certain results about system behaviour during traffic accidents will be analysed in terms of the ability to identify the influencing factors and their further evaluation through theoretical - experimental studies,

2. to form appropriate models and experimental system for such research. The first segment of the research is presented concisely, in this chapter, and the second in the following subsections.

The fact is that the motorcycles do not have seat belts or closed space for driver and passenger protection, thus they cannot prevent them from freely and unexpected moving in space at different stages of traffic accidents. In many cases, it was confirmed that the driver fell off the motorcycle before an accident occur; this is the reason why his injuries were more severe. It is found significant correlation between the number of falling of the driver from the motorcycle and incorrect braking. The term incorrectly braking, in traditional braking system, means untimely response, inadequate selection of braking strategy, or using prospective properties of braking only by the front, only by the rear wheel, with both wheels at the same time, or by the specified "algorithm", and then, panic braking over the limit of tire-road adhesion.

With the above quoted facts it should be noted that most modern motorcycles possesses separate braking systems; front wheels breaking by the manual control of the right hand, and the rear wheel breaking via foot controls by right leg. This concept of braking system gives the driver more options to choose the appropriate braking strategy in some regular conditions. However, the unexpected and stressful situations, this concept often leads to mistakes, in the form of reflex and panic braking [6], [7]. For these reasons, the structural integrity of the system, driver - motorcycle, i. e., the stability of its movement during braking is an actual problem, and that's why this subject is chosen to be studied in this paper work.

DYNAMIC MODELS OF MOTORCYCLES

As the base for simulation studies in this work was used the physical model of longitudinal - vertical dynamics of motorcycles, shown in Figure 1.b, which is created on the basis of appearance and technical characteristics of motorcycle, shown in Figure 1.a which was also used for the experimental researches.

In Figure 1.b are presented some basic parameters crucial for mathematic model creation, which are presented by the equations, (1), (2) and (3):

$$m\ddot{x} = F_x + R_f + R_v + R_\alpha \quad , \tag{1}$$

$$m\ddot{z} = f_z\left(Z_f, Z_r C_{zi}, v\right) \quad , \tag{2}$$

$$J_\theta \ddot{\theta} = f_\theta\left(Z_f, Z_r, a, b, l, h, F_x, C_{\theta i}, v\right) \quad , \tag{3}$$

where: F_x – is longitudinal force between contact surface of the road and the wheels, driving or braking force, or their resultant, depending on the observed cases, R_f, R_v, R_α - rolling resistance, air, inclination - respectively; Z_f, Z_r - vertical forces on the front and rear wheel - respectively; C_{zi}, $C_{\theta i}$ – parameters of aerodynamic forces and moments in the vertical - longitudinal plane, v - speed of movement, a, b, h - the coordinates of the center of masses, l – distance between the front and the rear wheel. Model (1) is given in the developed, explicit form, while models (2) and (3) are given in an implicit condition of variables and impacting parameters.

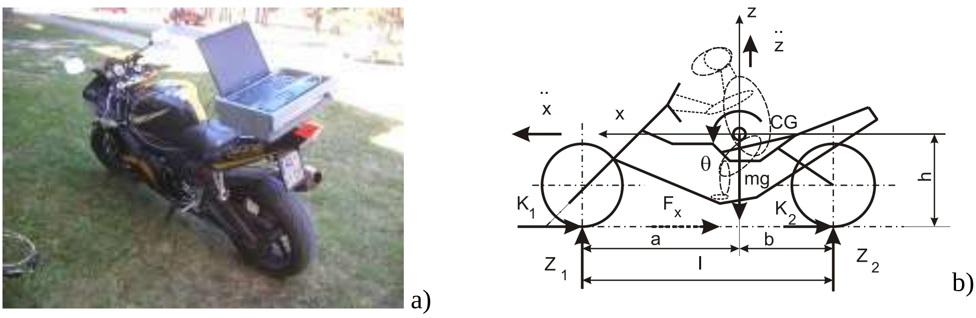


Figure 1 a) apperiance of experimental motorcycle, b) physical motorcycle model.

The structure and parameters of the mathematical models (1), (2) and (3) enable studying of interaction of relevant dynamic values in the longitudinal and vertical plane in the process of motorcycle's acceleration and braking, in order to establish criteria for evaluation of system stability at motion under these regimes. Some practical issues of stability at motion of the motorcycle in the longitudinal - vertical plane, related to the possibility of rolling over, blocking of the wheels, sliding, changing the trajectory, losing manoeuvrability and similar, were discussed in this paper work, using simulation models which were formed on the basis of above presented mathematical models, (1), (2), (3).

Illustrative examples of simulation results of braking process are given in Figure 2. Figure 2.a shows the redistribution of vertical dynamic loads on the wheels depending on longitudinal deceleration at braking. Based on this image it can be seen that increasing the intensity of braking, respectively, longitudinal deceleration on the rear wheel is relieved while the front, for the same grade is additionally burden in relation to the static loads. The graphics are given for two variants of distribution of the static load along the axle: 1/symmetric, G_1=G_2, and asymmetric, G_1<G_2, in both cases at x"=0. Appropriate variation of braking force depending on longitudinal deceleration, for these two cases, is presented in Figure 2.b. From motorcycle's stability at motion viewpoint characteristic is the braking regime when rear wheel loose the contact i.e., when it is being separated from the soil. For a symmetrical load distribution this will happen at longitudinal deceleration of 8.4 m/s^2 and for the asymmetric, at 10.2 m/s2, according to the conditions presented in Figure 2.a, Z_{2i}=0. In these conditions, front wheel receives the total weight of the motorcycle, Z_{1i}=G and achieves the total braking force, K_{1i}=K.. These relations can lead further to blocking of the front wheel, to its sliding in longitudinal-lateral direction and complex motorcycle movements along the front wheel, up to roll over.

Loosing stability of motion while motorcycle is braking, because one of the wheels is blocked, at the different strategies of braking, may be considered on the basis of the simulation results given in Figure 2.c, and Figure 2.d. For symmetrical load distribution, according to Figure. 2.c, and when braking is achieved only with the rear wheel, required adhesion coefficient φ_2, reaches a boundary value at decelerating of 2.8 m/s^2, and it leads to a wheel blocking, it means, it leads to further braking inefficiency and unstable movement. Braking only with the front wheel, the limit value of the required coefficient of adhesion, φ_1, is in the domain over 10m/s^2, of longitudinal deceleration values, that means, above the value of the deceleration at which the rear wheel lose the contact with the ground, for this case – above value 8.4 m/s^2. In the case of simultaneous braking with both wheels in the domain of stable movement, the boundary values of slowing reduction in contact between rear wheel and the ground, the values of the required coefficient of adhesion, φ are the lowest. In the case of asymmetric load distribution, as it is shown in Figure 2.d, the boundary values, for deceleration parameters which were analysed in the previous segment, were shifted for φ_2, at 3.8m/s^2, Z_2=0, to 10.2 m/s^2, at efficient and stable braking with both wheels and with front wheel even over 10 m/s^2, respectively.

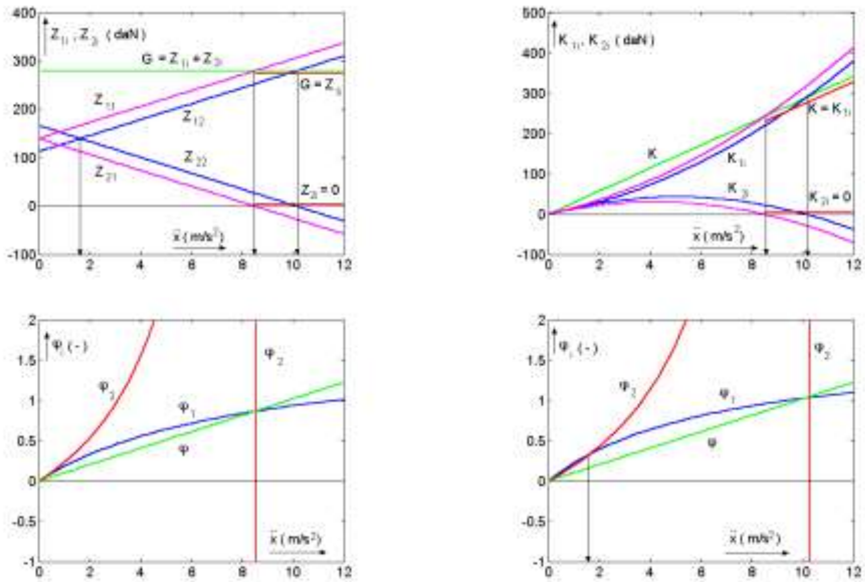
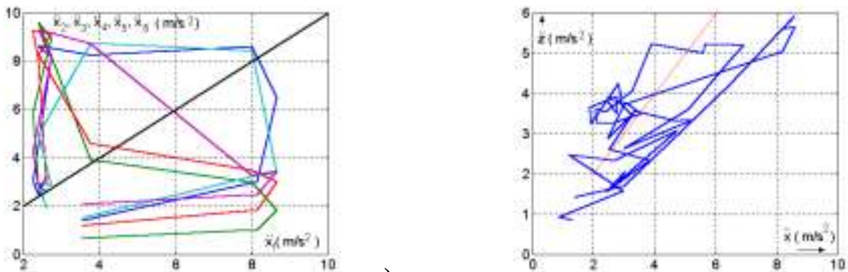


Figure 2 The results of motorcycle braking simulation depending on longitudinal deceleration: a/ vertical force, b/ braking force, c/ d/ required values of adhesion coefficient.

A part of the experimental results presented in this paper, should confirm some of the findings about simulation studies regarding boundary deceleration and domain of efficient braking and also about the stable movement of the motorcycle. Experiments were conducted with the motorcycle and the measurement system shown in Figure 1a. The measurement system includes 4 measuring locations, with six measuring values: vertical acceleration at the centers of the wheels, vertical, longitudinal and lateral acceleration of the center of mass of the system motorcycle-driver and turning angle of the steering forks. Measured signals were inserted into the PC electronic measurement system called "Spider 8" produced by "HBM", that includes the components for preparation, further processing, storage and transmission of data by the computer systems. In this specific case, from eight available channels, that measuring system possess, 6 of them were engaged, and for the purposes of this study, the data obtained from three measuring channels are presented in this paper, same as the components of the acceleration/deceleration of the center of mass of the system. The results are shown in Figure 3.a and Figure 3.b.

The results shown in Figure 3.a, show the mutual relations of the wheels deceleration for 6 repeated braking, at the same conditions and at the same initial speed. The condition of ideal repeatability for this experiment is defined by linear relation of deceleration variation in the first and subsequent experiments, which is presented by the straight line in the Figure 3a. Deviation of hysteresis loops from this direction presents the effects of many factors during experiments performing and also it shows the efforts of drivers to optimize their action, it means, to achieve a boundary deceleration at braking, and yet to maintain stable movement. In doing so, the extreme values of the deceleration up to 8.4 m/s2 at abscissa axis and up to 9.85 m/s2 on ordinate axis, (in some cases) were achieved, and they are compliant with the above analyzed simulation results. The same levels are also visible on the presentation of motorcycles vertical and longitudinal dynamics interaction presented in Figure 3.b.



a) b)

Figure 3 Experimental results about researching of motorcycle braking process a/ test of experiment repeatability , b/ interaction of vertical and longitudinal motorcycle dynamics.

CONCLUSIONS

Motorcycle as single trace vehicle, doesn't possess its own stability position nor the stability of direction. For these reasons it is difficult steering it and there is a high risk of causing traffic accidents and injuries of the driver. A common cause of traffic accidents is wrong braking or falling down of the driver from a motorcycle. The simulation and experimental results show that the critical braking regimes, in terms of the stability of motion of the system are, when the rear wheel loses the contact with the ground, as well as regimes in which the front wheel blocks. Boundary deceleration in these two regimes; defines the domain of stable and unstable braking. Simulation and performed experimental researching, as well as numerous expertise of traffic accidents where motorcycles participated, indicate the need for more extensive application of technology for active braking control in stressful situations.

REFERENCES

[1] Aleksandrović, B., Radonjić,R., Đapan, M., Janković, A. (2011). "The research of correlations between motorcycle oscillatory processes during the non-steady modes of motions". DEMI 2011, 10th Anniversary International Conference on Accomplishments in Electrical and Mechanical Engineering and Information Technology, p. 765-770.

[2] Danner, M., Langwieder, K., Sporner, A. (1985). "Accidents of Motorcyclists – increase of safety by technical measures on the basis of knowledge derived from real-

life accidents”. HUK-Verband, Insitut fur Zweirad Sicherheit, ESV-Conference, Oxford.

[3] Funke, J., Breuer, B. (2000). “Dynamische Vorderrad-Uberbremsung bei Motorraden. Forschungsbericht”, TU Darmstadt.

[4] Hurt, N., et al. (1981). “Motorcycle accident cause factors and identification of countermeasures”. Technical report, Traffic Safety Center, University of Southern California, p. 1-435.

[5] Road accident statistics in Europe.

[6] White, S. (2008). “Motorcycle safety and risk factors”. On line Journal of Population Healt, University New England, p. 1-4.

[7] Willumeit, H-P. (1994). Nick- und Hubbewegung, “Radlasten und Umfangskrafte beim Abbremsen eines Motorrades”. VDI Bericte, Motorrad-6.Fachtagung, Koln.

DETERMINATION OF PARAMETERS OF THE WEIBULL DISTRIBUTION BY APPLYING THE METHOD OF LEAST SQUARES

Dobrivoje Ćatić[1]*, Jasna Glišović, Sandra Veličković, Jasmina Blagojević, Marko Delić*

UDC:629.3.027.484;519.213.2

ABSTRACT: Weibull distribution is one of the most frequently used theoretical models for approximation of empirical distributions of random variables with continuous variation. Procedures for graphical, grapho-analytical and analytical determination of Weibull distribution parameters are described in detail in this paper. Based on the graphical method for determining the position parameters of three-parameter Weibull distribution, the analytical procedure is developed, which is based on the application of the method of least squares. The set of points is approximating with the square parabola, and based on the sign of the second derivative, the information for further proceedings is obtained. For the defined procedure, an algorithm of the computer program for determination of the Weibull distribution parameters is presented in paper. By using the program, based on data from the exploitation related to the operation time until failure, the reliability modelling of wheel's drum in braking system of light commercial vehicles was performed. The graphical and non-parametric tests were used to test the theoretical model of distribution.

KEY WORDS: Weibull distribution, the method of least squares, computer software determination, reliability of wheel's drum

ODREĐIVANJE PARAMETARA VEJBULOVE RASPODELE PRIMENOM METODE NAJMANJIH KVADRATA

REZIME: Vejbulova raspodela je jedan od najčešće korišćenih teorijskih modela za aproksimaciju empirijskih raspodela slučajnih promenljivih sa kontinualnom promenom. U radu su detaljno opisani postupci za grafičko, grafoanalitičko i analitičko određivanje parametara Vejbulove raspodele. Na osnovu grafičkog postupka za određivanje parametra položaja Vejbulove troparametarske raspodele, razvijen je analitički postupak, koji se zasniva na primeni metode najmanjih kvadrata. Skup tačaka se aproksimira kvadratnom parabolom i na osnovu znaka drugog izvoda dobija se informacija za dalji tok postupka. Za navedeni postupak u radu je dat algoritam programa za kompjutersko određivanje parametara Vejbulove raspodele. Primenom programa, na osnovu podataka iz eksploatacije o vremenu rada do otkaza, izvršeno je modeliranje pouzdanosti doboša točka sistema za kočenje lakih privrednih vozila. Za testiranje teorijskog modela raspodele korišćeni su grafički i neparametarski testovi.

KLJUČNE REČI: Vejbulova raspodela, metoda najmanjih kvadrata, programsko određivanje pomoću računara, pouzdanost doboša točka.

[1] *Received: November 2014, Accepted December 2014, Available on line January 2015*

Intentionally blank

DETERMINATION OF PARAMETERS OF THE WEIBULL DISTRIBUTION BY APPLYING THE METHOD OF LEAST SQUARES

Dobrivoje Ćatić[1], Ph.D, Full professor, Jasna Glišović[2], Ph.D, Assistant professor, Sandra Veličković[3], Ph.D, student, Jasmina Blagojević[4], Ph.D, student, Marko Delić[5], Ph.D, student

UDC:629.3.027.484;519.213.2

INTRODUCTION

Swedish scientist, Waloddi Weibull, conducted a series of tests, while researching dynamic durability of materials. When he conducted statistical analysis of gained data, he had found that normal distribution could not be used for modelling of statistical features. By generalisation of exponential distribution and adjustment of mathematical model according to empirical distribution, Weibull had reached a new distribution that today bears his name [1, 2].

Undoubtedly, Weibull distribution is used mostly in the area of reliability. This directly comes from its parametric character and wide possibilities to interpret very different laws of random variables by selection of corresponding values of parameters.

MATHEMATICAL MODEL OF WEIBULL DISTRIBUTION

Depending on number of parameters, there are the two- and three-parameter Weibull distributions. Expression for the survival function for a three-parameter model is [3, 4]:

$$R(t) = e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}, \ t \geq \gamma, \ \gamma \geq 0, \ \eta > 0, \ \beta > 0, \tag{1}$$

where:

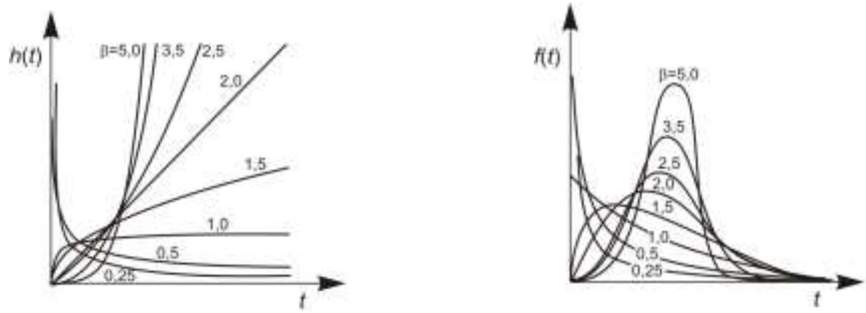
t – is independent variable (time),
γ - is location parameter (parameter of minimal operation until failure),
η - is scale parameter and
β - is shape parameter.

If location parameter is $\gamma = 0$, the two-parameter Weibull distribution is obtained. Figure 1 presents charts of failure intensity function and density of operation time until failure for the two-parameter Weibull distribution and different values of shape parameter β [5, 6].

[1] *corresponding author: Dobrivoje Ćatić, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, Kragujevac, caticd@kg.ac.rs*
[2] *Jasna Glišović, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, Kragujevac, jaca@kg.ac.rs*
[3] *Sandra Veličković, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, Kragujevac, sandravelickovic@gmail.com*
[4] *Jasmina Blagojević, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, Kragujevac, jasminamikovic@gmail.com*
[5] *Marko Delić, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, Kragujevac, delicmarko@gmail.com*

As it may be seen in the chart of failure intensity, $h(t)$, for different values of the shape parameter, β, this distribution may be used as approximate model for all three periods of exploitation of machine systems' elements [5, 6]. In addition, if $\beta < 1$, the two-parameter Weibull distribution corresponds to hyper-exponential distribution. For $\beta = 1$, exponential distribution is gained, while for $\beta = 2$, Rayleigh distribution is gained. For greater values of parameter, β, Weibull distribution gets closer to normal distribution. For values of β between 3 and 4, differences between these two distributions are negligible. Nevertheless, it should be noted that theoretical laws are never mathematically identical.

Considering the previous and based on the results of approximation of empirical distribution with Weibull distribution, a model of other hypothetical distribution is determined more closely.



a) *b)*

Figure 1. Charts of functions of a) failure intensity and b) density of operation time until failure for the two-parameter Weibull distribution

In order to approximate the empirical distribution with the two- or three-parameter Weibull distributions, it is necessary to linearize mathematical models of distributions. With the three-parameter model, starting from expression (1), elementary mathematical transformations may change the expression $R(t) = 1 - F(t)$ into [4, 5, 7]:

$$\ln\ln\frac{1}{1-F(t)} = \beta \cdot \ln(t-\gamma) - \beta \cdot \ln\eta \,. \qquad (2)$$

If the following substitutions are introduced:

$$y = \ln\ln\frac{1}{1-F(t)}, \qquad (3)$$

$$a_1 = \beta, \qquad (4)$$

$$x = \ln(t-\gamma) \text{ and} \qquad (5)$$

$$a_0 = -\beta \cdot \ln\eta\,, \qquad (6)$$

equation of the shape line is obtained:

$$y = a_0 + a_1 \cdot x \,. \qquad (7)$$

A straight line in a coordinate system where x-axis has logarithmic and y-axis has double logarithmic scale may represent expression for reliability function of the three-parameter Weibull distribution. Linearization of reliability function of the two-parameter Weibull distribution is done in similar way. The only difference is that, instead of substitute $x = \ln(t-\gamma)$, a substitute $x = \ln t$ is used during transformation of coordinates.

DETERMINATION OF PARAMETERS OF THE TWO-PARAMETER WEIBULL DISTRIBUTION

Determination of parameters of the two-parameter Weibull distribution may be achieved graphically or analytically.

Goode and Kao had developed a **graphical procedure** for determination of Weibull distribution by the aid of probability paper [8]. In the two-parameter Weibull model, procedure demands that points with transformed coordinates (x_i, y_i), that is with coordinates $(\ln t_i, \ln\ln\{1/[1-F(t_i)]\})$ are imported on Weibull probability paper (coordinate system with logarithmic scale on x-axis and double logarithmic scale on *y*-axis) [5]. If the arrangement of the points is approximately linear, the two-parameter Weibull distribution may be used for approximation. Procedure continues with approximation of a series of plotted points with a straight line. This approximation may be conducted graphically (by subjective assessment) or analytically (by the least squares method). If approximation is conducted with the least squares method, further course of graphical procedure has no meaning. Namely, based on determined coefficients a_0 and a_1 of regression line of the series, distribution parameters are easily achieved from expressions (4) and (6).

For graphical determination of scale parameter, η, the following condition is used:

$$t = \eta \quad \Rightarrow \quad F(t) = 1 - R(t) = 1 - \exp(-1) = 0.632\,. \qquad (8)$$

Based on this, parameter η is equal to *x*-coordinate of a point on approximate straight line that has *y*-coordinate equal to 0.632.

According to linearized model of Weibull distribution, shape parameter, β, represents inclination of approximate straight line in regard to *x*-axis. It is determined by drawing a line through point C on probability paper for Weibull distribution that is displayed within example in Figure 4 that is parallel to approximate line until it crosses a vertical line passing through point $x = -1$. From intersection point, a horizontal line is drawn until it crosses an axis for transformed *y*-coordinate. Value of parameter β is read directly on this axis with a plus sign.

During **analytical determination** of parameters of the two-parameter Weibull distribution using the least squares method, series of points with coordinates (x_i, y_i) is approximated by a straight line. The best of all approximate straight lines in a form (7) is the one for which the sum of squares of vertical offsets of the points from regression line is the smallest. Determination of coefficients a_0 and a_1 with the least squares method is done by previous determination of the expression for a sum of squares of ordinates offsets:

$$S(a_0, a_1) = (a_0 + a_1 x_1 - y_1)^2 + (a_0 + a_1 x_2 - y_2)^2 + \ldots$$
$$+ (a_0 + a_1 x_n - y_n)^2 = \sum_{i=1}^{n} (a_0 + a_1 x_i - y_i)^2. \qquad (9)$$

Necessary and sufficient condition for function $S(a_0, a_1)$ to achieve the maximum is expressed by equation:

$$\frac{\partial S}{\partial a_0} = 2 \cdot \sum_{i=1}^{n} \left(a_0 + a_1 x_i - y_i\right) = 0 ,$$
$$\frac{\partial S}{\partial a_1} = 2 \cdot \sum_{i=1}^{n} x_i \left(a_0 + a_1 x_i - y_i\right) = 0 , \tag{10}$$

from where a system of linear algebraic equations for determination of coefficients a_0 and a_1 is gained:

$$a_0 \cdot n + a_1 \cdot \sum_{i=1}^{n} x_i = \sum_{i=1}^{n} y_i ,$$
$$a_0 \cdot \sum_{i=1}^{n} x_i + a_1 \cdot \sum_{i=1}^{n} x_i^2 = \sum_{i=1}^{n} x_i y_i . \tag{11}$$

By determination of determinants of equation systems (11):

$$D = \begin{vmatrix} n & \sum x_i \\ \sum x_i & \sum x_i^2 \end{vmatrix}, \quad D_0 = \begin{vmatrix} \sum y_i & \sum x_i \\ \sum x_i y_i & \sum x_i^2 \end{vmatrix}, \quad D_1 = \begin{vmatrix} n & \sum y_i \\ \sum x_i & \sum x_i y_i \end{vmatrix}, \tag{12}$$

values of required coefficients are gained:

$$a_0 = \frac{D_0}{D} = \frac{\sum x_i^2 \cdot \sum y_i - \sum x_i \cdot \sum x_i y_i}{n \cdot \sum x_i^2 - \left(\sum x_i\right)^2},$$
$$a_1 = \frac{D_1}{D} = \frac{n \cdot \sum x_i y_i - \sum x_i \sum y_i}{n \cdot \sum x_i^2 - \left(\sum x_i\right)^2}. \tag{13}$$

Based on relationship between distribution parameters β , η and the coefficients of straight line equation, given by expressions (4) and (6), the following is obtained:

$$\beta = a_1 \text{ and } \eta = e^{-\frac{a_0}{a_1}} . \tag{14}$$

DETERMINATION OF PARAMETERS OF THE THREE-PARAMETER WEIBULL DISTRIBUTION

Procedures for determination of parameters of the three-parameter Weibull distribution are essentially different from previously described procedures. If operation time until the first failure occurs of the objects in the observed sample is not small in regard to total operation time, or if when entering the points onto probability paper, their layout is such that may be approximated by quadratic parabola convex upwards (in positive direction of y-axis), in that case, location parameter, γ, should be used. Value of this parameter is in the interval 0 to t_1, where t_1 is operation time until the first failure occurs on objects for a small sample or lower limit of the first interval for a large sample.

Value of location parameter, γ, of the three-parameter Weibull distribution may be determined graphically, graphically-analytically and analytically.

During **graphical determination** of location parameter, γ, after points with coordinates $\left(\ln t_i , \ln\ln\left\{1/\left[1 - F(t_i)\right]\right\}\right)$ are entered on Weibull probability paper and conclusion that it is the three-parameter distribution is made, value of $\gamma = 0.9 \cdot t_1$ is taken in the first step of the iterative procedure [5, 7]. Points are entered onto probability paper again, now with coordinates $\left(\ln(t_i - \gamma), \ln\ln\left\{1/\left[1 - F(t_i)\right]\right\}\right)$, and distribution of points is analysed. Feedback information for further steps of the procedure is gained based on distribution of points and possibility for approximation with a straight or a curved line, concave or convex upwards. Generally, three possibilities may occur in iterative procedure:

- if approximation curve obtained is still convex upwards, γ should be increased,
- if a straight line is obtained, γ is determined and procedure continues with determination of the rest of distribution parameters, and finally,
- if concave curve is obtained, γ should be decreased.

Iterative procedure continues until value of parameter γ is obtained, for which the points are located on a straight line. Afterwards, scale parameter, η, and shape parameter, β, are determined identically as for the two-parameter Weibull distribution.

In order to determine position parameter, γ, faster, **graphical-analytical** procedure has been developed. After entering the points onto probability paper and subjective approximation by a curved line, position parameter may be determined from the following expression [9]:

$$\gamma = t_2 - \frac{(t_3 - t_2)\cdot(t_2 - t_1)}{(t_3 - t_2) - (t_2 - t_1)}, \tag{15}$$

where:

t_1 – is *x*-coordinate of the first point of the curve (t_{min}),

t_2 – is *x*-coordinate of the point on the curve, which *y*-coordinate is arithmetic mean of *y* coordinates of points having *x* coordinates t_1 and t_3,

t_3 – is *x*-coordinate of the last point of the curve (t_{max}).

Value of t_2 is determined graphically. After determination of position parameter, γ, points with coordinates $\left(\ln(t_i - \gamma), \ln\ln\{1/[1 - F(t_i)]\}\right)$ are entered onto probability paper. Correctness of graphical-analytical procedure should be confirmed with the fact that points follow closely a straight line. After a best-fit straight line for a series of points is drawn, parameters η and β are determined in the same way as in the two-parameter Weibull distribution.

Analytical computer determination represents the third possibility for determination of parameter γ.

One of the possibilities for analytical computer determination of parameter γ is to approximate a series of points having transformed coordinates with a straight line. The idea is to approximate the points with the second order polynomial by the least squares method:

$$y = a_0 + a_1 x + a_2 x^2, \tag{16}$$

that is, by square parabola. Approximation of a series of points by the least squares method with square parabola is conducted in a similar way as approximation with a straight line. Firstly, an expression for a sum of squares of offsets is formed:

$$\begin{aligned} S(a_0, a_1, a_2) = {} & \left(a_0 + a_1 x_1 + a_2 x_1^2 - y_1\right)^2 + \\ & + \left(a_0 + a_1 x_2 + a_2 x_2^2 - y_2\right)^2 + \ldots \\ & + \left(a_0 + a_1 x_n + a_2 x_n^2 - y_n\right)^2 = \\ & = \sum_{i=1}^{n} \left(a_0 + a_1 x_i + a_2 x_i^2 - y_i\right)^2. \end{aligned} \tag{17}$$

By partial differentiation of expression (17) by coefficients a_0, a_1 and a_2, the system of linear algebraic equations for determination of these coefficients is obtained:

$$\begin{aligned} a_0 \cdot n + a_1 \cdot \sum_{i=1}^{n} x_i + a_2 \cdot \sum_{i=1}^{n} x_i^2 &= \sum_{i=1}^{n} y_i , \\ a_0 \cdot \sum_{i=1}^{n} x_i + a_1 \cdot \sum_{i=1}^{n} x_i^2 + a_2 \cdot \sum_{i=1}^{n} x_i^3 &= \sum_{i=1}^{n} x_i y_i , \\ a_0 \cdot \sum_{i=1}^{n} x_i^2 + a_1 \cdot \sum_{i=1}^{n} x_i^3 + a_2 \cdot \sum_{i=1}^{n} x_i^4 &= \sum_{i=1}^{n} x_i^2 y_i . \end{aligned} \quad (18)$$

By determination of determinants of the system of equations (18):

$$D = \begin{vmatrix} n & \sum x_i & \sum x_i^2 \\ \sum x_i & \sum x_i^2 & \sum x_i^3 \\ \sum x_i^2 & \sum x_i^3 & \sum x_i^4 \end{vmatrix} \qquad D_0 = \begin{vmatrix} \sum y_i & \sum x_i & \sum x_i^2 \\ \sum x_i y_i & \sum x_i^2 & \sum x_i^3 \\ \sum x_i^2 y_i & \sum x_i^3 & \sum x_i^4 \end{vmatrix},$$

$$D_1 = \begin{vmatrix} n & \sum y_i & \sum x_i^2 \\ \sum x_i & \sum x_i y_i & \sum x_i^3 \\ \sum x_i^2 & \sum x_i^2 y_i & \sum x_i^4 \end{vmatrix}, \qquad D_2 = \begin{vmatrix} n & \sum x_i & \sum y_i \\ \sum x_i & \sum x_i^2 & \sum x_i y_i \\ \sum x_i^2 & \sum x_i^3 & \sum x_i^2 y_i \end{vmatrix}, \quad (19)$$

values of required coefficients are obtained: $a_0 = \frac{D_0}{D}$, $a_1 = \frac{D_1}{D}$ i $a_2 = \frac{D_2}{D}$.

Based on curvature of the obtained squared parabola, that is on sign of coefficient a_2, it may be concluded whether the approximate curve is convex or concave in a positive direction of vertical curve. In this manner, similarly as in graphical procedure, feedback information is gained for further steps of the procedure. By searching through interval $0 \div t_1$, value γ is obtained for which the arrangement of points is closest to the straight line. For analytical determination of parameters of the three-parameter Weibull distribution with help of computer, a procedure shown by algorithm in Figure 2 is used.

According to this algorithm, a part of the computer program is formed for modelling the reliability. Searching through intervals of possible values of γ may be done in different ways. The algorithm solves this problem by halving the interval $0 \div t_1$ and investigating the curvature of the curve for $\gamma = t_1/2$. Based on a sign of second derivative of approximate polynomial (coefficient a_2), it may be concluded whether the value γ is smaller or larger than the used value. For $a_2 < 0$, γ takes value of a middle of the right interval ($\gamma = 0.75 \cdot t_1$), and for $a_2 > 0$, γ takes value of a middle of the left interval ($\gamma = 0.25 \cdot t_1$). Procedure continues until the width of the interval, where value of γ stands, becomes less than some value given in advance (e.g. ε = 0.001). If during iterative procedure, value $a_2 = 0$ occurs, this means that a straight line is obtained during approximation of a series of points, that is value of parameter γ is determined. If exiting from a cycle is a consequence of reduction of interval's width, a series of points is approximated by a straight line in order to determine coefficients of regression line. After the coefficients a_0 and a_1 are determined, the coefficients β and η are gained from the expression (14).

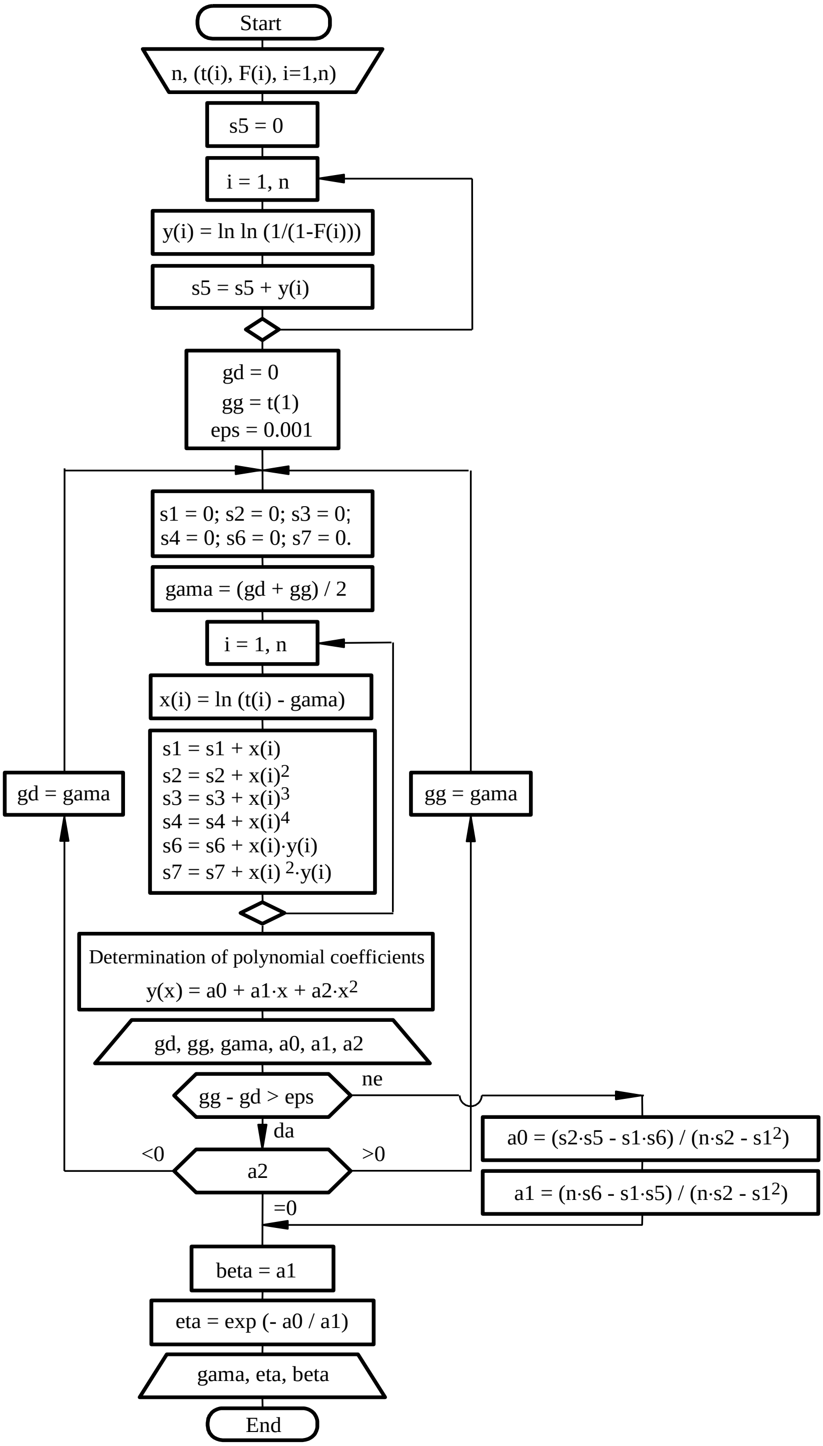


Figure 2. Algorithm of a program for determination of parameters of the three-parameter Weibull distribution

Graphical, graphical-analytical and analytical determination of parameters of the three-parameter Weibull distribution will be illustrated through the example of determining the distribution of operation time until failure of wheel's drum in the brake system of light commercial vehicles.

EXAMPLE

Sample of 65 identical drums in braking system of light commercial vehicles is tested for reliability assessment. Number of 7 intervals for grouping the values of random variable is adopted, based on expression $z = 1 + 3.3 \log n$. Calculated width of the interval is Δt = 40,000 km, based on maximal and minimal values of random variable. Obtained values of operation time until failure of wheel's drum are grouped in time intervals and shown in Table 1. Parameters of Weibull distribution used as theoretical model of operation time until failure of wheel's drum should be determined.

Table 1. Number of failures of the wheel's drum in braking system by time intervals

Distance travelled x [10^3 km]	110÷150	150÷190	190÷230	230÷270	270÷310	310÷350	350÷390
Number of failures	9	13	17	11	8	5	2

With application of software for determination of theoretical model of empirical distribution, described in detail in [10], numerical characteristics of statistical series are gained:

- mean value t_{sr} = 221,692;
- standard deviation σ = 63,429;
- median t_{50} = 214,706;
- mode M_o = 206,000;
- coefficient of asymmetry K_a = 0.417 and
- coefficient of flatness K_e = 2.439.

In continuation of a program, based on the procedures for assessment of functional indicators of the distribution of the random variable for a large sample (n> 30), estimated values of the number of correct objects $n(t)$, the reliability $R(t)$, the unreliability $F(t)$, density of operation time until failure $f(t)$ and failure intensity $h(t)$ of wheel's drum are gained for middles of time intervals and given in Table 2.

Table 2: *Estimated values of functional indicators of the distribution of the random variable*

i	*m(i)*	t_i	$n(t_i)$	$R(t_i)$	$F(t_i)$	$f(t_i)$	$h(t_i)$
1	9	130.00	60.5	0.93077	0.06923	0.34615E-02	0.37190E-02
2	13	170.00	49.5	0.76154	0.23846	0.50000E-02	0.65657E-02
3	17	210.00	34.5	0.53077	0.46923	0.65385E-02	0.12319E-01
4	11	250.00	20.5	0.31538	0.68462	0.42308E-02	0.13415E-01
5	8	290.00	11.0	0.16923	0.83077	0.30769E-02	0.18182E-01
6	5	330.00	4.5	0.06923	0.93077	0.19231E-02	0.27778E-01
7	2	370.00	1.0	0.01538	0.98462	0.76923E-03	0.50000E-01

Illustrations of graph charts of estimated values of density of operation time until failure, *f*(*t*), and failure intensity, *h*(*t*), wheel's drum, in the form of polygons and histograms, are given in Figure 3. In rough assessments, theses graph charts may serve for determination of hypothetical distribution models.

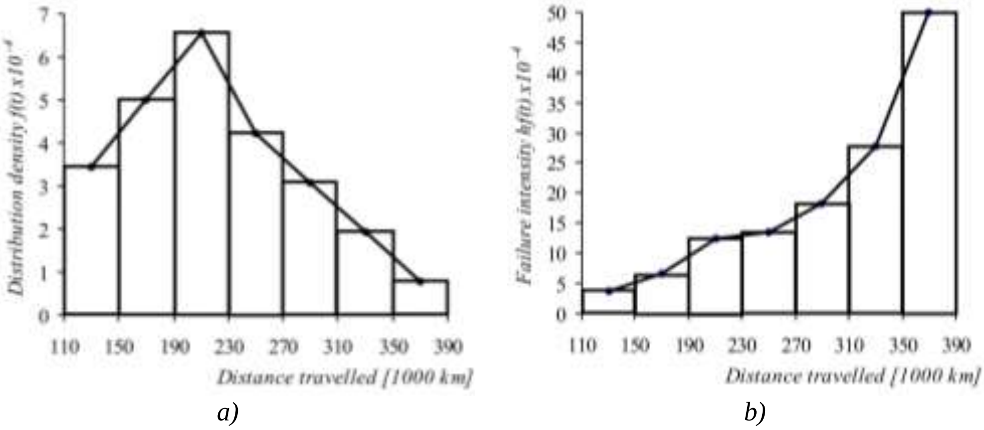


Figure 3. Graphical display of estimated values of: a) density and b) intensity of wheel's drum failure

• Graphical determination of parameters of Weibull distribution using probability paper.

Usually, at the first step of graphical solving of task, approximation of a series of points is done by the two-parameter Weibull distribution. By transformation of coordinates and using the expressions $x_i = \ln t_i$ and $y_i = \ln\ln\{1/[1-F(t_i)]\}$ and by entering the points onto probability paper for Weibull distribution (Figure 4), arrangement of points is gained that may be approximated by curve 1. Since the approximate function is convex, it means that the location parameter, γ, is positive. In the second step, series of points are approximated by the three-parameter Weibull distribution, with $\gamma = 0.9 \cdot t_1 = 99{,}000$ km. In this case, time, t_1 is a lower limit of the first interval. By repeated calculation of x_i coordinates according to expression $x_i = \ln(t_i - \gamma)$ and by entering the points onto probability paper, arrangement of points is obtained that may be approximated by curve 2. Since obtained curve is concave, γ should be smaller. Iterative procedure continues with decreasing values for γ with step $0.1 \cdot t_1$. Thus, for $\gamma = 0.7 \cdot t_1 = 77{,}000$ km approximately linear arrangement of point on probability paper is obtained. Parameter η value is equal to *x*-coordinate of the point on approximate straight line having *y*-coordinate 0.632, that is η = 163,000 km. Shape parameter, β, is determined as cathetus of right-angled triangle, whose other cathetus is equal to 1. Parameter value is read on auxiliary vertical axis for transformed coordinate *y*. In this particular case, value β = 2.38 is obtained.

• Graphical-analytical determination of location parameter γ.

In order to determine value of location parameter γ, according to expression (15), it is necessary to graphically determine the value for t_2. According to definition, t_2 is a value of *x*-coordinate of a point on approximate curve 1, whose *y*-coordinate is equal to arithmetic mean of *y*-coordinates of points with *x*-coordinates equal to t_1 and t_3. Thus, according to

Figure 4, orientation value of t_2 = 200,000 km is obtained. By using the expression (15), value of location parameter γ = 81,000 km, is obtained, which is nearly equal to the value obtained during graphical problem solving. By transformation of coordinates for calculated value for γ, arrangement of points that may be approximated by a straight line is obtained.

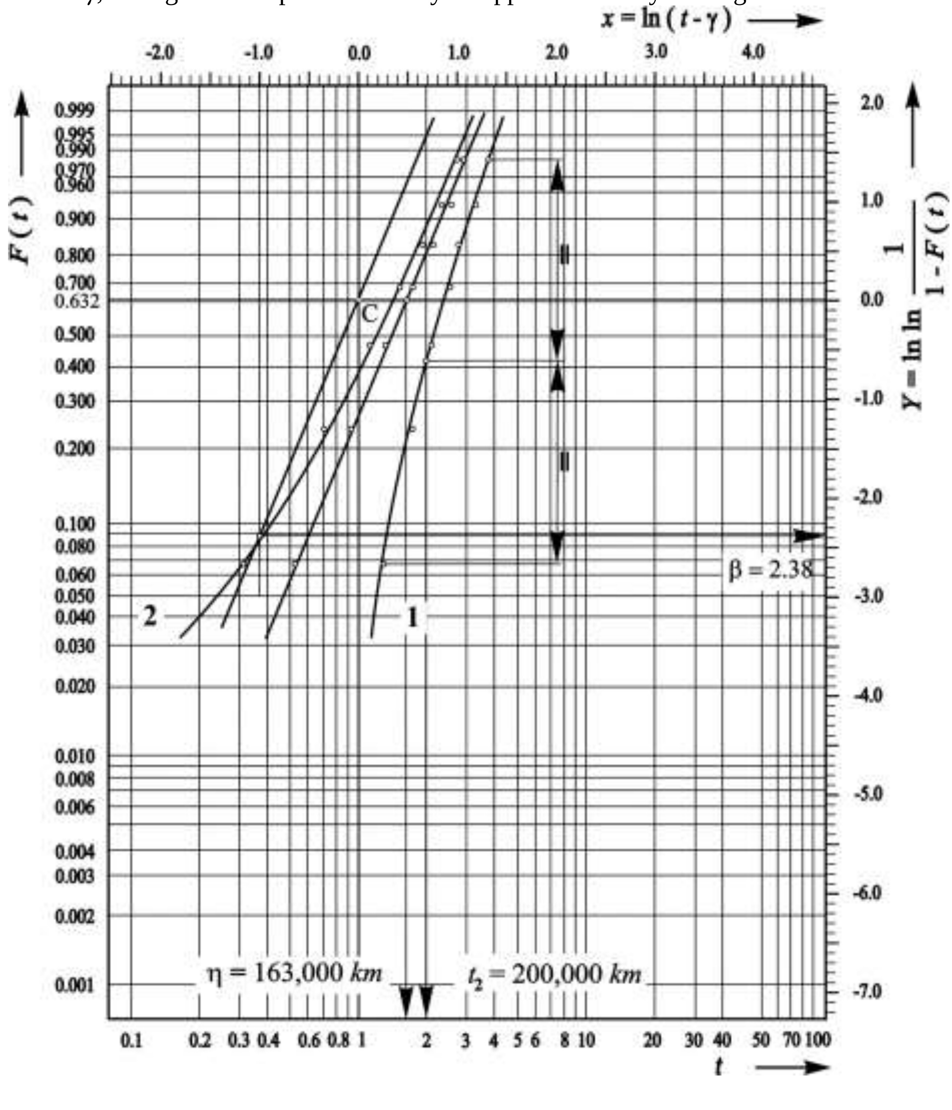


Figure 4. Determination of parameters of the three-parameter Weibull distribution using probability paper

- Analytical computer determination of parameters of Weibull distribution using the least squares method.

By approximation of empirical distribution of operation time until failure of wheel's drum by the three-parameter Weibull distribution and by using a computer program whose algorithm is presented in Figure 3, after 18 iterations by halving the intervals and determination of a sign of second derivative a_2, the parameters of the distribution are obtained: location parameter, γ = 76,115 km, scale parameter, η = 164,161 km and shape parameter, β = 2.355.

Based on this, the expression for probability of faultless operation of wheel's drum is:

$$R(t) = e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} = e^{-\left(\frac{t-76{,}115}{164{,}161}\right)^{2.355}} . \qquad (20)$$

In order to determine validity of approximation, graphical testing over probability paper for Weibul distribution and nonparametric testing were conducted using tests of Kolmogorov, Pearson and Romanovsky. Table 3 presents values of transformed *x* and *y* coordinated for particular value γ = 76,115 km and Figure 5 presents arrangement of points on probability paper for Weibull distribution.

Table 3. Values of transformed coordinates

No.	t_i	$F(t_i)$	x(i)	y(i)
1	130.0	0.0692	3.987	-2.635
2	170.0	0.2385	4.542	-1.300
3	210.0	0.4692	4.897	-0.457
4	250.0	0.6846	5.158	0.143
5	290.0	0.8308	5.365	0.575
6	330.0	0.9308	5.537	0.982
7	370.0	0.9846	5.683	1.429

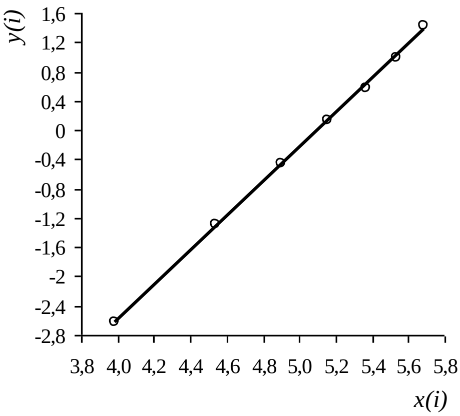


Figure 5. Arrangement of points on probability paper for Weibull distribution

Linear arrangement of the points in Figure 5 suggests that the approximate model satisfies conditions of graphical testing.

For testing of hypothetical distribution model, according to Kolmogorov test, it is necessary to determine the greatest absolute value of difference between theoretical model and estimated values of distribution functions of operation time until failure. Table 4 contains a segment of output list of a program that relates to this part. Figure 6 presents graphical representation of deviations of theoretical approximate model, $F_t(t)$, from empirical distribution, $F_e(t)$.

As it may be seen from Table 4, the largest deviation of theoretical model from empirical distribution is for the result No. 5 and amounts to 0.0143. For number of samples, *n* = 65 and given level of significance for Kolmogorov's test, α = 0.20, $\lambda_\alpha = 1.07$, permitted value of difference is:

$$D_n = \frac{\lambda_\alpha}{\sqrt{n}} = \frac{1.07}{\sqrt{65}} = 0.1327.$$

Since the maximal deviation is less than permitted value of difference, Weibull approximate distribution satisfies the Kolmogorov's test for adopted level of significance.

By application of Pearson's test procedure, value of $\chi^2 = 0.9711$ as a measure of deviation between empirical and approximate distribution is obtained. For number of intervals $z=7$ and number of distribution parameters $l=3$, number of degrees of freedom equals:

$$k = z - l - 1 = 7 - 3 - 1 = 3.$$

Table 4. Deviations of Weibull approximate curve from estimated values of distribution function of operation time until failure

No.	t_i	$F_e(t_i)$	$F_t(t_i)$	delta
1	130.0	0.0692	0.0700	0.0007
2	170.0	0.2385	0.2352	0.0032
3	210.0	0.4692	0.4613	0.0079
4	250.0	0.6846	0.6818	0.0028
5	290.0	0.8308	0.8451	0.0143
6	330.0	0.9308	0.9387	0.0080
7	370.0	0.9846	0.9806	0.0040

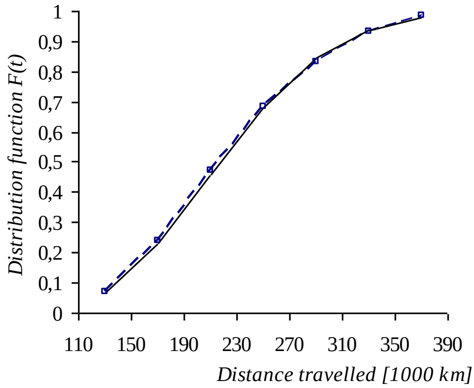


Figure 6. Graphical representation of deviations of Weibull approximate distribution from empirical distribution

By application of Pearson's test procedure, value of $\chi^2 = 0.9711$ as a measure of deviation between empirical and approximate distribution is obtained. For number of intervals $z=7$ and number of distribution parameters $l=3$, number of degrees of freedom equals:

$$k = z - l - 1 = 7 - 3 - 1 = 3.$$

Based on calculated values for χ^2 and number of degrees of freedom, *k*, and by looking at the table for χ^2 distribution, it may be concluded that Weibull distribution may be accepted as approximate model at level of significance $\alpha = 0.80$.

Comparable value for Romanovsky's test is:

$$R_o = \frac{\left|\chi^2 - k\right|}{\sqrt{2k}} = \frac{|0.9711 - 3|}{\sqrt{2 \cdot 3}} = 0.828,$$

which is smaller than 3 and it means that Weibull distribution meets criterion of Romanovsky's test.

CONCLUSIONS

Procedure for graphical determination of location parameter, *γ*, of the three-parameter Weibull distribution is long lasting and liable to errors due to imprecise entering of points onto probability paper, subjectivity during assessment of drawing of approximate straight lines and curves and impossibility to precisely read the parameter value.

Since graphic-analytic procedure is largely based on graphical representation of points on probability paper and corresponding approximations, everything that has been said on graphical method applies also to graphical analytical method.

Program determination of parameters of the three-parameter Weibull distribution enables gaining desired accuracy of the results with great speed. Thanks to that and known features of this distribution regarding possibility of approximation of empirical distribution of random variables, in great number of cases, Weibull distribution is optimal solution, with respect to other theoretical models.

Based on the graphic of the estimated values of failure intensity of wheel's drum in braking system of light commercial vehicles, it can be concluded that these are failure modes that occur during object aging. Theoretical approximate model of Weibull distribution satisfies graphics tests and analytical nonparametric tests with a high level of significance.

REFERENCES

[1] Weibull W., A statistical theory of the strength of material, Ing. Vetenskapa Acad. Handlingar 151, 1–45, 1939.

[2] Weibull W., A statistical distribution function of wide applicability, Journal of Applied Mechanics, 18, 293–297, 1951.

[3] British standard BS 5760, Part 2: Guide to the Assessment of Reliability. Reliability of Systems, Eequipments and Components, British Standards Institution, London, 1981.

[4] Smith JD., Reliability, Maintainability and Risk, Practical methods for engineers, Butterworth Heinemann, Oxford, Sixth edition, 2001.

[5] Kapur KC. & Lamberson LR., Reliability in Engineering Design, John Wiley & Sons, New York, 1977.

[6] Dodson B., The Weibull Analysis Handbook. Second Edition, ASQ Quality Press, Milwaukee, Wisconsin, 2006.

[7] Chin-Diew Lai DN, Pra Murthi, Min Xie., Weibull Distributions and Their Applications, in Springer Handbook of Engineering Statistics, Hoang Pham (Ed.), Springer-Verlag, London, pp. 63-78, 2006.

[8] Kao HJ., A summary of some new tehniques on failure analysis, Proceedings of the sixth National Symposium on Reliability and Quality Control in elektronics, p. 190-201, 1960.

[9] Ivanovic G., Stanivukovic D., Reliability of technical systems - Collection of solved problems (in Serbian), Faculty of Mechanical Engineering, Belgrade, 1983.

[10] Catic D., Development and application of reliability theory methods (in Serbian), Monograph, The Faculty of Mechanical Engineering from Kragujevac, Kragujevac, 2005.

MVM *Editorial Board*
University of Kragujevac
Faculty of Engineering
Sestre Janjić 6, 34000 Kragujevac, Serbia
Tel.: +381/34/335990; Fax: + 381/34/333192
www.mvm.fink.rs