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AI-driven Optimization Techniques for Tire Pollution Mitigation in EVs: A Conceptual Framework

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Abstract— *The burgeoning demand for electric vehicles (EVs) emphasizes the growing preference for sustainable transportation options. However, alongside the numerous benefits associated with EV adoption, there arises an insistent concern regarding tire pollution. Recent studies have revealed that a single EV can release approximately 4 kilograms of tire particles into the environment annually, exacerbating air quality issues. To mitigate this environmental challenge, the current study proposes several optimization techniques aimed at curbing tire particle emissions from EVs such as Modification of Tire Material Composition, Enhancement of Tire Layer Strength, Implementation of AI-Based Automatic Spraying Systems, and Deployment of AI-Based Automatic Tire Protection Systems. Employing these optimization techniques, will ameliorate tire wear resistance and mitigate the dispersal of particles into the air as pollutants. The selection of a specific technique for implementation on EV tires is contingent upon application requirements, customer preferences, and technological advancements. Moreover, these strategies guarantee ancillary benefits, including improvements in tire lifespan, temperature management, and overall performance. In summary, the present study endeavors to address the increasing issue of tire pollution associated with EVs through innovative optimization techniques. By prioritizing environmental sustainability and tire performance enhancement, this research strives to contribute to the ongoing evolution of eco-friendly transportation solutions.*

Index Terms— *Tire Pollution, Material Composition, Tire Layer Strength, AI-based Automatic Spraying Systems, AI-based Automatic Tire Protection Systems, Eco-friendly, Environmental Sustainability.*

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I. INTRODUCTION

The degrading Air Quality Index (AQI) is a pressing concern of the present generation. With the introduction of each new technology, comes the challenge of mitigating its impact on the environment. Over the past few decades with the proliferation of the vehicle industry, the environment has continued to suffer tremendously due to the direct and indirect consequences of vehicular emissions. Albeit electric vehicles (EVs) were adopted to curb the air pollution caused by conventional means of transportation, recent studies and reports indicate that EVs contribute substantially to air pollution through non-exhaust emissions (NEE). This minuscule yet hazardous particulate matter (PM) pollution further exacerbates the quality of air [1] [2]. PM is generally classified based on its size, either as PM25 (particles of $\leq 2.5\mu m$ diameter particles) or PM10 (particles of $\leq 10\mu m$ diameter), the PM from NEE of brake, tire, and road wear falls under the PM10 category. Several studies have suggested that due to the increased torque and acceleration coupled with the weight of the batteries in EVs, lead to amplified tire and road wear [3]. The chemical molecules of the NEE mainly comprise heavy metals such as iron (Fe), zinc (Zn), lead (Pb), and copper (Cu) [4]. Tire-pavement abrasion varies based on the size of the vehicle, driving behavior, and road conditions. According to several health reports and research, this PM released into the atmosphere has been known to increase mortality and cause diverse health complications, including cancer, lung, and heart disease along with neurodivergent disorders [5] [6] [7]. Scholars have concluded that PM has adverse effects even at low-level exposure [8], thereby underscoring the significance and urgency of mitigating PM emissions by adopting more sustainable alternatives.

While tire emissions are not exclusive to battery electric vehicles (BEVs), several studies have posited that the contribution of BEVs to PM10 emissions is comparatively greater [9]. Therefore, this study predominantly aims to propose a few conceptual alternatives that can be adopted in the manufacturing and maintenance of BEV tires to reduce abrasion thereby contributing significantly to the reduction of NEE and PM emissions. In addition to elucidating the challenges associated with tire abrasions, the present study offers comprehensive insights into four prospective solutions encompassing, tire material composition, tire layer strength, AI-based automatic spraying system, and tire protection system.

II. BACKGROUND

In a survey and interview study conducted by Raheb and Mats (2022 [10]) numerous users' experiences with tire wear has been investigated. The findings of the survey indicate that about 33% of private users and 12.5% of professional users observed accelerated tire wear in their EVs, compared to Internal Combustion Engine Vehicles (ICEVs). Overall, most professional users reported tire wear rates similar to those of ICEVs across all types of electric vehicles. Acceleration and vehicle weight emerged as the primary factors associated with increased tire wear, while driving behavior was cited most frequently as the reason for reduced tire wear compared to ICEVs [11]. In their study, Timmers and Atchen (2016 [12]) compared the running mass of EVs with their ICEV equivalents and deduced that there exists an average weight disparity of 24% leading them to hypothesize that road-tire abrasion escalates proportionally with vehicle weight, therefore concluded that EVs experience more tire-wear than the conventional ICEVs. While numerous studies, including those discussed, have highlighted the influence of tire abrasion and its association with Electric Vehicles (EVs), only a small fraction have proposed effective strategies to mitigate its environmental impact. In a research conducted by Papaioannou et al., (2021 [13]), the authors present a sensitivity analysis of the external and internal factors that affect tire wear and propose certain optimization of tire and suspension parameters to minimize tire wear and increase the comfort of the passengers and drivers. However, their research prioritizes the vehicle's condition and user comfort over addressing pollution generated by tire wear. Furthermore, it does not exclusively concentrate on EVs. Hence, the present study seeks to introduce sustainable optimization approaches that, if implemented in the production of EV tires, could substantially reduce tire pollution and NEE.

III. METHODOLOGY

In this section, along with the detailed explanation of each of the four conceptual approaches, all the corresponding factors and variables to each method are also briefed upon.

A. Refining Tire Material Composition by Integrating Urea Formaldehyde

The principal determinants of tire performance encompass material composition and its inherent properties. An optimal tire is characterized by superior wear resistance and elasticity (U.S Department of Transportation, 2006 [14]). This study proposes the integration of urea formaldehyde into rubber matrices owing to its notable abrasion resistance [15]. Leveraging urea formaldehyde in powdered form, the proposal advocates for its incorporation into rubber compounds at varying proportions, subject to empirical investigation to establish the optimal blend ratios. Subsequent to the determination of the composition, a series of tests should be conducted to evaluate key performance metrics, including but not limited to:

1) **Wear Resistance:**

The wear resistance of tires is crucial in determining their longevity and performance under varying road conditions. This parameter evaluates the ability of the tire to withstand abrasive forces exerted during vehicle operation, such as frictional contact with road surfaces and exposure to environmental elements [16]. Through standardized wear tests, including abrasion tests and tread wear evaluations, the resistance of the proposed urea formaldehyde-rubber composite to wear-induced degradation can be systematically tested [17]. Comparative analyses with conventional tire materials will provide insights into the effectiveness of the proposed composition in curbing wear-related issues.

2) **Elasticity**

Elasticity, characterized by the tire's ability to deform and recover its shape under applied loads, is a fundamental property influencing ride comfort, handling stability, and overall vehicle performance [18]. Several studies have deduced that the incorporation of urea formaldehyde into rubber matrices influences the elasticity of the resulting composite material by extensively reinforcing it [19] [20] [21]. Therefore, comprehensive mechanical tests, such as tensile tests and dynamic mechanical analyses, can be conducted to quantify the elastic modulus, resilience, and hysteresis of the composite material. These evaluations will elucidate the impact of urea formaldehyde content on the elasticity of the tire, guiding the optimization of composite formulations to achieve desired elastic properties.

3) **Fatigue Strength**

Fatigue strength assessment is imperative to ascertain the durability and structural integrity of tires subjected to cyclic loading conditions during vehicle operation [22]. Fatigue tests, such as the rolling fatigue test and the flexural fatigue test, can be performed to simulate real-world operating conditions and evaluate the resistance of the tire composite to fatigue-induced failure mechanisms, including crack propagation and material degradation [23]. By systematically varying the urea formaldehyde content and conducting fatigue tests under controlled conditions, the fatigue strength of the composite material can be determined, thereby providing more insights on the design considerations to ameliorate tire durability and longevity.

4) **Rolling Resistance**

Rolling resistance, defined as the force required to maintain the forward motion of a tire against the resistance of the road surface, directly impacts vehicle fuel efficiency and energy consumption [24]. Through standardized rolling resistance tests, the influence of urea formaldehyde content on the rolling resistance of the tire composite can be evaluated [25]. Comparative analyses with conventional tire materials will elucidate the potential for reducing rolling resistance and improving fuel efficiency through the incorporation of urea formaldehyde into the rubber matrix.

5) **Thickness Reduction per Particular Time Interval**

The assessment of thickness reduction over specified time intervals provides insights into the wear characteristics and material degradation of the tire composite during service life [26]. Through accelerated aging tests and field trials, the rate of thickness reduction of the tire tread and sidewall can be monitored under simulated operating conditions [27]. By correlating thickness reduction data with urea formaldehyde content and environmental factors, the durability and long-term performance of the composite material can be evaluated, facilitating the optimization of tire design and material formulations for extended service life.

Tire Pattern Printing Feasibility

The feasibility of tire pattern printing, encompassing the application of tread patterns onto tire surfaces, is crucial for ensuring optimal traction, handling, and safety performance [28]. Through experimental studies and computational simulations, the compatibility of the urea formaldehyde-rubber composite with tire pattern printing processes can be assessed [29]. Factors such as printability, pattern adhesion, and durability can be evaluated to determine the suitability of the composite material for incorporating customized tread designs. These analyses will inform design considerations for enhancing tire performance to prevent frequent wear.

These assessments are essential to gauge the efficacy of the proposed composition in enhancing tire durability and functionality. Furthermore, they serve as pivotal benchmarks for informing manufacturing practices and optimizing tire design for enhanced performance and longevity.

B. Enhancing Tire Layer Strength through Metal Reinforcement

Strengthening tire layers through the incorporation of metal reinforcement presents a promising avenue for strengthening structural integrity and load-bearing capacity. Even though not sufficient research has been conducted to understand the potential of incorporating metal sheets within the tire layers to increase its robustness and longevity, Kovac and Rodgers (1994 [30]) explored the notion of incorporating steel wires and brass plating. The addition of metal mesh sheets within the tire layers offers a robust solution to withstand mechanical stresses and fatigue-induced degradation, thereby extending tire lifespan and enhancing performance under varying operating conditions. By strategically integrating steel mesh sheets into the tire architecture, engineers can optimize load distribution and ameliorate resistance to deformation and puncture.

The proposed approach involves the implementation of multiple layers of metal mesh sheets arranged in a patterned format as shown in **Error! Reference source not found.**., to maximize reinforcement effectiveness. Specifically, a steel mesh sheet is positioned circumferentially along the tire circumference, providing fundamental support to withstand radial loads and lateral forces encountered during vehicle operation. Moreover, two additional mesh sheets are assembled in a zig-zag configuration over the circumference mesh, further enhancing structural stability and resilience.

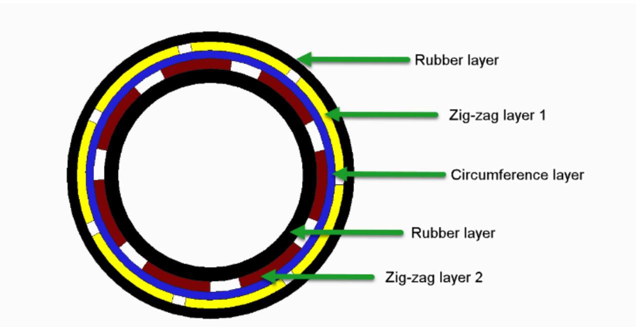

Fig. 1. Layering Metal Sheets

The strategic placement of metal reinforcement within the tire layers offers several benefits, including improved resistance to tread wear, enhanced puncture resistance, and optimized handling characteristics. Furthermore, the use of metal mesh sheets allows for customization of reinforcement patterns to address specific performance requirements and optimize material utilization.

Comprehensive testing protocols, including static and dynamic load tests, fatigue tests, and durability assessments, are essential to validate the effectiveness of the metal reinforcement strategy. Through systematic evaluation of mechanical properties, such as tensile strength, modulus of elasticity, and fatigue resistance, engineers can optimize the design and composition of the reinforced tire layers to achieve desired performance targets.

Overall, the integration of metal reinforcement represents a robust approach to enhancing tire layer strength and durability, offering significant potential to mitigate common failure modes associated with tire operation and improve vehicle performance and safety in whole.

C. AI-Based Automatic Spraying System for Mitigating Tire Particle Contamination

The implementation of an Artificial Intelligence (AI)-driven automatic spraying system [31] represents an innovative solution to mitigate tire particle contamination and ameliorate tire longevity and performance. By leveraging artificial intelligence algorithms, this automated system monitors tire condition and environmental factors in real-time, enabling proactive maintenance measures to mitigate wear and reduce particle emissions. Albeit this system has not been adopted in the automobile industry to curb emission, AI does offer an easy and substantial solution in the current age. With a similar purpose, Marcin et al., (2023 [32]) proposed the idea of AI in Tire Quality Control that would automatically detect any defects in the tire enabling predictive maintenance.

The core components of the automatic spraying system include a reservoir containing water-based solutions, a network of sensors for monitoring tire dryness and surface condition, and actuators for controlled spraying operations. The AI algorithm utilizes sensor data to dynamically adjust spraying frequency and volume based on tire usage patterns, environmental conditions, and wear characteristics.

The selection of water-based solutions for tire spraying offers several advantages, including biodegradability, eco-friendliness, and compatibility with tire materials [33]. Moreover, the controlled application of spraying liquids helps maintain tire surface integrity, reducing the likelihood of tread wear and abrasion-induced particle emissions.

The effectiveness of the AI-based automatic spraying system can be validated through extensive field testing and performance evaluation. By monitoring tire wear rates, particle emissions, and overall performance metrics, engineers can assess the system's efficacy in mitigating tire contamination and enhancing tire lifespan [34].

Overall, the integration of AI-driven automation offers a proactive approach to tire maintenance, promoting sustainable mobility practices and minimizing the environmental impact associated with tire wear and particle emissions. By harnessing advanced technologies and eco-friendly solutions, the automatic spraying system represents a significant advancement in tire maintenance and performance optimization.

D. Sizing of Graphics

The implementation of an AI-based automatic tire protection system, incorporating interim layers, represents a proactive measure to safeguard tires against wear and minimize environmental impact. This innovative system utilizes advanced artificial intelligence techniques to monitor road conditions in real-time and trigger the automatic engagement of protective interim layers when encountering rough terrain or adverse driving conditions [35].

The core components of the AI-based automatic tire protection system include sensors for detecting road surface irregularities, actuators for deploying interim layers, and an AI algorithm for decision-making and control. By continuously analyzing sensor data, the AI algorithm assesses road conditions and determines the optimal timing and extent of interim layer deployment to protect tires from abrasive surfaces and minimize wear.

Interim layers, composed of durable and resilient materials, are strategically deployed to cover tire surfaces and provide an additional barrier against abrasion and damage. These protective layers act as a shield, absorbing the impact of rough terrain and reducing wear-induced particle emissions into the atmosphere. By minimizing tire wear and extending tire lifespan, the automatic tire protection system contributes to environmental sustainability and promotes resource conservation.

The engagement and disengagement mechanisms of the interim layer deployment system are designed to seamlessly integrate with the vehicle's existing architecture, ensuring minimal disruption to driving dynamics and handling characteristics. The system is equipped with sensors and actuators positioned at the wheel hub and axle end, enabling precise control over interim layer deployment based on real-time road condition analysis.

Comprehensive testing and validation procedures are essential to evaluate the effectiveness and reliability of the AI-based automatic tire protection system. Through rigorous field testing and performance evaluation, engineers can assess system responsiveness, durability, and overall performance under diverse operating conditions.

Therefore, the integration of an AI-based automatic tire protection system offers significant benefits in terms of tire longevity, environmental sustainability, and driving safety. By leveraging advanced technologies and proactive maintenance measures, this innovative system represents a key advancement in tire protection and performance optimization for modern vehicles.

IV. CONCLUSION

In conclusion, the current study presents a conceptual proposal of optimization techniques aimed at curbing pollution caused by tire wear in EVs through the integration of AI and innovative engineering solutions. By addressing the pressing issue of NEE from tire abrasion, the paper underscores the significance of sustainable transportation practices and environmental stewardship.

The proposed optimization techniques, including refinement of tire material composition, enhancement of tire layer strength through metal reinforcement, implementation of AI-based automatic spraying systems, and deployment of AI-based automatic tire protection systems, offer promising avenues for reducing tire abrasion and minimizing particle emissions into the atmosphere.

The study also recommends meticulous methodology encompassing empirical investigation, mechanical testing, and real-world performance evaluation, the efficacy and feasibility of each optimization approach for rigorous assessment. These techniques not only aim to mitigate tire pollution but also offer ancillary benefits such as improved tire lifespan, fuel efficiency, and driving safety and comfort.

Overall, by prioritizing environmental sustainability and tire performance enhancement, the study contributes to the ongoing evolution of eco-friendly transportation solutions and underscores the need for future research in AI-based optimization techniques for reducing tire pollution caused by EVs. Through the integration of AI-driven automation and innovative engineering solutions, the paper paves the way for a more sustainable future in the realm of electric vehicle technology.

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