

**XII Triennial International
Scientific Conference
Engineering TODAY**

2026

CONFERENCE PROCEEDINGS

25 - 27 JUNE 2026, VRNJAČKA BANJA, SERBIA

**FACULTY OF MECHANICAL AND CIVIL ENGINEERING IN KRALJEVO
UNIVERSITY OF KRAGUJEVAC**

XII INTERNATIONAL TRIENNIAL SCIENTIFIC CONFERENCE

ENGINEERING TODAY ET 2026

Conference Proceedings

25 – 27 June 2026, Vrnjačka Banja, Serbia

Supported by:

Republic of Serbia

Ministry of Science, Technological Development and Innovation

PUBLISHER: Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac

EDITOR: Prof. Dr Goran Marković

TECHNICAL EDITOR AND COVER DESIGN:
Prof. Dr Mišo Bjelić

REVIEWS: All papers have been reviewed by the members of the Scientific Committee

PRINT: SaTCIP d.o.o., Vrnjačka Banja

PLACE AND YEAR OF PUBLICATION:
Kraljevo, 2026

CIRCULATION: 60 copies

ISBN 978-86-82434-15-3

CIP - Каталогизacija у публикацији Народна библиотека Србије, Београд

621(082)
629.3/.4(082)
621.86/.87(082)
681.5(082)
004(048)

TRIENNIAL International Scientific Conference Engineering Today (12 ; 2026 ; Vrnjačka Banja)

Conference Proceedings / XII International Triennial Scientific Conference Engineering Today 2026, ET 2026, 25 – 27 June 2026, Vrnjačka Banja, Serbia ; [editor Goran Marković]. - Kraljevo : University of Kragujevac, Faculty of Mechanical and Civil Engineering, 2026 (Vrnjačka Banja : SaTCIP). - 1 knj. (razl. pag.) : ilustr. ; 30 cm

Na nasl. str.: Republic of Serbia, Ministry of Science, Technological Development and Innovation. - Tiraž 60. - Str. 7: Preface / Goran Marković. - Bibliografija uz svaki rad. - Registar.

ISBN 978-86-82434-15-3

a) Производно машинство -- Зборници
b) Транспортна средства -- Зборници
v) Аутоматско управљање -- Зборници
g) Информациона технологија -- Зборници

COBISS.SR-ID 201872905

INTERNATIONAL SCIENTIFIC COMMITTEE

CONFERENCE CHAIRMAN

Prof. Dr Goran Marković, FMCE Kraljevo, Serbia

Scientific Committee Chairman

Prof. Dr Slaviša Šalinić, FMCE Kraljevo, Serbia

Scientific Committee Vice-Chairman

Prof. Dr Mišo Bjelić, FMCE Kraljevo, Serbia

MEMBERS OF THE SCIENTIFIC COMMITTEE

Prof. Dr M. Alamoreanu, TU Bucharest, Romania

Prof. Dr D. Atmadzhova, VTU Sofia, Bulgaria

Prof. Dr M. Banić, FME Niš, Serbia

Prof. Dr N. I. Gergova, VTU Sofia, Bulgaria

Prof. Dr M. Berg, KTH, Sweden

Prof. Dr S. Bikić, FTS Novi Sad, Serbia

Prof. Dr K. Krastanov, VTU Sofia, Bulgaria

Prof. Dr M. Bižić, FMCE Kraljevo, Serbia

Prof. Dr M. Blagojević, FE Kragujevac, Serbia

Prof. Dr H. Bogdevicius, VILNIUS TECH, Lithuania

Prof. Dr G. Bogdanović, FE Kragujevac, Serbia

Prof. Dr N. Bogojević, FMCE Kraljevo, Serbia

Prof. Dr S. Bošnjak, FME Belgrade, Serbia

Prof. Dr I. Božić, FME Belgrade, Serbia

Prof. Dr A. Bruja, TU Bucharest, Romania

Prof. Dr R. Bulatović, FMCE Kraljevo, Serbia

Prof. Dr S. Ćirić Kostić, FMCE Kraljevo, Serbia

Prof. Dr I. Despotović, FMCE Kraljevo, Serbia

Prof. Dr M. V. Dragoi, UNITBV, Romania

Prof. Dr B. Dragović, FMS Kotor, Montenegro

Prof. Dr Lj. Dubonjić, FMCE Kraljevo, Serbia

Prof. Dr R. Durković, FME Podgorica, Montenegro

Prof. Dr R. Đokić, FTS Novi Sad, Serbia

Prof. Dr K. Ehmann, NU Chicago, USA

Prof. Dr O. Erić Cekić, FMCE Kraljevo, Serbia

Prof. Dr V. Gašić, FME Belgrade, Serbia

Prof. Dr D. Golubović, FME East Sarajevo, BiH

Prof. Dr P. Gvero, FME Banja Luka, BiH

Prof. Dr B. Jerman, FME Ljubljana, Slovenia

Prof. Dr R. Karamarković, FMCE Kraljevo, Serbia

Prof. Dr M. Karasahin, DU Istanbul, Turkey

Prof. Dr K. Kocman, TU Brno, Czech Republic

Prof. Dr S. Kolaković, FTS Novi Sad, Serbia

Prof. Dr M. Kostić, NIU DeKalb, USA

Prof. Dr M. Krajišnik, FME East Sarajevo, BiH

Prof. Dr M. Králik, FME Bratislava, Slovakia

Prof. Dr E. Kudrjavcev, MGSU Moscow, Russia

Prof. Dr Đ. Lađinović, FTS Novi Sad, Serbia

Prof. Dr D. Marinković, TU Berlin, Germany

Prof. Dr M. Marašević, FMCE Kraljevo, Serbia

Prof. Dr A. Milašinović, FME Banja Luka, BiH
Prof. Dr I. Milićević, FTS Čačak, Serbia
Prof. Dr V. Milićević, FMCE Kraljevo, Serbia
Prof. Dr D. Milković, FME Belgrade, Serbia
Prof. Dr Z. Miljković, FME Belgrade, Serbia
Prof. Dr B. Milošević, FMCE Kraljevo, Serbia
Prof. Dr V. Milovanović, FE Kragujevac, Serbia
Prof. Dr G. Minak, UNIBO, Italy
Prof. Dr D. Minić, FME Kosovska Mitrovica, Serbia
Prof. Dr A. Nikolić, FMCE Kraljevo, Serbia
Prof. Dr E. Nikolov, TU Sofia, Bulgaria
Prof. Dr V. Nikolić, FME Niš, Serbia
Prof. Dr V. Nikolov, VTU Sofia, Bulgaria
Prof. Dr M. Ognjanović, FME Belgrade, Serbia
Prof. Dr J. Peterka, FMS&T Trnava, Slovakia
Prof. Dr D. Petrović, FMCE Kraljevo, Serbia
Prof. Dr J. Polajnar, BCU Prince George, Canada
Prof. Dr M. Popović, FTS Čačak, Serbia
Prof. Dr D. Pršić, FMCE Kraljevo, Serbia
Prof. Dr Francu Catalin, UTCB, Romania
Prof. Dr N. Radić, FME East Sarajevo, BiH
Prof. Dr B. Radičević, FMCE Kraljevo, Serbia
Prof. Dr V. Radonjanin, FTS Novi Sad, Serbia
Prof. Dr M. Savković, FMCE Kraljevo, Serbia
Prof. Dr D. Sever, FCE Maribor, Slovenia
Prof. Dr B. Sredojević, FMCE Kraljevo, Serbia
Prof. Dr V. Stojanović, FMCE Kraljevo, Serbia
Prof. Dr I. S. Surovcev, VGSU Voronezh, Russia
Prof. Dr J. Tanasković, FME Belgrade, Serbia
Prof. Dr Lj. Tanović, FME Belgrade, Serbia
Prof. Dr D. Todorova, VTU Sofia, Bulgaria
Prof. Dr K. Weinert, TU Dortmund, Germany
Prof. Dr N. Zdravković, FMCE Kraljevo, Serbia
Prof. Dr D. Živanić, FTS Novi Sad, Serbia
Prof. Dr N. Zrnić, FME Belgrade, Serbia
Prof. Dr R. Vujadinovic, FME Podgorica, Montenegro
Prof. Dr M. Jordović Pavlović, FMCE Kraljevo, Serbia
Prof. Dr Z. Đinović, ACMIT Wiener Neustadt, Austria
Prof. Dr Limonka Kocева Lazarova, UGD Štip, N. Maced.

ORGANIZING COMMITTEE

Chairman

Prof. Dr Vladimir Milićević, FMCE Kraljevo, Serbia

Vice-Chairman

Dr Nataša Pavlović, FMCE Kraljevo, Serbia

MEMBERS OF THE ORGANIZING COMMITTEE

Dr A. Petrović, FMCE Kraljevo, Serbia

Dr V. Grković, FMCE Kraljevo, Serbia

Dr M. Bošković, FMCE Kraljevo, Serbia

Dr M. Nikolić, FMCE Kraljevo, Serbia

Dr N. Stojić, FMCE Kraljevo, Serbia

Dr I. Franc, FMCE Kraljevo, Serbia

Dr M. Jovanović, FMCE Kraljevo, Serbia

Dr M. Nikolić, FMCE Kraljevo, Serbia

Dr V. Đorđević, FMCE Kraljevo, Serbia

Dr N. Petrović, FMCE Kraljevo, Serbia

Dr J. Bojković, FMCE Kraljevo, Serbia

Dr G. Bošković, FMCE Kraljevo, Serbia

TECHNICAL COMMITTEE

Chairman

Dr Vladimir Mandić, FMCE Kraljevo, Serbia

Vice-Chairman

Bojan Beloica, FMCE Kraljevo, Serbia

MEMBERS OF THE TECHNICAL COMMITTEE

M. Ivanović, FMCE Kraljevo, Serbia

M. Janićijević Milačak, FMCE Kraljevo, Serbia

S. Mihajlović, FMCE Kraljevo, Serbia

V. Sindelić, FMCE Kraljevo, Serbia

M. Todorović, FMCE Kraljevo, Serbia

S. Pajović, FMCE Kraljevo, Serbia

P. Mladenović, FMCE Kraljevo, Serbia

A. Jovanović, FMCE Kraljevo, Serbia

M. Adamović, FMCE Kraljevo, Serbia

M. Rasinac, FMCE Kraljevo, Serbia

J. Perić, FMCE Kraljevo, Serbia

PLENARY SESSION

Ž. Čojbašić, G. Petrović

[P1](#)

TRUSTWORTHY EDGE INTELLIGENCE IN ENGINEERING TODAY:
APPLICATIONS IN INDUSTRIAL CONTROL, ROBOTICS AND TRANSPORT ENGINEERING

V. Stojanovic, H. Tao, X. Li

[P11](#)

FROM DATA SCARCITY TO OPEN-SET GENERALIZATION:
A UNIFIED FRAMEWORK FOR ROBUST ROTATING MACHINERY FAULT DIAGNOSIS

SESSION A: EARTH-MOVING AND TRANSPORTATION MACHINERY

C. Sescu-Gal, M. Savaniu, C. Francu, O. Tonciu, B. Bebeselea

[A1](#)

MECHATRONIC SYSTEM FOR MONITORING CRANE LIFTING OPERATIONS

M. Urošević, N. Zrnić, X. Liu

[A9](#)

REMARKS ON THE INFLUENCE OF THE DYNAMIC BEHAVIOR OF BELT
CONVEYORS ON THE RESPONSE OF THE SPREADER SUPERSTRUCTURE

V. Naydenov, B. Burdin, D. Krastanov

[A17](#)

EXPERIMENTAL STUDY OF ENERGY EFFICIENCY OF A HYDROGEN VEHICLE

M. Katona, A. Zelić, D. Živanić, R. Đokić, T. Jojić, N. Ilanković

[A25](#)

COMPARATIVE OVERVIEW OF DETERMINING SERVICE CLASSES OF
INDUSTRIAL CRANES ACCORDING TO RELEVANT STANDARDS AND GUIDELINES

V. Jovanović, N. Petrović, J. Pavlović, B. Nikolić

[A33](#)

A FUZZY AHP APPROACH FOR EVALUATING CIRCULAR EFFICIENCY
OF HYDRAULIC EXCAVATOR SWING DRIVE SYSTEMS

N. Miloradović, R. Vujanac, M. Piskulić, J. Glišović

[A41](#)

COMPARATIVE ANALYSIS OF RACK LAYOUTS ACCORDING
TO THE STORAGE UNIT PLACEMENT METHOD

N. B. Zdravković, M. Savković, G. Marković, M. Todorović, P. Mladenović, G. V. Pavlović

[A51](#)

THE DETERMINATION OF THE DEFLECTION OF THE STEPPED
COLUMN BY THE FINITE DIFFERENCE METHOD

D. Živanić, V. Žerajić, N. Ilanković

[A59](#)

PHYSICAL ANALYSIS OF FORCES, MOMENTS, AND ENERGY EFFICIENCY OF MULTIROTOR
UNMANNED AERIAL VEHICLES FROM THE PERSPECTIVE OF FLIGHT CONTROL

V. Žerajić, D. Ružić, D. Živanić, N. Ilanković

[A69](#)

SEGMENT-BASED ENERGY BALANCE AND PROPULSION FEASIBILITY
ANALYSIS OF A LIGHT PASSENGER VTOL AIRCRAFT FOR A REGIONAL MISSION

S. Trifković, N. Radić, M. Milutinović, S. Samardžić

[A79](#)

ANALYSIS AND CALCULATION OF OVERHEAD CONVEYOR
FOR METAL HOUSINGS TRANSPORTATION

R. Đokić, J. Vladić, T. Jojić	A85
ANALYSIS OF ZIPLINE SYSTEMS WITH LARGE SPANS AND LOW INCLINATION ANGLES	
A. Stanković, G. Petrović, A. Trajković, P. Milić, M. Stanković, Ž. Čojbašić	A95
A HYBRID SWARA–MULTIMOORA APPROACH FOR PRODUCTION JOB PRIORITIZATION	

SESSION B: RAILWAY ENGINEERING

V. Nikolov, F. Kirilov	B1
STRENGTH-DEFORMATION ANALYSIS OF WHEEL REDUCER FOR METRO CARS	
D. Milković, S. Radulović, A. K. Miličić, G. Simić, O. Obradović	B11
TESTS FOR THE ASSESSMENT OF DEVICES FOR SECURING SEMI-TRAILERS DURING TRANSPORT ON A FREIGHT WAGON	
D. Atmadzhova, V. Ralev	B17
STRENGTH ANALYSIS OF AN ELECTRIC LOCOMOTIVE TRANSMISSION MECHANISM	
E. M. Mihaylov, E. Iontchev, E. Stoyanova	B29
IMPACT OF DETERIORATED TRAM TRACKS ON THE CURRENT COLLECTORS OF TRAMS	
B. Gavrilović, Ž. Avramović, Z. Stjepanović, D. Stjepanović	B35
MEASUREMENT OF DISTORTION POWER AND POWER FACTOR IN ELECTRIC TRACTION SUBSTATIONS “SERBIA RAILWAY INFRASTRUCTURE” WHEN POWERING ELECTRIC LOCOMOTIVES IN TRACTION AND RECUPERATIVE BRAKING	
J. Glišović, D. Miloradović, J. Lukić, N. Miloradović, S. Vasiljević	B41
COMPARATIVE ANALYSIS OF METHODS FOR THE INVESTIGATION OF BRAKE WEAR PARTICLES EMISSION OF RAILWAY VEHICLES	
M. Bižić, D. Petrović	B51
INFLUENCE OF SIGNAL-TO-NOISE RATIO ON THE ACCURACY OF EXPERIMENTAL DETERMINATION OF WHEEL–RAIL INTERACTION FORCES	
V. Zochinova, V. Pavlov	B59
SYSTEMS FOR PRECISION CONTROL OF MICROCLIMATE IN WORLD RAIL TRANSPORT: TECHNOLOGICAL STRUCTURE AND INTELLIGENT MANAGEMENT	
V. Pavlov	B65
METHODS OF INCREASING THE WEAR RESISTANCE WITH REPAIRS OF BDZ FREIGHT WAGON BOGIES	
I. Petrova	B69
IMPACT OF AUTOMATED SYSTEMS ON REDUCING THE HUMAN FACTOR IN RAIL TRANSPORT	
Z. G. Pavlović, A. Savić, V. Radičević, R. Vasiljević	B75
AN ELECTRONIC BUSINESS MODEL FOR THE REGULATION OF RAILWAY TRAFFIC AND TRANSPORT BASED ON ARTIFICIAL INTELLIGENCE	

K. Trifonov	B81
STATE OF DISPATCHER SYSTEMS IN BULGARIA AND THEIR ROLE IN THE LIBERALISED PASSENGER RAIL MARKET	
V. Ralev	B93
STUDY ON THE WEAR OF CYLINDRICAL GEARS OF TRANSMISSION MECHANISMS	
SESSION C: PRODUCTION TECHNOLOGIES, CAE AND MANAGEMENT	
E. Hozdić, E. Hozdić	C1
FROM INDUSTRY 4.0 TO INDUSTRY 5.0: THE TRANSITION FROM DIGITALIZATION AND CYBERNATION TO COGNITIZATION AND HUMAN-MACHINE SYNERGY	
V. Vujičić, I. Milićević, N. Mijailović, N. Dučić, V. Aleksić, M. Popović	C13
ROBOT-ASSISTED LATHE MACHINE SERVICING	
M. Madić, M. Trifunović, S. S. Nikolić, M. Milojković	C19
ENVIRONMENTAL IMPACT ANALYSIS OF LASER CUTTING: A CASE STUDY OF THIN STAINLESS STEEL AND ALUMINUM ALLOY SHEETS	
M. Rasinac, M. Bjelić, T. Dulović, J. Perić, M. Ivanović	C25
THREE-OBJECTIVE PARETO OPTIMIZATION OF GMAW PROCESS PARAMETERS USING A MODIFIED FORCE BALANCE MODEL	
S. Pajović, V. Grković, J. Perić, A. Petrović, B. Radičević	C37
INVESTIGATION OF THE INFLUENCE OF CUTTING PARAMETERS ON NOISE EMISSION DURING FACE TURNING OF BEECH WOOD	
J. Perić, M. Rasinac, S. Pajović, V. Grković, A. Petrović	C45
INVESTIGATION OF CUTTING PARAMETERS INFLUENCE ON VIBRATION DURING MILLING OF HDPE	
D. Milčić, M. Milčić, N. Zdravković, A. Đurić, D. Klobčar, T. Vuherer	C53
ENERGY EFFICIENCY AND CARBON FOOTPRINT OF WELDED, ADHESIVE AND HYBRID JOINING PROCESSES IN THE CONTEXT OF CIRCULAR ECONOMY	
N. Petrović, V. Jovanović, J. Mihajlović, B. Nikolić, S. Marković	C61
A FUZZY AHP-BASED APPROACH FOR OPTIMAL TRANSPORT MODE SELECTION	
A. Jovičić, D. Veljković, A. Mitrović, J. Baralić	C67
SELECTION AND ANALYSIS OF KEY OCCUPATIONAL SAFETY AND HEALTH INDICATORS: A CASE STUDY IN THE FOUNDRY INDUSTRY	
V. Vassilev, N. Ivanova Gergova	C77
BALANCING BETWEEN PUBLIC SERVICE OBLIGATIONS AND MARKET EFFICIENCY: MODERN CHALLENGES IN PASSENGER RAIL TRANSPORT	

SESSION D: AUTOMATIC CONTROL, IT AND ARTIFICIAL INTELLIGENCE

L. Kelić HYBRID SIMULATION OF AN INVERTED PENDULUM	D1
S. T. Radovic, D. Stavrov, G. Nadzinski, V. O. Latkoska INTELLIGENT CONTROL OF A UAV USING A SENSOR GLOVE	D11
Lj. Dubonjic, J. P. Z. Machado, D. Prsic, V. Stojanovic, X. Xie EVENT-TRIGGERED ADP FOR ASYMPTOTIC OUTPUT REGULATION OF UNKNOWN LINEAR SYSTEMS	D23
V. Stojanovic, D. Prsic, Lj. Dubonjic, M. Defoort, X. Song, S. Song DECENTRALIZED EVENT-TRIGGERED OUTPUT-FEEDBACK ADP FOR HYDRAULICALLY-DRIVEN PARALLEL ROBOT PLATFORMS	D31
S. Prodanovic, E. Bernardi, X. Luan, V. Stojanovic, W. Paszke EVENT-TRIGGERED OUTPUT-FEEDBACK ADP FOR SINGLE-JOINT ROBOTIC MANIPULATORS WITH UNKNOWN DYNAMICS	D41
V. Filipović, V. Đorđević MINIMUM POSITIONING-TIME FOR MECHATRONIC SYSTEMS	D49
V. Milićević, M. Jovanović, N. Biga, M. M. Živanović, I. Franc LEGAL ISSUES OF ETHICAL HACKING: A SYSTEMATIC REVIEW OF AUTHORIZATION, COMPLIANCE, AND LIABILITY FRAMEWORKS	D57
G. Katipoğlu, S. Utku REAL-TIME OBJECT RECOGNITION AND AUDIO FEEDBACK SYSTEM FOR VISUALLY IMPAIRED INDIVIDUALS	D69
Z. G. Pavlović, A. Savić, V. Radičević, R. Vasiljević MODEL OF APPLICATION OF ARTIFICIAL INTELLIGENCE IN HIGHER EDUCATION BASED ON INTERACTION BETWEEN USER AND COMPUTER SYSTEM	D75
M. K. Paneva, N. Stojkovikj, V. Kokalanov, V. Milićević ML ALGORITHM FOR COVID-19 OUTCOME PREDICTION BASED ON DEMOGRAPHIC FEATURES IN NORTH MACEDONIA	D81
M. J. Pavlović, T. Geroski, M. Nikolić DRUG CLUSTERING UPON TOXICITY EFFECTS ON LIVER SPHEROIDS – A DEEP LEARNING APPROACH	D87
M. Svičević, M. Pavković, N. Vučićević, A. Milenković, A. Milutinović COMPARING QLORA FINE-TUNING OF A GENERAL-PURPOSE AND A MATHEMATICALLY SPECIALIZED LLM ON SERBIAN MATHEMATICS COMPETITION TASKS	D97
S. Jančić, M. Jovanović, E. Jovanović, I. Franc DOMAIN-ADAPTED OPEN-WEIGHT LANGUAGE MODEL FOR KICAD PRINTED-CIRCUIT-BOARD DESIGN AUTOMATION	D105

SESSION E: THERMAL TECHNIQUE AND ENVIRONMENTAL PROTECTION

- G. Bošković, Ž. Kužet, M. Bošković, M. Todorović, Z. Čepić** [E1](#)
INTEGRATED RISK ASSESSMENT AND DIGITAL TWIN-BASED
SAFETY MANAGEMENT IN PHOTOVOLTAIC SYSTEMS
- G. Krunić, S. Vasković, S. Krile, A. Ijačić** [E11](#)
ANALYSIS OF THE INFLUENCE OF THE ROTATION SPEED OF THE DFIG
WIND TURBINE GENERATOR ON THE TEMPERATURE OF THE GENERATOR
- M. Timotijević, O. Erić Cekić, D. Rajnović, P. Janjatović** [E21](#)
INFLUENCE OF OVERHEATING EXPOSURE TIME ON THE MICROSTRUCTURAL
STABILITY AND MECHANICAL PROPERTIES OF HP40-0.63NB ALLOY
- V. Zochinova, M. Ivanova, T. Shalamanova** [E29](#)
ASSESSMENT OF THE MICROCLIMATE AND SUBJECTIVE PERCEPTION
OF THE THERMAL ENVIRONMENT IN SCHOOL
- I. Kuvač, D. Stupar, M. Schwai, I. Karan, B. Mrđa** [E35](#)
URBAN ACUPUNCTURE AND VISUAL ACTIVISM AS FOUNDATIONS FOR
ENVIRONMENTALLY RESPONSIBLE RIVERSIDE TRANSFORMATION:
THE CASE OF THE VRBAS RIVER IN BANJA LUKA
- S. Knežević, M. Milojević, A. Milošević** [E47](#)
APPLICATION OF ROBOTIC SYSTEMS IN INTENSIVE LIVESTOCK
FARMING FROM THE ASPECT OF ENVIRONMENTAL PROTECTION
- J. Belošević, S. Belošević, M. Đukić** [E55](#)
CHEMICAL POLLUTANTS IN THE SOIL OF NOVI PAZAR
AND ECOLOGICAL RISK ASSESSMENT
- J. Belošević, S. Belošević, M. Đukić** [E61](#)
MONITORING OF HEAVY METALS AND THEIR MOVEMENT
THROUGH THE ENVIRONMENT OF THE CITY OF KRAGUJEVAC

SESSION F: APPLIED MECHANICS

- B. Milenković, Đ. Jovanović, M. Krstić** [F1](#)
VOLUME OPTIMIZATION OF THE WORM GEAR USING SSO ALGORITHM
- Z. Petrović, R. Nikolić, Lj. Brzaković, M. Tufegdžić, S. Petrović Savić** [F7](#)
VIRTUAL TWIN MODELING OF THE MITSUBISHI RV-2FRL
INDUSTRIAL ROBOT IN THE MATLAB PROGRAMMABLE ENVIRONMENT
- V. Sindelić, A. Nikolić, S. Ćirić-Kostić, N. Bogojević, O. Cekić-Erić, N. Drvar** [F17](#)
NUMERICAL INVESTIGATION OF A STAR-SHAPED AUXETIC STRUCTURE
UNDER DIFFERENT IMPACT VELOCITIES

SESSION G: CIVIL ENGINEERING

- B. Paleva-Kadiyska** **G1**
ROAD SURFACE WEAR – ANALYSIS OF TESTS AND POSSIBILITIES
FOR APPLICATION OF NEW MATERIALS
- P. Stefanova** **G7**
COMPARATIVE STUDY OF BLEEDING PROCESS IN ORDINARY AND SELF-COMPACTING
CONCRETE – INFLUENCE ON THE RELIABILITY OF REINFORCED CONCRETE ELEMENTS
- J. Bojković, N. Stojić, V. Bulatović, I. Despotović, S. Mihajlović** **G13**
BIOCOMPOSITE BASED ON CORN COBS AS AN INNOVATIVE
THERMAL INSULATION MATERIAL
- S. Bajić, S. Milošević** **G19**
RECYCLED STEEL IN CONTEMPORARY ARCHITECTURE:
SUSTAINABLE POTENTIALS AND APPLICATIONS THROUGH CASE STUDIES
- M. J. Milačak, S. Mihajlović, B. Milošević, J. Bojković** **G27**
PUSHOVER ANALYSIS WITH VARIOUS MATERIAL NONLINEARITY MODELS
- B. Milošević, N. Kojić, M. J. Milačak** **G35**
EVOLUTION OF NONLINEAR ANALYSIS OF RC SECTIONS: FROM ITERATIVE
COMPUTATIONS TO RAPID MOMENT-CURVATURE PREDICTION USING ANN MODELS
- S. Mihajlović, M. Bižić, I. Despotović, J. Bojković, M. J. Milačak** **G45**
METHODOLOGY FOR MEASURING PRESSURE AT THE CONTACT SURFACE
BETWEEN A COLUMN FOOTING MODEL AND A SOIL LAYER LIMITED BY A
RIGID BASE USING EARTH PRESSURE CELLS

INDEX OF AUTHORS

Comparative analysis of methods for the investigation of brake wear particles emission of railway vehicles

Jasna Glišović^{1*}, Danijela Miloradović¹, Jovanka Lukić¹, Nenad Miloradović², Saša Vasiljević³

¹ University of Kragujevac, Faculty of Engineering/Department of Motor Vehicles and Motors, Kragujevac, Serbia

² University of Kragujevac, Faculty of Engineering/Department of Mechanical Structures and Mechanization, Kragujevac, Serbia

³ Academy of Professional Studies Šumadija Department in Kragujevac, Kragujevac, Serbia

ARTICLE INFO

* Correspondence: jaca@kg.ac.rs

DOI: <https://doi.org/10.46793/ET26.B06G>

PAGES: B41 – B49

ABSTRACT

The braking systems of railway vehicles are a key element for the safe and efficient operation of trains. Although according to official reports, the railway sector contributes less than 1% to total PM emissions in Europe, PM concentrations in enclosed spaces of underground railways are of great concern due to the confined nature of these spaces. Numerous studies have identified brake wear as the primary source of these emissions, as particles are generated during the braking process, under conditions of intense heating and wear in the contact zone between brake pads and discs. The aim of this paper is to critically analyze previous experimental studies to arrive at the most efficient and appropriate methodology that would provide knowledge about the mechanisms of particle generation caused by wear of brake pair elements in order to find ways to control the number and size distribution of particles in the air. In this regard, the advantages and disadvantages of various field tests with full-size brakes, laboratory tests on real brakes and reduced-scale brakes, as well as laboratory tests with a pin-on-disc machine were analyzed.

KEYWORDS

Railway vehicles, brakes, particle matter, methodology.

1. INTRODUCTION

In most cases, the transport of passengers and goods by rail is considered the most environmentally friendly mode of transport. With the increasing use of electrically powered motors in railway vehicles, exhaust emissions are no longer a main concern and attention is shifting to particulate matter from wear of brakes and others materials, as well as re-suspension from the ground. The task of the brakes is to maintain or reduce speed, that is, to stop vehicles in motion within a prescribed stopping distance, as well as to secure vehicles against self-movement.

The regulation on Brakes and Braking of Trains and Vehicles prescribes the types of brakes on vehicles and their parts, inscriptions and markings of brake devices, the method of braking trains and vehicles, the composition of trains with regard to the type of brakes, checking the correctness of brakes, calculating the brake power of a train and securing it against self-propulsion [1].

Mechanical friction brakes are the most important component necessary to achieve reliable, safe train traffic. Trains are generally considered a green energy and environmentally friendly transportation system, but airborne particulate emissions affect the accuracy of this picture. Metro systems around the world have been found to exhibit worrying levels of particulate pollution, exceeding those found in above-ground urban environments. Although human exposure in metro stations is relatively short, the intensity and the large number of people affected, including vulnerable groups such as the elderly or asthmatics, make the potential toxicity of particulates and emission reductions an urgent subject of research.

It must be noted that particulate emissions from rail transport have been much less studied than from road transport. Progress in legislation, toxicity studies or even mitigation alternatives in road transport can be used as a basis for future studies of rail transport emissions. Unlike road vehicles, a similar methodology is lacking for non-exhaust emissions from

rail transport. Abbasi et al. [2, 3] proposed a method for measuring the airborne wear particle emission rate (AWPER) from wheel-rail contacts and brake materials. This method can be used by manufacturers to demonstrate the competitive advantage of their products.

Studies of particle concentrations in metro systems around the world have attracted considerable attention in the past few decades. In 2011, Abbasi et al. [2] found that particle concentrations in metro systems in Stockholm, London and Budapest reached values of 300-1000 $\mu\text{g}/\text{m}^3$, which significantly exceeded the maximum limit of 50 $\mu\text{g}/\text{m}^3$ per day set by the EU for urban transport. By analyzing the materials present in the studied PM emissions from rail transport, about 84% can be attributed to mechanical friction processes, such as friction between the rail, the wheel, and the brake disc and pad. In situations of lower speed, such as approaching a metro station or in emergency situations, the mechanical braking system is activated and the brake system becomes one of the primary sources of airborne wear particles. Studies on brake wear emissions are still scarce, especially for disc brakes of high-speed trains. Available studies indicate that factors that have a significant influence on brake wear emissions include material composition, brake pressure, initial speed and contact temperature. Higher train speeds resulted in an increase in the total and maximum particle number concentrations, but also led to an increase in the particle number concentration for the peak diameter in the size distribution analysis. Higher speeds can also be associated with increased contact temperatures due to increased frictional heat and the thermal and chemical processes involved. The high temperatures resulting from increased disc speed and braking force can facilitate the formation of nanoparticles. Technical specifications of the vehicle, such as axle loads, technical specifications of the lifting table, material properties of the wheels and brakes, braking system and braking scheme, are important for particulate matter emissions. But in addition to factors related to the railway vehicles, emissions are also influenced by railway infrastructure conditions, such as technical specifications of the railway, track gauge, track substructure and track superstructure, track layout, switches and type of power transmission [4].

There are only few studies investigating the emission of wear particles from railway above ground. The aim of this paper is to perform a qualitative analysis and select the most optimal methodology to investigate the influence of railway braking conditions, such as contact pressure and disc temperature, in particular in terms of the range of emitted particles, their shape, size and composition. Knowledge of the nature of these particles (size, shape and composition) and their emission in real time is necessary for the development of efficient numerical models that can successfully predict the spread of particles near their origin. Based on the measurements, conditions would be obtained for the correct selection of friction conditions that give lower particle emission for a given dissipated kinetic energy and given rules for the injection properties of particles in a CFD model for studying their spread in a confined space, such as a metro station. In order to assess the influence of individual parameters on the nature of emitted PM, an experiment will be performed on a pair of railway braking materials, varying one parameter at a time, while maintaining the equivalent dissipated energy.

2. RAILWAY BRAKING SYSTEM

2.1. Railway Brakes

In the past, trains were equipped almost exclusively with mechanical brakes. Today, on modern high-speed trains, the braking system is usually controlled by a computer that allows variable distribution of braking power between different subsystems. The aforementioned braking subsystems usually include electro-dynamic and mechanical (friction) brakes. The application of newer technologies in railway vehicles and track infrastructure has also led to the introduction of inductive braking systems. Research into new linear induction motor techniques has been accompanied by increased weight. An overview of the different categories of brakes for rail vehicles is shown in Figure 1.

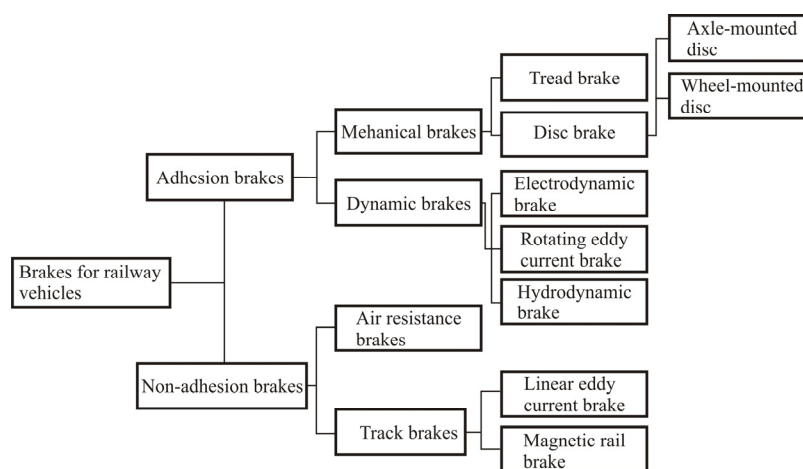


Figure 1: Different types of brakes on railway vehicles

Due to the frictional force developed between the brake pad and the brake disc, mechanical (friction) disc brakes are subject to a significant degree of wear, in contrast to electro-dynamic brakes which are much less susceptible. However, as the efficiency of electro-dynamic brakes depends on the speed of the railway vehicle, mechanical brakes are still

necessary for additional braking, especially at lower speeds. Usually below 60 km/h, friction brakes are activated to provide additional braking, and at speeds below 20 km/h, mechanical brakes take over the entire braking force. Mechanical brakes are also critical in the event of electro-dynamic brake failure or if it is necessary to reduce the speed of the train quickly, such as in emergency braking.

The two main types of friction braking systems are tread brakes (block brakes) and disc brakes. Tread brakes (Figure 2c) are still widely used on most freight trains in the EU, and disc brakes are fitted to many passenger trains, especially those operating at high speeds. The friction coefficient, and thus the efficiency of a disc brake, is very stable and almost independent of speed, and they exhibit good thermal properties and robustness. This type of brake can be mounted directly on the wheel or on the axle. Figure 2a shows a high-speed train, which uses axle-mounted disc brakes. Here, each axle is equipped with four brake discs and two pairs of brake pads on each side. A photograph of a disc brake pad mounted on a train wheel is shown in Figure 2b.

Brakes for high-speed trains must demonstrate superior properties and ensure safety, which means that they must withstand maximum temperatures during operation. This includes a high and stable coefficient of friction (COF), high thermal conductivity, as well as resistance to heat and wear, low absorption of water, oil or brake fluid, low aggressiveness towards the brake disc, high comfort properties, as well as reduced particle emissions and noise minimization. Organic brake pads have poor thermal stability and can therefore only be used when temperatures do not exceed 300°C. Since temperatures of up to 900°C can occur at the disc/pad interface during sudden braking of high-speed trains, sintered metal matrix composites are a suitable choice for this application because they can withstand temperatures of over 1000°C. These friction materials are obtained by powder metallurgy, i.e. they are pressed and sintered from a uniform mixture consisting mainly of metal powders as a matrix, matrix reinforcement materials, friction enhancers, and lubricants. Common matrix and matrix reinforcement materials are iron and copper, while metal and non-metal oxides or carbides are used as friction enhancers. To improve wear resistance, a lubricant such as molybdenum disulfide (MoS_2) is often used [5, 6].

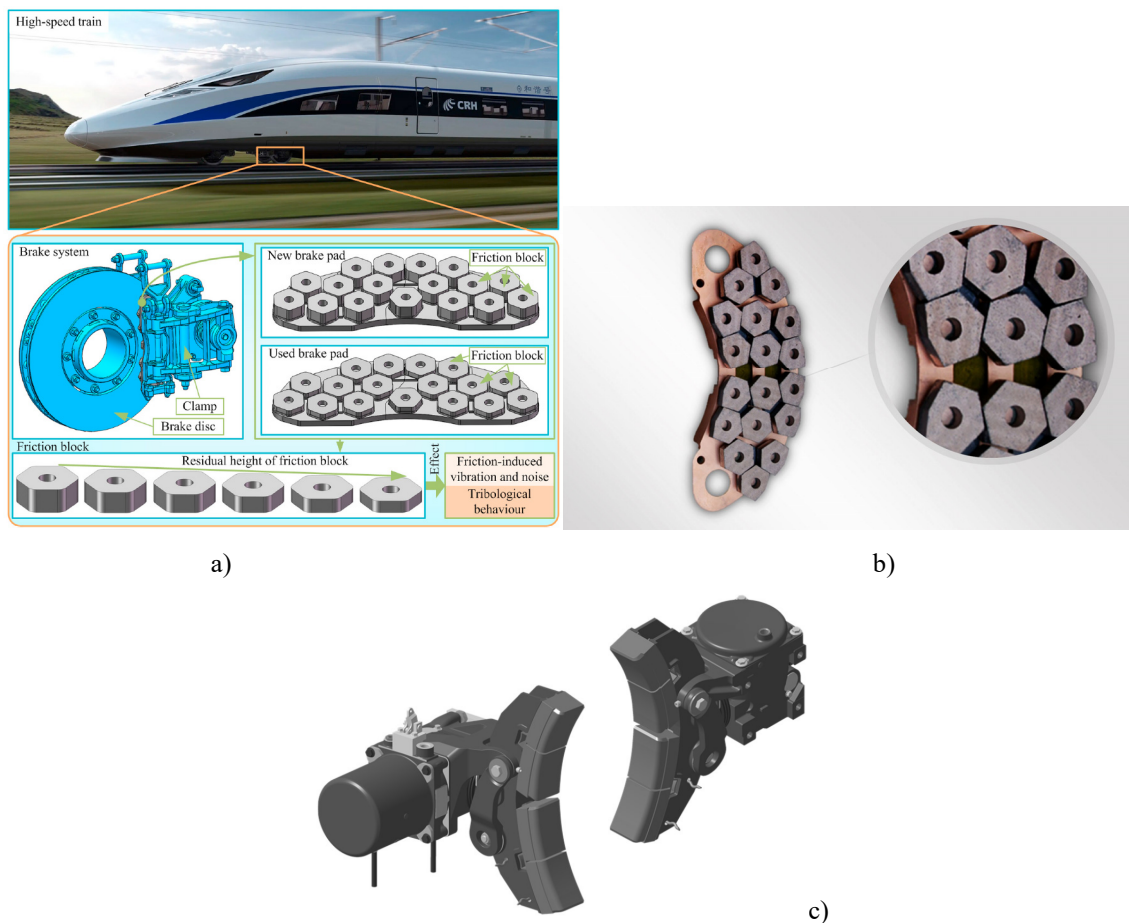


Figure 2: High-speed train disc and tread brake pad [7]

Research has proven that the friction and wear behavior of brake pad materials is primarily influenced by material characteristics, braking conditions, environmental conditions, surface conditions, and structural parameters. Train brake discs wear mainly due to the sliding contact between the pads and the disc. Abrasive and adhesive wear are the two primary wear mechanisms associated with disc brakes. The formation of brake wear particles is a result of abrasive and adhesive wear with oxidative processes. Two more specific wear modes that often occur in brake pads are fiber delamination, as well as fragmentary wear, such as induced pitting.

2.2. Brake Wear Particle Emission

Particulate matter can have harmful effects on the environment, climate, and human health, but the potential health risks of PM pollution were not widely investigated until the early 2000s. Results from many studies have indicated a link between exposure to PM particles and adverse health effects, but it has been established that health effects depend not only on particle concentration, but also on particle composition, as well as size, shape, and morphology. Larger particles are usually trapped and filtered in the nose and throat, while particles with a diameter of less than 10 μm can reach the lower respiratory tract. Ultrafine particles can further enter the bloodstream by penetrating the respiratory system, making them even more harmful than larger particles, as seen in Figure 3.

The travel distance and time until the particles settle on the ground due to gravity are dependent on the size and density of the particles. While coarse particles settle within hours, fine particles can remain suspended in the air for multiple weeks. About 90 % of PM is made up of fine and ultrafine particles under typical conditions. Non-exhaust emissions are a result of wear processes such as from the brakes, tires, clutch, engine and road surface, corrosion of vehicle parts, street signs and barriers as well as the re-suspension of settled particles on the road.

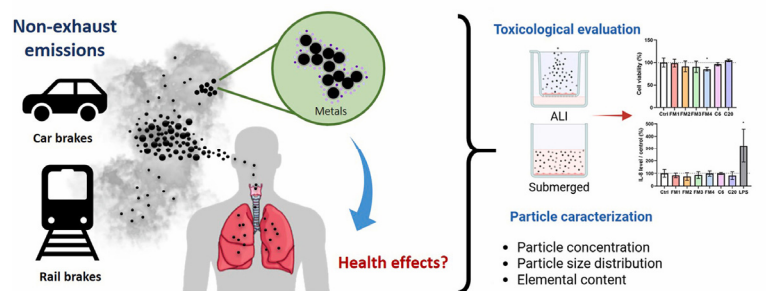


Figure 3: Human respiratory tract and deposition location of particles of different sizes.

2.3. Wear Particle Emissions in Rail Traffic

The data show that as of 2021, around 129,200 tonnes of $\text{PM}_{2.5}$ emissions and 201,400 tonnes of PM_{10} emissions in the EU are linked to transport as an industry, of which 171,300 tonnes of PM_{10} and 105,500 tonnes of $\text{PM}_{2.5}$ are from road transport alone. Rail vehicles contribute 38% of non-road PM_{10} emissions and 25% of $\text{PM}_{2.5}$ emissions. Strict regulations in the EU have contributed to a 55% reduction in annual $\text{PM}_{2.5}$ emissions and a 40% reduction in annual PM_{10} emissions between 2010 and 2019. However, 96% of urban residents are still exposed to levels of fine PM particles above the latest WHO (World Health Organization) guidelines. With stricter control of exhaust emissions, the relative share and importance of non-exhaust emissions are increasing. It has been found that up to 50% of non-exhaust PM_{10} emissions from road traffic are caused by disc brake wear. In car disc brakes, the braking torque on the rotor is generated by the friction force between the rotor and the brake pads. Since the rotor and the wheel are connected, the car will slow down due to the friction between the tire and the road. A similar situation applies to trains, where the braking force is transmitted by the contact between the wheel and the rail. During the friction braking process, wear occurs on the brake pads as well as on the rotor due to sliding contact. These brake wear particles can either deposit on the surface or be dispersed into the air. They have the potential to harm the environment and human health, as previously established. Studies have shown that it can be assumed that 35-50% of brake wear particles are in the air. Furthermore, brake wear has been found to be one of the main sources of metal particles in the air in cities.

Different types of brakes are widely used in railway transport, such as disc brakes and tread brakes. Fridell et al. [8, 9] observed in their research characteristic peaks in particle number concentration during deceleration phases, which, however, were not present in every braking process. The reason for this is the type of brake used in the braking process. Modern passenger trains are equipped with mechanical brakes as well as regenerative brakes (electric). Peaks in particle number concentration only occur if mechanical brakes are used for deceleration. Furthermore, the category of mechanical brakes must be divided into block brakes, which are widely used for freight trains, and disc brakes, which represent the standard braking system for passenger trains. While a wheel is usually equipped with one brake disc, axles can be equipped with two, three or even more brake discs.

The Euro 7 standard extends the regulatory requirements for the type-approval of braking systems and tyres with regard to particulate emissions and the abrasion process that occurs. The regulation applies to tyres of classes C1 (passenger cars and commercial vehicles), C2 (light commercial vehicles) and C3 (heavy commercial vehicles), in accordance with UN Regulation 117. As a result, the Euro 7 standard includes a requirement to limit the maximum emissions of PM_{10} particles from brake pads and tyres. Generally speaking, for electric cars the limit will be 3 mg/km, for combustion passenger cars, hybrids and hydrogen cars 7 mg/km, and for large vans and delivery vehicles 11 mg/km. The Euro 7 emission standard will first apply to the type-approval of new models of light vehicles and their braking systems 2.5 years after the entry into force of the regulation. A year later, all newly registered vehicles will have to meet the new Euro 7 requirements. Euro 7 for heavy goods vehicles will apply to new vehicle models 4 years after entry into force, and after 5 years to all new vehicles [10]. However, emission level limits have so far been based solely on the mass of particles per unit volume

of air, without considering particle number, composition and toxicity. The research community therefore suggests that this be taken into account for future limit values and assessment.

3. METHODS TO ANALYZE BRAKE WEAR EMISSIONS

The lack of standardized sampling and measurement methods for brake wear particle emissions in existing studies further complicates the comparison of results and conclusions. A major problem is that most studies are limited to automobile disc brakes, with very few examining other modes of transport, such as rail transport [11]. In order to evaluate braking performance and the influence of applied brake material, as well as to simulate different braking scenarios, a number of braking systems can be used, from small-scale ones, such as pin-on-disc tribometers, to component testing on a brake dynamometer, and even full-scale field tests (Figure 4). Compared to brake dynamometers, their main advantages are the small dimensions of the test platform and lower operating costs. Brake dynamometers with disc brakes are mainly used for homologation testing and evaluation of damage mechanisms of various disc brake systems. However, in recent years, these devices have been used more frequently to generate brake wear particles due to their ability to replicate vehicle and kinetic energy data under controlled laboratory conditions that are very close to those in the real world.

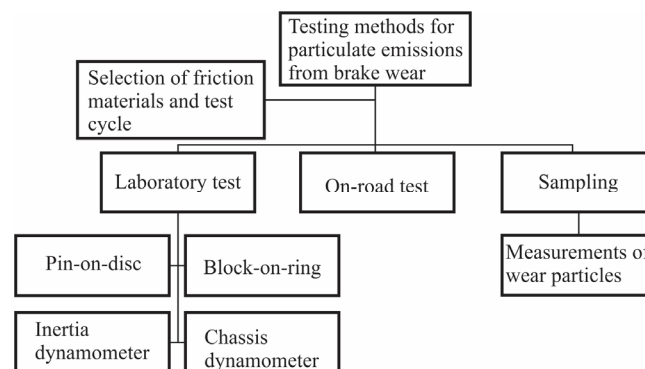


Figure 4: Overview of different laboratory and on-road testing methods for particulate emissions from brake wear

The pin-on-disc test is a robust method for studying the formation of airborne particles, based on the similarity of morphology and size distribution, with the prerequisite that the same contact conditions are used in laboratory tests as in field tests. Pin-on-disc tribometers are often used to generate brake wear particles in air under controlled operating parameters (contact pressure, sliding speed and friction material temperature) [12, 13, 14].

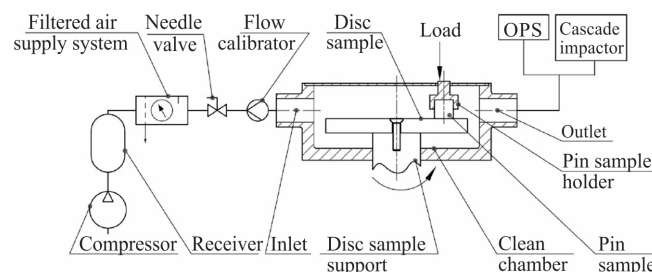


Figure 5: Schematic of the experimental set-up based on a pin-on-disc tribometer [12]

One of the few published on-board measurements was conducted by Fridell et al. [8, 9], who reported particle characteristics and emission factors for wear particles from a running Regina train. They investigated particles size in 7 intervals and aimed to investigate 27 elements among collected particles. The curve negotiation effects were not traceable in his work as they used one sampling point that was located between the two coaches. The main objective of field test conducted by Abbasi et al. [3] was to study the characteristics of particles generated by disc brakes on a moving train using a measurement system installed on the train. Two points were defined for sampling airborne particles, one close to the disc brake pad-rotor contact and the other below the frame, not close to the mechanical brake or wheel-rail contact; the number and size distribution of the detected particles were recorded and evaluated under different conditions (Figure 6). The difference in the distance from the sampling point to the main sources of particles resulted in different results. The morphology and elemental composition of the collected particles were also studied. Different realistic operating conditions were taken into account, such as train acceleration, train deceleration or train movement through a curve. This type of research could pave the way for the development of significantly simpler and cheaper sensors that can be mass-produced and used in a wide range of applications, e.g. where there are potential operational disruptions (e.g. due to faulty braking systems), thereby reducing particulate emissions to an absolute minimum.

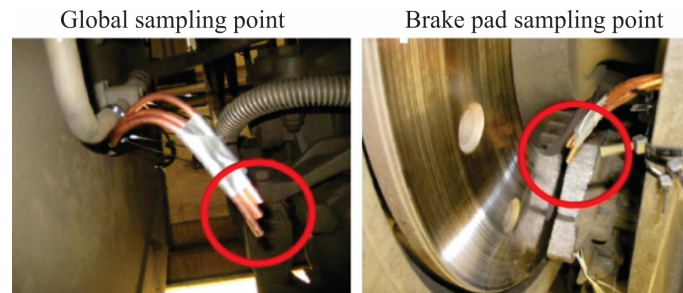


Figure 6: Particle measurement devices, along with connecting tubes arrangement [3]

To study the emission of wear particles from subway trains, it is necessary to measure both the particle concentration and the air flow. A common method for this is to use a tunnel because the tunnel design provides a given volume and cross-section that facilitate air flow estimates (Figure 7). The particle concentration is usually measured at the tunnel exit with a sampling frequency of the order of 1 Hz, together with two-dimensional wind flow measurements. Two pairs of diode laser/photodetectors placed on the side of the track can be used to measure the speed and length of the test trains. To assess the emission from individual trains, the particles emitted in the tunnel must be ventilated between each train passage, and therefore it is necessary to choose a tunnel where the train frequency is low, from only one to a few trains per hour. The tunnel is ventilated by both the flow caused by passing trains and the ambient wind, but choosing a tunnel whose length is the same as the length of the train facilitates wind-induced ventilation. The small cross-sectional area facilitates train-induced ventilation, but probably limits wind-induced ventilation. The use of a stationary particle measurement method allows for the estimation of the emission coefficient at the tunnel exit, where there is a well-defined measurement volume, and allows for the comparison of emission levels between passenger and freight train types [8].

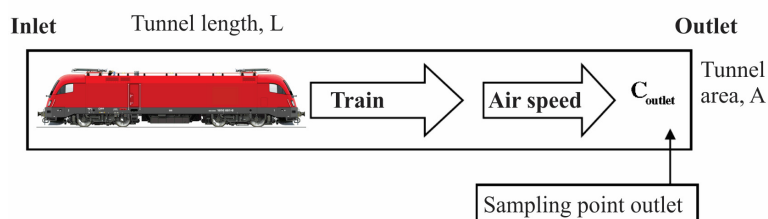


Figure 7: Tunnel measurements of particle emissions [8]

A tribological test in the laboratory can be carried out on an inertial dynamometer type test bench to simulate the braking performance of a high-speed train and to examine the influence of the residual height of the friction block on the vibration and noise characteristics caused by friction [7]. A customized test bench for simulating the braking performance of a high-speed train is shown in Figure 8. Test bench of this type are often also made in a reduced scale of 1:2 to simulate the friction, load and speed ratios of a real braking system. This test device can be used to test the friction of brakes under different conditions and operating modes (traction braking, emergency braking, etc.), as well as to simulate the tribological behavior and particle emissions of the braking system. The samples of discs and blocks used in this study must be reduced to an appropriate scale.

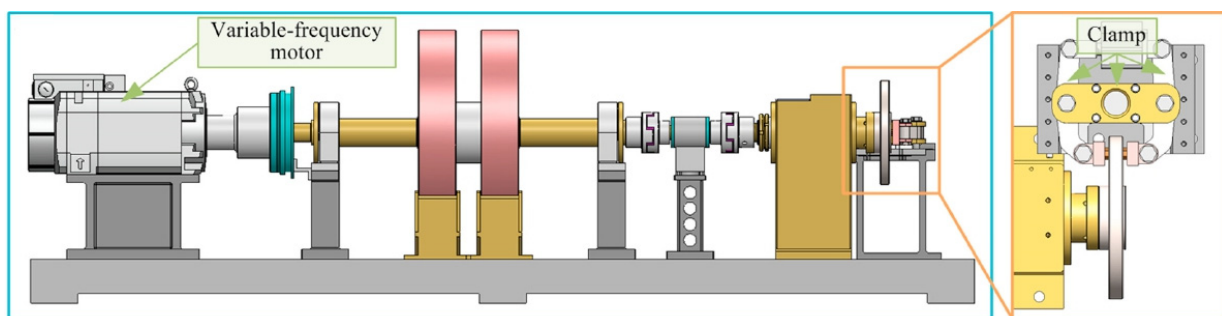


Figure 8: The test device to analyze high-speed train braking performance: control console schematic diagram of test device [7]

The newly built test bench for railway brakes (Figure 9) was put into operation in 2023 at the Graz University of Technology. This test bench allows the testing of disc brake systems as well as tread brakes (block brakes). The kinetic energy of the vehicle is simulated using an electric mass simulation. The drive motor accelerates the drive train of the test bench to any speed in the range from 0 to 3,000 rpm. This also allows the testing of brakes on high-speed trains, which operate at a maximum speed of 500 km/h [15, 16, 17].

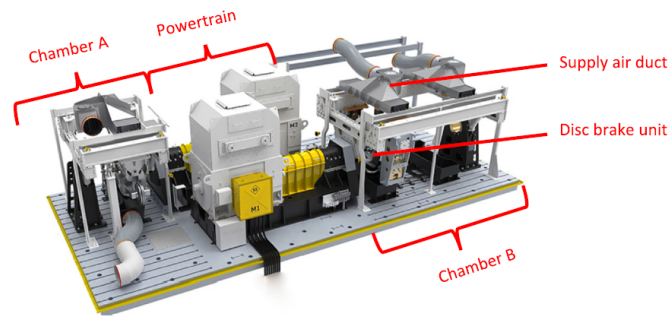


Figure 9: Scheme of the brake test bench at Graz University of Technology [15, 16]

4. DESIGN OF EXPERIMENTS

Two approaches are used for particle characterization: a particle collection approach for off-line analysis and an instantaneous measurement approach with on-line particle size distribution measurement.

The aim of future research is to analyze the influence of railway braking conditions, such as contact pressure and disc temperature, in particular with regard to the range of emitted particles, their shape and composition. Knowledge of the nature of these particles (size, shape and composition) and their emission in real time is necessary for the development of numerical fluid models that can correctly predict their propagation near the zone of their generation. An important aspect of the research is the selection of friction conditions that give lower particle emission for a given dissipated kinetic energy and the given rules for the particle injection properties in the CFD model to study their propagation in a confined space, such as a metro station. The assessment of the influence of these parameters on the nature of emitted PM particles will be carried out on a different railway braking materials, varying one parameter at a time, while maintaining the equivalent dissipated energy.

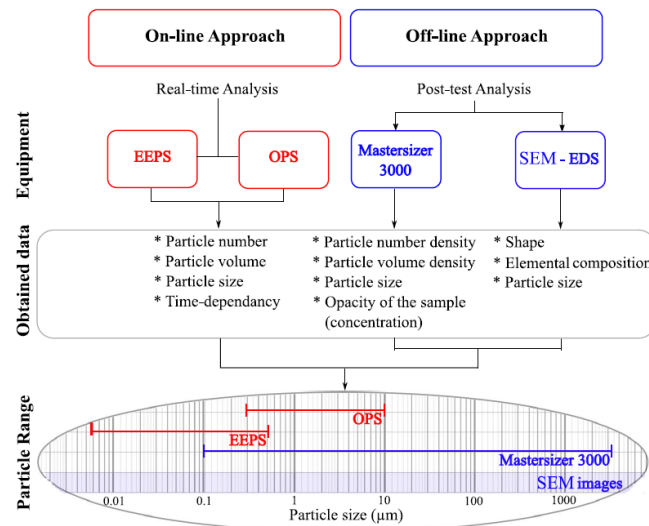


Figure 10: Description of the experimental approach [18]

4.1. On-Line Measurements of Particle Emissions

It is important to recognize that this type of experiment only provides qualitative insight into how sliding speed and contact pressure can affect wear, friction, and airborne particle emissions. The quantitative results cannot be translated into real-world scenarios, as factors such as the detection range and calibration of particle sampling instruments and the difference in contact area compared to actual disc brakes affected these results. In addition, many studies have found that the brake temperature has a significant effect on the generation of brake wear particles. Therefore, many experimental setups include thermocouples or infrared cameras to record the temperature at the contact surface [5].

The advantage of inertial brake dynamometers is that the device tests real brakes that are also used on road vehicles under controlled conditions. Such tests belong to the group of tests that are closest to the actual braking process on a vehicle. An inertial brake dynamometer (BrakeDyno 2020) was developed at the Faculty of Engineering of the University of Kragujevac. In order to simulate the kinetic energy of one quarter of the vehicle, an inertial mass is applied, which is driven by an electric motor, and at the end of the shaft is the rotor itself, i.e. disc brakes. Changing the number of revolutions of the flywheel enables the selection of the value of the kinetic energy, thus changing the simulated initial braking speed and the load of one quarter of the vehicle. The brake is activated using pneumatic and hydraulic mechanisms. The entire braking process, starting speed, pressure and load of one quarter of the vehicle is controlled

electronically. BrakeDyno 2020 contains a series of sensors that can be used to monitor various output parameters (brake pad temperature, braking torque, braking time, ...). Bearing in mind that the inertial dynamometer has been developed so that adaptations can be made for various measurements and research, Figure 11 shows the appearance of BrakeDyno 2020, which has been modified in order to measure the concentration of particles that result from the wear of friction pairs of brakes.

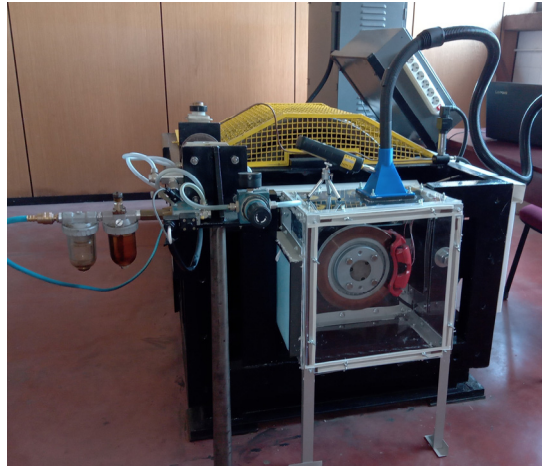


Figure 11: BrakeDyno 2020 in the process of adaptation for particle measurement

The directly measured variables are: angular velocity of the disc, number of revolutions of the disc, braking time, brake pressure, i.e. pressure in the brake installation, both in the hydraulic and pneumatic parts of the brake installation, braking torque, brake pad temperature, ambient temperature, air humidity, PM_{2.5} and PM₁₀ particle concentrations.

The variables determined by recalculation are: simulated vehicle speed, kinetic energy, deceleration, coefficient of friction between friction pairs. Such research, which would require modification of the test bench for railway vehicle brakes, could:

- Identify the factors influencing the concentration of particles generated by the wear of brake friction pairs;
- Determine whether factors (parameters) can differently affect the concentration of particles by changing their intensity, depending on the brake pad used;
- Identify whether the applied brake pads also have an impact on the concentration of particles in terms of their composition and design characteristics;
- Analyze the influence of individual factors on the resulting concentration of PM₁₀ and PM_{2.5} particles individually;
- Determine the influence of individual factors on the relationship between the concentrations of PM₁₀ and PM_{2.5} particles individually.

4.2. Off-Line Analysis of Particles

In the post-test characterization approach, collection experiments are conducted to further characterize the generated particles and compare different size analysis methods. These results provide information about the nature and shape of the large particles.

5. CONCLUSIONS

As we have not yet reached definitive conclusions regarding the toxicity of railway brake wear particles, it is essential to pursue a preventive approach aimed at reducing particle emissions. This is particularly important given evidence from previous research suggesting that brake wear particle components, such as iron, can induce oxidative stress in cells. As trains continue to rely on mechanical brakes without the widespread adoption of alternative technologies such as inductive braking, it is crucial to develop strategies to reduce particle emissions. These efforts are essential to minimize potential adverse health and environmental impacts.

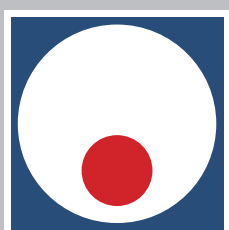
A test that provides results similar to real conditions is the use of an inertial brake dynamometer, where the same friction elements as those on a real vehicle are used. Since the measurement is performed in laboratory conditions, it is much easier to isolate the emissions resulting from brake wear. The inertial brake dynamometer is usually modified by installing a housing in which the brake assembly is located. In laboratory conditions, it is much easier to set and control the braking factors, but also to identify other parameters that have an impact on the resulting particle emissions, such as the temperature between the friction pairs, relative humidity, ambient temperature, etc.

ACKNOWLEDGEMENTS

Paper is financially supported by The Ministry of Science, Technological Development and Innovation of the Republic of Serbia, Contract No. 451-03-65/2024-03/200107.

REFERENCES

- [1] Pravilnik o kočnicama i kočenju vozova i vozila, ("Sl. glasnik RS", br. 68/2021)
- [2] S. Abbasi, J. Wahlström, L. Olander, et al. "A study of airborne wear particles generated from organic railway brake pads and brake discs", *Wear*, Vol. 273(1), pp. 93-99, <https://doi.org/10.1016/j.wear.2011.04.013>, (2011)
- [3] S. Abbasi, L. Olander, C. Larsson, U. Olofsson, A. Jansson, U. Sellgren, "A field test study of airborne wear particles from a running regional train", *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, Vol. 226(1), pp.95-109, <https://doi.org/10.1177/0954409711408774>, (2012)
- [4] S. Abbasi, A. Jansson, U. Sellgren & U. Olofsson, "Particle Emissions From Rail Traffic: A Literature Review", *Critical Reviews in Environmental Science and Technology*, Vol. 43(23), pp. 2511–2544, <https://doi.org/10.1080/10643389.2012.685348>, (2013)
- [5] L. Tanzeglock, "Particle Emissions of Train Brakes", Master Thesis, Division of Production and Materials Engineering, Lund University, Lund (Sweden), (2024)
- [6] Y. Lyu, L. Tanzeglock, Q. Zhang et al. "Friction, wear and particle emissions from copper-based train brakes", *Proceedings 22st Nordic Seminar on Railway Technology*, KTH Royal Institute of Technology, Stockholm (Sweden), 18-19 June 2024, (2024)
- [7] Z.Y. Xiang, J.K. Zhang, S.L. Xie, et al. "Friction-induced vibration and noise characteristics, and interface tribological behavior during high-speed train braking: The effect of the residual height of the brake pad friction block", *Wear*, Vol. 516–517, pp. 204619, <https://doi.org/10.1016/j.wear.2023.204619>, (2023)
- [8] E. Fridell, A. Björk, M. Ferm, A. Ekberg, "On-Board Measurements of Particulate Matter Emissions from a Passenger Train", *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, Vol. 225(1), pp. 99-106, <https://doi.org/10.1177/09544097JRRT407>, (2011)
- [9] E. Fridell, M. Ferm, A. Ekberg, "Emissions of particulate matters from railways – Emission factors and condition monitoring", *Transportation Research Part D: Transport and Environment*, Vol. 15(4), pp. 240-245, <https://doi.org/10.1016/j.trd.2010.02.006>, (2010)
- [10] Z. Stępień, "Vehicle related non exhaust particle emissions – Euro 7 requirements", *Combustion Engines*. Vol. 199(4), pp.15-29, <https://doi.org/10.19206/CE-190606>, (2024)
- [11] A. T. Juárez-Facio, M. Introna, A. M. Montes, et al. "In vitro toxicity of car and train brake wear emissions using Air-Liquid Interface and submerged exposure models", *Atmospheric Environment: X*, Vol. 29, p. 100426, <https://doi.org/10.1016/j.aeaoa.2026.100426>, (2026)
- [12] Y. Lyu, Q. Zhang, L. Tanzeglock, et al. "Mapping of friction, wear and particle emissions from high-speed train brakes", *Wear*, Vol. 572–573, p. 206027, <https://doi.org/10.1016/j.wear.2025.206027>, (2025)
- [13] Y. Tsybrii, I. Zglobicka, M. Kuciej, et al. "Airborne wear particle emission from train brake friction materials with different contents of steel and copper fibres", *Wear*, Vol. 504–505, p. 204424, <https://doi.org/10.1016/j.wear.2022.204424>, (2022)
- [14] Y. Tsybrii, O. Nosko, I. Zglobicka, M. Kuciej, "Emission and properties of airborne wear particles from train brake friction materials based on novolac phenolic resins and butadiene rubbers", *Wear*, Vol. 546–547, p. 205332, <https://doi.org/10.1016/j.wear.2024.205332>, (2024)
- [15] D. Fruhwirt, P. Sturm, T. Nöst, et al. "PM emissions from railways – Results of tests on a wheel-rail test bench", *Transportation Research Part D: Transport and Environment*, Vol. 122, p. 103858, <https://doi.org/10.1016/j.trd.2023.103858>, (2023)
- [16] D. Fruhwirt, T. Nöst, P. Leonhardt, et al., "Characterization of emissions from axle-mounted rail disc brakes", *Transportation Research Part D: Transport and Environment*, Vol. 130, p. 104181, <https://doi.org/10.1016/j.trd.2024.104181>, (2024)
- [17] D. Fruhwirt, T. Nöst, P. Leonhardt, et al. "Emission characteristics of railway tread brakes", *Atmospheric Environment: X*, Vol. 25, p. 100320, <https://doi.org/10.1016/j.aeaoa.2025.100320>, (2025)
- [18] C. Octau, D. Méresse, M. Watremez, J. Schiffler, M. Lippert, et al. "Characterization of particulate matter emissions in urban train braking - An investigation of braking conditions influence on a reduced-scale device", *Environmental Science and Pollution Research*, Vol. 27(15), pp.18615-18631, <https://doi.org/10.1007/s11356-020-08337-8>, (2020)



**FACULTY OF MECHANICAL AND
CIVIL ENGINEERING IN KRALJEVO**
UNIVERSITY OF KRAGUJEVAC
Dositejeva 19, 36000 Kraljevo, Serbia

