



ГОДИНА  
ФАКУЛТЕТА ИНЖЕЊЕРСКИХ НАУКА У КРАГУЈЕВЦУ  
1960-2020



Ministry of Education,  
Science and Technological Development

**8<sup>th</sup> International Congress**  
**Motor Vehicles & Motors 2020**  
**ECOLOGY -**  
**VEHICLE AND ROAD SAFETY**  
**- EFFICIENCY**  
**Proceedings**



University of Kragujevac



Faculty of Engineering



Department for motor vehicles  
and motors



International Journal for Vehicle  
Mechanics, Engines and  
Transportation Systems

October 8<sup>th</sup> - 9<sup>th</sup>, 2020  
Kragujevac, Serbia

**8<sup>th</sup> International Congress  
Motor Vehicles & Motors 2020**

**ECOLOGY -  
VEHICLE AND ROAD SAFETY  
- EFFICIENCY**

**BOOK OF PROCEEDINGS**

October 8<sup>th</sup> - 9<sup>th</sup>, 2020  
Kragujevac, Serbia

*Publisher:* Faculty of Engineering, University of Kragujevac  
Sestre Janjić 6, 34000 Kragujevac, Serbia

*For Publisher:* Prof. Dobrica Milovanović, Ph.D.  
Dean of the Faculty of Engineering

*Editors:* Prof. Božidar Krstić, Ph.D.  
Assoc. prof. Danijela Miloradović, Ph.D.

*Technical preparation:* Asisst. Nadica Stojanović, M.Sc.  
Assist. Ivan Grujić, M.Sc.

*Cover:* Nemanja Lazarević

*CD printing:* Faculty of Engineering, University of Kragujevac, Kragujevac

*ISBN:* 978-86-6335-074-8

*Year of publication:* 2020.

*Number of copies printed:* 200

CIP - Каталогизacija u publikaciji  
Narodna biblioteka Srbije, Beograd

629.3(082)(0.034.2)  
621.43(082)(0.034.2)

INTERNATIONAL Congress Motor Vehicles and Motors (8 ; 2020 ; Kragujevac)  
Ecology - vehicle and road safety - efficiency [Elektronski izvor] : proceedings / 8th  
International Congress Motor Vehicles & Motors 2020, October 8th - 9th, 2020  
Kragujevac, Serbia ; [congress organizers University of Kragujevac [and] Faculty of  
Engineering of the University of Kragujevac, Department for Motor Vehicles and Motors,  
FE Kragujevac [and] International Journal "Mobility & Vehicle Mechanics" ] ; [editors  
Božidar Krstić, Danijela Miloradović]. - Kragujevac : Faculty of Engineering, University,  
2020 (Kragujevac : Faculty of Engineering, University). - 1 elektronski optički disk (DVD) ;  
12 cm

Sistemski zahtevi: Nisu navedeni. - Nasl. sa naslovne strane dokumenta. - Tiraž 200. -  
Bibliografija uz svaki rad.

ISBN 978-86-6335-074-8

a) Моторна возила -- Зборници б) Мотори са унутрашњим сагоревањем -- Зборници  
в) Електрична возила -- Зборници г) Хибридна електрична возила -- Зборници  
COBISS.SR-ID 22017545

Copyright © 2020 Faculty of Engineering, University of Kragujevac

*Publishing of this CD Book of proceedings was supported by  
Ministry of Education, Science and Technological Development of the Republic of Serbia*

## SCIENTIFIC BOARD

### **President**

Prof. Božidar Krstić, Ph.D., UniKg, FE, Serbia

### **Secretaries**

Assist. Nadica Stojanović, M.Sc., UniKg, FE, Serbia

Assist. Ivan Grujić, M.Sc., UniKg, FE, Serbia

Assist. Slavica Mačužić Saveljić, M.Sc., UniKg, FE, Serbia

### **Members**

Prof. Dragan Aleksendrić, Ph.D., UniBg, FME, Serbia

Assoc. Prof. Boris Antić, Ph.D., UniBg, FTTE, Serbia

Prof. Giovanni Belingardi, Ph.D., PoliTo, Italy

Prof. Ranko Božičković, Ph.D., UniSa, FTTE, RS, Bosnia and Herzegovina

Prof. Murat Ciniviz, Ph.D., SelUni, FT, Turkey

Prof. Adrian Clenci Ph.D., UniPit, Pitesti, Romania

Prof. Zoran Ćurguz, Ph.D., UniSa, FTTE, RS, Bosnia and Herzegovina

Assoc. Prof. Aleksandar Davinić, Ph.D., UniKg, FE, Serbia

Prof. Miroslav Demić, Ph.D., UniKg, FE, Serbia

Assoc. Prof. Jovan Dorić Ph.D., UniNS, FTS, Serbia

Prof. Mohamed Ali Emam, Ph.D., Helwan Uni, FE, Cairo, Egypt

Prof. Ivan Filipović, Ph.D., UniSa, FME, Bosnia and Herzegovina

Assoc. Prof. Jasna Glisović, Ph.D., UniKg, FE, Serbia

Prof. Valentina Golubović Bugarski, Ph.D., UniBL, FME, RS, Bosnia and Herzegovina

Prof. Emil Hnatko, Ph.D., Croatian Academy of Engineering, Zagreb

Prof. Rosen Hristov, Ph.D., TU Varna, Bulgaria

Prof. Aleksandra Janković, Ph.D., UniKg, FE, Serbia

Assist. Prof. Aleksandar Jovanović, Ph.D., UniKg, FE, Serbia

Prof. Srđan Jović, Ph.D., UniPr, FTS, Serbia

Prof. Hakan Kaleli, Ph.D., YTU, Istanbul, Turkey

Prof. Dimitrios Koulocheris, Ph.D., NTUA, Athens, Greece

Prof. Krsto Lipovac, Ph.D., UniBg, FTTE, Serbia

Prof. Zbigniew Lozia, Ph.D., WUT, Warsaw, Poland

Prof. Jovanka Lukić, Ph.D., UniKg, FE, Serbia

Prof. Zoran Lulić, Ph.D., UniZg, FME, Croatia

Assoc. Prof. Danijela Miloradović, Ph.D., UniKg, FE, Serbia

Assoc. Prof. Slavko Muždeka, Ph.D., UniDef, MA, Serbia

Assist. Prof. Boban Nikolić, Ph.D., UniNi, FME, Serbia

Prof. Alexander Novikov, Ph.D., OSUni, Orel, Russia

Prof. Patrizio Nuccio, Ph.D., PoliTo, Italy

Prof. Radivoje Pešić, Ph.D., UniKg, FE, Serbia

Assoc. Prof. Dalibor Pešić, Ph.D., UniBg, FTTE, Serbia

Prof. Snezana Petković, Ph.D., UniBL, FME, RS, Bosnia and Herzegovina

Prof. Boran Pikula, Ph.D., UniSa, FME, Bosnia and Herzegovina

Prof. Vladimir Popović, Ph.D., UniBg, FME, Serbia

Prof. Ralph Pütz, Ph.D., UniAS, Landshut, Germany

Prof. Dragoljub Radonjić, Ph.D., UniKg, FE, Serbia

Assoc. Prof. Dragan Ružić, Ph.D., UniNS, FTS, Serbia

Prof. Lazar Savin, Ph.D., UniNS, FA, Serbia

Prof. Mikhail Shatrov, Ph.D., MADI, Moscow, Russia

Prof. Hristo Stanchev, Ph.D., UniRu, FT, Ruse, Bulgaria

Prof. Dragoslava Stojiljković, Ph.D., UniBg, FME, Serbia

Assoc. Prof. Dragan Taranović, Ph.D., UniKg, FE, Serbia

Academician Dusan Teodorović, Ph.D., UniBg, FTTE, Serbia

Prof. Milan Tomić, Ph.D., UniNS, FA, Serbia

Prof. Miroljub Tomić, Ph.D., UniBg, FME, Serbia

Prof. Stevan Veinović, Ph.D., UniKg, FE, Serbia



## **ORGANIZATIONAL BOARD**

### ***President***

Assoc. prof. Danijela Miloradović, Ph.D., UniKg, FE, Serbia

### ***Secretaries***

Assist. Nadica Stojanović, M.Sc., UniKg, FE, Serbia

Assist. Ivan Grujić, M.Sc., UniKg, FE, Serbia

Assist. Slavica Mačužić Saveljić, M.Sc., UniKg, FE, Serbia

## **CONGRESS ORGANIZERS**

University of Kragujevac  
Faculty of Engineering of the University of Kragujevac  
Department for Motor Vehicles and Motors, FE Kragujevac  
International Journal "Mobility & Vehicle Mechanics"

## **CONGRESS PATRONS**

Ministry of Education, Science and Technological Development of the Republic of Serbia  
City Council of Kragujevac

# PREDGOVOR

8. međunarodni kongres „Motorna vozila i motori 2020“ organizovan je u neobičnim okolnostima. Dok je svetom vladala pandemija CORONA virusa, vredni autori iz zemlje i inostranstva pripremali su svoje radove u okviru motoa Kongresa „Ekologija–Vozilo i bezbednost saobraćaja-Efikasnost“. Imajući u vidu trenutnu situaciju, odziv autora je bio više nego zadovoljavajući. Za prezentaciju na Kongresu su prihvaćena ukupno 44 rada, koji su recenzirani i vezani sa jednom od postojećih glavnih tema Kongresa:

- Tehnologija sistema prenosa snage,
- Konstrukcija i proizvodnja vozila,
- Dinamika vozila i sistemi inteligentne kontrole,
- Interfejs vozač/vozilo, informacioni sistemi i sistemi za pomoć vozaču i
- Bezbednost drumskog saobraćaja.

Naši uvodničari, eminentni stručnjaci u oblasti motornih vozila i bezbednosti saobraćaja, pripremili su četiri uvodna predavanja koja predstavljaju savršen okvir za ostala istraživanja prezentirana na Kongresu. Akcenat uvodnih predavanja je bio na trendovima i perspektivama u bezbednosnom dizajnu vozila, dilemama u vezi postizanja nulte emisije vozila, kao i stanju bezbednosti drumskog saobraćaja i zakonske regulative vezane za vozila u Srbiji.

Tematske sekcije Kongresa potvrdile su multidisciplinarnost tehnologija vozila i važnost bezbednog okvira njegovog funkcionisanja. Prezentirani su radovi iz oblasti hibridnih vozila, alternativnih pogona, novih materijala i tehnologija u proizvodnji vozila, primene industrije 4.0, naprednih metoda smanjenja potrošnje energije i uticaja vibracija na putnike i raznih aspekata bezbednosti saobraćaja.

Uz tradicionalnu podršku Ministarstva nauke, prosvete i tehnološkog razvoja, Univerziteta u Kragujevcu, Fakulteta inženjerskih nauka i Međunarodnog časopisa „*Mobility and Vehicle Mechanics*“, organizatori Kongresa su odlučili da se, zbog preventivne zaštite zdravlja učesnika, Kongres po prvi put organizuje na Internet mreži (*online*). Organizovana je plenarna sekcija, kao i više radnih tematskih sekcija, na kojima su razmenjena dragocena iskustva stručnjaka iz oblasti automobilske industrije, istraživačkih instituta i akademskih institucija.

Nadamo se da će idući Kongres, čije je održavanje planirano za dve godine, da privuče još veći broj učesnika sa novim, aktuelnim temama primerenim brzom razvoju tehnologija motornih vozila.

Kragujevac,  
8. oktobar 2020. godine

Naučni i Organizacioni odbor  
Međunarodnog kongresa „Motorna vozila i motori 2020“

# FOREWORD

The 8<sup>th</sup> International Congress "Motor Vehicles and Engines 2020" was organized in unusual circumstances. While the CORONA virus pandemic ruled the world, hardworking authors have been preparing their papers within the motto of the Congress "Ecology - Vehicle and Traffic Safety - Efficiency". Given the current situation, the response of the authors was more than satisfactory. A sum of 44 papers was accepted for presentation at the Congress. All papers were reviewed and linked to one of the existing main topics of the Congress:

- Power Train Technology,
- Vehicle Design and Manufacturing,
- Vehicle Dynamics and Intelligent Control Systems,
- Driver/Vehicle Interface, Information and Assistance Systems and
- Road Traffic Safety.

Our keynote speakers, eminent experts in the field of motor vehicles and traffic safety, have prepared four introductory lectures that provide the perfect framework for other research presented at the Congress. The emphasis of the introductory lectures was on trends and perspectives in vehicle safety design, dilemmas regarding achieving zero vehicle emissions, as well as the state of road traffic safety and legal regulations related to vehicles in Serbia.

The thematic sections of the Congress confirmed the multidisciplinary nature of vehicle technologies and the importance of a safe framework for its functioning. Papers in the field of hybrid vehicles, alternative drives, new materials and technologies in vehicle production, application of Industry 4.0, advanced methods for reducing energy consumption and the impact of vibration on passengers and various aspects of traffic safety were presented.

With the traditional support of the Ministry of Science, Education and Technological Development, University of Kragujevac, Faculty of Engineering and the International Journal "Mobility and Vehicle Mechanics", the organizers of the Congress decided to organize the Congress on the Internet network (online) for the first time. A plenary section was organized, as well as several working thematic sections, where valuable experiences of experts from the automotive industry, research institutes and academic institutions were exchanged.

We hope that the next Congress, which is planned to be held in two years, will attract an even larger number of participants with new, current topics appropriate to the rapid development of motor vehicle technologies.

# CONTENT

## INTRODUCTORY LECTURES

MVM2020-IL1	Giovanni Belingardi Dario Fiumarella Filippo Germanetti Alessandro Scattina	RECENT ADVANCE, TRENDS AND PERSPECTIVES IN THE SAFETY DESIGN OF VEHICLES	3
MVM2020-IL2	Boris Antić	ROAD TRAFFIC SAFETY: SERBIA 2020	15
MVM2020-IL3	Ralph Pütz	TOWARDS ZERO EMISSION: ARE E-FUELS A PROMISING OPTION?	23
MVM2020-IL4	Saša Mitić Ivan Blagojević Dragan Stamenković	VEHICLE LEGISLATION - SERBIA VS. EUROPE	33

## SECTION A Power Train Technology

MVM2020_001	Giovanni Belingardi Nicola Amati Angelo Bonfitto	ELECTRIC AND HYBRID VEHICLES: ARE WE READY FOR THE NEW MOBILITY ERA?	43
MVM2020_009	Ivan Grujić Nadica Stojanović Jovan Dorić Aleksandar Davinić Saša Vasiljević	NUMERICAL ANALYSIS OF THE DUAL FUEL IC ENGINE WORKING CYCLE	55
MVM2020_010	Zoran Masoničić Dragan Vašalić Ivan Grujić Aleksandar Davinić Radivoje Pešić	SOME ASPECTS CONCERNING APPLICATION OF ALTERNATIVE FUELS AS REGARDS FLUID FLOW PATTERN AND FLAME PROPAGATION IN PARTICULAR COMBUSTION CHAMBER WITH STRONG MACRO FLOWS	61
MVM2020_011	Slobodan Mišanović Dragan Taranović Pavle Krstić Dušan Živić	MEASUREMENT OF RECOVERY ELECTRICITY ON THE E-BUS HIGER KLQ6125GEV3 ON EKO 1 LINE IN BELGRADE AND IMPACT ON ENERGY EFFICIENCY	67
MVM2020_024	Predrag Mrđa Nenad Miljić Slobodan Popović Marko Kitanović	STATIONARY TEST PLAN OPTIMISATION USING SLOW DYNAMIC SLOPE ENGINE SCREENING	77
MVM2020_025	Marko Kitanović Slobodan Popović Nenad Miljić Predrag Mrđa	A NEURAL NETWORK-BASED CONTROL ALGORITHM FOR A HYDRAULIC HYBRID POWERTRAIN SYSTEM	85
MVM2020_027	Natalija Aleksić Danijela Nikolić Vanja Šušteršić	REVIEW OF SOLAR ENERGY APPLICATION IN AUTOMOTIVE INDUSTRY	95
MVM2020_040	Luka Ponorac Aleksandar Grkić Slavko Muždeka	HYBRID POWER TRAINS FOR HIGH-SPEED TRACKED VEHICLES	105

## SECTION B

### Vehicle Design and Manufacturing

MVM2020_007	Saša Vasiljević Jasna Glišović Blaža Stojanović Nadica Stojanović Ivan Grujić	COMPOSITION OF BRAKE PADS AND INFLUENCE FACTORS AFFECTING THE WEAR INTENSITY OF THE BRAKE PADS ON VEHICLES	117
MVM2020_012	Alexander Novikov Alexey Rodichev	APPLICATION OF PLAIN BEARINGS WITH CONTROLLED WEAR ON AUTOMOTIVE VEHICLES	123
MVM2020_015	Mirko Blagojević Miloš Matejić Milan Vasić	COMPARATIVE OVERVIEW OF CALCULATION OF NORMAL FORCE ON CYCLOIDAL GEAR TOOTH	131
MVM2020_017	Onur Güler Sandra Gajević Slavica Miladinović Hamdullah Çuvalcı Blaža Stojanović	OPTIMIZATION OF ZINC-BASED HYBRID NANOCOMPOSITES USING TAGUCHI GREY RELATION ANALYSIS	139
MVM2020_019	Aleksandar Poznić Boris Stojić	A CONTRIBUTION TO THE DEVELOPMENT OF AUTOMOTIVE MAGNETORHEOLOGICAL BRAKE	149
MVM2020_028	Dragan Čukanović Aleksandar Radaković Gordana Bogdanović Danilo Dragović	STATIC ANALYSIS OF PLATE MADE OF FUNCTIONALLY GRADED MATERIAL AS MODERN COMPOSITE USED IN MOTOR VEHICLE INDUSTRY	157
MVM2020_036	Vladimir Dunić	SHAPE MEMORY ALLOYS IN AUTOMOTIVE INDUSTRY – OVERVIEW, APPLICATION, MODELING	165
MVM2020_037	Aleksandar Radaković Dragan Čukanović Dragan Milosavljević Gordana Bogdanović Sanel Husović	NEW SHAPE FUNCTION IN BUCKLING ANALYSIS OF COMPOSITE LAMINATES USED IN TRANSPORT VEHICLES	169
MVM2020_039	Sonja Kostić Zorica Đorđević Dragan Rajković Milan Đorđević	EXPERIMENTAL METHOD FOR CALCULATION OF RADIAL STIFFNESS FOR SINGLE-ROW BALL BEARING	175
MVM2020_044	Ivan Miletić Marko Miletić Saša Milojević Robert Ulewicz Ružica Nikolić	THE BUCKLING ANALYSIS OF A ELASTICALLY CLAMPED RECTANGULAR PLATE	183
MVM2020_051	Milan Blagojević Milan Bojović Saša Milojević Petar Marković Dragan Lazarević	MODIFICATION OF RACING CAR CYLINDER HEAD USING 3D DIGITIZATION AND REVERSE ENGINEERING	191
MVM2020_052	Miloš Lazarević Vladica Živković Bogdan Nedić	APPLICATION OF PROCESSING BY EXPLOSION IN THE AUTOMOTIVE INDUSTRY	197

## SECTION C

### Vehicle Dynamics and Intelligent Control Systems

MVM2020_004	Miroslav Demić Danijela Miloradović	CONTRIBUTION TO RESEARCH OF TIRE ROLLING RESISTANCE OF MOTOR VEHICLES	207
-------------	--	--	-----



MVM2020_005	Isak Karabegović Edina Karabegović Mehmed Mahmić Ermin Husak	THE APPLICATION OF INDUSTRY 4.0 IN PRODUCTION PROCESSES OF THE AUTOMOTIVE INDUSTRY	217
MVM2020_006	Nadica Stojanović Oday I. Abdullah Ivan Grujić Jasna Glišović Saša Vasiljević	STRESSES DISTRIBUTION IN FUNCTION OF CONSTANT ACTING PRESSURE AND GENERATED TEMPERATURE ON THE BRAKE DISC	223
MVM2020_016	Liubov Sladkova	WHEEL OF VEHICLE INCREASED SURVIVABILITY	231

## SECTION D

### Driver/Vehicle Interface, Information and Assistance Systems

MVM2020_026	Dragan Ružić	ADVANCED METHODS TO REDUCE ENERGY CONSUMPTION FOR FARM TRACTOR CAB AIR- CONDITIONING	239
MVM2020_030	Slavica Mačužić Saveljić Jovanka Lukić	EFFECTS RELATED TO RANDOM WHOLE-BODY VIBRATION AND POSTURE ON A PASSENGERS	247
MVM2020_032	Slavica Mačužić Saveljić Igor Saveljić Nenad Filipović	EFFECT OF VIBRATION ON SEMICIRCULAR CANAL DURING WHOLE BODY VIBRATION	253
MVM2020_038	Marian Florin Mitroi	RELIABILITY AND VIABILITY OF THE VEHICLES IN CONTEXT OF THE FUTURE TECHNOLOGY - IoT	259

## SECTION E

### Road Traffic Safety

MVM2020_003	Victor I. Popov Lev M. Monosov Igor V. Polischuk	ENVIRONMENTAL PROBLEMS AND THEIR SOLUTION DURING CONSTRUCTION AND OPERATION OF ST. PETERSBURG BARRIER FLOOD PROTECTION	269
MVM2020_008	Saša Vasiljević Jasna Glišović Nadica Stojanović Ivan Grujić Jens Wahlström	ON THE IMPACT OF AIRBORNE BRAKE WEAR EMISSIONS ON ENVIRONMENTAL SAFETY	275
MVM2020_018	Perić Sreten Bučko Mihael Nedić Bogdan Radovanović Radovan	CONDITION MONITORING THROUGH ENGINE OIL ANALYSIS TESTS	281
MVM2020_022	Angelina Pavlović Goran Bošković Nebojša Jovičić	SIMULATION OF ROAD TRAFFIC NOISE POLLUTION IN KRAGUJEVAC USING QGIS SOFTWARE	291
MVM2020_033	Snežana Petković Valentina Golubović Bugarski Željko Đurić Gordana Globočki Lakić	ANALYSIS OF ENERGY EFFICIENCY OF DIFFERENT MODALITIES OF TOURIST TRANSPORT	307
MVM2020_034	Valentina Golubović-Bugarski Snežana Petković Gordana Globočki-Lakić	THE EFFECT OF CORROSION ON A STRUCTURAL INTEGRITY AND VEHICLE SAFETY	317

MVM2020_041	Nenad Marković Dalibor Pešić Boris Antić Dušan Graovac	ANALYSIS OF THE INFLUENCE OF VEHICLE FACTORS ON THE ORIGIN AND WEIGHT OF THE CONSEQUENCES OF TRAFFIC ACCIDENTS USING DEPTH ANALYSIS - CASE STUDY FOR THE CITY OF BELGRADE	327
MVM2020_042	Dragan Vašalić Zoran Masoničić Saša Milojević Ivan Ivković Radivoje Pešić	SOME ASPECTS CONCERNING MANAGEMENT OF ROAD TRANSPORT OF DANGEROUS GOODS USING CONTEMPORARY INFORMATION SYSTEMS	337
MVM2020_043	Zoran Papić Andrijana Jović Nenad Saulić Milja Simeunović	THE IMPORTANCE OF LONGITUDINAL CG POSITION FOR THE CAR MOVEMENT IN THE POST-IMPACT PHASE	343
MVM2020_046	Branislav Đorđević Saša Mitić	THE POSSIBILITIES FOR IMPLEMENTATION OF EVENT DATA RECORDERS IN USED VEHICLES	351
MVM2020_048	Vojislav Krstić	POSSIBILITIES DETERMINATION OF THE OPTIMAL STRATEGY FOR PREVENTIVE MAINTENANCE OF THE MOTOR ENGINE USING THE MULTICRITERIA OPTIMIZATION	359
MVM2020_049	Vojislav Krstić Boris Antić Siniša Božićković	ANALYSIS OF TECHNICAL CORRECTNESS OF LIGHTING AND LIGHT-SIGNALING DEVICES OF VEHICLES	365
MVM2020_050	Vojislav Krstić	MODELING AND SIMULATION OF TRAFFIC FLOWS TO ENSURE THE SECURITY OF TRAFFIC	373



International Congress  
Motor Vehicles & Motors 2020  
Kragujevac, Serbia  
October 8<sup>th</sup> - 9<sup>th</sup>, 2020



**MVM2020-036**

**Vladimir Dunić<sup>1</sup>**

## **SHAPE MEMORY ALLOYS IN AUTOMOTIVE INDUSTRY – OVERVIEW, APPLICATION, MODELING**

**ABSTRACT:** Shape Memory Alloys (SMA) are widely known as smart materials used as actuators in many engineering systems. SMA are known as very thermo-sensitive materials, which have different responses in various environments. Also, the loading or deformation rate of SMA structures has a significant influence on the material temperature change. The reason is the complex phase-transformation process between the austenite and martensite what results in complex thermo-mechanical behavior. These properties are essential for efficiently applying such materials to actuate specific processes by the phenomena of superelasticity or shape memory effects, which exhibit under proper conditions. With the overview of SMA's current application in the automotive industry, in this paper, the recent research results in SMA modeling and simulation are analyzed to propose the possibilities, limitations, and directions of future research in this field of application.

**KEYWORDS:** shape memory alloys, automotive industry, application, modeling, actuators

### **OVERVIEW OF SMA BEHAVIOR**

Shape Memory Alloys (SMA) are a multifunctional type of materials that can manifest two phenomena: superelasticity effect and shape memory effect. The same material can exhibit both effects depending on the exploitation temperature of the material. To define the effects, firstly, it is essential to identify SMA characteristic phase transformation temperatures: austenitic start  $A_s$  and finish  $A_f$ , and martensitic start  $M_s$  and finish  $M_f$  temperature, presented in Figure 1. The superelasticity effect occurs when the material operates above the austenitic finish temperature. In that case, the phase transformation from austenite to detwinned martensite is stress-driven by mechanical loading. The shape memory effect occurs when the material is deformed at the temperature below the martensitic finish temperature. After heating above the austenitic finish temperature, the material will recover its shape. The shape memory effect can be one-way or two-way. Both superelasticity and shape memory effects are described in Figure 1. These effects and large inelastic deformation (up to 10%) of SMAs offer the possibility of exploitation in various applications, but the most often are actuators and sensors. The material behavior depends on the composition of SMA, thermomechanical processing, and the working environment. Material properties (Young's modulus, electrical resistivity, thermal conductivity, and thermal expansion coefficient) of SMA are different in the martensitic and austenitic phases. The actuator's design challenges investigated in [1] are transferring the heat into and out of the active element, low energy efficiency, durability, and reliability what leads to the conclusion that SMA elements should be prevented from overheating, overstressing, and overstraining.

### **APPLICATION OF SMA IN AUTOMOTIVE INDUSTRY**

The application of SMA is wide in industry and engineering: automotive, aerospace, biomedical. In the automotive industry, there is an increasing need for actuators for luxury features. According to [1], there are about 200 actuation tasks controlled by SMA actuators. Actuators in automobiles are usually DC motors or solenoids. SMA simplifies and reduces the cost of many automotive actuators [2]. One of the first articles related to the application in the automotive

<sup>1</sup> Vladimir Dunić, University of Kragujevac Faculty of Engineering, Sestre Janjić 6, Kragujevac, Serbia, [dunic@kg.ac.rs](mailto:dunic@kg.ac.rs)

industry was related to the actuators. Stoeckel [3] presented the SMA actuators' entering the automotive industry in the early 90s. The SMA actuators were used as thermal and electrical. At that time, only Cu-Zn-Al alloys and the Ni-Ti alloys were available. In the automotive industry, Ni-Ti was preferred due to the high strength and electrical resistivity, large recovery strains, good workability, and corrosion resistance. He proposed thermal actuators by patent literature surveys such as a temperature-sensitive governor valve, pressure control in an automatic transmission, and smoother shifting at low temperatures, temperature-sensitive boost compensators, and a temperature-compensated valve lifter, shape-memory washers to reduce gearbox noise. Also, SMA electrical actuators were applied as remote fog-lamp louver opening devices and windshield wipers. The problems were noticed when the ambient temperature approaches the transformation temperature of the shape memory alloy. The same author extended his research in [4] when he investigated fastener rings, which can be used to terminate shielding braid to a connector or an oxygen sensor, fix the location of a bearing or gear, assemble radially disposed of elements. At the beginning of 21 century, Wu et al. [5] investigated SMA's industrial application. However, they noticed the automotive industry as very interesting due to SMA actuators' wide application in transmission fluid control, plug for sealing high-pressure diesel engine injectors. A decade later, Williams and Elahinia in [2] investigated the SMA actuator's design, modeling, and experimental behavior for the position of a rear-view mirror. They designed and fabricated a prototype of an SMA actuated mirror. In 2011, Strittmatter and Gümpel in [6] considered SMA actuators' application for the bonnet lifting system. Gheorghita et al. investigated SMA's application in safety systems in the car industry [7]. They found out that the amount of dissipated energy increases with the loading rate and gives higher forces necessary for SMA actuators. Jani et al. in 2013 [1], considered the share of SMA related publications and patents and found out that there are more than 20,000 worldwide patents have been issued on SMAs. However, that real application was at a low level, although SMA sensors or actuators can find their application in various parts of the automobiles such as the engine, transmission, brake, battery, engine control unit, climate control, wiper, airbags, mirrors, seats, dashboard, roof, safety belts, spoilers, boot, fuel cup, suspensions, doors, exhaust, bumpers, fog lamp, headlight, engine hood. They also noticed that SMA has very high work density (25 times greater than electric motors) what qualify them for actuators that offer significant forces.

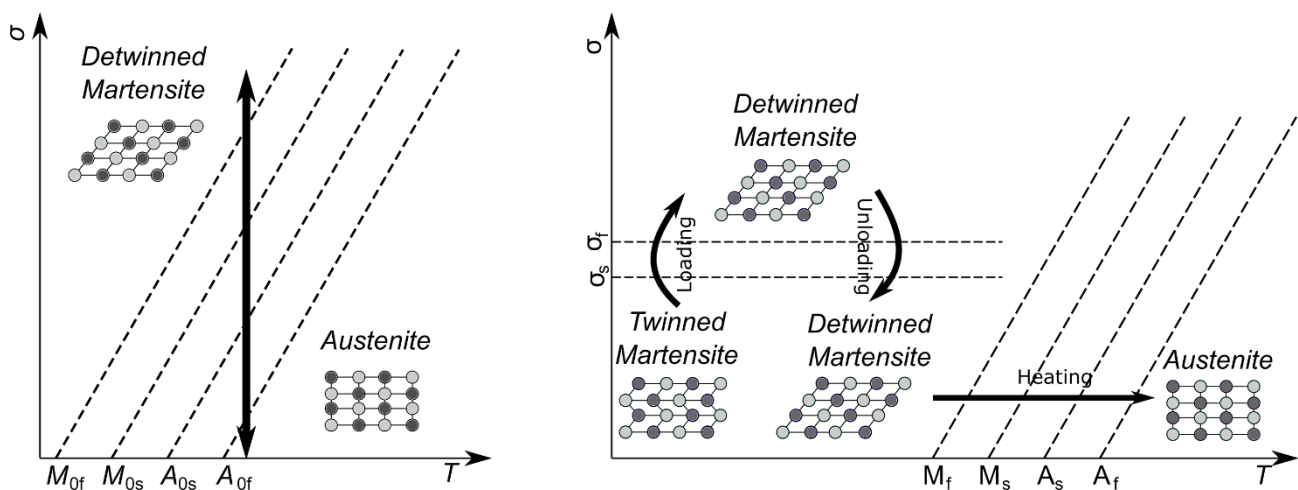


Figure 1 Superelasticity and shape memory effect in SMA

## MODELING OF SMA

The researchers and engineers tend to develop the SMA constitutive model, which is simple but, at the same time, gives more simulation details. Also, demand is a few material constants. There are several approaches in the scientific literature, but the two major groups are micromechanics-based models and phenomenological models. More details are given in Dunić et al. [8]. In the last several years, at the Faculty of Engineering, the phenomenological SMA model has been implemented into the finite element method (FEM) software PAK for structural analysis. The model is improved [9], and thermo-mechanical coupling [10] is realized in a staggered iterative scheme. Those features allowed more accurate simulation of SMA structures that are essential for the automotive industry application where the SMA is used as sensors and actuators. The simulation of the loading rate influence [11] and the martensitic phase transformation-induced creep behavior in SMA is investigated and successfully demonstrated [12].

### A brief review of SMA constitutive model

One of the most developed SMA constitutive models is based on the Lagoudas theory [13]. It is based on Gibbs's free energy  $g(\sigma, T, \xi, \mathbf{e}_tr)$ , where variables are the stress  $\sigma$ , the temperature  $T$ , and the internal state variables  $\xi$ ,  $\mathbf{e}_tr$ . "Any change in the current microstructural state of the material is strictly a result of a change in the martensitic volume fraction" is an assumption which is mathematically described by equation [13]:

$$\dot{\mathbf{e}}_{tr} = H \mathbf{n}_{tr} \dot{\xi}, \quad (1)$$

where  $H$  is the maximum of achievable transformation strain and  $\xi$  is the fraction of martensite in the volume. The transformation strain vector  $\mathbf{n}_{tr}$  is given concerning the direction of the martensitic phase transformation:

$$\mathbf{n}_{tr} = \begin{cases} \frac{3\mathbf{S}}{2\overline{S}}; & \dot{\xi} > 0 \\ \frac{\mathbf{e}_{tr}}{\overline{e}_{tr}} & \dot{\xi} < 0 \end{cases}. \quad (2)$$

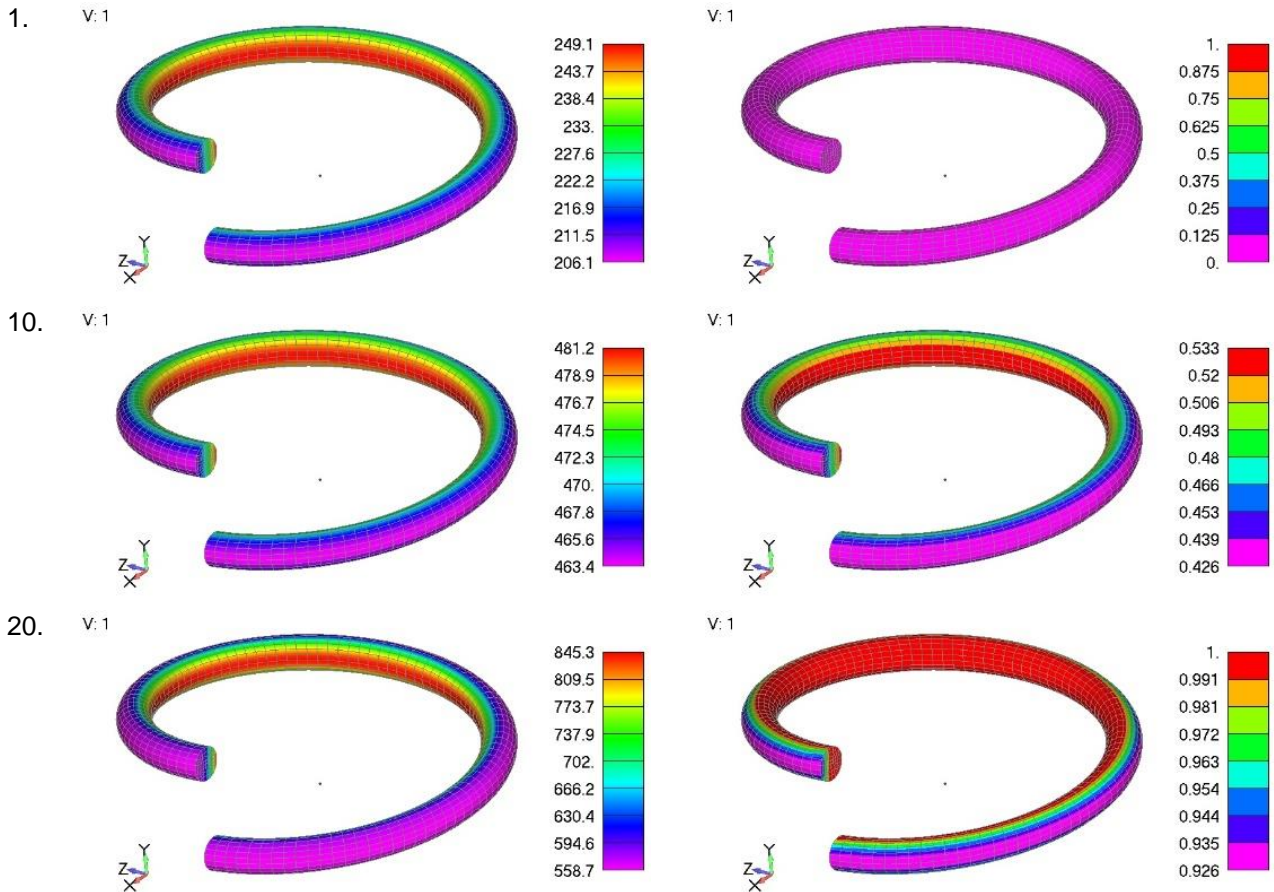
The transformation function is defined by Lagoudas [13] as follows:

$$\Phi = \begin{cases} \Pi - Y; & \dot{\xi} > 0 \\ -\Pi - Y; & \dot{\xi} < 0 \end{cases} \quad (3)$$

where  $\Pi(\boldsymbol{\sigma}, T, \xi)$  is the thermodynamic force and  $Y$  is the threshold value. The assumption of constant integration direction (deviatoric stress or transformation strain) of the stress integration procedure is used in [9]. The separation of the total stress on the deviatoric and mean part provided the possibility to reformulate the transformation function in an effective manner and solve only one equation on the integration point level. More details are given in [9] and [14].

**Table 1** Material parameters of the SMA

$E_A$ [MPa]	$E_M$ [MPa]	$\nu$ [-]	$M_{0s}$ [K]	$M_{0f}$ [K]
62000	31000	0.33	251.3	213
$H$ [-]	$r\Delta s_0^M$ [MPa / K]	$r\Delta s_0^m$ [MPa / K]	$A_{0s}$ [K]	$A_{0f}$ [K]
0.047	-0.364	-0.364	260.3	268.5



a) effective stress field                      b) martensitic volume fraction field  
**Figure 2** SMA spring segment



## Application of modeling in the automotive industry

The FEM modeling of mechanical engineering structures is essential in product design. The SMA constitutive model provides the possibility to predict the behavior in exploitation conditions. The example of the ring segment of spring is proposed. One end of the segment is fixed, while the second end is loaded by 7 mm of prescribed displacements in the y-direction. The segment is constrained in the x, z – plane to simulate the behavior in the tube. Figure 2 shows the effective stress field, the displacement field, and the martensitic volume fraction field. The material parameters used for the simulation are given in Table 1. The model is considered to be at the constant room temperature. The nonlinear analysis is performed in 20 equal time steps. As can be noticed, the effective stress field has the same distribution overall loading range. Simultaneously, the martensitic volume fraction is different at the beginning, in the middle and at the end of the loading.

## CONCLUSIONS

SMA are smart, multifunctional materials that can be used in the automotive industry as sensors or actuators. Superelasticity and shape memory effects are phenomena that depend on the exploitation temperature of the SMA structure. In this scope, some automotive industry parts can be made of SMA. One of the main disadvantages is high production costs and complicated material processing due to SMA's high thermosensitivity. To decrease costs, FEM modeling of the SMA structures would be essential. Various authors in the last few decades successfully simulated the behavior of SMA specimens, and the most significant achievements are the thermo-mechanical coupling of the SMA constitutive model and application of large strain theory in an effective manner. The SMA spring segment simulation is presented to show the specific behavior of the SMA structures, the distribution of the martensitic volume fraction for the most common type of loading.

## REFERENCES

- [1] Jani, J. M., Leary, M., Subic, A., Gibson, M. A.: "A review of shape memory alloy research, applications and opportunities", *Materials and Design*, Vol. 56, 2014, pp. 1078-1113. Doi: [10.1016/j.matdes.2013.11.084](https://doi.org/10.1016/j.matdes.2013.11.084)
- [2] Williams, E., Elahinia, M.H.: "An automotive sma mirror actuator: modeling, design, and experimental evaluation", *Journal of Intelligent Material Systems and Structures*, Vol. 19, No. 12, 2008, pp. 1425–1434. Doi: [10.1177/1045389X07087328](https://doi.org/10.1177/1045389X07087328)
- [3] Stoeckel, D.: "Shape memory actuators for automotive applications", *Materials & Design*, Vol. 11, No. 6, 1990, pp. 302-307. Doi: [10.1016/0261-3069\(90\)90013-A](https://doi.org/10.1016/0261-3069(90)90013-A)
- [4] Stoeckel, D., Borden, T.: "Actuation and fastening with shape memory alloys in the automotive industry", *Metall Wissenschaft + Technik*, Vol. 7, 1992, pp. 668-672.
- [5] Wu, M.H., Schetky, L.M.: "Industrial application for shape memory alloys" in *Proceedings of the International Conference on Shape Memory and Superelastic*, 2000, Pacific Grove, California.
- [6] Strittmatter, J., Gümpel, P.: "Long-time stability of ni-ti-shape memory alloys for automotive safety systems", *Journal of Materials Engineering and Performance*, Vol. 20, No. 4-5, 2011, pp. 506-510.
- [7] Gheorghita V., Gümpel P., Chiru A., Strittmatt J., "Future applications of Ni-Ti alloys in automotive safety systems," *International Journal of Automotive Technology*, Vol. 15, No. 3, 2014, pp. 469-474. Doi: [10.1007/s12239-014-0049-z](https://doi.org/10.1007/s12239-014-0049-z)
- [8] Dunić, V., Slavković, R., Pieczyska, E.: "Properties and behavior of shape memory alloys in the scope of biomedical and engineering applications", in *Biomaterials in Clinical Practice*, Springer, 2018, pp. 303-331.
- [9] Dunić, V. Slavković, R.: "Implicit stress integration procedure for large strains of the reformulated Shape Memory Alloys material model", *Continuum Mechanics and Thermodynamics*, Vol. 32, 2020, pp. 1287–1309. Doi: [10.1007/s00161-019-00842-7](https://doi.org/10.1007/s00161-019-00842-7)
- [10] Dunić, V., Busarac, N., Slavković, V., Rosić, B., Niekamp, R., Matthies, H., Slavković, R., Živković, M.: "A thermo-mechanically coupled finite strain model considering inelastic heat generation", *Continuum Mechanics and Thermodynamics*, Vol. 28, No. 4, 2016, pp. 993-1007. Doi: [10.1007/s00161-015-0442-5](https://doi.org/10.1007/s00161-015-0442-5)
- [11] Dunić, V., Pieczyska, E., Tobushi, H., Staszczak, M., Slavković, R.: "Experimental and numerical thermo-mechanical analysis of shape memory alloy subjected to tension with various stress and strain rates", *Smart Materials and Structures*, Vol. 23, No. 055026, 2014. Doi: [10.1088/0964-1726/23/5/055026](https://doi.org/10.1088/0964-1726/23/5/055026)
- [12] Dunić, V., Pieczyska, E., Kowalewski, Z., Matsui, R., Slavković, R.: "Experimental and numerical investigation of mechanical and thermal effects in tini sma during transformation-induced creep phenomena", *Materials*, Vol. 12, No. 6, 2019, p. 887. Doi: [10.3390/ma12060883](https://doi.org/10.3390/ma12060883)
- [13] Lagoudas, D.: "Shape memory alloys: modeling and engineering applications", 2010, New York: Springer
- [14] Dunić, V.: "Development and implementation of thermo-mechanical constitutive model for numerical analysis of shape memory alloys", PhD Thesis, 2015, Faculty of Engineering University of Kragujevac, Kragujevac

ISBN 978-86-6335-074-8



9 788663 350748