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MBSE APPROACH FOR FACILITATING THE APPLICATION OF STANDARDS IN THE VEHICLE DEVELOPMENT PROCESS

Elena Angeleska [1], Vasko Changoski [2], Tashko Rizov[3], Sofija Sidorenko[4]*

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RESEARCH ARTICLE

ABSTRACT: The development of complex vehicle systems that integrate latest trends and user needs with regulations, standards, and engineering requirements needs to rely on a strong multi-disciplinary collaboration between experts who exchange information from all relevant fields included in the vehicle development process. Constantly following, updating and applying the input information from various sources when working on vehicle systems can be a daunting task. The Model-Based Systems Engineering (MBSE) approach can provide a strategy for easier coping with the complexity of vehicle systems. This is extremely beneficial since it helps to create an information base where the information is represented in an integrated and consistent system model rather than in isolated documents. This paper presents a concept of an information platform based on MBSE. The goal of the platform is to become an engineering tool for incorporating all relevant data (requirements, standards, regulations) in a manner that they can be directly linked to the adequate system components, simple to interpret and be used by all members of the development team. The purpose of this platform is to: (1) facilitate the development process and interdisciplinary collaboration; (2) help to follow regulations correctly and avoid mistakes; and (3) keep all project data systematized.

KEY WORDS: *Vehicle Design, Platform, MBSE, Regulations*

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MBSE PRISTUP ZA OLAKŠANU PRIMENU STANDARDA U PROCESU RAZVOJA VOZILA

REZIME: Razvoj složenih sistema vozila koji integrišu najnovije trendove i potrebe korisnika sa propisima, standardima i inženjerskim zahtevima treba da se oslanja na jaku multidisciplinarnu saradnju između stručnjaka koji razmenjuju informacije iz svih relevantnih oblasti uključenih u proces razvoja vozila. Stalno praćenje, ažuriranje i primena ulaznih informacija iz različitih izvora prilikom rada na sistemima vozila može biti složen zadatak. Pristup inženjeringa sistema zasnovanog na modelu (MBSE) može da obezbedi strategiju za lakše suočavanje sa složenošću sistema vozila. Ovo je izuzetno korisno, jer pomaže u stvaranju informacione platforme u kojoj su informacije predstavljene u integrisanom i konzistentnom modelu sistema, a ne u izolovanim dokumentima. Ovaj rad predstavlja koncept informacione platforme zasnovane na MBSE. Cilj platforme je da postane inženjerski alat za primenu svih relevantnih podataka (zahteva, standarda, propisa) na način da se mogu direktno povezati sa adekvatnim komponentama sistema, jednostavni za interpretaciju i koristiti ih svi članovi razvoja. tim. Svrha ove platforme je da: (1) olakša proces razvoja i interdisciplinarnu saradnju; (2) pomogne u pravilnom poštovanju propisa i izbegavanju grešaka; i (3) sve podatke o projektu čuva sistematizovano.

KLJUČNE REČI: *projektovanje vozila, platforma, MBSE, regulativa*

MBSE APPROACH FOR FACILITATING THE APPLICATION OF STANDARDS IN THE VEHICLE DEVELOPMENT PROCESS

Elena Angeleska, Vasko Changoski, Tashko Rizov, Sofija Sidorenko

INTRODUCTION

Today's vehicles are complex systems consisted of not only the essential mechanical components, but also an increasing amount of electrical, electronic and software components, as well as features based on latest technological advancements, aiming to be more safe, smart, convenient, reliable, and environmentally-friendly. Vehicle developers are aiming to offer all these qualities in new vehicle models to respond to the ever-changing user needs and gain market advantage. Moreover, to achieve those goals, companies have also been moving the emphasis from just engineering, technology and manufacture aspects, to an understanding of how the products are perceived by users and how they interact with them to provide user-centered design solutions which are likely to be safer and more desirable [1]. As author Tumminelli states, todays vehicles represent much more than means of transport, they are link between people and places, they reflect current trends, they define the appearance of urban environments and the way of life [2].

However, the freedom of following human-centric principles, new technologies and trends is extremely limited and must be handled carefully because in the same time vehicle manufacturers are under the increasing pressure to meet the strict regulatory requirements regarding safety and environment preservation. They are required to follow specific regulations for the design of components, their manufacturing and placement, reuse and recycling, reducing emissions, improving fuel economy and the overall efficiency. This does not only impose limitations in the design and development process, but can be difficult to follow by all team members. All input information strongly influences the design of nearly all vehicle interior and exterior elements and should be considered from the earliest planning stages and be included in all phases of the development process of a new vehicle.

If we take a look at tasks that are part of the vehicle development phases (from product planning and assumptions, to finalizing the main project), it is clear that all of them require a combination of information inputs from a number of disciplines and sources:

•defining the main vehicle characteristics depends on market analysis and characteristics of the customer population (which also includes gathering anthropometric data and transferring customer needs to engineering specifications using methods such as the quality function deployment tool, QFD);

- regulations (such as those by The United Nations Economic Commission for Europe, UN/ECE) are followed in the development of all exterior and interior components;
- national road safety regulations are used for defining multiple dimensions, masses, performances and characteristics of the vehicles;
- standards (such as SAE J-standards by the International Society of Automotive Engineers) help to safely position the occupants, define their envelopes, reach zones and filed of view;
- directives (such as the directive 2000/53/EC on end-of-life-vehicles [3]) dictate the material choice for all components, etc.

The new vehicle development process, all its main phases and tasks are shown on the block diagram below (Figure 1). The diagram is generated based on literature review from authors Bhise, Macey and Wardle, and Danev [4], [5], [6] and shows how the requirements (input information from different fields) guide all the development tasks in all phases.

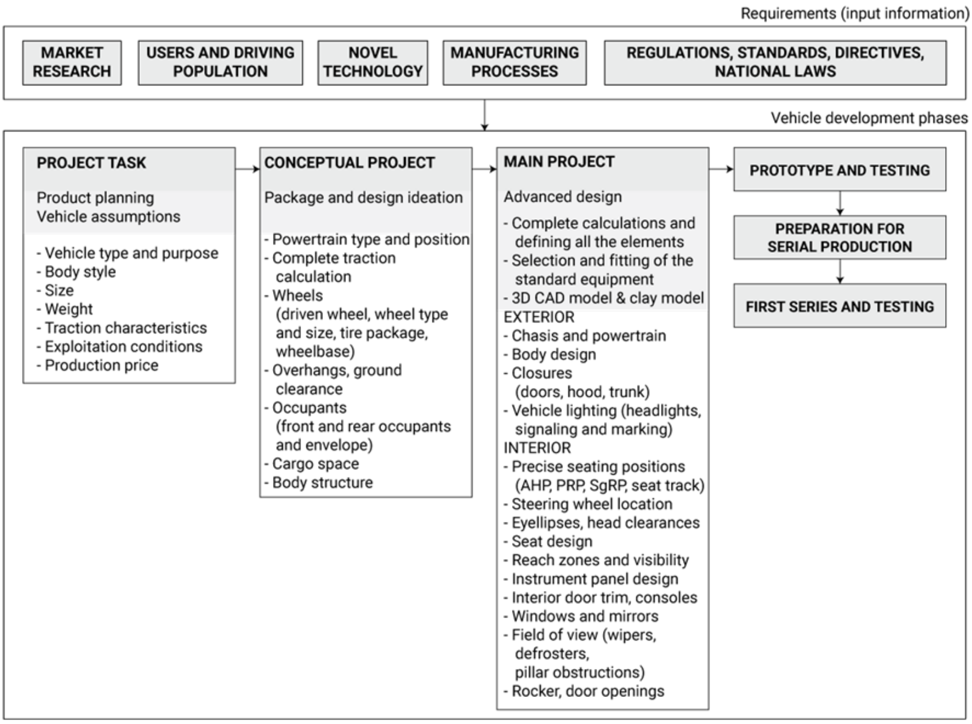

Figure 1. Vehicle development process – phases, tasks, and input information (requirements)

The diagram is a simple representation of how the vehicle design and development process is a daunting task which includes the use of a wide range of multi-disciplinary information and is under the influence of strict regulations. Therefore, there is a need for an assisting tool to support the development tasks. In this paper, such a tool is proposed in the form of a concept for an information management platform based on Model-Based Systems Engineering methods which were applied to offer a solution for systematizing the information, facilitating their use and reducing the risk of making mistakes.

1. REQUIREMENTS IN THE VEHICLE DEVELOPMENT PROCESS

As elaborated in the introduction, there are multiple sources of information that are included in the vehicle development process. The most crucial task is to gather all detailed requirements to be met in order to obtain vehicle approval, as well as requirements related to occupant safety and environmental preservation, and include them during the development of all vehicle systems and components.

For example, if we take the vehicle interior as a separate subsystem of the whole vehicle, there are specific regulations which refer to vehicle interiors and the components they are equipped with. The main UN/ECE interior regulations are Regulation No. 21 and No.17.

Regulation No. 21 of the Economic Commission for Europe of the United Nations (UN/ECE) — titled „Uniform provisions concerning the approval of vehicles with regard to their interior fittings“ [7], includes requirements for: placement of parts in the reference zone; parts of the control panel above the level of the panel; design and manufacture of contact control handles, levers, buttons and all other projecting objects; design of projecting parts of the roof; seat energy dissipation in the head impact zone; control of switches and safety devices; etc.

Regulation No. 17 of the Economic Commission for Europe of the United Nations (UN/ECE) — titled „Uniform provisions concerning the approval of vehicles with regard to the seats, their anchorages and any head restraints“ [8], includes requirements for: locking systems, adjustment and displacement systems for seats; design and surface characteristics of the rear parts of the seats; seat frame and seat attachment to prevent failure; installation of head restraints; seat backrest location; etc.

Moreover, special regulations are given for different types of interiors. For example, the regulation for interiors of M2 and M3 category vehicles is Regulation No. 107 of the Economic Commission for Europe of the United Nations (UN/ECE) — titled „Uniform provisions concerning the approval of category M2 or M3 vehicles with regard to their general construction“ [9], among other information, includes rules (with sketches) regarding: determination of unobstructed access to doors; width of passenger seats; permitted intrusion at shoulder height, in lower part of passenger space, above the seat; seat-cushion depth and height; space for feet of seated passengers behind a seat or at a seat facing the gangway; seat spacing; space for seated passengers behind a partition or other rigid structure other than a seat; etc.

In addition, standards for vehicle interiors help generate safe and ergonomic interior solutions. The largest base of vehicle development standards are the J – standards of the International Society of Automotive Engineers, SAE. One segment of these standards provide support for the design of vehicle interiors: SAE J826 defines and measures the H-point (estimate hip point of occupant in a seat) which is the primary reference point for occupant accommodation; SAE J287 defines a method for calculating the reach zones; SAE J941 suggests a method to define the drivers eye locations (eyellipse); SAE J1052 defines the head position contours; etc. [4], [10].

The main regulations and standards that need to be studied before beginning the design of interiors and choosing the components with which they need to be equipped are illustrated on Figure 2. The illustration visually demonstrates how all the components of the subsystem „vehicle interior“ are under the influence of specific rules and how the rules and requirements from different sources overlap in certain aspects.

Each subsystem of the vehicle is under the influence of multiple rules that need to be followed. The rules for vehicle interiors can also contain data concerning some other subsystems of the vehicle and their components (exterior). In addition, documents concerning the exterior subsystem can also have an influence on some aspects of the vehicle interior and its features. For example, the national road safety regulations contain information regarding permitted vehicle dimensions which also need to be considered in the interior development. The vehicle interior is elaborated as an example, but the same applies to all other vehicle subsystems.

Therefore, in order to successfully systematize and manage the information, a precise definition of the vehicle systems, subsystems and elements is needed. This can be done using Systems Engineering techniques (as explained in Chapter 3). By conducting a system analysis, all the input rules and requirements can be assigned to the correct vehicle subsystems on which different teams are working, avoiding possible omitting of important data.:

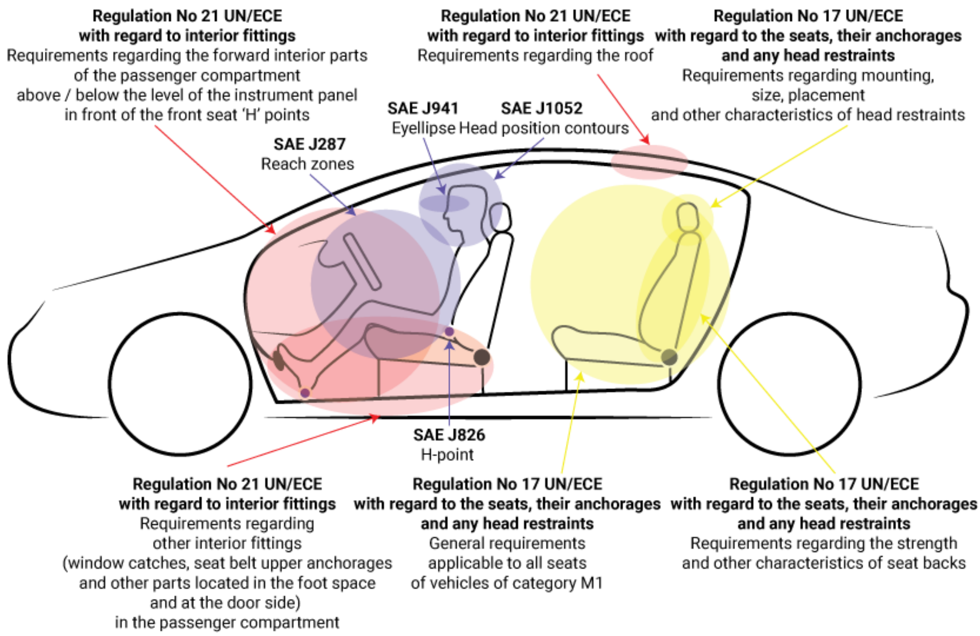

Figure 2. Main regulations and standards followed in the vehicle interior design process

2. VEHICLE SYSTEM ANALYSIS

One product (system) is composed of a set of interrelated components which work together to achieve the main purpose of the product (system). When complex systems are being developed, dividing them into smaller units (subsystems) helps to simplify the process of allocating the requirements and proceed with analysing the systems and defining their functions [11]. This is done by viewing the system as a whole and then breaking it down into components which are studied separately (Systems Engineering). This is also referred to as system modularity – complex systems are divided into modules at different levels which are „tightly coupled within, and loosely connected to the rest of the system“, which are actually complex systems themselves [12].

For the purpose of this study, the product „vehicle“ is analysed as a complex, dynamic system of systems. In order to propose a suitable method for easier monitoring of the defined requirements needed for developing this complex system (through an information management platform), an overview of the main vehicle groups of systems and subsystems was needed. Branching out the main system in order to compose the vehicle system hierarchy is the initial step in generating the model of the system which can be used as a base for systematizing the input requirements (standards, regulations, etc.).

Based on a literature review [5], [13], [14], the main subsystems of the vehicle were identified as: powertrain, wheels and tires, suspension and chassis, body, interior, electrical system, and electronic system. These main subsystems are composed of their own subsystems at different levels, which in the end, contain single elements. Further branching out of the level 1 subsystems was done in order to create a realistic representation of the basic vehicle hierarchy. This was done without great detailing due to the conceptual nature of the information management platform which is proposed in this paper. The identified subsystems and levels 2, 3 and 4 of the subsystems at level 1 are illustrated on the block diagram below (Figure 3).

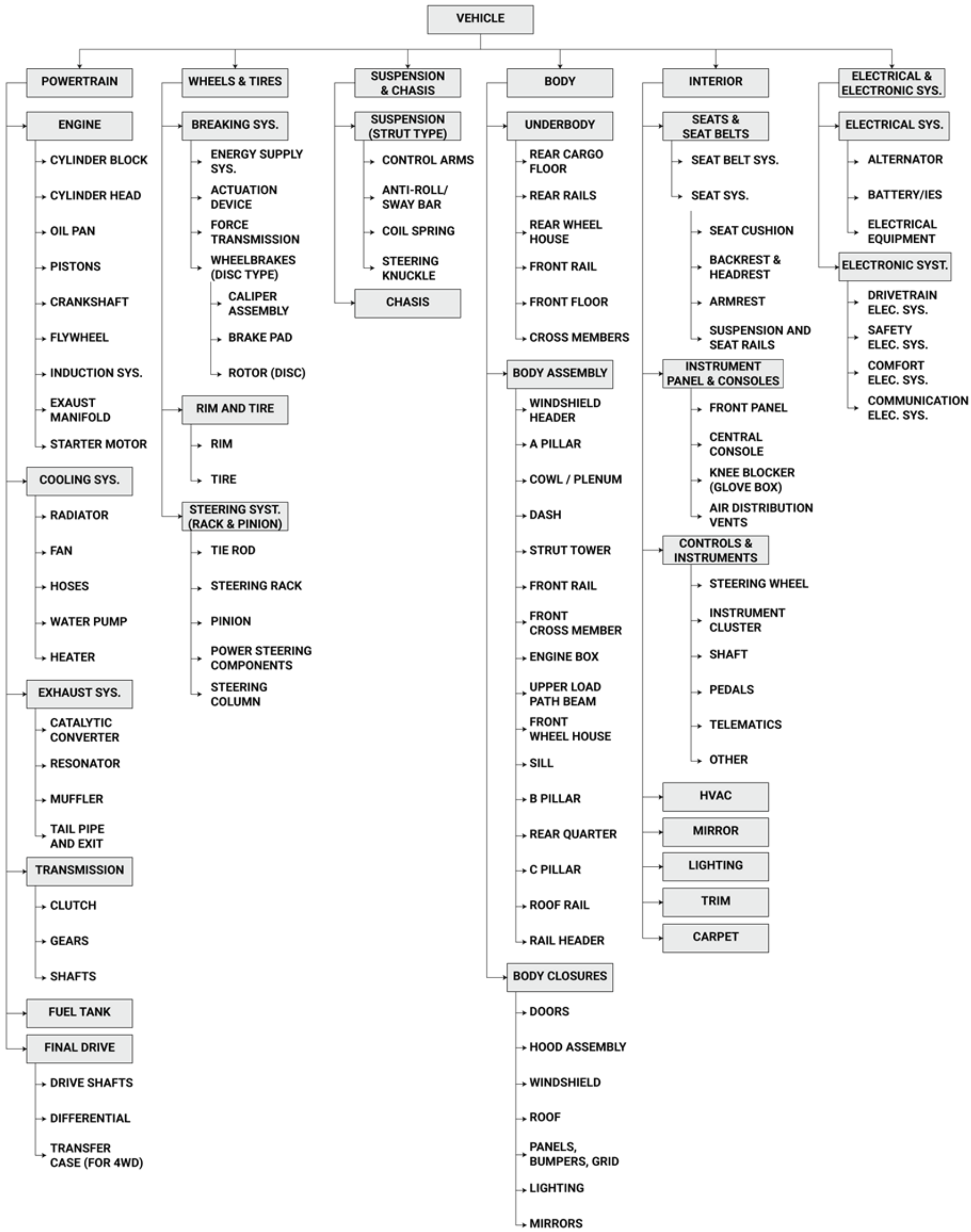

Figure 3. Basic hierarchy of the vehicle system

3. INFORMATION MANAGEMENT PLATFORM (MBSE APPROACH)

Model-Based Systems Engineering is a suitable approach for dealing with the challenges of modular systems (system of systems). The benefit of using Model-Based Systems Engineering models is the integrated representation of the information in four main domains of the consistent system model: requirements, behaviour, architecture, validation, which is a better solution than representing the information in separate documents [15], [16]. Such models are used for interdisciplinary product development [17], and to achieve product standardization, such as modular, platform or type series design [15]. System modelling languages (such as SysML) are commonly used to aid the creation of model-based representation of systems. Typically, models are generated by: firstly, constructing a product functional decomposition (functional model represented by functional flow block diagrams) where the goals are expressed as system functions; secondly, the functional model leads to a creation of a logical system hierarchy that defines the concept solution; then, the internal functional and logical architecture is described; and finally, relationships (allocations) are established which serve the purpose to link requirements with the functional and logical architecture [17]. Commercial software for vehicle system design based on these principles are available as product lifestyle management (PLM) cloud-based tools helping to manage requirements, product data and various product processes (for example: https://www.plm.automation.siemens.com/global/en/products/teamcenter). Model-Based Systems Engineering is a crucial part of these tools that commonly use function models (or standardized hierarchical functions) to generate functional design solutions [18].

However, the described approach requires an in-depth understanding of all systems and subsystems functions, components that can satisfy those functions, and their allocations and behaviours, which is not entirely possible at the early, preparation stages. It is often difficult to translate the given requirements into specific functions to be achieved.

When new vehicle models are being developed, multiple teams are assigned to work on different subsystems of the vehicle. Those teams are consisted of many members from various fields of expertise – managers, mechanical engineers, electrical engineers, industrial designers, etc. In order to facilitate the development process and avoid mistakes, all team members need to have access to the requirements they ought to use in the concept development of their assigned subsystem. This can be done only by presenting the requirements in an understandable manner for all members who need to easily review and select the required data.

Here we suggest a concept for an information management platform for easier application of requirements in the vehicle design and development process. The concept is based on Model-Based Systems Engineering methods, but on a more abstract level, suitable to be used as an assisting tool by all members of the research and development team. The requirements (primarily mandatory requirements such as standards, regulations, directives) are saved in a large information database. Each requirement is assigned a name, unique code, link to the document (which can be easily updated when needed) and keywords which describe what the requirement referrers to. The vehicle subsystems at different levels are saved in a different database. Each subsystem is assigned a name, unique code, and a code of its parent (or subsystem at a higher level that it belongs to). The hierarchical representation (which is actually the BOM list of the product) and individual codes and parent codes provide a simplified view of the main system and a possibility for a simple addition of new subsystems at different levels. The connection between the requirements and the subsystems is made using the codes of the requirements and codes of the subsystems. One requirement can be assigned to one or more subsystems, and one subsystem can contain information from one or more requirements. The concept for the information management platform is given on the class diagram on Figure 4.

The idea for the practical application of the platform is illustrated on Figure 5. The user (member from the development team working on an assigned subsystem) reviews the information database where the requirements are stored. After selecting specific data, the user selects the adequate subsystem from the system hierarchy and inputs the selected requirements by defining them as subsystem characteristics (width, length, mass, performance, etc.) and specifications for those characteristics (specific dimensions, distances, weight, energy consumption, etc.). This type of systematized representation of the requirements is stored in a tabular format and made available through the platform to all team members who can review, edit and insert new data. The final step is using the defined specifications for generating the systems morphological matrix where different options for the subsystems which satisfy the defined specifications are explored. Combining the different options results with various subsystem and system concepts.

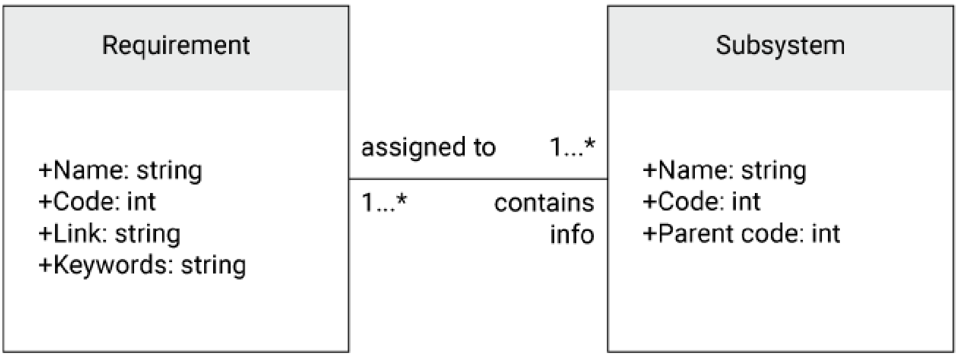

Figure 4. Concept for an information management platform for following and application of requirements in the vehicle development process

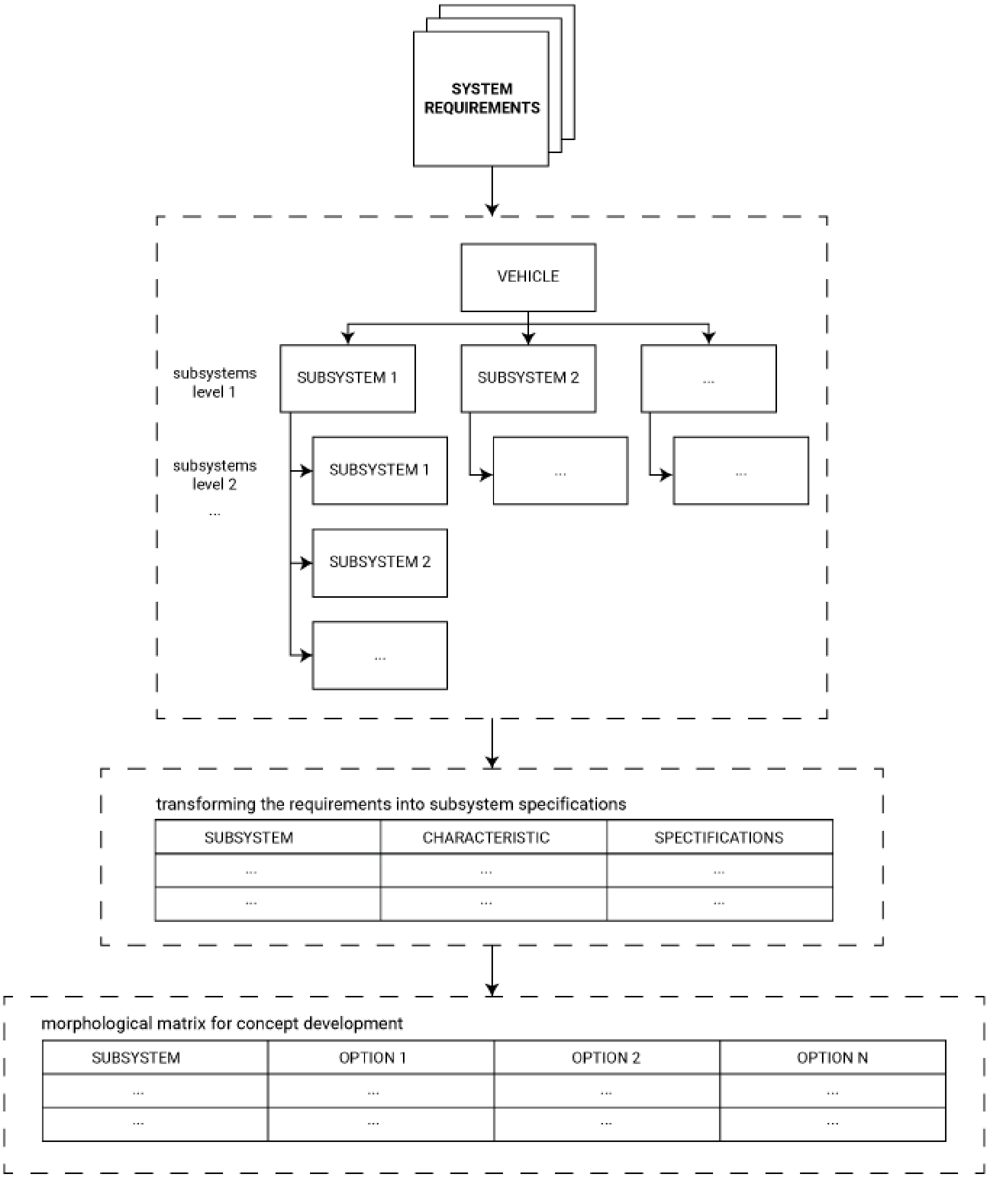

Figure 5. Architecture of the proposed platform – practical use

4. SUMMARY AND FUTURE WORK

Vehicles are complex systems composed of multiple subsystems at different levels which are planned, conceptualized and developed during all of the phases of the vehicle development process, from project planning and working on the conceptual project, to preparing the advanced project and forwarding it for prototyping and testing. It is well known how strict requirements in the form of international and national laws, regulations, standards and directives strongly influence how all those vehicle subsystems and components are designed and constructed. The difficulty of following all the input information, selecting it, combining it and applying it to offer vehicle subsystem solutions that meet the given requirements and are not only suitable to obtain approval, but are also highly safe, ergonomic and environmentally friendly, requires the use of assisting tools for data management. Model-Based Systems Engineering solutions are already being used to represent the system (or product) requirements, functionalities, and logical elements (as well as their relations and connections) in an understandable manner. However, this is usually done at a more advanced level when the requirements can be transferred to specific system functions and technical solutions. What lacks is an assisting tool for systematization of the requirements in an understandable and useable manner which can be used by all team members.

This paper suggests a concept for an information management platform that provides a solution for linking the information from various sources with specific vehicle subsystems and components. This platform is intended to be used at the earliest stages for analyzing and selecting all relevant data that is needed for the development of concepts for specific subsystems – data that helps to properly choose materials, position elements in the interior, choose commercial products that need to be ordered, label components, etc. The benefit of this platform is the possibility to systematize all requirements, update them on a regular basis, avoid omitting important data, and saving all used data for specific projects which can be reviewed by all team members.

However, since the platform is only described at a concept level and illustrated by a class diagram, its practical application cannot be captured at this point. What remains a task for future research is to collaborate with programmers to develop a functional prototype and evaluate it through design case study where a simplified version of one of the vehicles subsystems can be developed. This process will reveal the strengths and weaknesses of the proposed platform and provide directions for further development and improvement.

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SIMULATION OF A PEDESTRIAN COLLISION AVOIDANCE USING THE PEDESTRIAN PROTECTION SYSTEM

Ioana Alexandra Rosu [1]*, *Ioana Diana Buzdugan* [2], *Laurentiu Carabulea* [3], *Csaba Antonya* [4]

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RESEARCH ARTICLE

ABSTRACT: Autonomous vehicles are a growing concern nowadays, therefore the knowledge and expectations regarding pedestrian safety have risen substantially. Additionally, ensuring pedestrian safety has become a crucial requirement for autonomous driving. The current research focuses on the contribution of the Pedestrian Protection System (PPS) in the prevention of pedestrian collision impact. The simulation technology that Simcenter Prescan and Simulink are providing, has been used to develop the virtual traffic scenario which highlights the performance of the main sensors: camera and RADAR (radio detection and ranging). The Simcenter Prescan simulation framework includes realistic vehicle dynamic models and virtual traffic infrastructure along with sensors that were placed in several locations on the vehicle to capture the position of the pedestrian. Three variations of speed were analysed in order to observe where the collision is avoided considering the safety conditions. The results of the considered speed were primarily observed using the visualization output of the sensors from the PPS system. To develop trustful autonomous vehicles, it is fundamental to incorporate efficient pedestrian crash avoidance systems that increase traffic safety.

KEY WORDS: *braking system, Prescan, autonomous vehicle*

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SIMULACIJA IZBEGAVANJA SUDARA PEŠAKA PRIMENOM SISTEMA ZA ZAŠTITU PEŠAKA

REZIME: Autonomna vozila su danas sve veća briga, stoga su znanje i očekivanja u vezi sa bezbednošću pešaka značajno porasla. Pored toga, osiguranje bezbednosti pešaka postalo je ključni zahtev za autonomnu vožnju. Ovo istraživanje se fokusira na doprinos sistema za zaštitu pešaka (PPS) u prevenciji sudara. Tehnologija simulacije koju pružaju Simcenter Prescan i Simulink, korišćena je za razvoj scenarija virtuelnog saobraćaja koji naglašava performanse glavnih senzora: kamere i RADAR (radio detekcija i domet). Simulacioni ram Simcenter Prescan uključuje realne dinamičke modele vozila i virtuelnu saobraćajnu infrastrukturu zajedno sa senzorima koji su postavljeni na nekoliko lokacija na vozilu da bi locirali poziciju pešaka. Analizirane su tri varijacije brzine kako bi se uočilo gde se sudar izbegava s obzirom na uslove bezbednosti. Rezultati analiziranih brzina su prvenstveno posmatrani vizuelnim prikazom podataka senzora iz PPS sistema. Za razvoj pouzdanih autonomnih vozila, od suštinske je važnosti ugraditi efikasne sisteme za izbegavanje sudara pešaka koji povećavaju bezbednost u saobraćaju.

KLJUČNE REČI: *sistem za kočenje, Prescan, autonomna vozila*

SIMULATION OF A PEDESTRIAN COLLISION AVOIDANCE USING THE PEDESTRIAN PROTECTION SYSTEM

Ioana Alexandra Rosu, Ioana Diana Buzdugan, Laurentiu Carabulea, Csaba Antonya

INTRODUCTION

Traffic injuries remain a frequent root of human injuries, deterioration of goods and deaths of millions of people. The large expansion in the numbers of vehicles on the road has leaded to an intensification of research to find solutions regarding traffic congestion, pollution, and road safety. The adoption of automated cars is expected to provide an effective solution to this issue, since they are predicted to reduce the number of such accidents by 80%, by the year 2040 [1]. Regardless of their potential as life-saving vehicles, autonomous cars have yet to step forward into insuring as much as possible the safety of all the participants involved in the traffic system. Autonomous vehicles are in terms of safety accelerating fast. The potential to influence even more this category of intelligent system is of huge interest above all for pedestrian safety improvement. The capacity to accelerate pedestrian safety represents an important effort to prevent road traffic injuries. Pedestrian collision is both predictable and preventable, like other categories of road traffic accidents, and can be avoided using intelligent systems that are incorporated in nowadays vehicles. Ensuring that autonomous vehicles are part of developing a road infrastructure where both driver and pedestrian safety is one of the top priorities and represents a must for researchers and industries.

There are a large variety of systems implemented in autonomous vehicles like: pedestrian protection systems, advanced emergency braking system and many more that can make a significant difference in decreasing the number of lives that are being lost on the world's roads. Therefore, developing pedestrian safety systems requires complex information about pre-crash data, risk estimation and advanced vehicle dynamics control (steering and breaking).

The complex environment requires autonomous vehicles that deals with unpredicted situations in order to reach a high level of safety, especially in the nowadays situations. In order to provide advanced solutions for a major category of situations a large area of complex technology contributes to the performance of the autonomous vehicles from sensors, computer vision systems, vehicle control systems, navigation systems to human interaction setup. Simulation software can assist to overcome the challenges regarding the sensors, vehicle dynamics controls system and scenario creation and also support design and evaluation of different safety systems. One of such simulation software used in this study is Prescan, which is a leading software tool that can be used for designing and evaluating ADAS and IV systems that are based on sensor technologies such as radar, laser, camera, ultrasonic, GPS, and C2C/C2I communications (car to car/car to infrastructure) [2].

In the following sections, we outline our approach on how autonomous vehicles can increase their potential and contribute to a better and safer transportation. The main purpose of this study is to determine the effectiveness of the Pedestrian Protection System at a low, medium, and high speed under the presented testing condition, where the vehicle encounters a pedestrian crossing the street.

1. RESEARCH BACKGROUND

Transportation system has been constrained to improve substantially by many parts like manufacturers and researchers to handle the high numbers of vehicles and deficit of traffic law obedience by both drivers and pedestrians. The research and industry are expanding their struggle to enlarge the safety and automation competence of autonomous vehicle in order to create a secure road infrastructure and avoid road collisions.

There are several advantages of the implementation of autonomous vehicles: efficient usage of the road networks, comfort expansion of the passenger by eliminating the need of the driver to perform driving correlated tasks, opportunities for different categories of people who were not included in the transportation vehicles due to mobility limitations. Increasing the number of autonomous vehicles will influence road disasters, protect a vast category of people, and decrease traffic congestion. Autonomous Vehicles (AVs) are widely anticipated to alleviate road congestion, improve road safety by eliminating human error, and free drivers from the burden of driving, allowing greater productivity and/or time for rest, along with a myriad of other foreseen benefits [3]. There are growing research and development attempts to enhance the safety and automation capability of AVs, prevent traffic accidents and create a better road infrastructure. In particular, reduced traffic congestion and safety assurance are two significant promises of autonomous vehicles [4].

The main stages of vehicle autonomy are called perception, localization, planning and control. Perception represents the stage where autonomous vehicles is collecting meaningful information using sensor data. The relative localization of an AV refers to vehicle referencing its coordinates in relation to the surrounding landmarks, while absolute localization refers to the vehicle referencing its position in relation to a global reference frame (world) [5]. Since the localization and perception of the vehicles help to determine its position, the system will further proceed with the planning of the trajectory. The planning includes more than moving from the initial point to the destination, it contains also the behavior planning which includes how the vehicle reacts to objects and the humans that it may meet along the way. The control of the vehicles refers to the generation of commands using sensor data in order to perform the required maneuvers of the vehicle.

Autonomous vehicles incorporate multiple navigations and sensing technologies (high-definition cameras, LiDAR, GPS), and rely on sophisticated artificial intelligence, as well as high-definition geospatial and street-level data [6]. Sensors represent an important category of elements in the overall autonomous vehicle system, their capabilities and performance determine the contribution to higher or lower safety for the participants in the traffic. The choice of the right sensors represents a challenge that will highly influence all the systems of the vehicle. Since each type of sensor has advantages and disadvantages their choice and combination need to be done carefully.

Cameras can detect both moving and static obstacles within their field of view and provides high-resolution images of the surroundings. These capabilities allow the perception system of the vehicle to identify road signs, traffic lights, road lane markings and barriers in the case of road traffic vehicles and a host of other articles in the case of off-road vehicles [7]. LiDAR or Light Detection and Ranging sensor use light pulse to create a three-dimensional map with the surrounding environment. The output from the LIDAR is the sparse 3D points reflected from the objects, with each point representing an object’s surface location in 3D with respect to the LIDAR [8]. This type of sensors along with the camera is the main core of the perception stage to determine the object position of the existing obstacles along the way.

Radar (radio detection and ranging) sensors transmit high-frequency electromagnetic waves and receive the reflection of that wave to estimate the position and velocity of present objects. The distance to a target is determined using the time delay between the transmitted and a received signal [9]. The Global Navigation Satellite System, also known as Global Positioning System, has a well-defined purpose inside the structure of the autonomous vehicles, providing real-time vehicle localization. GPS can be used for both localization and perception submitting an accurate position of the vehicle [10].

2. VIRTUAL TESTING

When automated vehicles are deployed in the real world, they are subjected to an unforeseeable number of situations. This requires extensive testing during their development to ensure safety, especially with regard to motion planning [11]. Vehicles that have a high level of performance must assure and operate within the limits of safety without affecting the good well-being of the participants in the road traffic. The development of the autonomous vehicle systems relies on the conception of a large range of critical scenarios that can cover a highly possible situation that can occur in real life. Critical scenarios are an important milestone in terms of safety for the automated vehicle system in order to strengthen the design but also to the verification and validation stages. As autonomous vehicle performance has increased in a vast range of scenarios, it is crucial to find events where the systems are likely to drop to cover even the most unfeasible events.

Virtual testing of automated vehicles using simulations is essential during their development. When it comes to the testing of motion planning algorithms, one is mainly interested in challenging, critical scenarios for which it is hard to find a feasible solution. However, these situations are rare under usual traffic conditions, demanding an automatic generation of critical test scenarios [12].

Several systems like ADAS (Advanced Driving-Assistance Systems), AEBS (Advanced Emergency Braking System) system, PPS (Pedestrian Protection) contribute to the high performance of autonomous vehicles in order to ensure safety, comfort and to face the challenges of real unpredictable events. The complexity and uncertainty of the driving environment, and the complexity of the driving task itself, imply that the number of possible scenarios that an Automated Driving Systems (ADS) or Advanced Driving-Assistance Systems (ADAS) may encounter is virtually infinite [13]. Automated Driver Assistance Systems (ADAS) focus on increasing the comfort, support and safety while driving. ADAS performance is relying on the overall system performance, on the driver behaviour and on the driving context. The implementation of ADAS is significantly lowering the number of vehicle crashes. Advanced Emergency Braking System (AEBS) is based on a controller algorithm that detects the object or the pedestrian and checks the well-established distance and warns the driver and activates the braking. The AEBS control algorithm consists of two parts: obstacle detection part and main controller part. In the obstacle detection part, front obstacle information was measured and collected for the main controller's decision [14].

One important system that has huge importance in people’s live and it is of very interest to researchers as well as to industries is the pedestrian protection system which is used mainly for avoiding the collision between the vehicle and a pedestrian. In advance of a certain frontal collision, the pedestrian protection system is activated by the feedback of the sensors which is sending a warning to the driver and changing the behavior of the vehicle.

2.1 Pedestrian Protection System

Pedestrian Protection System is a forward looking, predictive safety system that aims to avoid or reduce the severity of a collision with pedestrians. The joint use of radar and camera sensors allows for automated recognition of the pedestrian and evaluation of the risk or the inevitability of an accident [15]. PPS is based on a combination of sensors, primarily camera and radar which offers a high potential for eliminating fatalities and detecting the pedestrian and its position. The PPS relies on multiple advanced technologies like brake assistance, driver caution and control collision avoidance which are in high demand in the automotive industry and in continuous need of improvement. Therefore, a safe automated vehicle is required to have a robust algorithm whose performance is capable of dealing with all types of events, especially in critical situations. This study presents an approach to increase the knowledge about the weak and strong points of the pedestrian protection system and investigate the response in a critical situation where a pedestrian is crossing the street in an unmarked space.

2.2Simulation architecture

The simulations in this research have been carried out by using Simcenter Prescan and one of Matlab’s modules, Simulink, to design and simulate autonomous vehicles which were exposed in critical safety scenarios and analysed from a safety point of view.

Simcenter Prescan is a software that focuses on solving a large variety of automated vehicles functionality based on real-world traffic scenarios (roads, infrastructure, weather, road signs, pedestrians). Also, it has a substantial number of automated systems that contains sensors along with algorithms for data processing, decision making and control, used to design a more realistic simulation that can be later compared with results from physical experiments.

Simulink is a MATLAB-based graphical programming environment for modelling, simulating, and analysing multidomain dynamical systems. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries. It offers tight integration with the rest of the MATLAB environment and can either drive MATLAB or be scripted from it. Simulink is widely used in automatic control and digital signal processing for multidomain simulation and model-based design [16][17]. Simulink provides methods to design and simulated different automated systems that are integrated in autonomous vehicles and allows the exploration of reusable components from different libraries and algorithm development before moving to hardware experiments.

The development of the simulation using Simcenter Prescan and Simulink has three main stages: pre-processing, calculation and post-processing. The first stage is realized in Simcenter Prescan, where the elements of the visualization were adopted like environment, infrastructure of the traffic scenario, actors or participants to the traffic, trajectories of the vehicles along with parametrization of the selected systems. The second stage is the calculation one the parameters, vehicle system, the systems along with the actors and the associated trajectories, from Simcenter Prescan were translated and calculated in the Simulink using specific blocks. Related with the third stage, the post-processing or visualization of the results, this is done using both Simulink and Simcenter Prescan, in Simulink we can visualize the parameters of specific systems, plot different graphs, and check different algorithm results, in Simcenter Prescan the animation of the driving scenario can be viewed along with different sensors output and warning checks.

2. 3 Scenario construction

The current study presents an automated vehicle which avoids a collision with a pedestrian. The focus is on the effectiveness of the pedestrian protection system (PPS) with the main purpose of assuring the avoidance of collision with the pedestrian and contributing to a highly safe automated system traffic environment.

The scenario presents an Audi A8 which is entering a roundabout, moving forward, and avoiding a pedestrian walking across the street in an unmarked location.

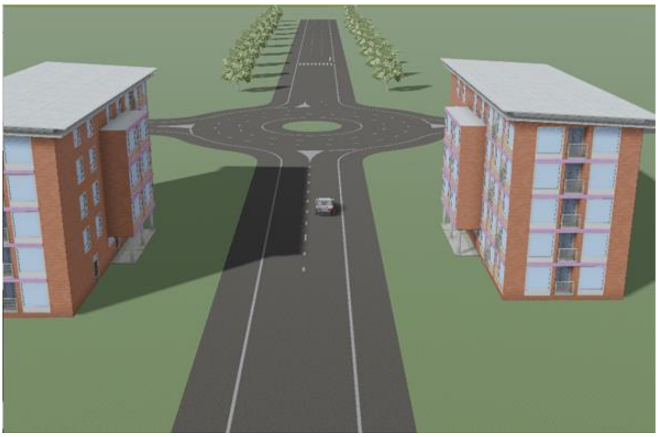

Figure 1. Overview of the driving scenario

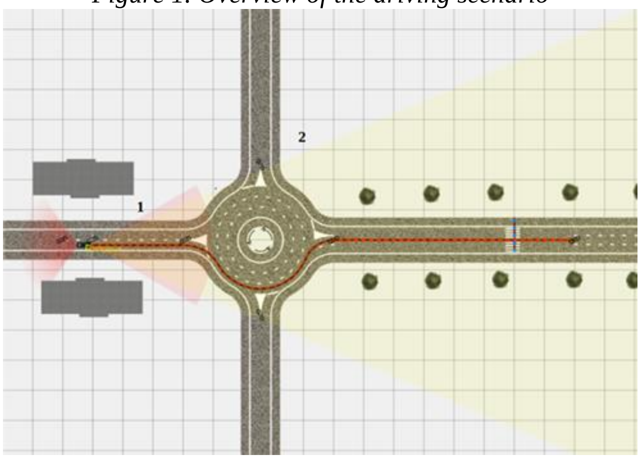

Figure 2. TIS and camera representation of the autonomous vehicle in Prescan

The vehicle has a Technology Independent Sensor (1) or TIS, which is used to increase the performance of the radar (2) sensor at a system level. This sensor has a great impact on the performance of the tracking and tracing algorithms by validating the standard specifications of the active scanning sensors. Together with the TIS is attached a camera on the front part of the vehicle in order to capture the object along the road.

The main system which is required to react in this study to avoid the collision with the upcoming pedestrian is the PPS. The pedestrian protection system uses two essential sensors in order to reduce the severity of the collision or to completely avoid: the camera and a radar. The radar sensors present in the PPS is a mid-range radar (MRR) whose range is 40 m and a beam width of 60 degrees. The data taken from the mid radar sensor is used to regulate the speed between the vehicle and the pedestrian and also used to calculate the velocity of the pedestrian.

The PPS algorithm based on the data received till the moment the object appears in the range of the camera will consider that the vehicle is moving strictly forward to determine the point where the collision will take place. The time to collision (TTC) is used in this situation as a core value to be calculated and the results are compared with the set values. TTC is defined as the time needed for two vehicles to collide if these two vehicles meet. The minimum value of TTC is an indicator for the severity of the encounter and a lower value of TTC indicates a higher risk of collision. If the time of the collision between the vehicle and the object is below 2s the contact is considered dangerous. Certainly, there is a difference between an object and a pedestrian, and therefore the pedestrian detection algorithm relays on the camera sensors in order to determine whether the object is a pedestrian. The warning for the driver is turned on if the TTC drops below 1.6s in case the collision object is identified as a pedestrian. The additional time allows the driver to react to the event and avoid contact with the pedestrian. In case that the TTC is below 0.6 which means that the impact with the pedestrian is considered unavoidable, the full braking is applied to reduce the impact speed. In Prescan an animation representation of the braking light and warning was added in the viewer to represent the PPS work and how the driver will get informed about the emergency braking. Also, the driver has the option of turning the indicator on which automatically deactivates the system.

After the construction of the scenario in Prescan, a Simulink models of the experiment elements are available on the compilation sheet, this includes the dynamics models, automated systems, the vehicle trajectory, chosen standard sensor models, actors, and visualization setup. The PPS block (Figure3) is exposed in the compilation sheet with the overview block from the entire scenario. Along with the overview blocks of the entire scenario in the compilation sheet is the PPS block which is using the data coming from the vehicle (velocity and yaw rate), the TIS sensor (range, derivative of range, angular position of the detected object), the camera sensor (captured monochrome image), the driver (indicator lights on/off, applied braking pressure and throttle percentage).

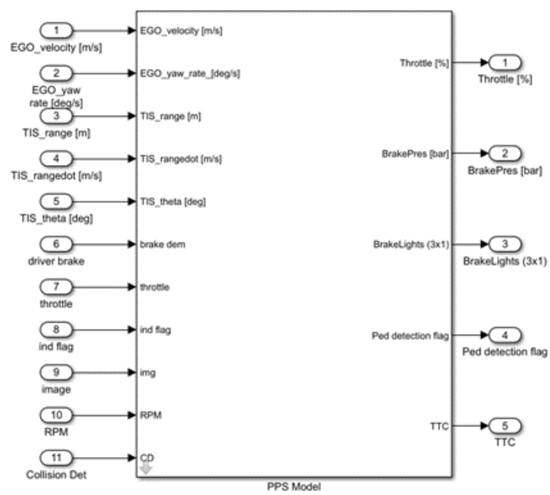

Figure 2. Pedestrian protection system Simulink block.

Regarding the input and the output of the pedestrian protection system block, these are presented in Table 1 and Table 2.

Table 1. Input parameters of the PPS.

Parameter	Description	Unit
EGO_velocity	Host vehicle actual velocity	[m/s]
EGO_yaw_rate	Host vehicle actual yaw rate	[deg/s]
TIS_range	TIS sensor range	[m]
TIS_dopplervelocity	TIS sensor Doppler velocity	[m/s]
TIS_theta	TIS sensor azimuth	[deg]
Driver Brake	Brake pressure. Input from Path Follower (or given directly)	[bar]
Throttle	Throttle percentage. Input from Path Follower	[%]
Ind flag	Binary input activating (1) or deactivating (0) the indicators and, hence, deactivating (1) or activating (0) the PPS	[-]
Image	Output from Camera Sensor Block	[-]
RPM	Engine angular speed (input from Vehicle Dynamics block)	[rpm]
Collision Det	Binary flag indicating a collision between actors	[-]

Table 2. Output parameters of the PPS.

Parameter	Description	Unit
Throttle	Percentage of maximum throttle	[%]
Brake Pres	Brake pressure	[bar]
Brake Lights	Brake Light, that can be connected with Light Source Animation [3x]	[-]
Ped detection flag	Output high level when pedestrian is detected as collidable object	[-]
TTC	Actual time to collision (TTC) of the closest collidable object	[s]

The vehicle which possessing a PPS system is running at different speed (30 km/h, 60km/h, 90km/h) and encounters a pedestrian crossing the road on an unmarked area.

3. RESULTS

The results have been defined using Prescan and Matlab several visualization outputs. The main parameters of the system operation are displayed in the driver console (Figure 4). The TTC value for object detection, TTC value for pedestrian detection, TTC for driver warning, TTC for full braking, the status and speed of the collision (if not avoided) and driving parameters like speed, engine RPM, percentage of braking pressure. Also, it displays the status of the collision, after the full stop of the vehicle the collision avoidance is showing green, meaning that the pedestrian avoidance was successful.

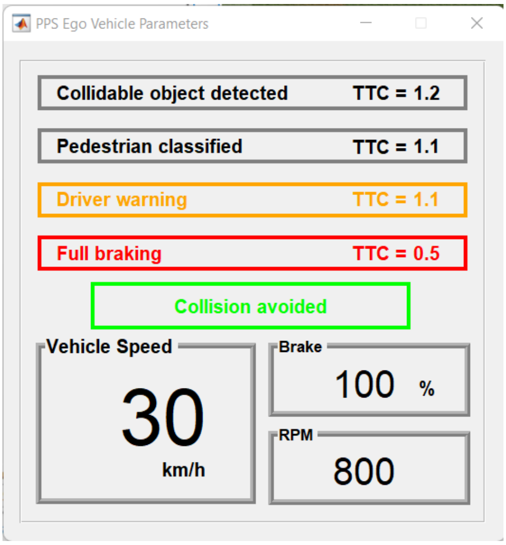

Figure 4. PPS of the driver console.

The radar output graph as part of the PPS is showing the top radar view (Figure 5), which helps identifying the pedestrians along the way. The objects detected by the radar that are highlighted in green are the objects with which a collision is possible but of reduce risk and the ones highlighted in red are the objects of major risk (pedestrian).

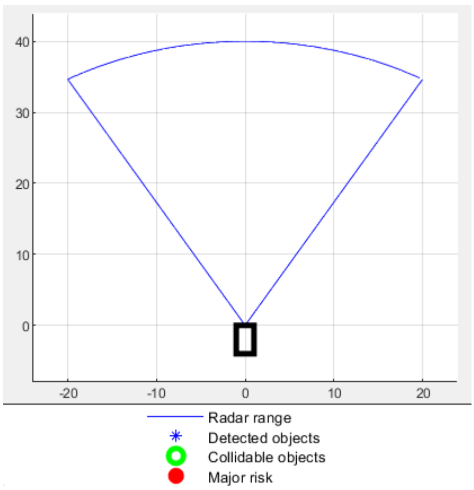

Figure 5. PPS Radar Display.

Another output measurement is the camera (Figure 6), which marks the area around the objects detected by the systems. The camera is making a classification of the processed image, which is used as an input to be decoded by the Pedestrian Classification Algorithm to detect if the object is a pedestrian or not (Figure 7).

At a speed of 30km/h, the vehicle stops, assuring the safety conditions for the pedestrian.

At a speed of 60 km/h, the radar still detects the pedestrian (Figure 8) at all the stages of the object detection using the TTC, the PPS determines that the moving object is a pedestrian and starts decreasing the speed, managing to avoid the collision.

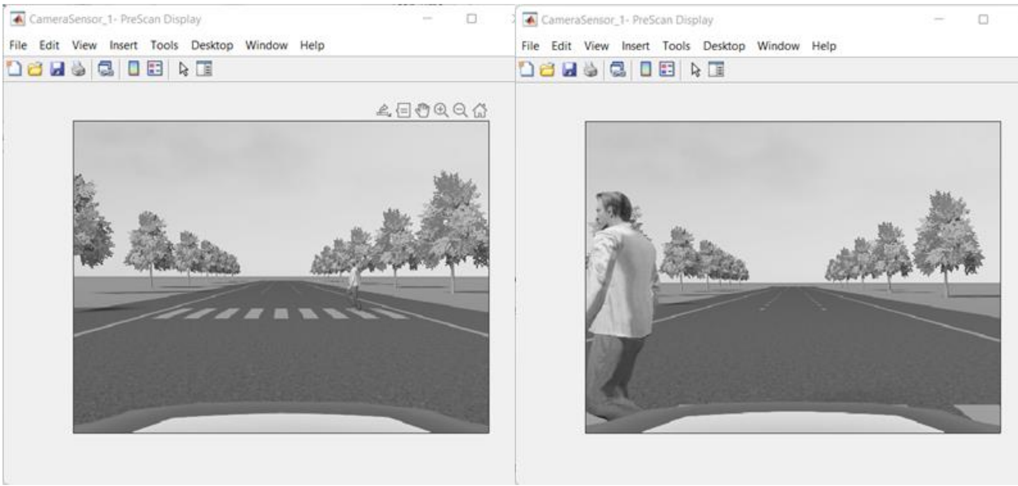

Figure 6. Camera output (video).

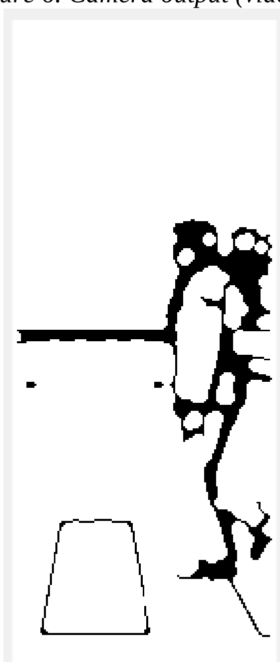

Figure 7. Input to the Pedestrian Classification Algorithm.

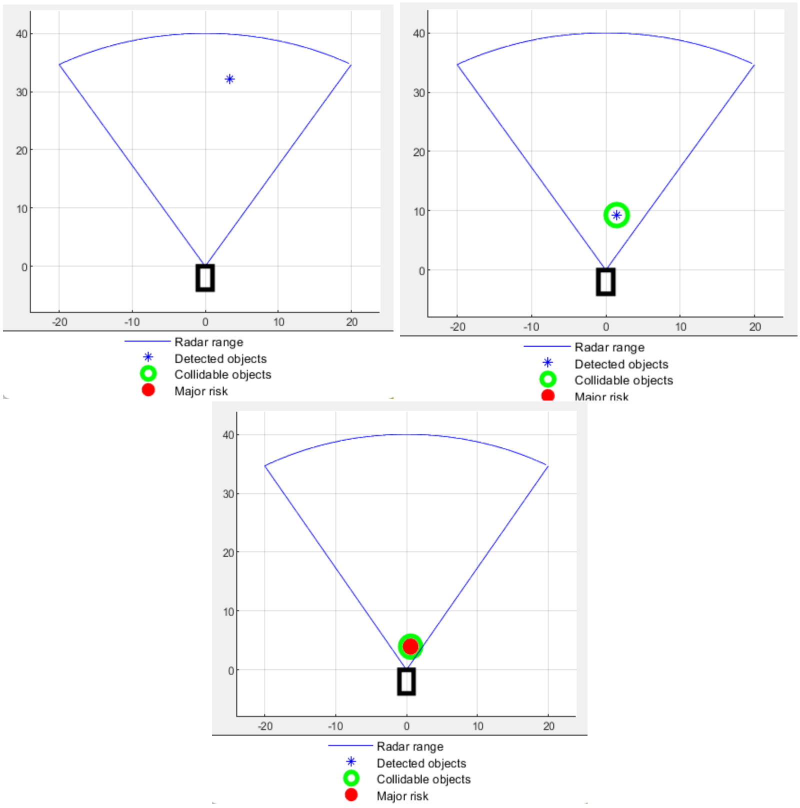

Figure 8. Radar detection of the vehicle with 60 km/h speed.

At a speed of 90 km/h, the radar is detecting the object but it does not classify it as a pedestrian (Figure 9) due to the high speed, the PPS systems does not have time to react and to apply 100 % of the brake, this happens only in a later stage and the collision is not avoided even if the brake is hit, it is too late (Figure 10).

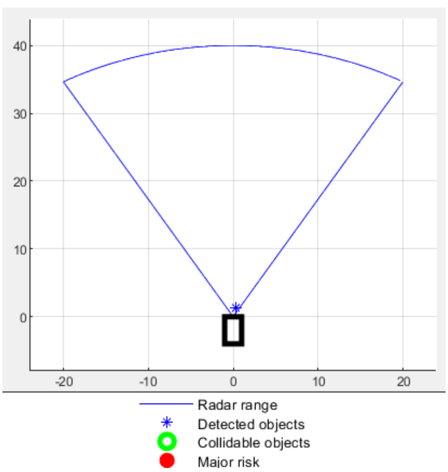

Figure 9. Radar detection of the vehicle with 90 km/h speed.

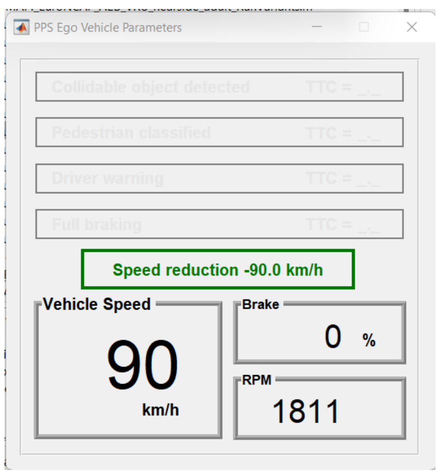

Figure 10. Driver console for a vehicle speed of 90 km/h.

The driver console (Figure 10) is indicating that the speed has been reduced but the collision was not avoided showing that at a higher speed, the PPS system needs to have a TTC with a higher value so that the time in which the vehicle react is larger.

4. CONCLUSIONS

In this paper, a critical scenario is presented where a vehicle runs at various speed (30 km/h, 60 km/h, 90 km/h) and encounters a pedestrian crossing the street. The vehicle is analysing the object and determining if the object is a pedestrian using the Pedestrian Protection System. At 30 km/h and 60 km/h, the vehicle is able to fully stop in safety conditions and assures the avoidance of the collision with the pedestrian proving that the TTC value is properly selected to assuring safety conditions even in unpredictable events like a pedestrian encounter. At 90 km/h, the PPS is not able to determine the classification of the object as a pedestrian in the defined TTC in order to avoid the pedestrian, the vehicle does stop but too late to avoid the collision. This proves that for a higher speed of the vehicle, the PPS needs to enlarge the time of the TTC since the reaction time needs to be bigger when the speed is higher. In further works, we will expand the proposed scenario and observe the PPS system with a more complex driving condition in order to improve the efficiency of the system.

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CONTRIBUTION TO THEORETICAL-EXPERIMENTAL INVESTIGATION OF TRANSVERSE VIBRATIONS OF THE STEERING ROD OF A COMMERCIAL MOTOR VEHICLE

*Miroslav Demić [1]**

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RESEARCH ARTICLE

ABSTRACT: During exploitation, commercial motor vehicles are exposed to vibrational loads that lead to fatigue of the users and materials of their components. Therefore, they need to be studied in the earliest design phase, using mathematical models, experiments, or their combinations. In theoretical considerations, vibrations of concentrated masses are usually observed, although recently, with the development of numerical methods (especially finite element methods), attention is also paid to the vibrations of elastic systems of these vehicles. In such cases, simplifications are usually made, especially regarding exploitation conditions and the interrelationships of vehicle components. This paper attempts to develop a method for identifying vibrational loads on the steering rod under exploitation conditions, using a two-parameter frequency analysis with the use of 2D Fourier transform. The applicability of the procedure is illustrated on an idealized model of the steering rod, and the conducted research has shown that the two-parameter frequency analysis can also be used to generate transverse vibrations of the steering rod in laboratory conditions.

KEY WORDS: *Commercial motor vehicle, steering rod, transverse vibrations, two-parameter frequency analysis*

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PRILOG TEORIJSKO-EKSPERIMENTALNOM ISTRAŽIVANJU POPREČNIH VIBRACIJA SPONE UPRAVLJAČA TERETNOG MOTORNOG VOZILA

REZIME: Teretna motorna vozila su, tokom eksploatacije, izložena vibracijskim opterećenjima koja dovode do zamora korisnika i materijala njihovih agregata. Zbog toga se one moraju izučavati još u najranijoj fazi projektovanja, uz korišćenje matematičkih modela, eksperimenata, ili njihovih kombinacija. U teorisjkim razmatranjima se, obično, posmatraju vibracije koncentrisanih masa, mada se, u poslednje vreme, sa razvojem numeričkih metoda (posebno metode konačnih elemenata), pažnja poklanja i vibracijama elastičnih sistema pomenutih vozila. Tada se, obično, čine idealizacije, naročito u pogledu eksploatacionih uslova i međusobnih veza agregata vozila. U ovom radu je učinjen pokušaj razvoja metode za identifikaciju vibracijskih opterećenja spone upravljača u eksploatacionim uslovima, pri čemu je za dvo-parametarsku frekventnu analizu korišćena 2D Furijeova transformacija. Ilustracija mogućnosti primene postupka je izvršena na idealizovanom modelu spone upravljača, a izvršena istraživanja su pokazala da se dvo-parametarska frekventna analiza može koristiti i pri generisanju poprečnih vibracija spone upravljača u laboratorijskim uslovima.

KLJUČNE REČI: *Teretno motorno vozilo, spona upravljača, poprečne vibracije, dvo-parametarska frekventna analiza*

CONTRIBUTION TO THEORETICAL-EXPERIMENTAL INVESTIGATION OF TRANSVERSE VIBRATIONS OF THE STEERING ROD OF A COMMERCIAL MOTOR VEHICLE

Miroslav Demić

INTRODUCTION

During exploitation, commercial motor vehicles are exposed to vibrational loads that lead to fatigue of the users and materials of their components [1,2]. Therefore, they need to be studied in the earliest design phase, using mathematical models, experiments, or their combinations.

In theoretical considerations, vibrations of concentrated masses are usually observed, although recently, with the development of numerical methods (especially finite element methods [3-5]), attention is also paid to the vibrations of elastic systems of vehicles. In such cases, simplifications are usually made, especially regarding exploitation conditions and interrelationships of vehicle components [6]...

The specificity of exploitation conditions for commercial motor vehicles is their random nature [6], which significantly complicates theoretical considerations using models, making experiments practically irreplaceable. Despite significant progress in the development of software for automatic vehicle design and calculation [5], the final judgment on their characteristics is based on experimental research. Therefore, experimental methods remain important today.

When it comes to the steering system of a commercial motor vehicle subject to random excitations that cause random vibrations, the problem of identifying their parameters often arises. In this regard, methods for their identification have been developed, such as modal analysis [7,8]. In laboratory conditions, vibration modes are practically determined. However, a problem arises when real exploitation conditions are necessary to generate transverse vibrations of the steering rod on test benches because the modal analysis does not provide sufficient possibilities for generating signals in the time domain...

As known [9], during the calculation of the steering rod, its distortion verification is often performed. Since there is an axial force in the steering rod of commercial motor vehicles, there is a risk of distortion, so it was considered useful to further study its transverse vibrations in this paper.

In this sense, this paper aims to develop procedures for identifying parameters of transverse vibrations of the steering rod, which will enable their generation in laboratory conditions. One possibility is frequency analysis using Fourier transformation, which allows determining the frequency content of a signal by calculating the spectrum magnitudes and phase angle [10]. By using inverse Fourier transformation, the original time-dependent signal can be generated, which is routinely performed in cases when the signal depends only on time [10].

However, vibrations of elastic systems depend on multiple parameters (dimensions and time) [11-14], which suggests that a multi-parameter Fourier transform should be used. In the case of an idealized model of the steering rod, which is modeled as an elastic beam, transverse vibrations change along its length and depend on time, so-called two-parameter Fourier transformation (2D) must be applied [14]

This paper will analyze the possibilities of applying the two-parameter Fourier transform to create conditions for investigating transverse vibrations of the steering rod in laboratory conditions.

Therefore, the general expression for the Fourier transformation in the case of multiple variables [14] is given:

$$F(\xi_1, \xi_2, \ldots, \xi_n) = \int_{R^n} e - 2\pi i\left(x_1\zeta_1 + x_2\zeta_2 + \ldots + x_n\zeta_2\right) * f\left(x_1, x_2, \ldots, x_n\right) dx_1 dx_2 *** dx_n \quad , \qquad (1)$$

where:

- $f\,(x_1, x_2 \ldots . x_n)$ - a function of n variables,
- $x_1, x_2, \ldots . x_n$ - variables,
- $\xi_1, \xi_2 \ldots \ldots \xi_n$ - circular frequency, and
- $\int_{R^n}$ - multiple integral (for 2D - double, 3D - triple, etc.)

1. METHOD

As already mentioned, this study aims to explore the possibility of applying two-parameter frequency analysis (2D Fourier transform) in identifying the parameters of transverse vibrations of the steering rod of commercial vehicles. In the absence of experimental data on registered transverse vibrations of the rod, the method is illustrated with data obtained from dynamic simulation using its mathematical model. It was considered appropriate to first define in detail the load that the steering rod is subjected during exploitation.

First, the kinematics of the steering system will be defined, Figure 1.

$$\begin{aligned} AB &= l_p \varphi = l_s \beta \\ \varphi &= \frac{\gamma(t)}{i_u} \quad , \\ \beta &= \frac{l_p \gamma(t)}{l_s i_u} \end{aligned} \qquad (2)$$

where:

- $\gamma(t)$ - steering wheel angle,
- l_p - length of the steering arm, and
- l_s - length of the steering rod.

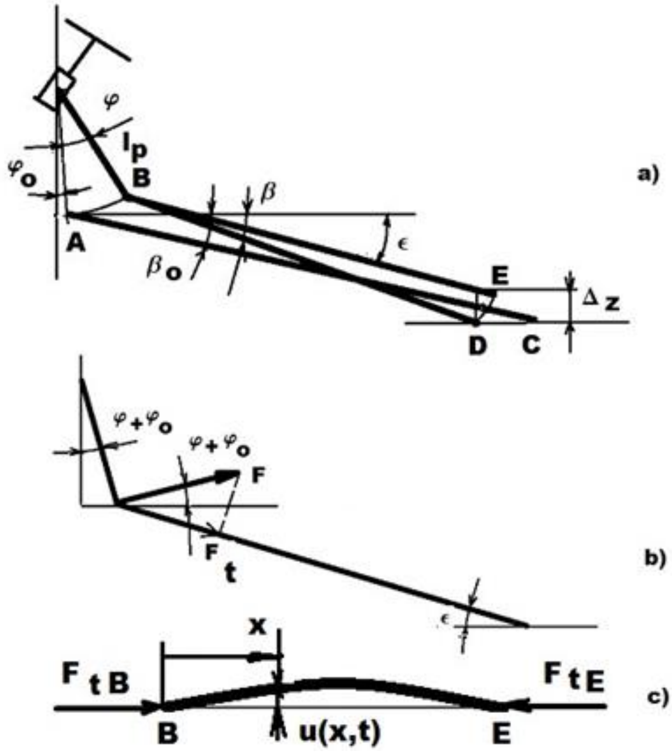

Figure 1. Schematic representation of the kinematics of the steering rod a), force b), and rod transversal vibration model c)

Due to the relative displacement of the joint of spindle arm D, a change of the angle in the vertical plane occurs depending on the sign of (it decreases for positive values and increases for negative values), i.e.:

$$CD = l_s \beta_1 \approx l_s \sin\beta_1 \approx \Delta z$$

$$\beta_1 = \frac{\Delta z}{l_s} \quad , \tag{3}$$

Finally, based on (2) and (3), the angle of the steering rod in the vertical plane can be calculated (assuming that the steering rod joint moves upwards):

$$\varepsilon = \beta_0 + \frac{l_p \gamma_p(t)}{l_s i_u} - \frac{\Delta z}{l_s}, \tag{4}$$

where:

- β_0 - is the angle of the steering rod in the static position of the vehicle.

From Figure 1 b), it can be seen that the axial force of the steering rod represents the projection of the force F to the its direction, i.e.:

$$F_t = F\cos(\varphi_0 + \varphi + \varepsilon), \tag{5}$$

The force F can be expressed in terms of the torque at the steering wheel M, the gear ratio in the steering system i_u, and the steering efficiency η_u :

$$F = \frac{M(t) i_u \eta_u}{l_p}, \tag{6}$$

For further analysis, a simplified model of the steering rod shown in Figure 1 c) is used. When defining a model to describe the transverse vibrations of the steering rod, the following assumptions were made:

- the curvature of the rod is small during transverse vibrations,
- the influence of torsional, and other dynamic loads is neglected,
- the cross-section of the rod is tubular with constant radii along its length,
- the mass of the rod is uniformly distributed along its length,
- the influence of friction and clearances in the rod joints is neglected, and
- the steering rod moves in the vertical plane.

Considering that the partial differential equation that describes the transverse vibrations of an elastic beam, as detailed in [11-13], will not be done here, only the final form will be presented. Based on the introduced assumptions, the forced transverse vibrations of the rod are described by the partial differential equation [11]:

$$\frac{\partial^2 u}{\partial t^2} + \frac{EI_x}{\rho A}\frac{\partial^4 u}{\partial x^4} = F(x,t), \tag{7}$$

where:

- $u = u(x, t)$ - transverse vibrations of the rod,
- x- coordinate along the length of the rod,

F(x, t) - perturbing axial force (excitation function) originating from the driver's action on the steering wheel and the random nature of micro-unevenness of the road,

- t - time,
- I_x - moment of inertia of the cross-section of the rod,
- ρ - material density of the rod,
- E - modulus of elasticity, and
- A - cross-sectional area of the rod.

The area and moment of inertia of the tubular cross-section of the steering linkage are given by the expression:

$$A = \pi\left(R^2 - r^2\right); I_x = \frac{\pi}{4}\left(R^4 - r^4\right), \tag{8}$$

where:

- R - outer radius, and
- r - inner radius of the steering rod.

The magnitudes of forces at the ends of the steering rod were calculated based on experimental data from [15], which were obtained during the free driving of the FAP 1118 vehicle on an asphalt road. The corresponding spectra of the steering wheel angle, steering wheel torque, and vertical relative displacement of the joint of spindle arm are shown in Figures 2-4.

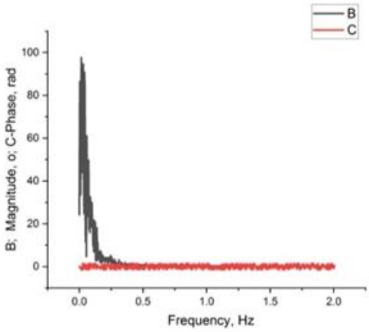

Figure 2. Spectra of the steering wheel angle during free driving on an asphalt road

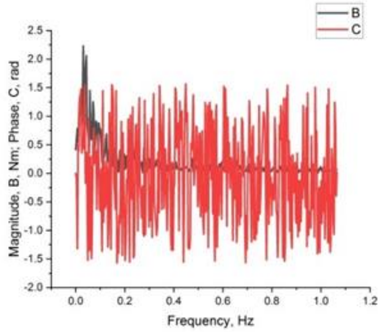

Figure 3. Spectra of the steering wheel torque during free driving on an asphalt road

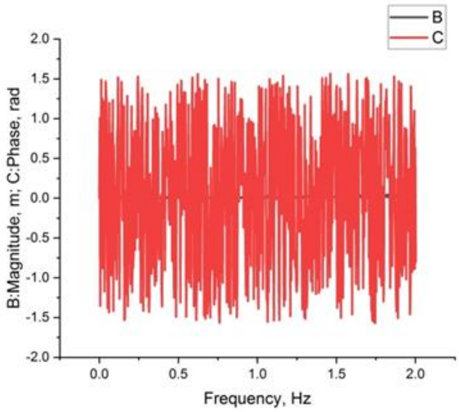

Figure 4. Spectra of the vertical relative displacement of the steering rod joint during free driving on an asphalt road.

The time series of these quantities were calculated using the inverse Fourier transform and are shown in Figure 5. From the displayed figure, it can be seen that the recorded quantities belong to the group of random processes.

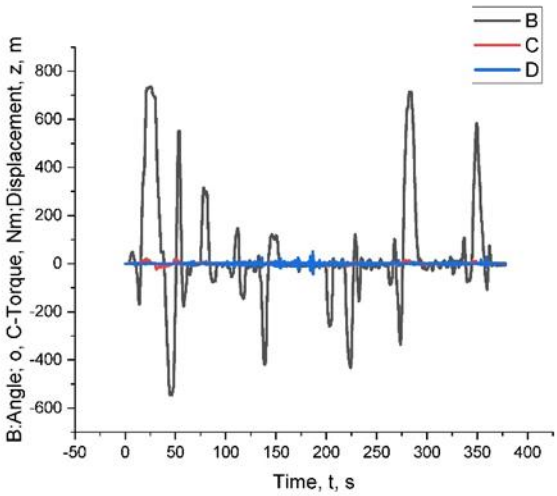

Figure 5. The dependence of the steering wheel angle, steering wheel torque, and relative displacement of the joint of spindle arm, were calculated using the inverse Fourier transformation.

As known [11-14], to find the general integral of the partial differential equation (7), it is necessary to know the boundary and initial conditions. In this specific case, it is assumed that both ends of the steering rod are connected by a spherical bearing [13], so the torques at the ends are equal to zero, and the forces due to vibrations are equal to the applied forces, i.e.:

$$\begin{aligned} & -EI_x \frac{\partial^2 u(0,t)}{\partial t^2} = 0; -EI_x \frac{\partial^2 u(l_s,t)}{\partial t^2} = 0 \\ & EA\frac{\partial u(0,t)}{\partial x} = F_{tB}; \frac{-EA\partial u(l_s,t)}{\partial x} = F_{tE} \end{aligned}, \qquad (9)$$

where:

- F_{tB} and F_{tE} - forces at the ends of the steering rod, which will be discussed later.

For dynamic simulation, it is assumed that the displacements at the spherical joint are zero at the initial moment, i.e.:

$$u(x,0) = 0; u(l_s,0) = 0\,, \qquad (10)$$

It should be noted that in the case of a numerical solution of the partial differential equation (7), sometimes it is necessary to introduce additional initial conditions [14].

Based on equation (5), the disturbance force can be defined as:

$$F(x,t) = F_{tB}(0,t) - F_{tE}(l_s,t), \qquad (11)$$

The integral of the partial differential equation (7), with boundary and initial conditions (9), (10), and disturbance force (11), can only be sought in the case of harmonic excitation [14]. An attempt was made to solve it using the Wolfram Mathematica 13.2 program [14].

However, difficulties arose with listing numerical data and the fact that the mentioned program solves only partial differential equations up to the second order, so it was decided to solve the problem numerically [16], using the finite difference method. Since this procedure is known from [16], it will not be discussed here, and the problem was solved using a developed program in Pascal.

The dynamic simulation was performed for a steel steering rod using the following data:

$E=2.1*10^5$ N/mm^2; $\rho=8*10^{-6}$ kg/mm^3; $R=40$ mm; $r=30$ mm; $n_x=40$; $h_x=40$ mm; $n_t=1000$; $h_t=0.02$ s; $i_u=5$; $\eta_u=0.999$.

Since the transverse vibrations of the steering rod depend on two parameters, 3D graphics need to be applied for their graphical representation.

The integration of the partial differential equation (7) was performed numerically, and the results are shown in Figure 6. From Figure 6, it can be seen that the transverse vibrations of the steering rod depend on the position along the x coordinate and the time of wave motion observation. Considering the random nature of the excitation forces, the transverse vibrations have a random character, which is by [11].

Based on the aforementioned, for frequency analysis, it is necessary to apply 2D Fourier transform. To implement it, the author developed software in Pascal, for 2D Fourier and Inverse Fourier transform. However, considering the available commercial software on the market, it was deemed appropriate to use Origin 8.5 [17] for further analysis, as potential users will have easier access to this software.

Using the mentioned software, the magnitudes and phase angles of the two-parameter Fourier transform were calculated, and the results, for illustration purposes, are shown in Figures 7 and 8.

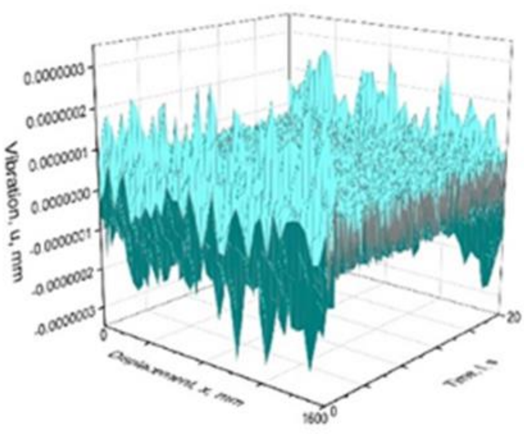

Figure 6. Transverse vibrations of the steering rod

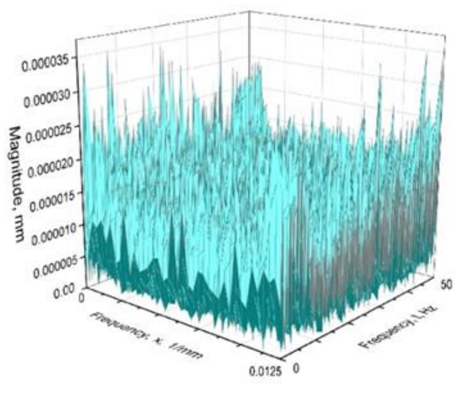

Figure 7. Magnitude spectrum of transverse vibrations of the steering rod

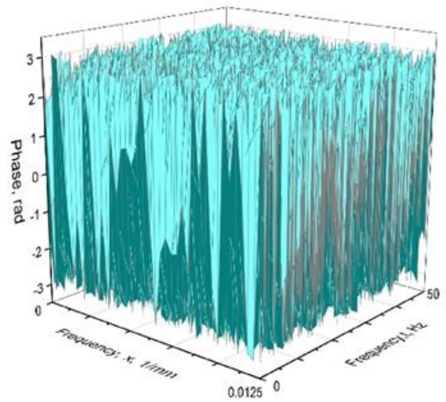

Figure 8. Phase angles of the spectrum of transverse vibrations of the steering rod

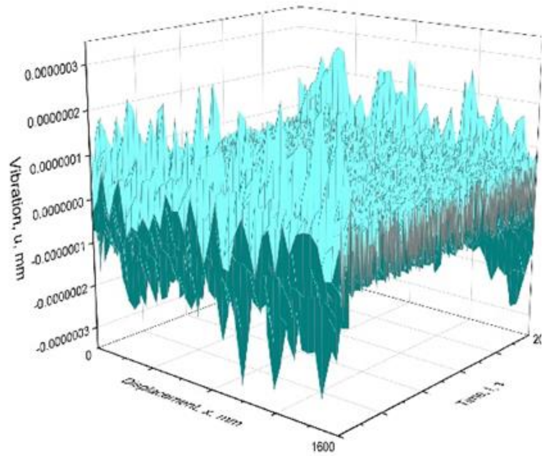

Figure 9. Transverse vibrations of the steering rod obtained by inverse 2D Fourier transformation

2. DATA ANALYSIS

By analyzing the data from Figures 7 and 8, it can be determined that the vibrations (magnitude and phase angle of the spectrum) vary along the length of the steering rod and depend on time. It is evident that the vibrations propagate in the form of random waves, and the magnitudes are higher near the ends of the steering rod, which can be explained by the fact that disturbance forces acted there. This fact confirms the theoretical knowledge about transverse vibrations of the elastic beam [11-14]. The magnitude and frequency of harmonics depend on the design parameters of the steering rod and the time excitation.

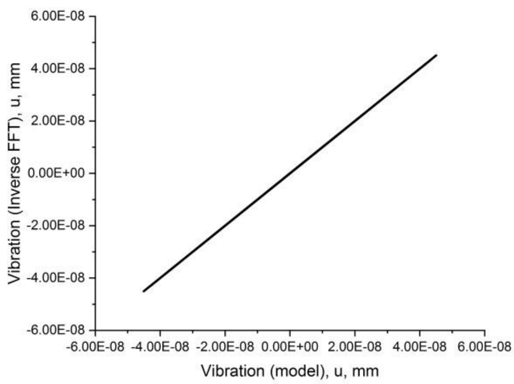

Figure 10. Comparison of transverse vibrations of the steering rod obtained from the model and inverse 2D Fourier transform

It should be noted that the study aims to investigate the possibility of applying a two-variable frequency analysis in testing steering rod in the laboratory. In such cases, it is often required to generate data that correspond to those in exploitation, so it is justified to use 2D Inverse Fourier transform, which allows calculating experimental values of vibrations based on the magnitudes and phase angles of the spectrum. The Inverse Fourier transform can be realized using the mentioned software Origin 8.5 [17]. By applying the mentioned software, the Inverse 2D Fourier transform was calculated, and the results are shown in Figure 9.

To determine the reliability of the data obtained based on the Inverse Fourier transform, the numerical data from Figures 6 and 9 were compared. The result of the comparison is shown in Figure 10. Since their dependence is a straight line, it is evident that the results match, which is also by mathematical laws [14]. Of course, slight differences may occur at the micro level as a result of numerical operations [16]. Considering the high agreement between the data obtained by Inverse 2D Fourier transformation and the experimental data (in this case, calculated based on the mathematical model (7)), the procedure could be used in laboratory conditions [6,18]. During the performance of exploitation tests, it is necessary to record the parameters of transverse vibrations of the steering rod (stresses, displacements, velocities, or accelerations of selected points) along its length, over a longer period. The minimum and maximum frequencies depend on the length of the steering rod, i.e., the length of the time signal and the discretization step.

First, it is necessary to adopt the maximum interesting frequencies fxmax and ftmax, and then the setting of the sensor and the sampling of the time signal are defined based on the expression (Nyquist frequency) [10].

$$h_x = \frac{1}{2 f_{x\max}} \; h_t = \frac{1}{2 f_{t\max}}$$

The minimum interesting frequency is obtained based on the length of the steering rod ($l_s = n_x * h_x$) and the length of the time signal ($t = n_t * h_t$) according to the expressions:

$$f_{x\min} = \frac{1}{n_x h_x} \; f_{t\min} = \frac{1}{n_t h_t}$$

It should be noted that for two-parameter Fourier transformations, there are no explicit procedures for calculating spectral analysis errors, as in the case of 1D Fourier transform [10]. Considering this, as well as the fact that this study aims to illustrate the potential application of two-parameter frequency analysis in investigating transverse vibrations of the steering rod, statistical error analysis was not specifically performed.

Finally, it should be emphasized that the developed procedure has created conditions for analyzing the influence of the integration step on the accuracy and stability of the solution of the partial differential equation (7), the influence of design parameters on transverse vibrations of the steering rod, the influence of disturbance forces, etc. However, considering that the results of dynamic simulation in this study served as a substitute for missing experimental results, it was assessed that a more detailed analysis is not necessary.

3. CONCLUSION

Based on the conducted research, it can be stated that the two-parameter Fourier transform reliably enables the analysis of data on transverse vibrations of the steering rod of commercial motor vehicles.

Calculated magnitudes of spectra and phase angles, using the inverse 2D Fourier transformation, enable the generation of identical vibrations in the laboratory as in exploitation conditions.

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EXPERIMENTAL AND NUMERICAL STUDIES OF REDUCING DRAG FORCE A SEMI-TRAILER TRUCK MODEL USING THE CABIN SPOILER

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RESEARCH ARTICLE

ABSTRACT: The paper obtains the procedure of design and analysis of the geometric parameters of the aerodynamic spoiler on the cabin of a semi-trailer truck. The procedure was included in order to obtain the optimal geometric shape and position of the spoiler, which would reduce the drag force of a semi-trailer truck. The procedure of optimizing the geometric shape and position is based on Design of Experiments and Response Surface Methodology. The research includes physical experiments in a wind tunnel and Computational Fluid Dynamics simulation. A scaled model of a semi-trailer truck is used as object of the optimization process.

KEY WORDS: *CFD, optimization, HVAC, efficiency*

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EKSPERIMENTALNA I NUMERIČKA ISTRAŽIVANJA SMANJENJA SILE UZGONA POMOĆU SPOJLERA KABINE NA MODELU TEGLJAČ-POLUPRIKOLICA

REZIME: U radu je prikazan postupak projektovanja i analize geometrijskih parametara aerodinamičkog spojlera na kabini poluprikolice. Procedura je imala za cilj dobijanje optimalnog geometrijskog oblika i položaja spojlera, čime bi se smanjila sila otpora poluprikolice. Procedura optimizacije geometrijskog oblika i položaja zasnovana je na dizajnu eksperimenata i metodologiji površine odgovora. Istraživanje uključuje fizičke eksperimente u aerotunelu i simulaciju računarskom dinamikom fluida. Objekat optimizacije je bio skalirani model tegljača-poluprikolice.

KLJUČNE REČI: *CFD, optimizacija, HVAC, efikasnost*

EXPERIMENTAL AND NUMERICAL STUDIES OF REDUCING DRAG FORCE A SEMI-TRAILER TRUCK MODEL USING THE CABIN SPOILER

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INTRODUCTION

The aerodynamics of a semi-trailer truck is an important scientific discipline which includes many aspects regarding the proper behaviour of vehicles during operation. Most often unfavourable aerodynamic shapes and large dimensions make a semi-trailer truck a reasonable test object. Also, a large number of kilometres travelled during exploitation, increases the need for improvement in the field of external aerodynamics. By reducing the aerodynamic drag on specific parts of the semi-trailer truck, as well as by changing the air flow, the overall aerodynamic drag of the semi-trailer truck will be reduced, which directly reflects on a lower fuel consumption. Filippone and Mohamed in their paper [1] indicate the importance of aerodynamics in long-distance commercial vehicles. In paper [1], the authors present a model for calculating the fuel consumption of commercial vehicles. Unfavourable geometric shapes of a semi-trailer truck and large air gaps between the elements of the body contribute to the creation of local aerodynamic drag in the form of vortex air flow. This phenomenon, as well as the definition of the areas in which the greatest local drag occurs, are presented by Tyrrell in [4] and Wood in [3]. Some simple solutions of aerodynamic spoilers of commercial vehicles and their analysis authors Wood and Bauer are presented in their work [2]. They achieved fuel savings of 10% at three different velocities. Computational Fluid Dynamics (CFD) is a useful tool for describing phenomena in the field of vehicle aerodynamics through simulations. The air flow analysis by CFD simulations in the area between the road and the vehicle floor is presented in [5] by Huminic A. and Huminic G. A 3D air flow simulation of was performed using a RANS (Reynolds Average Navier-Stokes) model for a larger spectrum of velocities and the values of Reynolds number between 2.4x106 and 14.1x106. In scientific field exists a large number of mathematical procedures and methods using to find an optimum in the problem to be solved. A presently optimization procedure, which leads to a good enough setting of the experiment, is the Design of Experiment (DoE). The procedure was used by McCallen et al. in [6], where they presented the analysis of existing as well as the creation of improved aerodynamic spoilers. The paper combines the use of CFD simulations and experimental measurements in a wind tunnel. Norouzi et al. in [7] were done a numerical research of medium-heavy trucks, for the purpose of reducing the force of aerodynamic drag for the values of Reynolds number between 7x105 and 1.6x106. The Finite Volume Method were used for simulate the flow field and pressure distribution around the truck. For the turbulent model, the standard k-epsilon was used to simulate the turbulent flow characteristics. Resourcing the relevant literature which include the optimization of aerodynamic spoilers of a semi-trailer truck, the authors of the paper found some interesting details as well as airfoil shape and position for the purpose of its application in an aerodynamic spoiler on a semi-trailer truck cabin. This motivated the authors to do a research in that direction. To that end, an optimization procedure has been devised, combining a few known methods. Firstly, a scaled CFD model of a semi-trailer truck without a spoiler has been created and verified in the wind tunnel by experiment. After that, the verified model has been used in the optimization procedure of airfoil parameters. The first step of the optimization procedure was defining airfoil parameters. The analysis was performed for all level combinations of parameter by using

Full Factorial DoE with impact to identify the zone of the optimal solution. The analysis implied adapting the parameter boundaries, as well as increasing the number of parameter levels. This used the Response Surface Methodology (RSM) based on Central Composite Design. By applying regression analysis on the RSM results, the response surface equation was formed. Finally, by mathematical minimizing the equation of response surface the optimal shape and position of the airfoil were found.

1. TESTING OBJECT

The testing object of the research is a semi-trailer truck. A 3D CAD model of truck and semi-trailer, scaled 1:10, was created, with some simplifications that do not have a direct issue on the aerodynamics. Figure 1 shows the CAD model of a startup configuration of a semi-trailer truck with dimensions.

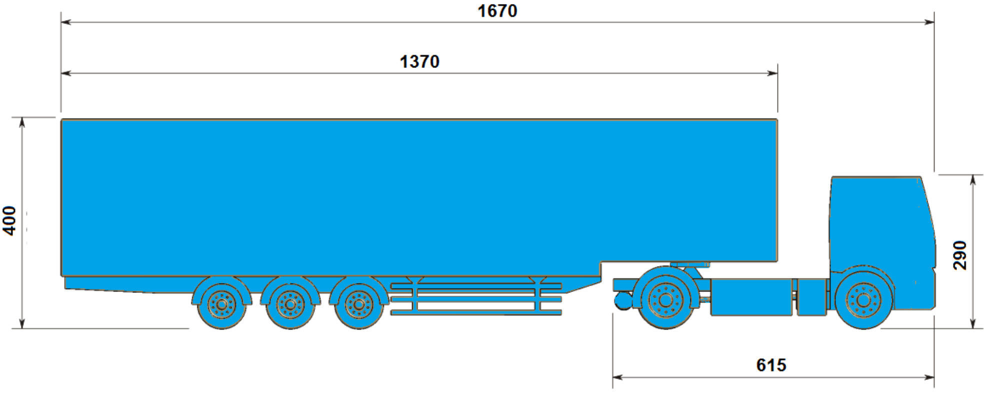


Figure 1. CAD model of the testing object with dimensions

In the reason of aerodynamics analysis, the CAD model was transformed to CFD (Computational Fluid Dynamics) model with adding virtual testing around which imitate a real wind tunnel. The model of the wind tunnel around the CAD model is a half cylinder 6000 mm long and radius of 700 mm. The CAD model has a frontal area of 0.0979 m^2. For better air flow spreading around the model and to minimise the impact of stationary floor, the CAD model was lifted up from the bottom of the wind tunnel for the value of 5 mm.

Some important properties within CFD model is shown in table 1.

Table 1. CFD important set-up

Parameter (or function)	Value (or explanation)
Software	AC Adapco - Star CCM+
Boundary conditions	Tunnel entrance - Velocity Inlet, Tunnel exit - Pressure Outlet, Tunnel and model - Wall
Inlet air flow velocity	Range between 60 and 90 km/h, with increment of 5 km/h
Reynolds number	Range between 1.8x106 and 2.7x107
Turbulent model	RANS k-Epsilon
Mesh type	Prismatic Polyhedral volumetric
Base cell size	100 mm for tunnel and 5 - 10 mm for all CAD model parts
Number of mesh cells	around 300,000

The values of base cell was adopted by mesh independency analysis, which included two mesh types (k-Epsilon and k-Omega) and a few values of base size (between 20 and 200 mm). Figure 2 shows CFD mesh model of the semi-trailer truck in the wind tunnel.

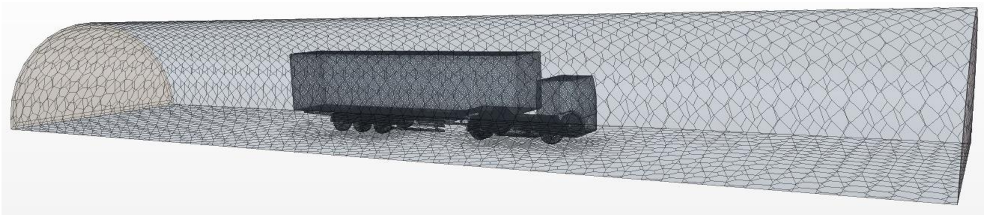


Figure 2. CFD mesh view of the testing model

After CFD set-up, the simulation was done for seven different velocity modes. Main outlook parameter was the value of model drag force. Table 2 shows values of drag force for seven air flow velocities.

Table 2. CFD initial results

Air flow velocity [km/h]	*Drag force [N]*
90	41.92
85	37.47
80	33.22
75	29.22
70	25.48
65	21.99
60	18.81

2. OPTIMIZATION PROCEDURE

The main purpose of this part of the research is to find optimal shape and position of a spoiler on the top of the truck cab. The optimization procedure includes a few steps. The initial spoiler had a shape of airfoil defined over four variable parameters and some constant parameters. Figure 3 shows the initial shape and position of the spoiler on the top of the truck cab.

2. 1 Factorial Design of Experiments

This part of the optimization procedure has aim to find best position and shape of the spoiler over CFD virtual simulations where was changed variable parameters H, L, R1 and R2. All simulations done for the highest air flow velocity of 90 km/h. The real variable parameter values were changed on the three levels, shown in the table 3. Four parameters with three levels gave 81 combinations of a different virtual CFD experiments.

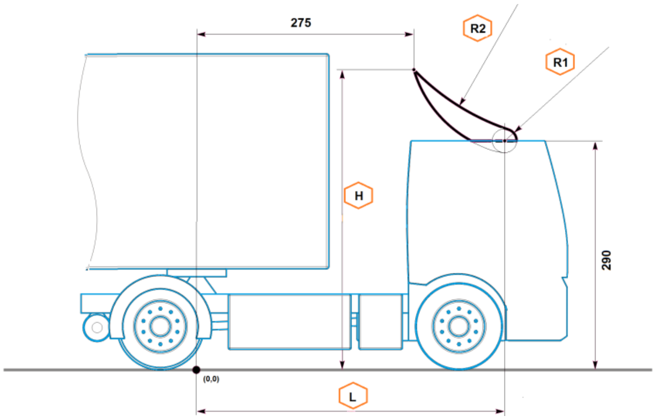


Figure 3. Initial position of the spoiler with parameters

Table 3. Full Factorial DoE values

	Values of parameters			
Level code	H [m]	L [m]	R1 [m]	R2 [m]
-1	0.35	0.35	0.010	0.1
0	0.39	0.38	0.015	0.3
1	0.42	0.40	0.020	0.5

Table 4 shows results of Full Factorial DoE. Combination number 16 gave the lowest drag force of 32.98 N. Also, Full Factorial DoE shows which level code of variable parameters has tendency for lower drag force.

Table 4. Full Factorial DoE results

Combination №	Factor level code				CFD simulation results	
	L	H	R1	R2	Drag coefficient, c_W [-]	Drag force, F_W [N]
1	-1	-1	-1	-1	0.942	34.02
2	-1	-1	-1	0	0.942	34.01
⋮	⋮				⋮	⋮
16	**-1**	**0**	**1**	**-1**	**0.913**	**32.98**
⋮	⋮				⋮	⋮
81	1	1	1	1	1.064	38.41

2. 2 Response Surface Method

In this part of the optimization procedure Full Factorial DoE is expended by using five-level Central Composite Design (CCD). Four parameters over five level code is 625 combinations of Full Factorial DoE, but thanks to CCD that number is reduced only on the 31 experiments. Table 5 shows the values of five level codes. Table 6 gives results of CCM within Response surface method. With this part of the optimization procedure the drag force was reduced to value of 31.93 N. The CCD yields 31 possible experimental settings, the last 7 of which are the central points of the design. The coefficients in the response surface function of aerodynamic drag force, Equation 1, are obtained by regression analysis of the dates from Table 6. The response surface coefficients are derived for uncoded parameter units.

Table 5. Level codes of parameters of CCM

Level code	L [m]	H [m]	R1 [m]	R2 [m]
-2	0.34	0.38	0.010	0.3
-1	0.35	0.39	0.015	0.4
0	0.36	0.40	0.020	0.5
1	0.37	0.41	0.025	0.6
2	0.38	0.42	0.030	0.7

Table 6. Results of Central Composite Design

Combination №	Factor level code				CFD simulation results		Combination №	Factor level code				CFD simulation results	
	L	H	R1	R2	Drag coefficient cw [-]	Drag force Fw [N]		L	H	R1	R2	Drag coefficient cw [-]	Drag force Fw [N]
1	-1	-1	-1	-1	0.945	34.11	17	-2	0	0	0	1.033	37.32
2	1	-1	-1	-1	0.943	34.06	18	2	0	0	0	0.991	35.78
3	-1	1	-1	-1	0.948	34.23	**19**	**0**	**-2**	**0**	**0**	**0.884**	**31.93**
4	1	1	-1	-1	0.936	33.79	20	0	2	0	0	0.896	32.36
5	-1	-1	1	-1	0.966	34.88	21	0	0	-2	0	0.897	32.41
6	1	-1	1	-1	0.917	33.10	22	0	0	2	0	0.918	33.15
7	-1	1	1	-1	0.970	35.03	23	0	0	0	-2	0.886	31.99
8	1	1	1	-1	0.901	32.55	24	0	0	0	2	0.905	32.69
9	-1	-1	-1	1	0.946	34.15	25	0	0	0	0	0.887	32.03
10	1	-1	-1	1	0.940	33.95	26	0	0	0	0	0.887	32.03
11	-1	1	-1	1	0.949	34.26	27	0	0	0	0	0.887	32.03
12	1	1	-1	1	0.926	33.45	28	0	0	0	0	0.887	32.03
13	-1	-1	1	1	0.962	34.74	29	0	0	0	0	0.887	32.03
14	1	-1	1	1	0.904	32.64	30	0	0	0	0	0.887	32.03
15	-1	1	1	1	0.977	35.26	31	0	0	0	0	0.887	32.03
16	1	1	1	1	0.908	32.79							

$$\begin{aligned} F_{Wth} &= 44.53-5.910\cdot H-0.561\cdot L-0.422\cdot R1-0.968\cdot R2+1.2114\cdot H^2+ \\ &+0.1106\cdot L^2+0.2688\cdot R1^2+0.1599\cdot R2^2-0.1291\cdot H\cdot L-0.4578\cdot H\cdot R1-\text{'} \\ &-0.0523\cdot H\cdot R2+0.0513\cdot L\cdot R1+0.0519\cdot L\cdot R2+0.0159\cdot R1\cdot R2 \end{aligned} \quad (1)$$

Presented equation describes the model behaviour with an accuracy of 95.8%. The parameter values that provide the minimum of the aerodynamic drag force response function are determined by numerical quasi-Newton minimization, Table 7.

By applying parameter values from the Table 7 to the CFD model, an aerodynamic drag force of 31.75 N was obtained. Figure 4 shows the optimized spoiler design.

Table 7.
Parameter values that provide the minimum aerodynamic drag

Parameter	Value [m]
H	0.3627
L	0.4002
R1	0.0210
R2	0.4912

Figure 4. Optimized spoiler on the top of the truck cab

3. EXPERIMENTAL PROCEDURE

The aim of the experimental testing is to verify the CFD simulations. The experimental testing was done in the “Miroslav Nenadović” wind tunnel within the Faculty of Mechanical Engineering in Belgrade, Serbia. That is a close type of underground wind tunnel with a circular air flow. The main dimensions of the testing area are 6000x2900x2100 mm. Maximum air velocity of around 400 km/h is reached by a four-blade fan with the motor electrical power of 210 kW.

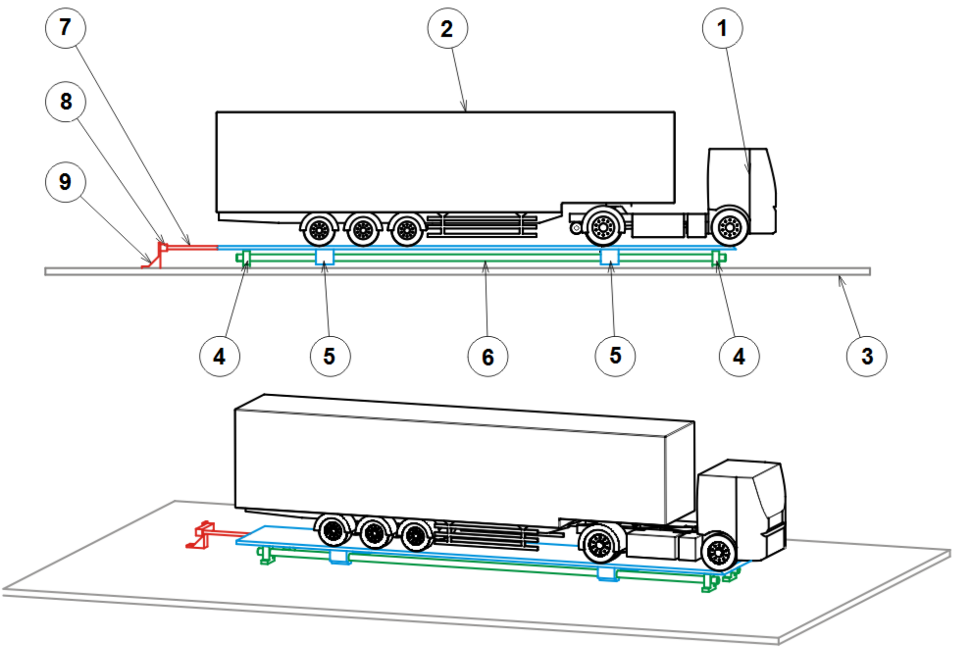


Figure 5. Experimental testing facility

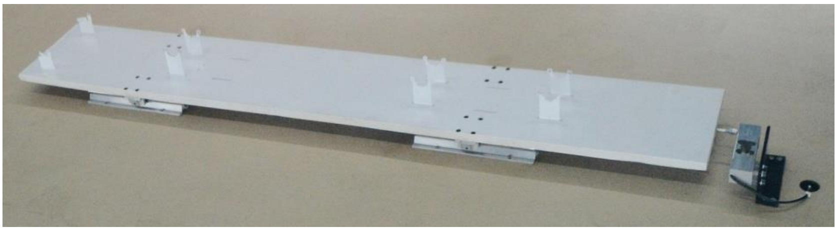
For the aim of measuring aerodynamic drag force, which is a horizontal component of vehicle resistance, an aerodynamic drag force measuring facility was built. Figure 5 shows a schematic representation of the facility for measuring the drag force of the semi-trailer truck model in a wind tunnel. This model, with dimensions of 1670x255x400 mm, is made of wood in a scale of 1:10 compared to the actual semi-trailer truck. The models of the truck 1 and the semi-trailer 2 are joined to the board 9 via a support. The models 1 and 2 are lifted up above the board for a vertical distance of 5 mm, same in CFD model. The board 9 is fastened via sliders 5 to sliding guides 6 through which the longitudinal translational movement of the board 9 is provided, together with models 1 and 2. The board 9 rests at the force measuring cell 8. The measuring cell CZL623B was used with the comprehensive full scale error 0.03% and rated output 2 ± 0.02 mV/V. The signal from the measuring cell is transferred to the universal measuring amplifier HBM QuantumX MX840A. Data acquisition was performed by the software HBM catman Easy -AP ver. 3.5.1.

Experimental measurements were performed on the following configurations of the measuring facility:

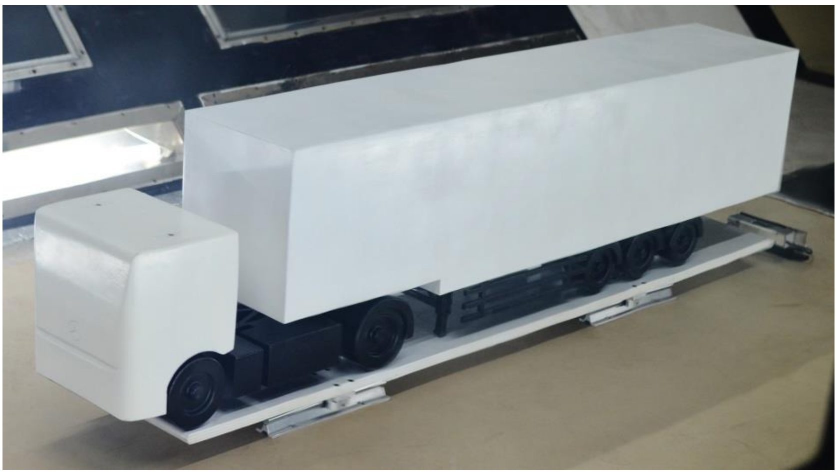
- drag force measurement of board 9 only, without the semi-trailer truck model.
- drag force measurement of the semi-trailer truck model without an aerodynamic spoiler;
- drag force measurement of the semi-trailer truck model with aerodynamic spoiler on the cabin of the truck.

Figure 6 shows the actual model configurations during measurements in the wind tunnel.

a)



b)



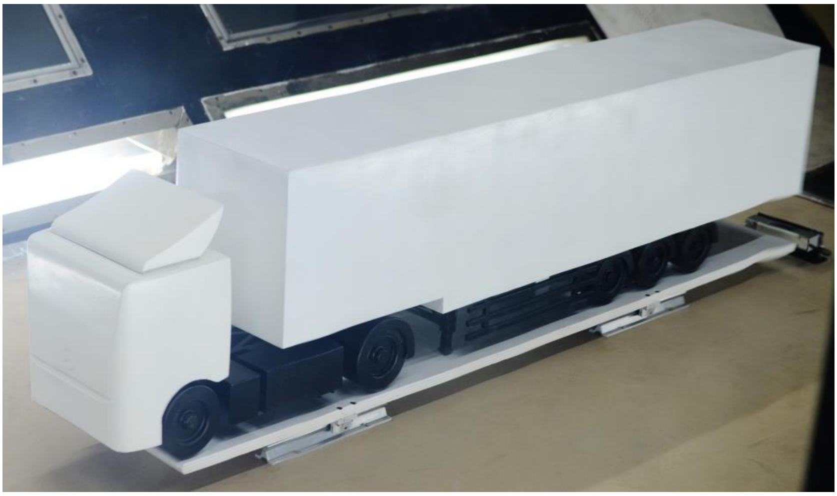
c)


Figure 6. Testing models by three configurations in the wind tunnel

Within each measuring facility configuration, one measurement involved reading the aerodynamic drag force value at a single air flow velocity mode. Measurements were performed at seven velocity values in the range of 60 to 90 km/h, with an increment of 5 km/h. At each velocity mode, two measurements were performed for about 20 seconds.

4. RESULTS

Table 7 gives a comparative view of the results obtained by CFD simulations and experimentally for all three considered configurations and all velocity values. The obtained results in Table 7 show an acceptable agreement between the results achieved by CFD simulations and experimental tests in the wind tunnel. The adopted type of mesh and turbulent model within the CFD simulation provides good repeatability of the results for all considered airflow velocity values and all configurations of the measuring facility. The tested model during the experimental measurement showed stability and balance at the highest velocity values of air flow. The results of CFD simulations show that the value of aerodynamic drag force is higher than the corresponding one obtained experimentally by 1.5 to 3 N, at all the velocities. This deviation occurred because the CFD model did not take into account the friction force between sliders and their guide rails in the experimental facility. Due to the correct rounding design of the board leading edge and its distance in relation to the tested model, a very small aerodynamic drag force of the board without the model was observed, with a value of order of 2 N at the highest considered air flow velocity.

Table 7. Comparison results between simulations and experiments

Configuration of the measuring facility	v [km/h]	$F_{W\,CFD}$ [N]	$F_{W\,EXP\,1}$ [N]	$F_{W\,EXP\,2}$ [N]
a)	60	1.01	0.88	0.90
	65	1.18	1.04	1.04
	70	1.35	1.19	1.18
	75	1.55	1.36	1.37
	80	1.75	1.55	1.53
	85	1.97	1.53	1.77
	90	2.20	1.92	1.99
b)	60	18.81	16.44	16.78
	65	21.99	20.01	20.23

	70	25.48	23.13	23.59
	75	29.22	26.87	27.09
	80	33.22	30.79	30.88
	85	37.47	34.95	35.17
	90	41.92	38.23	38.68
c)	60	14.06	12.57	12.91
	65	16.48	15.10	15.42
	70	19.09	16.90	17.07
	75	21.88	19.70	19.89
	80	24.96	22.40	23.06
	85	28.13	25.64	26.13
	90	31.52	29.89	30.35

5. CONCLUSION

The goal of the research was to develop an optimizing procedure of the geometric shape and position, used as an aerodynamic spoiler on a semi-trailer truck cabin. The research included virtual experiments and physical experiments. The procedure was conceived as a combination of several known methods: Full Factorial Design of Experiments, Central Composite design, regression analysis and minimization of Response Surface equation.

Four parameters (top edge height from the ground - H, horizontal position of spoiler front radius centre - L, spoiler front edge radius - R1 and spoiler leading edge radius - R2) defining the spoiler shape and position. It turned out that parameter H has a dominant influence on the aerodynamic drag force. The influence of the parameter R2 is significantly smaller, while the parameters L and R1 have the least impact on the drag force.

As a result of Central Composite design of experiments, a quadratic response surface function of drag force was generated. Spoiler parameters are optimized by minimizing the response surface function. CFD simulation results were validated by testing in the wind tunnel.

The procedure presented in the research can also be performed by adding more parameters, including parameters that describe variations in the third dimension of the spoiler. Although such a research requires much more virtual experiments to be performed, it could lead to further improvement of truck aerodynamics.

ACKNOWLEGMENTS

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THE INFLUENCE OF BATTERY ELECTRIC AND PLUG-IN HYBRID ELECTRIC VEHICLE APPLICATION ON CO_2 EMISSIONS

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RESEARCH ARTICLE

ABSTRACT: This paper provides an overview of the growth in sales of Battery Electric Vehicles (BEVs) and Plug-in Hybrid-Electric Vehicle (PHEVs) in the world, Europe, and Montenegro for the period from 2011 to 2020. The percentage share of sold EVs (Electric vehicles) (BEVs and PHEVs) in the total number of vehicles sold for the mentioned period is also shown. It can be noted that the number of BEVs and PHEVs sold in the world and in Europe is constantly increasing for the period from 2011 to 2020. It was noticed that there is also an increase in the share of BEVs and PHEVs, but it is still very small. As BEVs and PHEVs (when powered by an electric motor) use electricity for propulsion, it is very important to explore the way electricity is produced by sources, which was done in the paper. Electricity is produced not so cleanly, but there is a constant increase in the share of renewable energy sources (RES) in electricity production. Electricity production in the world is dominated by coal and natural gas. An overview of electricity consumption by sector in the world, Europe, and Montenegro is given. For the period from 2011 to 2020, this paper provides an overview of CO_2 emissions by sector. The largest amount of CO_2 emission is emitted in the electricity generation and heating sector. The transport sector also emits a large amount of CO_2 emissions. The transport sector and the electricity/heating production sector are the two sectors that have been targeted as the main culprits for the constant increase in CO_2 emissions. In Europe, the total CO_2 emission is in a slight decline, which is a consequence of the EU's great efforts to reduce this emission from the mentioned two sectors. In this paper, it was shown that the number of BEVs and PHEVs, as well as their share in the total number of vehicles, is still too small to significantly impact the reduction of CO_2 emissions at the global level.

KEY WORDS: *electric vehicles, ecology, CO_2 emission, electricity, decarbonization*

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UTICAJ PRIMJENE ELEKTRIČNIH I HIBRIDNIH VOZILA NA CO_2 EMISIJU

REZIME: U ovom radu dat je pregled rasta prodaje Battery Electric Vehicles (BEV) i Plug-in Hybrid Electric Vehicle (PHEV) u svijetu, Evropi i Crnoj Gori za period od 2011. do 2020. godine. Takođe prikazan je i procentualni udio prodatih EV (Electric vehicles) vozila (BEV i PHEV) vozila u ukupnom broju prodatih vozila za pomenuti period. Može se primijetiti da je u svijetu i Evropi broj prodatih BEV i PHEV vozila u stalnom porastu za period od 2011. do 2020. godine. Primjećeno je da je prisutan i rast udjela BEV i PHEV vozila, ali je on i dalje veoma mali. Kako BEV i PHEV (kada je pogon preko elektromotora) vozila koriste za pogon električnu energiju veoma važno je sagledati način proizvodnje električne energije po izvorima, što je u radu urađeno. Električna energija se proizvodi na ne tako čist način, ali je prisutan stalan porast udjela obnovljivih izvora energije (OIE) u proizvodnji električne energije. Proizvodnjom električne energije u svijetu dominiraju ugalj i prirodni gas. Dat je pregled i potrošnje električne energije po sektorima u svijetu, Evropi i Crnoj Gori. Za period od 2011. do 2020. godine u ovom radu dat je pregled CO_2 emisije po sektorima. Najveća količina CO_2 emisije emituje se u sektoru proizvodnje električne energije i grijanju. Transportni sektor takođe emituje veliku količinu CO_2 emisije. Transportni sektor i sektor proizvodnje električne energije i grijanja su dva sektora koja su targetirana kako glavni krivci za stalno povećanje CO_2 emisije. U Evropi ukupna CO_2 emisija je u blagom padu što je posledica velikih napora EU da smanje ovu emisiju iz pomenuta dva sektora. U ovom radu pokazano je da je broj BEV i PHEV vozila, kao i njihov udio u ukupnom broju vozila i dalje veoma mali da bi imao neki primjetno značajniji uticaj na smanjenje CO_2 emisije na globalnom nivou.

KLJUČNE REČI: *električna vozila, ekologija, CO_2 emisija, električna energija, dekarbonizacija*

THE INFLUENCE OF BATTERY ELECTRIC AND PLUG-IN HYBRID ELECTRIC VEHICLE APPLICATION ON CO_2 EMISSIONS

Marko Lučić, Jasna Glišović, Ivan Grujić

INTRODUCTION

Improving the quality of life in cities is one of the biggest challenges facing society today. Over the years, various studies have been conducted to identify the sources of pollution, among which transport plays a leading role. Therefore, scientific research conducted in search of reducing the negative impact of transport on the environment is predominantly focused on the development of electromobility [1]. We live in a time when it is necessary to make various decisions to minimize the negative impact of transport on the environment. Oil is the dominant source of energy in the transport sector, especially in road traffic. Heavy dependence on fossil fuels makes transport a major contributor to greenhouse gases, and it is also one of the few industrial sectors where emissions are still growing. The impact of transport on climate change is not limited to vehicle emissions, because fuel production and distribution, as well as vehicle production, contribute significantly to the production of greenhouse gases. For example, consideration of the total CO_2 emissions from an average car showed that 76% of this emission comes from the combustion of fuel in the internal-combustion engine (ICE) of the vehicle, while as much as 9% come from the production of the vehicle itself, and an additional 15% come from losses in the system for fuel supply. The fact that, despite great efforts in recent years to reduce the negative impact of transport on the environment, we still live in the age of oil, shows that solving this problem is not very simple [2]. Global transport emissions have grown rapidly over the past decade. The energy transition in transport is currently lagging behind other sectors, and changes in vehicle and fuel technology, as well as pressures to reduce the sector's impact on climate change, may enable a very different future. Large reductions in emissions can be achieved by decarbonizing fuels or vehicles, or a combination of both. Options for reducing emissions include switching from conventional vehicles to electric and hybrid vehicles and switching from fossil fuels to biofuels. Despite strong support from agricultural interest groups, first-generation biofuels have faced availability constraints, sustainability concerns, and public opposition. Instead, attention has shifted to advanced biofuels derived from non-edible lignocellulosic residues and wastes due to their potential to offer significant quantities of low-GHG fuels on a large scale while avoiding many of the problems associated with first-generation biofuels [3]. Electrification is also widely recognized as a very powerful way to reduce greenhouse-gas emissions in transport. However, the study [4] showed that although the number of new electric vehicles in China increased four times from 2016 to 2019, the growth rate of emissions from road traffic is still around 20,5%. The current electrification of road traffic in China can reduce only 0,6% of the total emissions in this sector, but this reduction could be increased to 1,4% if the electricity was completely obtained cleanly, from RESs. The transport sector in China could reach the peak of carbon dioxide emissions in 2030, with 1330,98 Mt. The electrification of transport would not be able to meet the climate goals of 2060, and the continuation of the inertia of conventional vehicles will significantly slow down the path of road traffic towards the complete elimination of carbon dioxide [4]. Two technical ways to reduce greenhouse-gas emissions from the transport sector are [5]:

- increasing the energy efficiency of the drive system i
- reduction of emissions from energy sources.

First, improving energy efficiency can reduce energy consumption, which directly reduces greenhouse-gas emissions. Electric motors are more energy efficient for transport use compared to ICEs, due to their high efficiency over a wide speed range. It is electric and plug-in hybrids that use this advantage to reduce greenhouse-gas emissions during the operation. Second, the release of emissions during the electricity production plays a very important role in the decarbonization process. Propulsion systems using renewable fuels are also considered low-carbon propulsion systems. Replacing fossil fuels with fuels that have a low-carbon content has the potential to significantly reduce CO_2 emissions from the transport sector in a progressive manner [5]. In the paper [6], four strategies for the decarbonization of the transport sector at the global level until 2050 are investigated, using the MEDEAS-W model that combines different options of electrification, vehicle replacement, and demand-side management. It is important to note that conventional studies in the literature reveal only that the decarbonization of transport, on a global scale, is only possible under the unreliable assumption that in the future currently uncertain technologies such as advanced biofuels, hydrogen, fuel cells will be widely available commercially and at a sustainable level. The transport sector has been identified as one of the most complicated sectors for decarbonization. Otherwise, the transport sector is also characterized as the sector with the fastest growth in greenhouse-gas emissions compared to other sectors [6].

In this paper, the impact of increasing the number of BEVs and PHEVs in the world, Europe, and Montenegro on CO_2 emissions for the period from 2011 to 2020 is analyzed. As the way of obtaining electricity that will be used by BEVs and PHEVs has a great influence on the decarbonization of road traffic through electrification, this paper also analyzed the production of electricity by sources for the period from 2011 to 2020. As it is expected that in the relatively near future the transport sector, with an increasing share of BEVs and PHEVs on the roads, will be one of the most important consumers of electricity, the consumption of electricity by sector for the period from 2011 to 2020 is also shown.

1. BEV$_S$ AND PHEV$_S$ - BENEFITS AND CONSIDERATIONS

One of the main ways to decarbonize road traffic is to change the drive of road transport vehicles. In this way, traditional vehicles that use liquid petroleum fuels to achieve propulsion are replaced by vehicles with alternative drives. Vehicles with alternative drives enable incomparably better environmental characteristics compared to conventional vehicles that burn liquid petroleum fuels. The electric drive of road vehicles is the most common and popular type of alternative drive. There are also hybrid-electric vehicles, which have both an electric motor and an ICE. Hybrid-electric vehicles (specifically plug-in hybrid vehicles) are vehicles that are intended to use the ICE on long intercity routes and electric drive in cities. As cities are otherwise the most vulnerable areas that are exposed to the negative impact of traffic in terms of exhaust emissions, but also noise emissions caused by the operation of ICEs, the use of electric drive can reduce these emissions in the mentioned urban areas. Electric vehicles and plug-in hybrid vehicles (when they use only an electric drive) can be considered zero-emission vehicles, but only in the area of use of these vehicles. If we look at the use of electric and plug-in hybrid vehicles on a global level, the achievement of zero emissions depends on the method of producing electricity that the mentioned vehicles use for propulsion. Achieving zero emissions on a global level by using electric and plug-in hybrid vehicles is only possible if the necessary electricity is produced from RES. The production of the necessary electricity, for example, by burning coal in thermal power plants, releases various harmful combustion products, but also CO2 emissions, so in this case we cannot discuss about achieving zero exhaust emissions on a global level. In the last few years, electric vehicles have experienced greater and greater expansion. The number of sold passenger BEVs and PHEVs in the world for the period from 2011 to 2020 is shown in Figure 1, and in Europe in Figure 2, according to data from the International Energy Agency (IEA) [7].

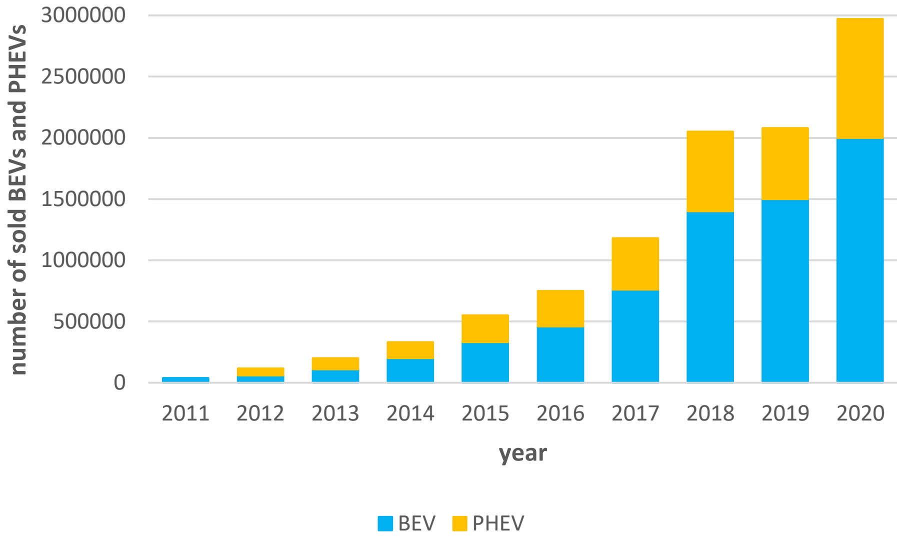

Figure 1. Number of sold BEVs and PHEVs in the world [7]

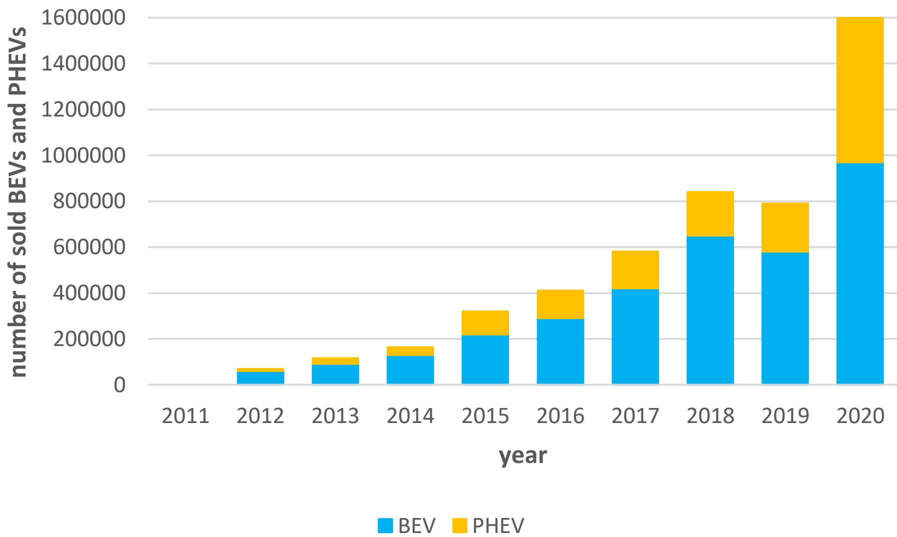

Figure 2. Number of sold BEVs and PHEVs in the Europe [7]

For a better understanding of the complete situation related to BEVs and PHEVs, a very important piece of information is the share of these vehicles in the total number of vehicles sold. The total share of BEVs and PHEVs in the world and Europe is shown in Figure 3, according to data from the International Energy Agency (IEA) [7].

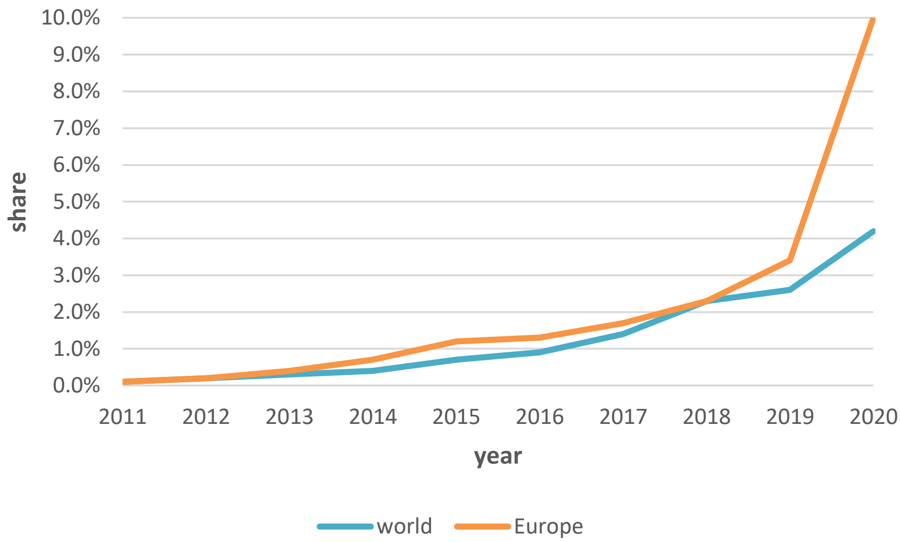

Figure 3. Cumulative share of sold BEVs and PHEVs in the world and Europe [7]

Apart from the number of BEVs and PHEVs sold, as well as the percentage share of these vehicles in the total number of vehicles sold, it is very important to show the number of these vehicles in the total number of vehicles. Figure 4 shows the total number of BEVs and PHEVs in the world, and Figure 5 in Europe for the period from 2011 to 2020 [7].

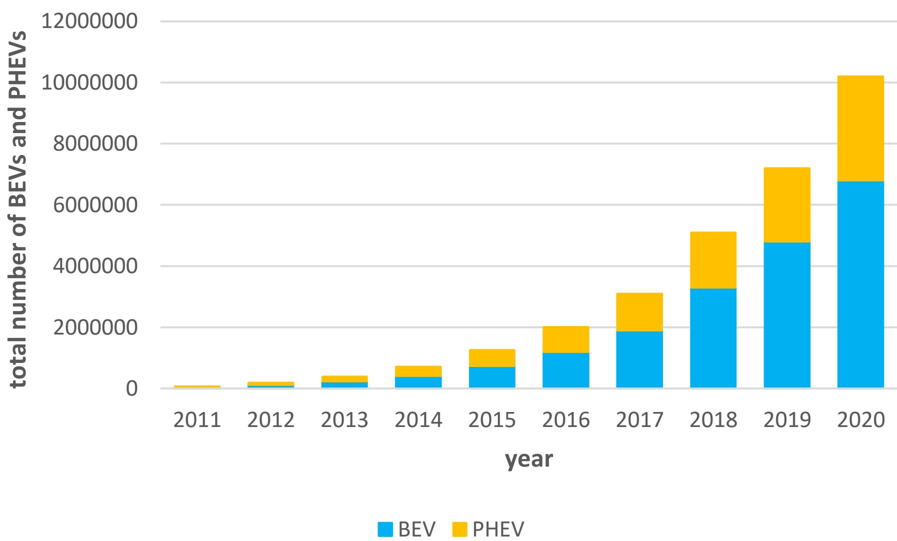

Figure 4. Total number of BEVs and PHEVs in the world [7]

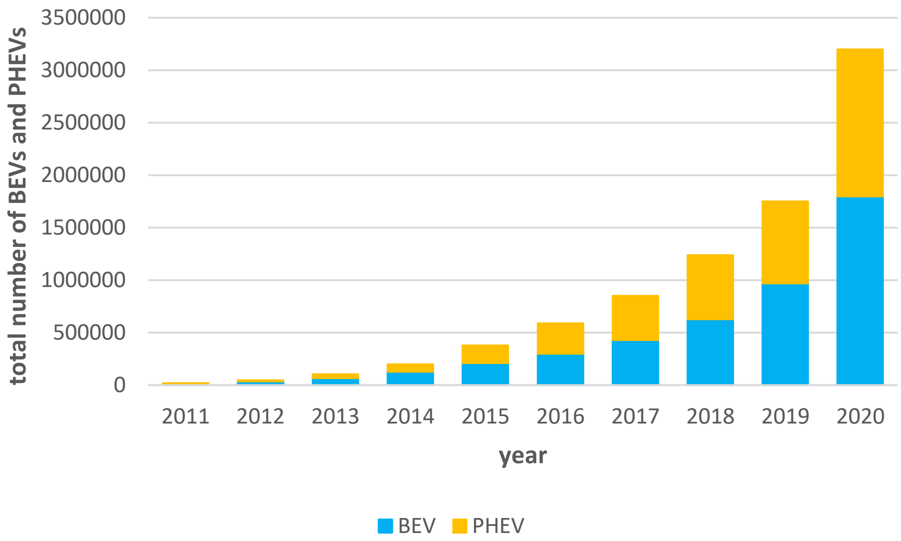

Figure 5. Total number of BEVs and PHEVs in Europe [7]

Data on the number of BEVs and PHEVs sold in Montenegro is not available, but data on the total number of BEVs are available on the website of the Republic of Montenegro Statistical Office, so the total number of BEVs for Montenegro is shown in Figure 6 [8]. In Montenegro, there was also a constant growth of BEVs from year to year. The first such vehicle was registered only in 2013, and in this year there were only 7 registered BEVs.

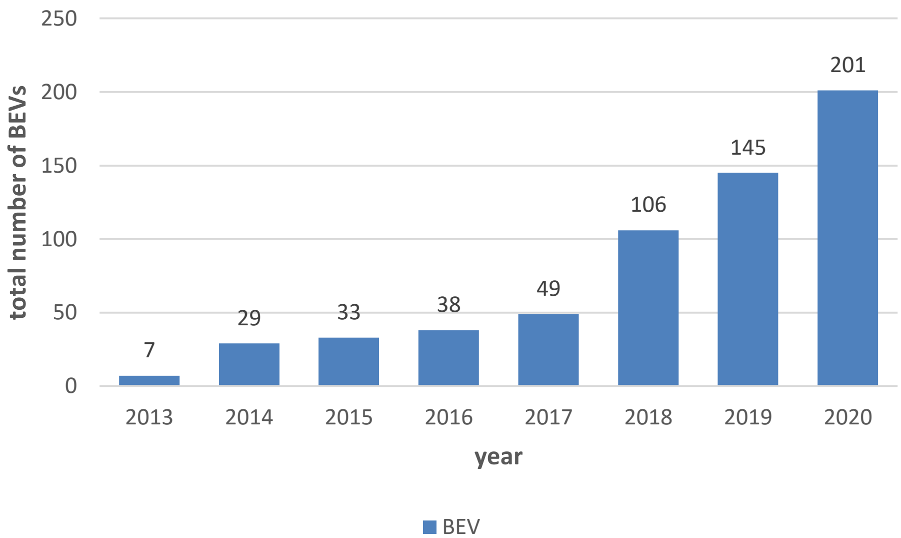

Figure 6. Total number of BEVs in Montenegro [8]

In addition to knowing the total number of sold and the general total number of BEV and PHEV vehicles, it is very important to present the share of BEV and PHEV vehicles in the total number of vehicles. Figure 7 shows the combined share of BEV and PHEV vehicles in the total number of vehicles in the world and Europe [7]. For better visibility, the total number of BEVs in Montenegro is shown in Figure 8 [8].

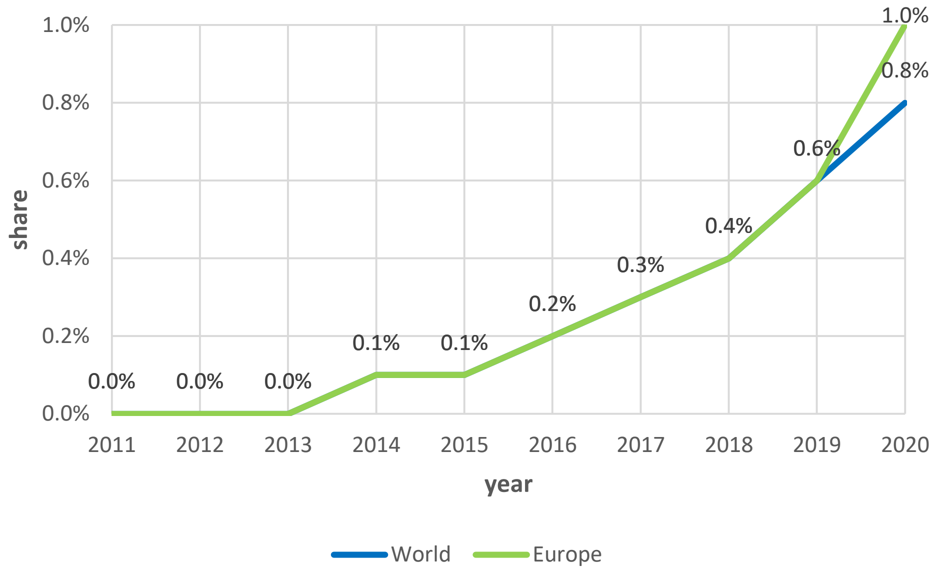

Figure 7. Cumulative share of BEVs and PHEVs in the world and Europe [7]

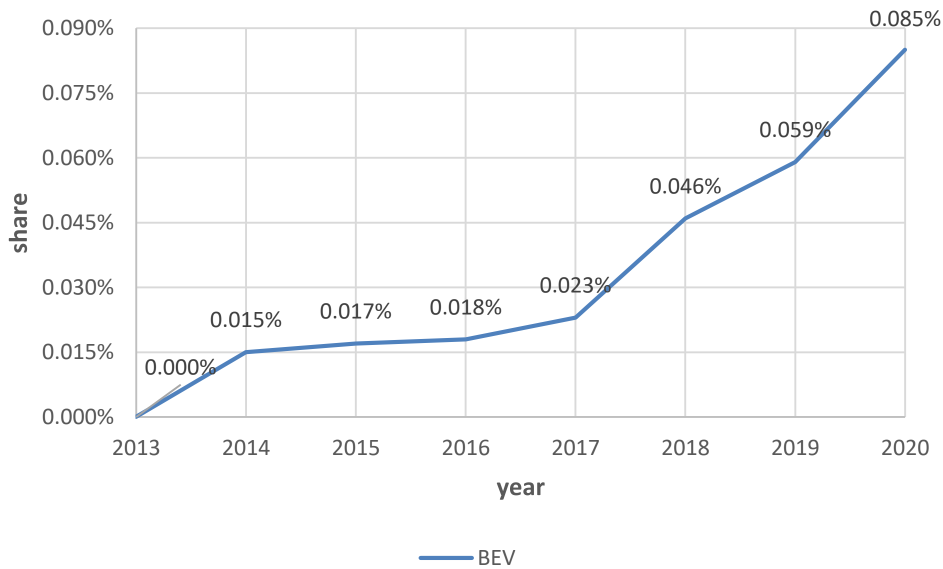

Figure 8. Total number of BEVs in Montenegro [8]

The number of BEVs and PHEVs in the world and Europe has a constant growing trend in the period from 2011 to 2020. Furthermore, the number of BEVs in Montenegro for the period from 2011 to 2020 has a growing trend. A growing trend was also recorded when it comes to the number of BEVs and PHEVs sold in the world and Europe in the period from 2011 to 2020. It is noted that the share of sold BEVs and PHEVs in the total number of vehicles sold, as well as the share of these vehicles in the total number of vehicles, has a growing trend in the world and Europe for the period from 2011 to 2020. The share of BEVs and PHEVs in the total number of vehicles, despite the growing trend, is relatively very small. In the observed period, when it comes to the total share of BEVs and PHEVs, the maximum was reached at the end of the analyzed period, i.e. in 2020, both in the world and in Europe. In this year, the combined share of BEVs and PHEVs in Europe was only 1%, and even 0,8% in the world. When it comes to the share of BEVs in Montenegro, with constant growth from year to year during the observed period, the maximum was also reached in 2020, which is significantly below the world and European level and amounts to only 0,085%. It is very important to point out that if we look only at the total number of EVs (BEVs and PHEVs) in the world in 2020 (Figure 4), PHEV vehicles are represented by 33,33%, and BEVs by 66,67%. On the other hand, in Europe in 2020 (Figure 5), PHEV vehicles are represented by 43,8%, and BEVs by 56,2% in the total number of EVs (BEVs and PHEVs). This highlights the reason that PHEV vehicles have a very significant share in the total number of EVs (BEVs and PHEVs) in the world and Europe, and it is very difficult to estimate their contribution to the consumption of electricity for their movement. As PHEV vehicles have two types of drives, electric motor drive, and ICE drive, the use of one of these two drives depends on the way the vehicle is driven. Although PHEV vehicles are designed to use an electric drive for relatively short distances in city driving, and ICE drive for longer distances, the decision to use one of these two drives is often a subjective decision of the driver.

2. ELECTRICITY PRODUCTION BY SOURCES

In this chapter, an analysis of electricity production by sources in the world, Europe, and Montenegro was carried out. Electric vehicles use electricity to move, so the way they get the electricity is very important. The concept of electric vehicles as zero-emission vehicles at the global level depends on the way of producing the electricity that these vehicles use for propulsion. The data on electricity production in this chapter was taken from the International Energy Agency [9].

2.1. Production of electricity by sources in the world and Europe

The production of electricity by source in the world, based on data from the International Energy Agency, for the period from 2011 to 2020 is shown in Figure 9 [9]. It can be noticed that the production of electricity in the world is constantly increasing from year to year for the period from 2011 to 2020. Coal has the largest share in electricity production in each year of the analyzed period, followed by natural gas, hydropower, and nuclear energy. It can also be noted that the amount of electricity produced from RES (solar and wind) is constantly increasing. The production of electricity by burning oil has a very small share, and it is noticeable that it is constantly decreasing. Also, biomass, tide, geothermal energy, and other energy sources have a very small share in the total production of electricity in the world for the period from 2011 to 2020. The energy mix of electricity production in 2020 in the world looked like this: coal 35,2%, natural gas 23,6%, hydropower 16,6%, nuclear energy 10,0%, and other sources around 15,5%.

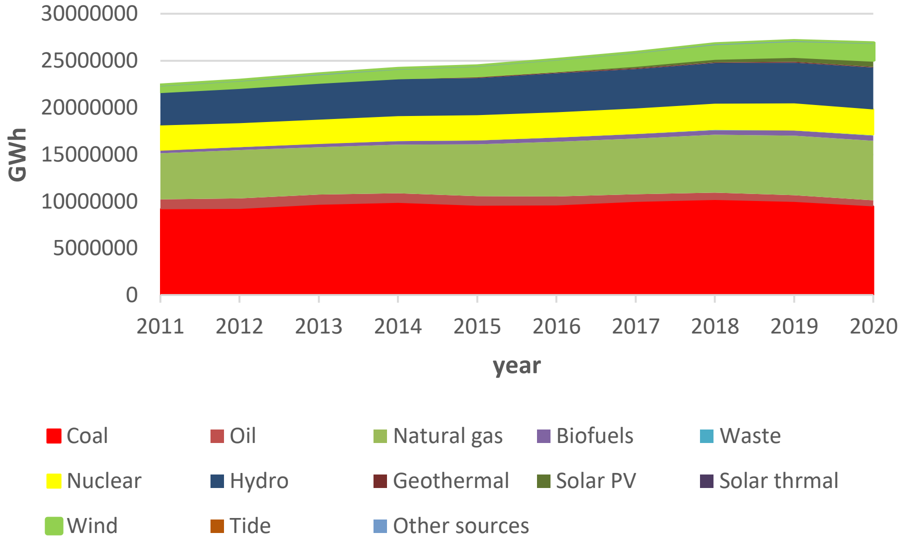

Figure 9. Electricity production by sources in the world [9]

Electricity production by sources in Europe is shown in Figure 10 [9].

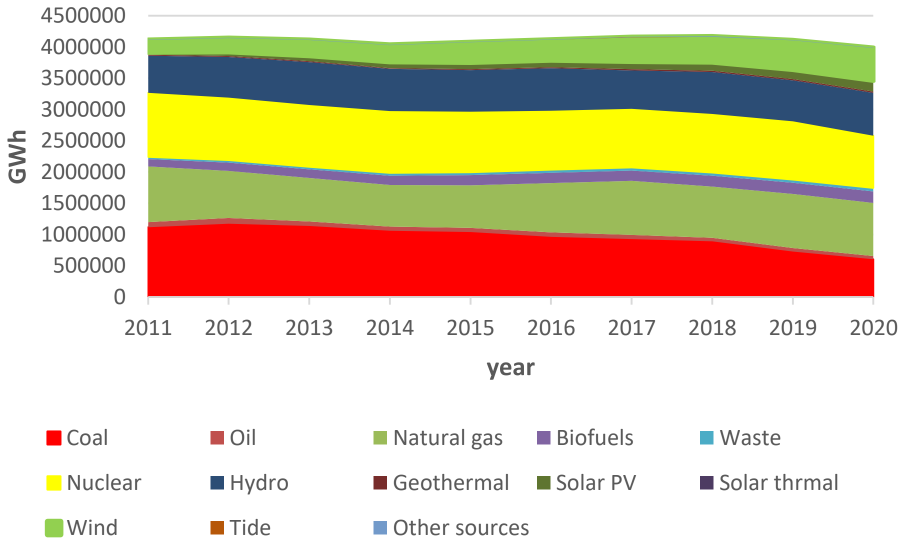

Figure 10. Electricity production by sources in Europe [9]

Electricity production in Europe for the period from 2011 to 2020 is more or less at the same level, and in the last few years, it has been on the decline, which is caused by the consequences of European policies in the area of reducing energy consumption and energy efficiency. One of the main goals of the EU is the decarbonization of the energy sector, which is reflected to a large extent in the territory of Europe. The consequence of EU policies can best be seen through the fact that the production of electricity from coal in the period from 2011 to 2020 is constantly decreasing. Furthermore, very important is the fact that the production of electricity from coal in Europe in 2020 is almost two times less compared to 2011. In Europe in 2020, electricity was produced from the following sources: natural gas (21,3%), nuclear energy (20,9%), hydropower (17,2%), and only then coal (15,1%), wind (12,8%) and other energy sources (12,7%).

2.2. Electricity production by sources in Montenegro

The Montenegrin energy system is very simple. The largest amount of electricity in Montenegro is produced in a thermal power plant and two large hydropower plants. Also, in the last few years, electricity in Montenegro has been produced using two wind power plants and several small hydroelectric power plants. Electricity production by sources in Montenegro is shown in Figure 11 [9]. Electricity production in Montenegro in 2020 took place according to the following energy mix: coal (47,8%), hydropower (42,9%) and wind (9,3%). If you look at the entire period from 2011 to 2020, you can see that electricity production in Montenegro is oscillatory, which is a consequence of the different amounts of electricity produced in hydroelectric power plants per annum during the observed period. Electricity production from hydroelectric power plants varies depending on the amount of precipitation. The main production facilities in Montenegro are [10]:

- HPP "Perućica", installed power 307 MW,
- HPP "Piva", installed power 342 MW,
- TE "Pljevlja", installed power 210 MW.

In 2018, the "Krnovo" power plant with an installed capacity of 72 MW began operating, and in 2019, the "Možura" power plant with an installed capacity of 46 MW began operating [11].

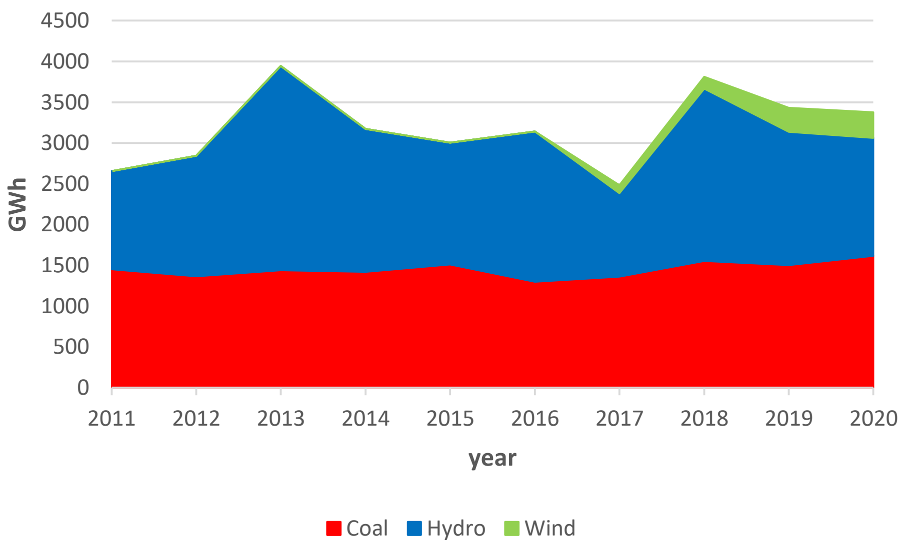

Figure 11. Electricity production by sources in Montenegro [9]

3. ELECTRICITY CONSUMPTION BY SECTORS

When analyzing the impact of the use of electric vehicles to decarbonize road traffic, it is very important to know how electricity is consumed in a certain sector. This chapter presents how electricity is consumed by different sectors in the world, Europe, and Montenegro, according to data from the International Energy Agency [9].

3.1. Electricity consumption by sector in the world and Europe

Electricity consumption by sector in the world for the period from 2011 to 2020 is shown in Figure 12 [9]. It can be seen that the total consumption of electricity is constantly increasing in the mentioned period. The largest consumer of electricity in the world in each year of the observed period is the industry sector, followed by the residential sector, then the public and service sectors. Electricity consumption in the transport sector is very small and mostly refers to rail traffic. The consumption of electricity in the industry is constantly increasing from year to year during the observed period from 2011 to 2020. The largest consumers of electricity in the world in 2020 are: industry (41,7%), residential sector (27,6%), public and service sector (20,2%), agriculture (3,2%), transport (1,8%) and other consumers (5,5%).

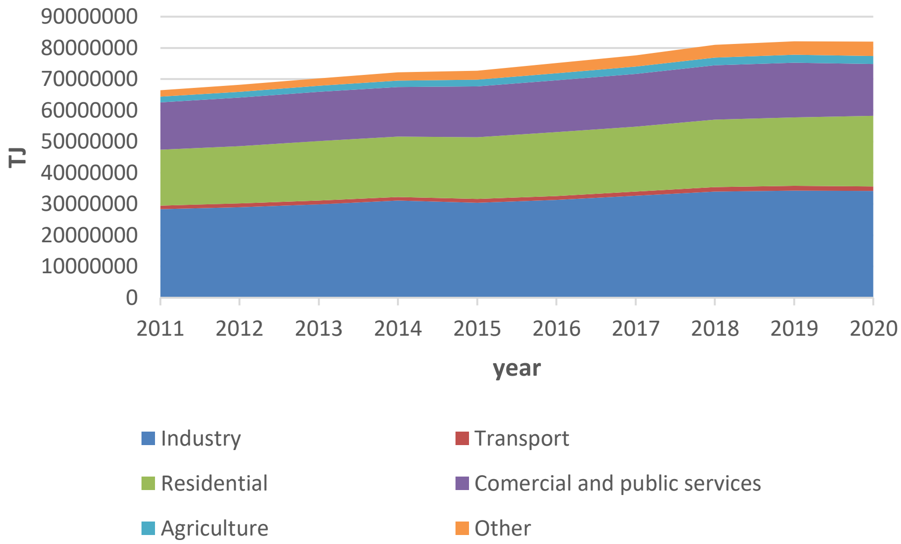

Figure 12. Electricity consumption by sector in the world [9]

Electricity consumption in Europe is maintained at an approximately constant level in the observed period from 2011 to 2020. The three largest consumers of electricity in Europe are the same as in the world. A very small consumer of electricity is the transport sector, mostly rail traffic. Electricity consumption in Europe by sector for 2020 looked as follows: industry (37,1%), residential sector (30,7%), public and service sector (27,4%), agriculture (2,3 %), transport (2,1%) and other consumers (0,4%). Electricity consumption by sector in Europe for the period from 2011 to 2020 is shown in Figure 13 [9].

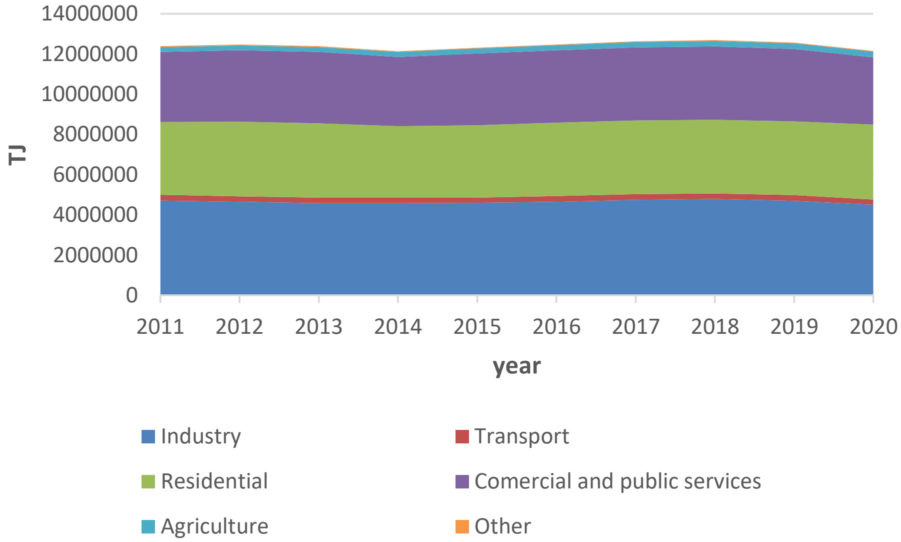

Figure 13. Electricity consumption by sector in Europe [9]

3.2. Electricity consumption by sector in Montenegro

Electricity consumption by sector in Montenegro for the period from 2011 to 2020 is shown in Figure 14 [9]. At the beginning of the observed period, industry was the largest consumer of electricity, but in 2014 it significantly decreased and remained at approximately the same level until 2020. It can also be noted that the public sector and the service sector had a very low consumption of electricity at the beginning of the analyzed period because it was probably calculated together with the residential sector. Electricity consumption by sector in

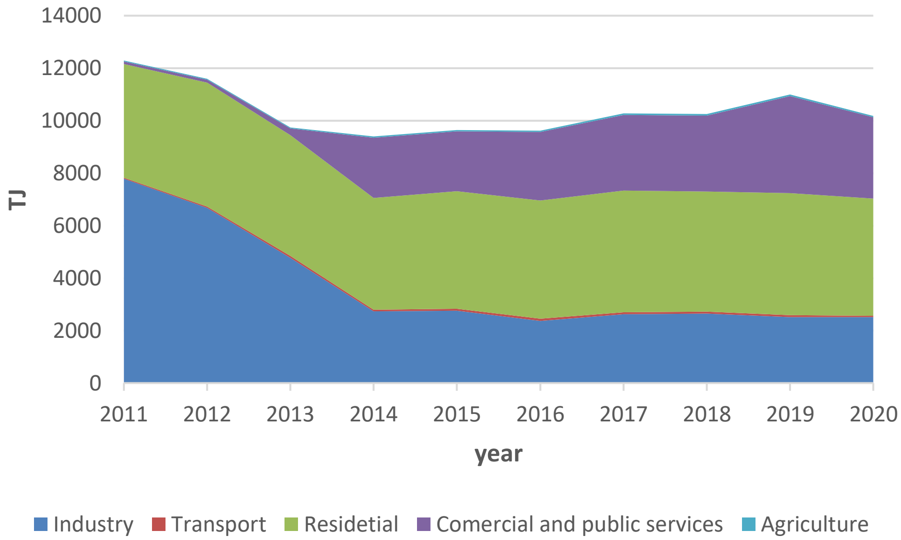

Figure 14. Electricity consumption by sector in Montenegro [9]

Montenegro for 2020 was as follows: residential sector (43,9%), public and service sector (30,4%), industry (24,8%), agriculture (0,5%) and transport (0,4%). In Montenegro, the transport sector is the smallest consumer of electricity in the entire observed period. Furthermore, the transport sector burdens the electric power system of Montenegro to a very small extent, and mostly rail traffic as a sub-sector of transport.

4. CO_2 EMISSION

This chapter provides an overview of CO_2 emissions by sector in the world, Europe, and Montenegro. Data on CO_2 emissions were taken from the International Energy Agency [9]. Data on CO_2 emissions by sector for Montenegro are not available in the source [9], so they were taken from [12].

4.1. CO_2 emissions by sector in the world and Europe

The emission of CO_2 by sector in the world for the period from 2011 to 2020 is shown in Figure 15 [9]. The CO_2 emission in the period from 2011 to 2020 had an increasing trend. In 2020, a significantly lower CO_2 emission was emitted, which was mostly caused by the significant suspension of industry and transport this year due to the pandemic of the COVID19 virus. The largest amount of CO_2 emissions were emitted in the electricity generation and heating sector, followed by the transport sector and the industrial sector in the entire period from 2011 to 2020. The fact that the most CO_2 emissions were emitted in the electricity generation and heating sector is not surprising because most of the electricity in the world is produced by burning coal. The most CO_2 emissions in 2020 in the world were emitted by the following sectors: electricity production and heating (42,9%), transport (22,4%), industry (19,5%) and other sectors (15,2%).

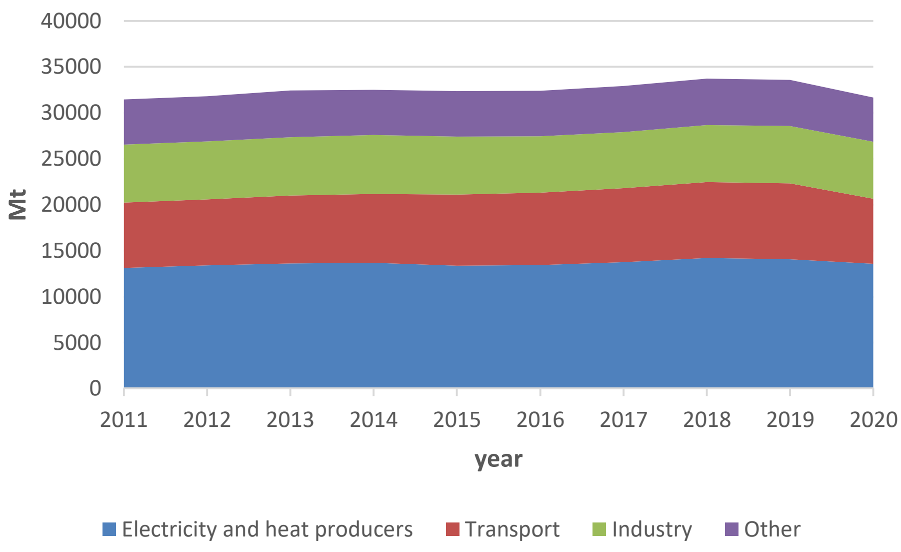

Figure 15. CO_2 emissions by sector in the world [9]

CO_2 emission by sector for the period from 2011 to 2020 in Europe is shown in Figure 16 [9]. Europe recorded a significant decrease in CO_2 emissions throughout the period, which is a consequence of various policies related to energy efficiency, reduction of fuel consumption, and decarbonization of the energy and transport sectors. In Europe, the highest emissions in 2020 were responsible for: electricity production and heating (32,4%), transport (27,7%), industry (14,7%), and other sectors (25,2%).

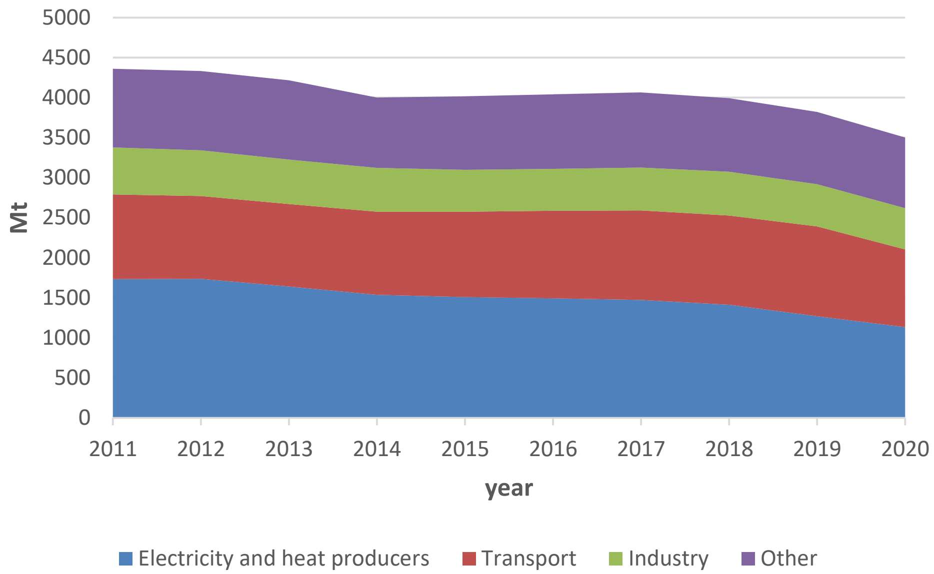

Figure 16. CO_2 emissions by sector in Europe [9]

4.2. CO_2 emissions by sector in Montenegro

Data on annual CO_2 emissions by sector are not available on the website of the International Energy Agency, as mentioned earlier, so this emission is shown according to the data of the website Our World in Data [12]. Figure 17 shows annual CO_2 emissions by sector in Montenegro for the period from 2011 to 2020 [12]. According to the data from the website Our World in Data, CO_2 emissions are shown from the electricity and heating production sectors, as well as from the transport sector. The highest CO_2 emissions in Montenegro in each year of the observed period come from the electricity and heating production sector. In 2020, CO_2 emissions in the electricity and heating production sector in Montenegro were 61,1%, and in the transport sector 38,9%. In the last few years of the observed period, there has been an increase in carbon dioxide emissions in the transport sector, but for example, in 2020, fewer CO_2 emissions were emitted in this sector compared to 2019. This decrease in the amount of carbon dioxide emissions in 2020 was probably caused in large part by the COVID-19 pandemic virus.

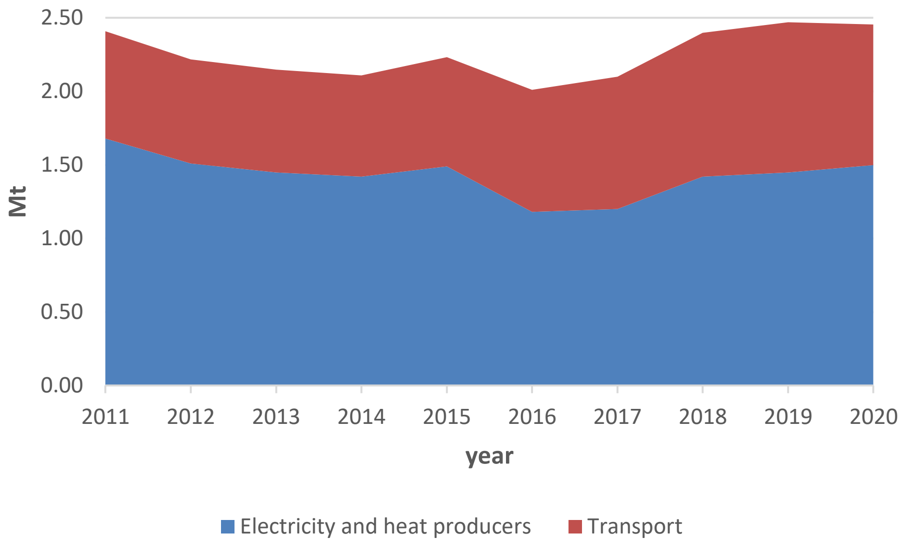

Figure 17. CO_2 emissions by sector in Montenegro [12]

4.3. CO_2 emissions per capita

In order to better compare the trends in the world, Europe, and Montenegro in terms of annual CO2 emission, it is necessary to show the amount of this emission per capita, which is done in this chapter. The annual CO_2 emission per capita for the period from 2011 to 2020 is shown in Figure 18 in the world, Europe, and Montenegro according to data from the International Energy Agency website [9]. The emission of CO_2 per capita in the world is maintained at an approximately constant level with a significant decrease in 2020, which was caused as a result of the COVID-19 virus. Europe, when it comes to emitted CO_2 emissions per capita, has a downward trend. In Montenegro, CO_2 emissions per capita from 2011 to the end of 2020 remained at an approximately constant level.

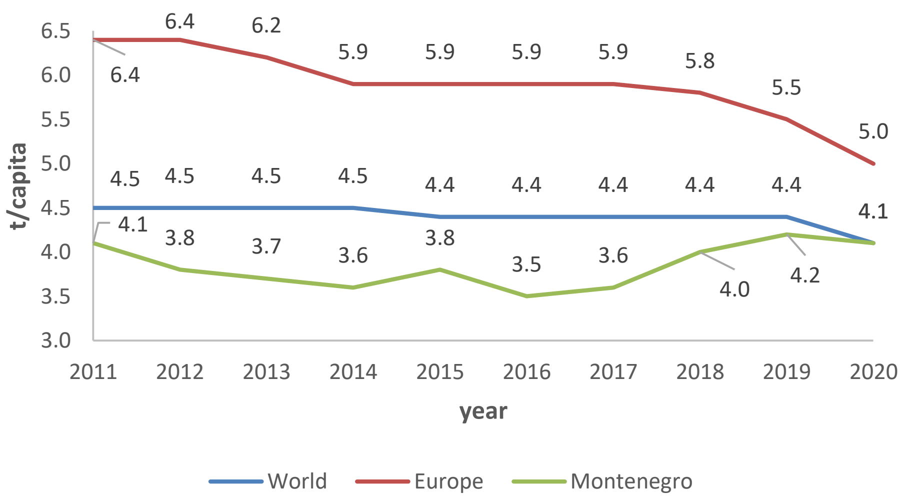

Figure 18. CO_2 emissions per capita in the world, Europe, and Montenegro [9]

5. CONCLUSION

Decarbonization of road traffic is one of the main priorities facing the world, and electrification is characterized as the most popular solution to this problem. In the world and Europe, a steady increase in sales of BEVs and PHEVs was recorded in the period from 2011 to 2020. The share of these vehicles in the total number of vehicles sold is also growing from year to year for the observed period from 2011 to 2020. However, despite the growth in the number of sold BEVs and PHEVs, as well as the growth of their share in the total number of vehicles, these vehicles still have a very small share in Europe of even 1%, and only 0,8% in the world in 2020. Montenegro has a very small percentage share of BEVs in the total number of vehicles in 2020, only 0,085%. Although the percentage share of BEVs and PHEVs in the total number of vehicles is relatively small, both in the world and in Europe, but also in Montenegro, an increase in the percentage share was recorded. Given the relatively small percentage shares of BEVs and PHEVs, it is not surprising that very little electricity is consumed in the transport sector. When it comes to the production of electricity by sources in the world, coal has the largest share. A relatively very small share of electricity both in the world and in Europe is produced from renewable-energy sources, if we exclude production in hydroelectric power plants, as a traditional renewable energy source. For the period from 2011 to 2020, a constant increase in the production of total electricity in the world is noticeable. In the world, for the mentioned period, the production of electricity from coal and natural-gas is increasing from year to year. In 2020, slightly more than 35% of electricity in the world was obtained from coal and slightly more than 23% from natural gas power plants. As shown in this paper, the largest share of electricity in the world is still produced in a not very clean way, which can have a very unfavorable impact on the decarbonization of road traffic through electrification. Montenegro receives most of its electricity from a thermal power plant and two large hydroelectric plants, but the share of new renewable-energy sources is also constantly increasing (two wind farms have been built in the last few years). Considering the very small share of BEVs and PHEVs, it is currently very difficult to discuss about the impact of these vehicles on CO_2 emissions. In the world for the period from 2011 to 2020, the total emission of carbon dioxide is constantly increasing. The sector with the largest share of carbon dioxide emissions is the electricity generation and heating sector. The second sector with the highest emission of carbon dioxide is the transport sector. A constant trend of increasing CO_2 emissions in the transport sector was recorded, with a very small decrease in 2019. Given that the transport sector in this paper includes all types of traffic, it would be important to see how much each type of transport has a share in the total carbon dioxide emissions in the transport sector, although when it comes to carbon dioxide emissions, road traffic plays a significantly dominant role. A large reduction in total CO_2 emissions was recorded in all sectors in 2020. The biggest impact on this reduction was the pandemic of COVID-19 virus because in 2020, all, industry was interrupted for a long period, and mobility was significantly reduced. In Europe, there is a decrease in total carbon dioxide emissions, which is a consequence of the great efforts of the European Union to reduce CO_2 emissions in the energy and transport sectors, through various policies and strategies. Despite the great efforts of the EU to reduce carbon dioxide emissions in the transport sector, if we look at the period from 2011 to 2020, in 2019 a record was achieved in terms of annual emissions in the transport sector when 1123 Mt of CO_2 emissions were emitted. The current share of BEVs and PHEVs in the total number of vehicles is relatively very small, so accordingly it has almost no influence on the total CO_2 emission, nor the CO_2 emission of the transport sector in the world, Europe, and Montenegro.

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