BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 73(2), 2025, Article number: e152609
DOI: 10.24425/bpasts.2024.152609

MECHANICAL AND AERONAUTICAL ENGINEERING, THERMODYNAMICS

Radial force variation parameter as a factor of tire uniformity

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Abstract. Market demands and trends related to ecology and sustainability significantly influence various industries, including the tire market. Tires are required to meet multiple performance criteria, such as braking efficiency, wet grip, and noise levels, while also conforming to uniformity parameters evaluated during the manufacturing process. Increasing the fuel efficiency of tires, which is directly related to reducing rolling resistance, results in a modification of tire materials, dimensions, and weight. As a result, components with lighter properties are used in tire construction, and at the same time, tires are subjected to higher loads. Research indicates that the green tire building process at the tire building machine has a key impact on the values and waveform of the tire radial force. The methodology of this study involved introducing controlled changes in the angular alignment of the individual drums participating in the green tire assembly process. This approach enabled the isolation and analysis of specific factors contributing to the shaping of the radial force variation (RFV) characteristics. For each configuration, a sample population of 20 tires was evaluated, with measurements taken for both RFV and waveform values. From these measurements, average RFV characteristics were generated. Each resulting characteristic was then compared to a reference specification in order to quantify the influence of the modified angular positions on RFV values and waveform behavior.

Keywords: waveform; tire assembling machine; green tire; radial force variation (RFV).

1. INTRODUCTION

1.1. Economic background

The global human population has grown steadily and rapidly since the second half of the 20th century. Between 1950 and 2023, the world population tripled to over 8 billion people [1]. Projections estimate that the global population will reach approximately 8.5 billion by 2030, 9.7 billion by 2050, and 10.9 billion by 2100 [2]. This unprecedented population growth has triggered significant transitions in the global economy. Rapid economic expansion during the second half of the 20th century and into the 21st century has driven a sharp increase in human demand for goods and services [3]. The transportation sector, a key pillar of the global economy, plays a crucial role in the lives of people. Increasing levels of mobility and trade have been observed, which, while facilitating economic development, have introduced environmental side effects. Transportation contributes to increased emissions and urban pollution [4], accounting for 65% of global oil consumption and 28% of total energy use. If current trends continue, transportation global energy demand is projected to double by 2050 [5]. In terms of greenhouse gas (GHG) emissions, transport is responsible for 14% of direct global emissions (Fig. 1). Furthermore, if oil consumption and discovery rates remain constant, global reserves could be exhausted by 2038 [6, 7]. This has led to growing concerns about resource depletion and a significant increase in CO_2 emissions, which drive global warming [9]. The fear of running out of natural resources and the worldwide fuel shortages together with efforts to protect the planet and the environment have created new challenges. These are also major drivers of the revolution in global industry aimed at sustainability [3]. To address the environmental impacts of population growth and transportation development, decisive actions were undertaken. One of them was proposed by the International Energy Organization in 2015. The challenge is to reduce the amount of greenhouse gas emissions from the transportation sector by at least 25%. However, the goal is to achieve a "net zero" level of greenhouse gas emissions by 2050 [10, 11]. The growth in population and vehicle ownership, combined with rising environmental pollution, significantly influences the goals of the automotive industry. Reducing emissions and mitigating the ef-

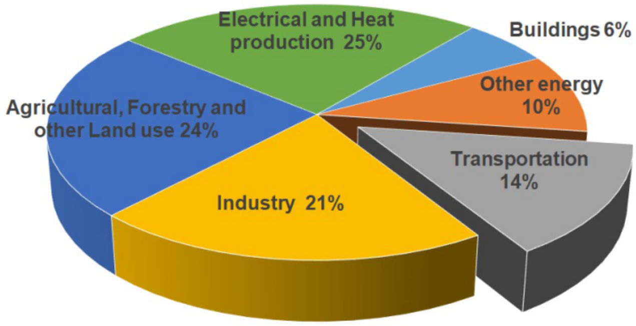

Fig. 1. Contribution of various economic sectors to greenhouse gas production [8]

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Manuscript submitted 2024-04-25, revised 2024-10-30, initially accepted for publication 2024-10-31, published in March 2025.

fects of industrialization have become major objectives, with a shift toward zero-emission vehicles during both manufacturing and usage [12]. Concerns about environmental and social issues have led to a change of economic, environmental, and social priorities in EU policy to remain viable and competitive. The European Parliament set out a detailed vision to transform Europe into the first climate-neutral continent by 2050. The goal of the member states is to eliminate pollution while increasing the competitiveness of European industry and ensuring a fair transition for affected regions and workers [13]. As a result, a turnaround in the transportation sector has been observed. Most research and development activities have been directed at achieving high efficiency, clean, and safe transportation. Electric vehicles (EVs), hybrid electric vehicles, and fuel cell vehicles have been proposed to replace conventional internal combustion vehicles in the near future [6]. Battery electric vehicles (BEVs), in particular, offer the advantage of zero tailpipe emissions, making them a compelling solution for reducing urban air pollution. BEVs also contribute to noise reduction [14]. Car manufacturers signed a declaration at COP26 to phase out combustion engine vehicles by 2035 or 2040 [15]. A noticeable shift toward electric mobility has been observed, with the electric vehicle market expanding significantly between 2010 and 2023 (Fig. 2). According to the International Energy Agency's annual report, the sale of EVs has risen sharply in recent years, with nearly 14 million electric vehicles sold worldwide in 2023. Market share for EVs increased from 9% in 2021 to 14% in 2022, and 18% in 2023 [16]. It is projected that by 2030, EVs will account for 30% of global car sales [17]. The economic and environmental trends also have an impact on the tire industries. The tire market is largely dependent on the automobile sector, known as the "industry of industries". This dependence causes difficulties in tire production that are closely linked to activity in the automobile market [18]. Economic development, population growth, environmental pollution, and source shortages of fossil fuels, among other things, have forced changes in the transportation sector in the European Union heavily geared toward the development of electric cars. While this transition offers numerous advantages, it also presents substantial challenges for both the automotive and tire industries.

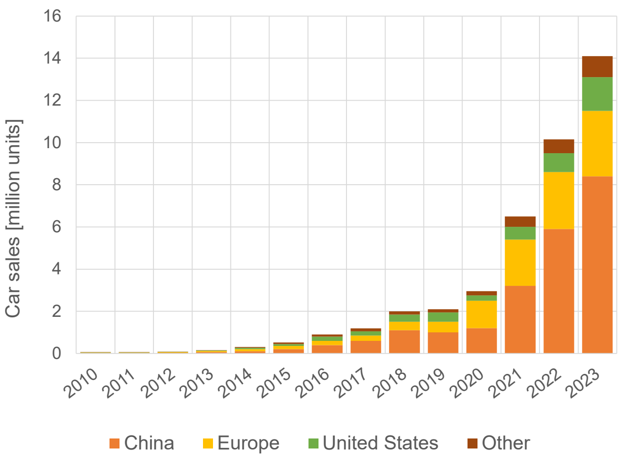


Fig. 2. Electric car sales 2010–2023 [16]

1.2. Economic and environmental impact on the tire industry

The development of electric cars is also reshaping the approach to tire design and production. Tires have a number of significant parameters for mobility and are fundamental for the safety of vehicles. Among other things, tires play several critical roles, including supporting the weight of the vehicle, transferring load to the road surface, providing grip for braking and acceleration, and acting as vibration absorbers. These functions enhance road comfort, improve safety, and contribute to the overall performance of the vehicle [19]. However, the requirement for an electric car is primarily range. This parameter is influenced especially by the capacity of the battery and its wear rate, the aerodynamics of the car, the weight, but also the quality of the tires, and their fuel efficiency. Figure 3 presents the increase in fuel consumption depending on the class of tires. Tires must meet the minimum requirements outlined in Regulation 2020/740 to be approved for sale in the EU market. One of the key parameters highlighted on the EU tire label is fuel efficiency. Tires are rated on a scale from A to E, with A representing the highest fuel efficiency and E indicating the lowest. This labeling system provides consumers with a clear understanding of how tire performance can affect vehicle fuel consumption or range, particularly for electric vehicles [21]. In the case of internal combustion engine cars, this means a reduction in fuel consumption, while in the case of electric cars. It means an increase in range. Fuel efficiency and consequently the range of an electric vehicle can also be improved by reducing tire rolling resistance. Rolling resistance is a critical parameter that significantly influences both economic and environmental factors. In terms of environmental impact, it affects CO_2 emissions, particularly when the energy source is nonrenewable. Variations in rolling resistance between different performance classes can result in an average fuel consumption difference of approximately 80 liters over the lifespan of tires in internal combustion engine vehicles. For battery electric vehicles, these variations can translate into differences of several tens of kilometers in driving range per charge [22]. The negative impact of the tire industry on environmental pollution is mainly related to rolling resistance and friction by tires. The stage of tire use is estimated to have an impact of up to 63%–96% on environmental pollution throughout its life cycle [8,23]. This is the fundamental reason to increase the fuel efficiency of a tire, which means reducing its rolling resistance. Rolling resistance is defined as the loss of energy per unit of distance travelled [24].

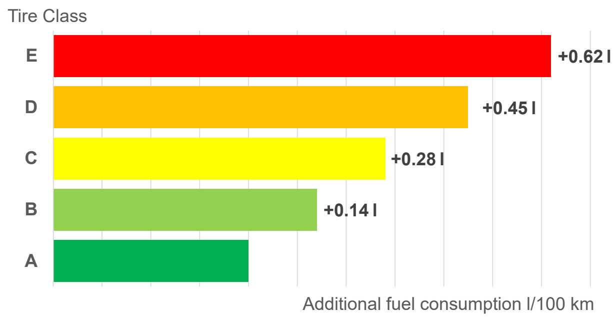


Fig. 3. Additional fuel consumption 1/100 km per tire class [20]

This energy loss is due to tire deformation, air drag, and friction at the contact path and depends on the aspect ratio of the tire, the materials applied, and the design [25]. Challenges faced by tire manufacturers extend beyond simply reducing rolling resistance; they must also ensure that other performance parameters are at least maintained, if not improved, simultaneously. These parameters include durability, wet and dry traction, braking efficiency, noise reduction, and ride comfort. Additionally, modern tire designs must align with market trends emphasizing ecological responsibility and sustainability. This primarily entails improving fuel efficiency, which is directly linked to reducing rolling resistance, as well as extending the overall lifespan of the tire. On the other hand, other parameters, and requirements, such as safety or comfort, cannot be ignored [26]. The solution to such a problem in the tire industry is called the "magic triangle" which highlights the need to balance three often conflicting requirements: rolling resistance, wear resistance, and grip (Fig. 4). Successfully optimizing these factors is crucial for achieving overall tire performance improvements. This balance is especially important in the context of electric vehicles, where reducing rolling resistance can significantly enhance energy efficiency and extend vehicle range, without sacrificing safety, durability, or comfort. Developing a compromise between high wear resistance, low rolling resistance, and high wet skid resistance is called "green tires" [27]. This means that no parameter in the "magic triangle" is omitted. The various components of the tire contain particular rubber compounds. For each of these, modifications are made to the compound formula to achieve the desired fuel class as indicated on the EU tire label. Additionally, efforts to reduce CO_2 emissions during tire manufacturing, especially by substituting fossil-based materials with biobased or recycled alternatives, are frequently highlighted as part of a green, sustainable approach. Examples of such alternative materials include rice husk ash silica, derived from the rice industry, and recycled black carbon, sourced from scrap tires [28]. Reducing tire weight is crucial, and to achieve this, components with lighter properties, as well as renewable rubber materials, are incorporated into tire construction [19, 27]. Research demonstrates that modifications to tire dimensions can further contribute to lowering rolling resistance. These adjustments not only enhance overall tire performance but also support improved fuel efficiency and range for electric vehicles. Rolling resistance decreases as the outer diameter increases. Furthermore, the tire aspect ratio, which is the ratio of its height to its width, also affects rolling resistance. An increase in the aspect ratio leads to higher energy dissipation, which can reduce tire efficiency by increasing rolling resistance. Therefore, optimizing both the outer diameter and the aspect ratio is essential for minimizing energy loss and enhancing fuel efficiency [11, 25, 29].

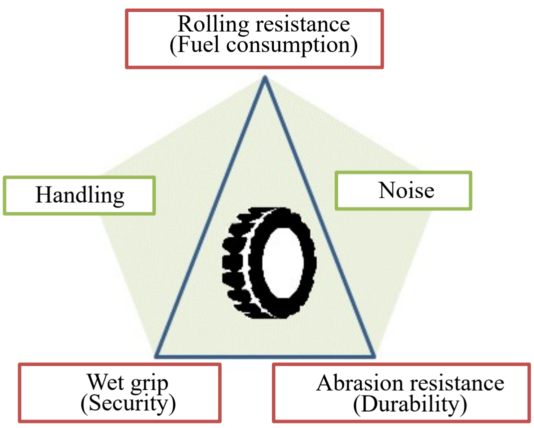


Fig. 4. Graphical illustration of tires "magic triangle" [19]

1.3. Uniformity parameters in the manufacturing process

In addition to meeting the performance requirements outlined in the "magic triangle" (rolling resistance, wear resistance, and grip), tire manufacturers must also satisfy stringent requirements for tire uniformity. This involves measuring parameters related to the interaction of forces within the tire to ensure consistent performance across different operating conditions. As ecological trends in tire production (such as the use of sustainable materials) and transportation (with the rise of electric vehicles) evolve, tires are now subjected to new and more demanding standards. Modern tires must simultaneously meet the requirements for:

- Uniformity;
- Reduced rolling resistance;
- Wear resistance;
- Wet grip;
- Noise;
- Handling;
- Durability.

Maintaining tire uniformity within specified limits is notably important for tire manufacturers. Uniformity directly influences production efficiency, as it reduces the number of tires rejected due to deviations in uniformity measurements. Ensuring consistent uniformity not only enhances the quality of the final product but also positively impacts business performance by minimizing waste, reducing production costs, and optimizing resource use. Moreover, consistent uniformity contributes to better vehicle performance, improving ride comfort and safety. The increased weight of electric vehicles compared to their internal combustion counterparts (Table 1) further complicates tire design.

Table 1
EVs vs ICEs weight [30]

Electric vehicle (EV)	Kerb weight EV (kg)	Internal combustion engine (ICE)	Kerb weight ICE (kg)
Peugeot 2008 II e-2008	1548	Peugeot 2008 II BlueHDi	1205
Peugeot 208 II e-208	1455	Peugeot 208 1.2 PureTech	1033
Volkswagen e-UP!	1530	Volkswagen Cross Up!	1300
Mercedes B 250e	1735	Mercedes B 250	1495
Mercedes SLS AMG Electric	2110	Mercedes SLS Black Series	1625

The compound and construction of the tire must support this additional weight, leading to a higher load index. The German WDK procedure recommends applying load based on the tire load index, which represents the maximum load-carrying capacity of the tire at a specific inflation pressure. This method ensures that tires are tested under conditions that accurately reflect the loads they will experience in real-world applications [31]. By aligning testing loads with the tire load index, manufacturers can better evaluate uniformity and performance, particularly under higher stress, such as in electric vehicles that typically have a higher load index due to their increased weight. This means that tires designed for electric vehicles undergo testing under higher loads when assessing uniformity, which can impact the results of measurements like RFV. These increased loads create conflicting demands on tire design, making it challenging to optimize all aspects of tire performance simultaneously. The measurement of tire uniformity parameters involves using a measuring drum to assess individual forces and under defined pressure and load conditions. Low-speed uniformity measurements, typically conducted at 60 rpm, are used to evaluate radial force variation (RFV). Data are recorded by strain gauges mounted on the axis of the measuring drum (Fig. 5).

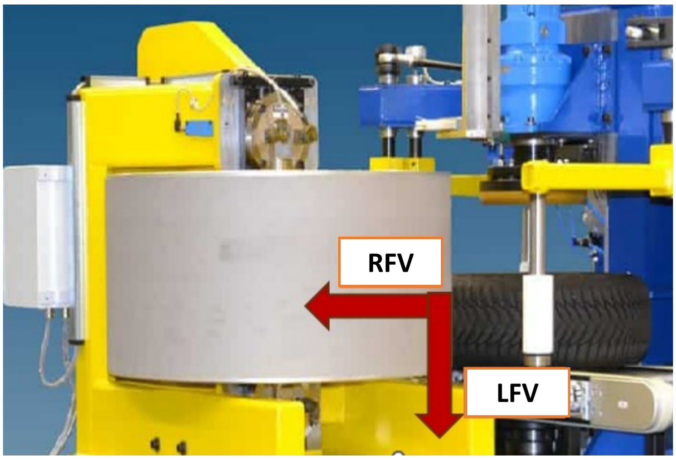


Fig. 5. Tire uniformity measuring drum [32]

While some customers may require high-speed uniformity testing, this is less common than low-speed testing.

During uniformity testing, both force variation and geometrical parameters are recorded:

- RRO (radial run out);
- LRO (lateral run out);
- RFV (radial force variation) and harmonics analysis;
- LFV (lateral force variation);
- CON (conicity).

This article focuses mainly on RFV and RFV1H (radial force variation 1st harmonic). RFV represents the force acting perpendicularly to the spindle of the low-speed uniformity test machine, reflecting the magnitude of the load applied to the tire [33]. RFV is often explained using a model of a ring with springs of varying lengths and constants. As the tire rotates, the springs compress upon contacting the surface and return to their original length when no longer in contact. The springs are characterized by different lengths and elastic constants, which results in a variable radial force during one rotation (Fig. 6). RFV serves as a key quality parameter, describing tire uniformity under load by quantifying the variation (the difference between maximum and minimum values) in the load applied to a vehicle axle during a single tire rotation [34]. RFV might be affected by many factors during tire production. It is possible to influence the uniformity parameters at each stage of production from materials preparation and green tire building on the tire assembling machine, to curing and final inspection of forces and moments. As automotive design has evolved, maintaining acceptable uniformity values has become increasingly challenging. Vehicle constructions are becoming lighter, while electric vehicles, according to researchers at the University of Leeds, are on average 312 kilograms heavier than their internal combustion engine counterparts due to the weight of their batteries [36]. Consequently, tires undergo uniformity testing under increased loads, further complicating the control of these parameters.

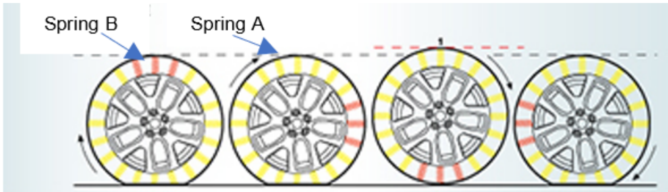


Fig. 6. Radial force variation spring model [35]

In scientific literature, the analysis of tire uniformity, particularly when tested at low speeds, is seldom discussed. Instead, much of the focus is on tire performance characteristics that influence driving dynamics, as outlined in Section 1.2. Research on tire manufacturing processes is rarely available mainly due to manufacturers' reluctance to share sensitive production data. Some information can be found in patent literature, where methodological details are often presented. However, these patents generally do not provide detailed results, making it challenging to evaluate the effectiveness of the proposed methodologies.

2. RESEARCH PROBLEM

Uniformity parameters can be influenced at any stage of production. At the same time, correction of RFV parameters is possible in individual stages. This article focuses on the green tire building stage which is a complex process requiring multiple stages and the application of several components. Particular types of machines produce green tires, consisting of two, three, and even four drums [37]. The study described here was conducted on a machine with three drums, as illustrated in Fig. 7.

Materials are applied to the drums located on both sides of the machine. On the carcass drum, components such as the inner liner, sidewall, and one or two body plies are applied. Depending on the tire design, additional materials such as textiles or a run-flat insert may also be included. Steel belts, cap plies, and tread are applied to the B&T (belt and tread) drum. Once the carcass drum diameter is expanded, the bead is applied, and the drum is moved toward the shaping drum. The carcass is then captured by the carcass transfer ring and transported to the shaping drum. On the other side of the tire-building machine, materials (belt, cap plies, and tread) are captured by the B&T transfer ring and are also transferred over the shaping drum. Under pressure, the carcass is expanded and bonded with the materials from the B&T drum, completing the shaping process.

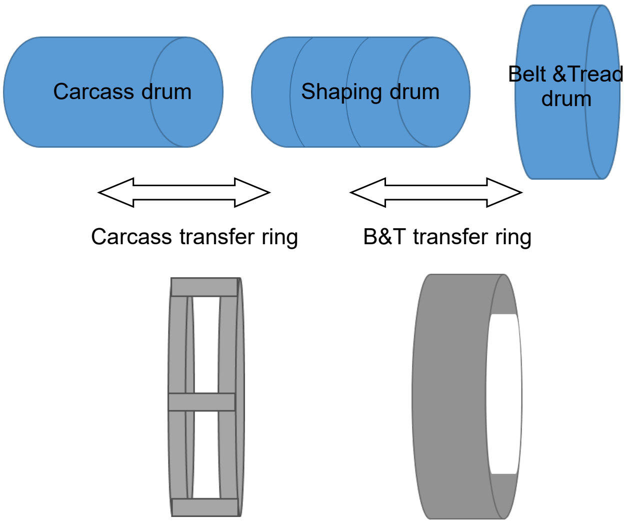


Fig. 7. Green tire building at tire building machine – scheme

As depicted in Fig. 7, the green tire manufacturing process involves several sequential steps. During the building of a green tire, materials are systematically applied to different drums (such as the B&T and carcass drums), then bonded and transferred via transfer rings, where the green tire is shaped under pressure on the shaping drum. Given the wide range of materials involved in tire construction such as the inner liner, body plies, sidewalls, belts, and tread the uniformity of the cured tire can be affected at any stage of the green tire assembly process. Each phase introduces the potential for variations that may impact the final uniformity of the tire.

Exceedances in RFV and RFV1H values can stem from numerous sources. Shifting the angular position of individual drums allows one to specify the element that affects tire nonuniformities. To determine the root cause of tire nonuniformities, it is necessary to compare the results of RFV and harmonic parameters, as well as to analyze the waveforms from individual experiments.

3. RESULTS AND DISCUSSION

The research presented in this article was conducted using one of the most popular tire sizes, 245/45 R19. The rotation of the selected drums of the tire assembling machine was used to assign the influence of each machine element on the uniformity parameters of the tire. While transfer rings only move horizontally and lack the rotational capability, an 180° rotation of specific drums during material application and transfer ring capture was implemented. To determine the influence of each machine element, measurements were taken for six different experimental conditions:

- Reference specification.
- Carcass transfer ring factor (carcass and shaping drum rotation).
- Shaping drum factor (carcass and B&T drum rotation).
- B&T transfer ring factor (B&T and shaping drum rotation).
- B&T drum transfer ring factor (material application position to B&T drum and B&T drum rotation).
- Reference parameters recovery.

All tires were tested under a 5 kN load and inflated to 0.2 MPa. For each experimental condition, at least 16 tires were produced, and the average results for each version are presented in Fig. 8. Compared to the reference specification, there is a significant increase in the RFV and RFV1H values for the carcass transfer ring and shaping drum. In contrast, the lowest values were recorded for the B&T transfer ring, with RFV at 59 N and RFV1H at 39 N. Similarly for the average characteristics of RFV (Figs. 9–14a), the most significant discrepancy in RFV waveform for the B&T transfer ring is noticeable. In most versions, the minimum of the waveform occurred around 130°. However, for the B&T transfer ring, the waveform magnitude was reduced, and its minimum shifted to approximately 270°. The radial force variation for the B&T transfer ring factor version (Fig. 10) is the lowest among the radial force variation plots presented in Figs. 9–14. The waveforms of radial force variation for each tested version are depicted in Figs. 9–14b. Across all plots, the repeatability of the waveforms is highly consistent, with similar phase, magnitude, and waveform shape, indicating reliable experimental results. Figure 15 presents a schematic representation of the methodology employed in the study. This schematic outlines the key steps involved in the process.

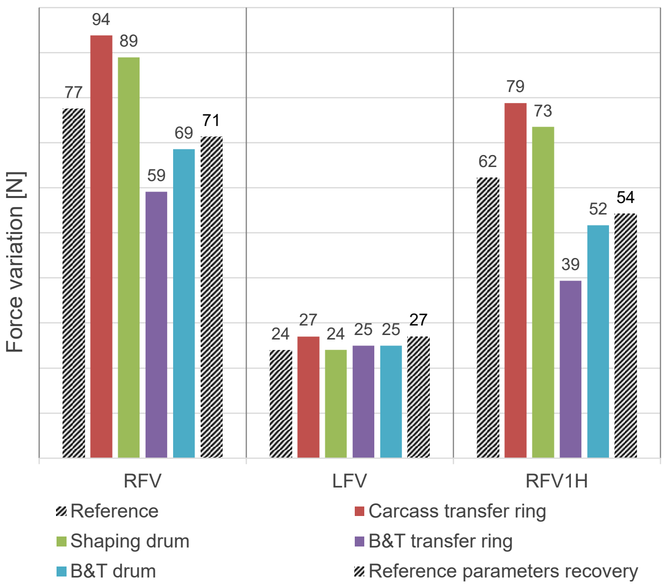
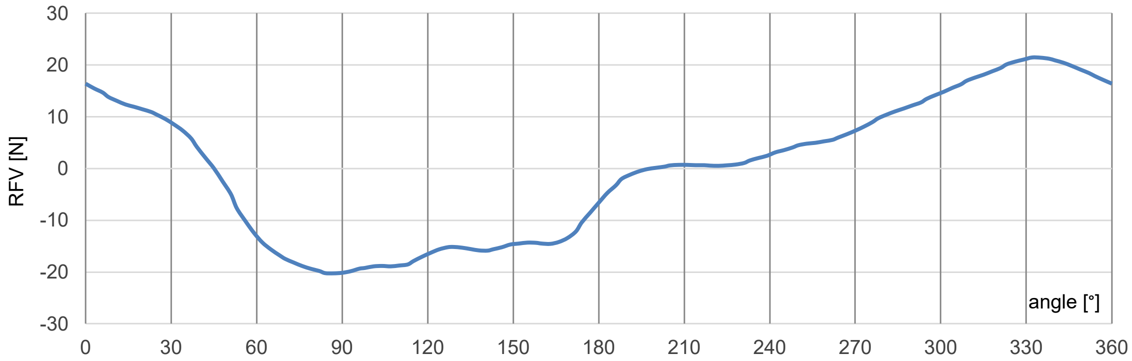


Fig. 8. Average results of selected uniformity parameters for 245/45R19



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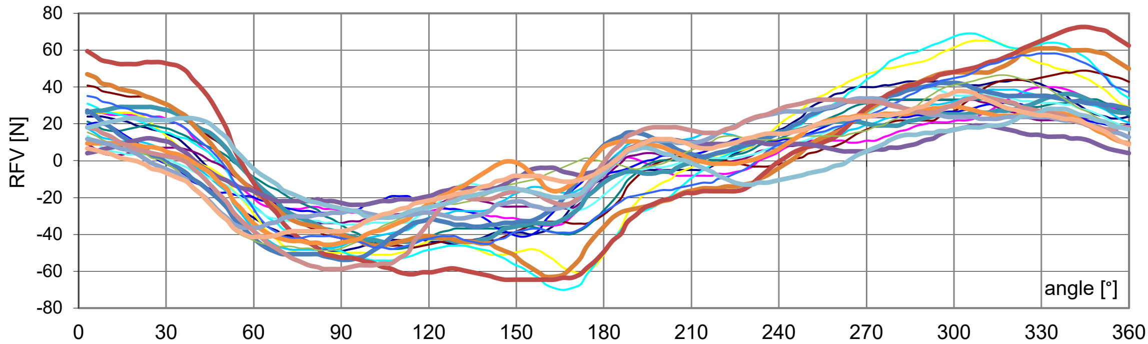
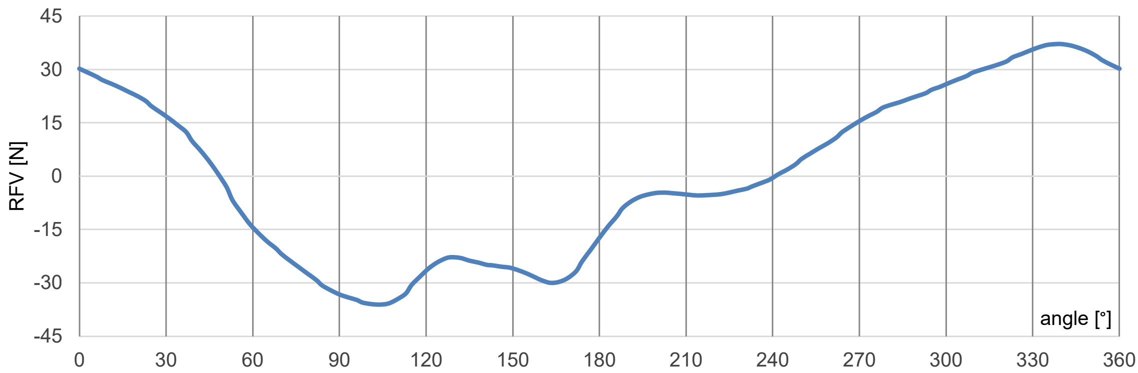


(b)

Fig. 9. Reference specification: (a) average waveform; (b) partial waveforms



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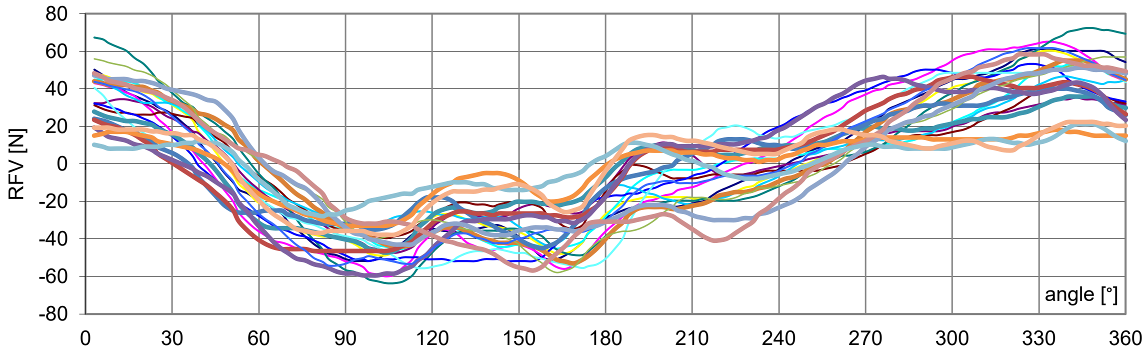
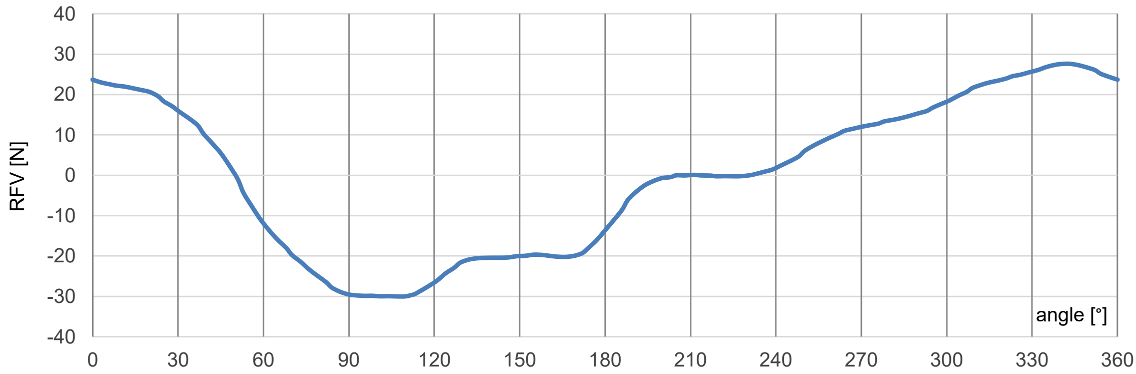


(b)

Fig. 10. Carcass transfer ring factor: (a) average waveform; (b) partial waveforms



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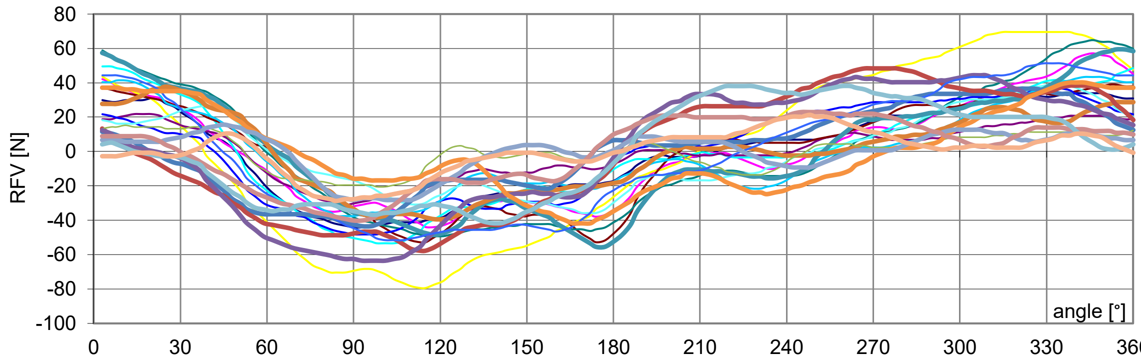
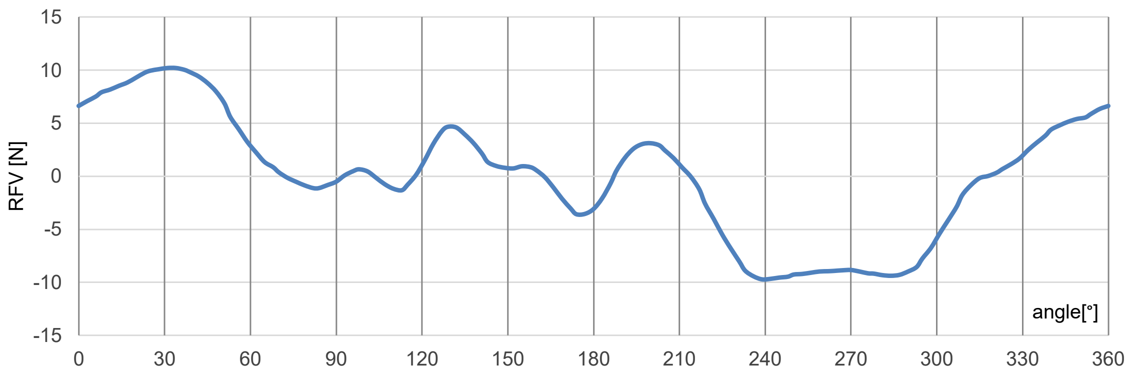


(b)

Fig. 11. Shaping drum factor: (a) average waveform; (b) partial waveforms



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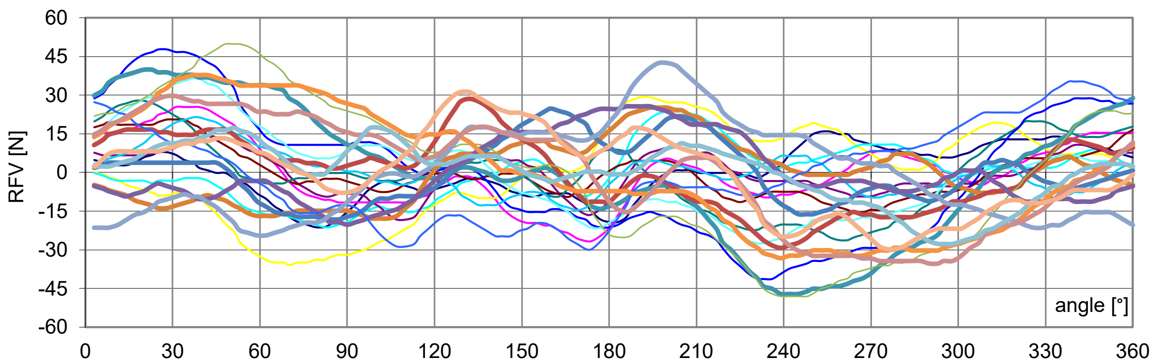

(b)

Fig. 12. B&T transfer ring factor: (a) average waveform; (b) partial waveforms

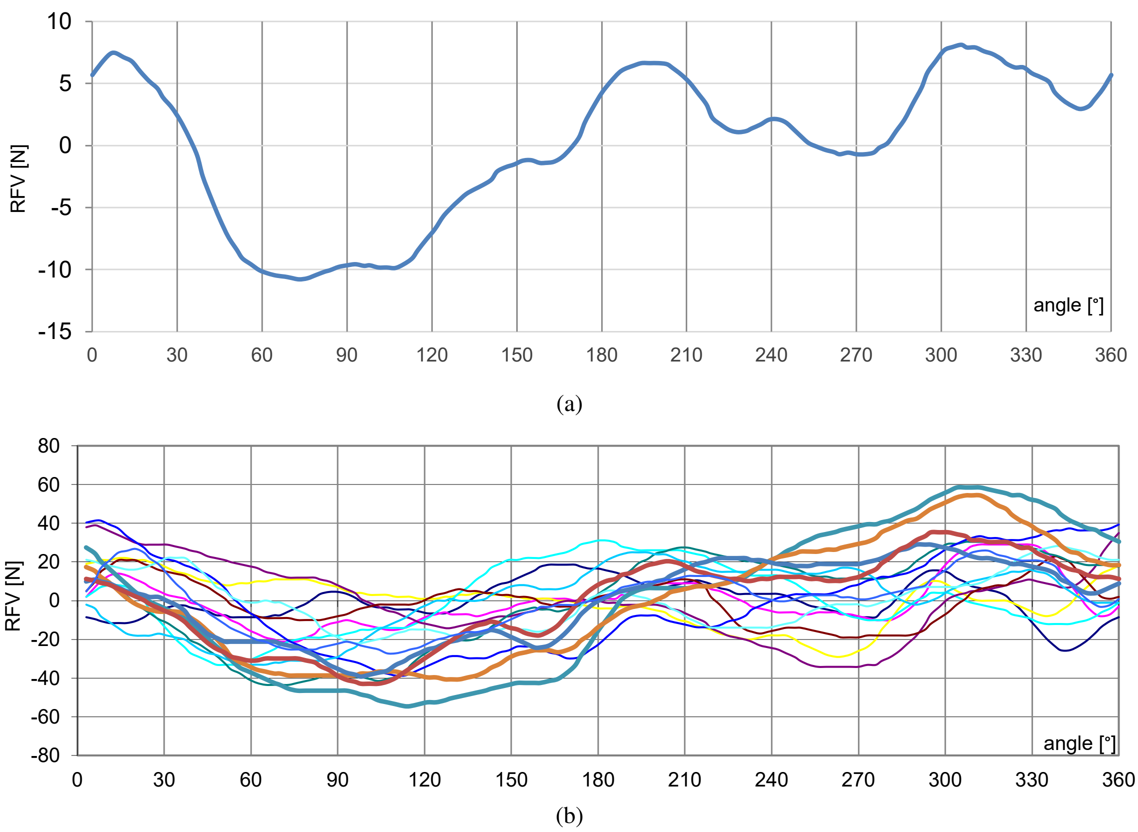

Fig. 13. B&T drum: (a) average waveform; (b) partial waveforms

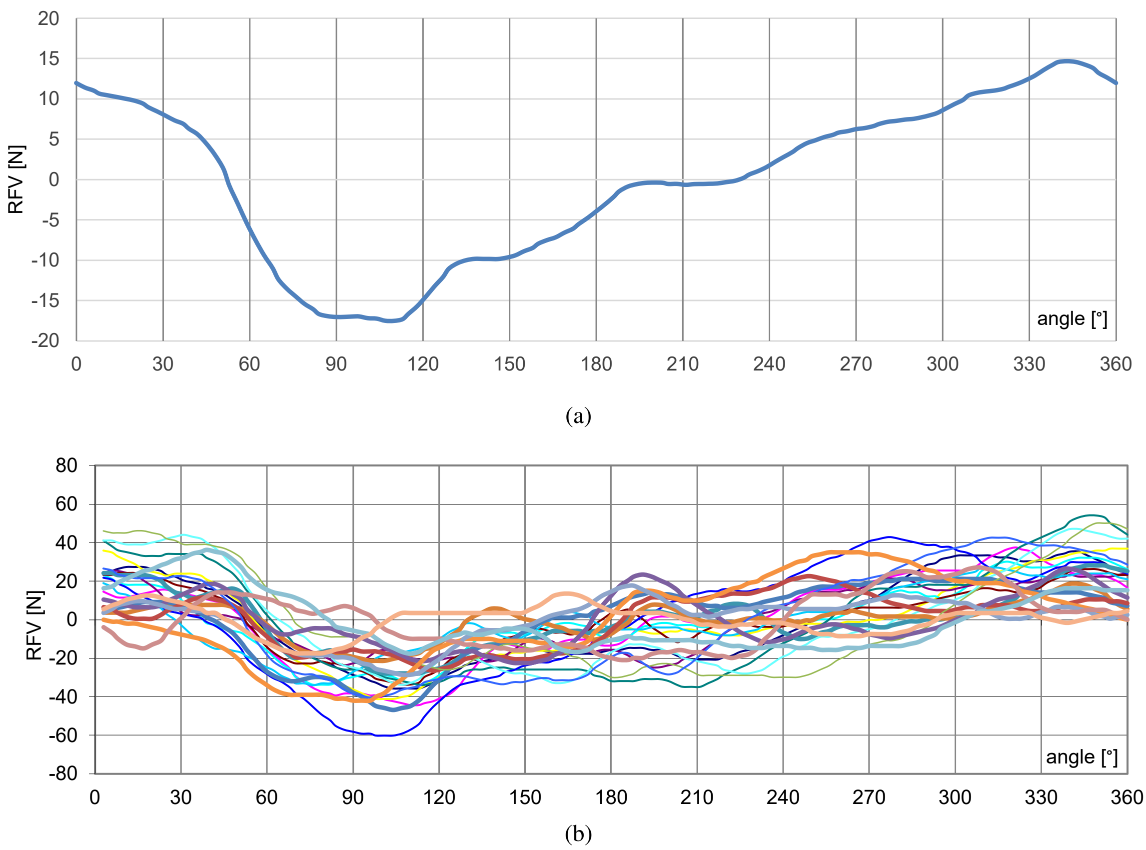

Fig. 14. Reference parameters recovery: (a) average waveform; (b) partial waveforms

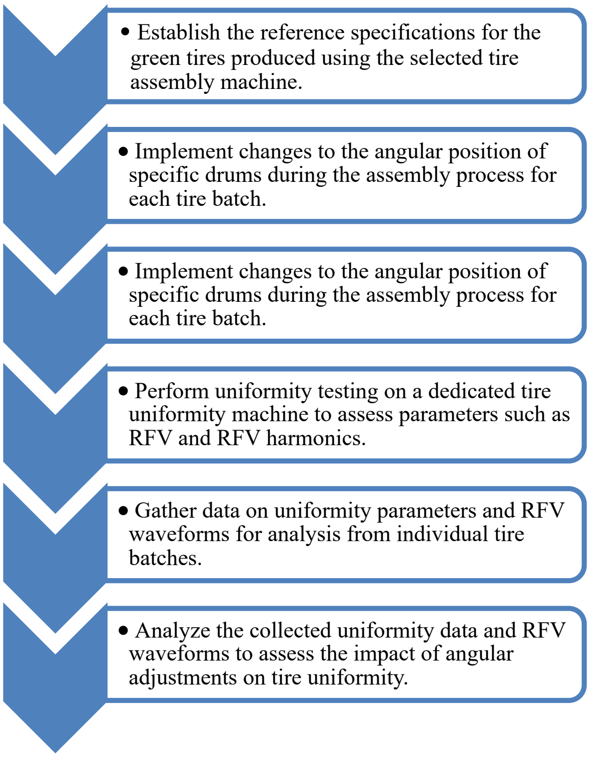

Fig. 15. Research methodology flowchart

4. CONCLUSIONS

The presented research clearly demonstrates the influence of individual elements of the tire assembly machine on the uniformity of the cured tires. Variability in the uniformity parameters, particularly in RFV and RFV1H values, as well as in the shape of the RFV waveform, is evident. Experiments conducted by adopting an analogous method definitely show that tire production on a tire assembly machine has a major impact on the measured uniformity parameters of a cured tire, mainly RFV and RFV harmonics. However, while this study highlights the impact of elements such as the B&T transfer ring on tire uniformity, it does not fully resolve the challenge of controlling these parameters. Based on the experiments, it is hypothesized that the geometry of the tire assembly machine and the interactions between its components contribute to variations in RFV and RFV1H values, as well as the resulting waveform patterns. Future work will aim to identify the root causes behind the shaping of the final RFV characteristics. Detailed geometric measurements of the tire assembly machine will be conducted to determine which components exert the greatest influence on the forces generated in the cured tire. Geometric values (e.g., concentricity) will be directly correlated with RFV waveforms and generated forces. This approach will allow for the development of a preliminary predictive model for radial force variation, based on the geometric characteristics of the tire assembly machine.

ACKNOWLEDGEMENTS

The authors thank the Polish Ministry of Education and Science for financial support (Applied Doctorate Program, No. DWD/6/0175/2022).

This research was funded by the Ministry of Science and Higher Education grant no. 0614/SBAD/1579 and no. 0614/SBAD/1586.

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