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Design and Fabrication of a Built-in Tire Sensor for Green Energy Saving

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The environmental impact stemming from scrapped tires has indirectly affected ecological sustainability. One effective approach to mitigate the impact of tires on the environment is to enhance the wear resistance of tires. However, balancing wear resistance and meeting performance control requirements can be challenging. Therefore, improving drivers' driving habits can be regarded as another way of prolonging tire usage. In this study, we aim to develop a suitable sensor for tires that can detect tire overcontrol to reduce the possibility of excessive wear. However, commercially available sensors are designed for use within the interior of tires and are commonly used rigid parts and components to detect microstrains. Hence, the primary objective of this study is to develop and design a special strain gauge for tires while discussing and recording the tire strain characteristics during tire operation and after the sensor is embedded into the tire. This approach helps in finding the critical value of tire overcontrol. The findings of this study can be integrated into in-car systems to remind drivers, prompting them to reduce their control to extend the service life of tires, ultimately reducing the environmental impact associated with excessive tire replacements.

1. Introduction

The application of AI has attracted significant attention in recent years. Technological advancements related to the automobile industry, particularly in the field of assisted driving, have been steadily progressing for years. As the technologies become widespread, the availability of driving assistance systems has become a key factor affecting consumer choices in the automobile market. The National Highway Traffic Safety Administration (NHTSA) and the Society of Automotive Engineers International jointly classified autonomous driving assistance systems into five levels, which serve as a helpful guide for consumers to identify the capabilities of intelligent systems. Currently, most vehicles in the market are at Level 1, wherein the vehicle remains under the driver's control, but certain individual devices sometimes function, such as

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the lane departure warning, forward collision warning, electronic stability program, and automatic brake system (ABS). Few vehicle models have reached Level 2, providing an easier driving experience and reducing potential traffic accidents. Compared with Asian countries, the EU area is vast in territory and the likelihood of using vehicles under bad weather conditions for commuting needs is notably high. Therefore, the Economic Commission for Europe (ECE) introduced the ECE-R117 standard as early as 2009,[(1)] which strictly stipulates that automobile tires intended for sale in European countries must meet specific criteria depending on tire specifications and usages. These criteria include fuel efficiency, wet grip, rolling resistance, and noise level. Strandroth *et al.*[(2)] examined the traffic accidents and mortality rates from vehicles with and without the ESC system in Sweden during winter. The results revealed that 82% of the traffic accidents were collisions resulting from drivers' oversteering, leading to the loss of property or life. Notably, the intervention of active safety control systems is crucial, especially on slippery roads. Both active and passive systems primarily base their intervention decision on tire speed and image recognition systems combined with the existing ABS of the vehicle. This integration aims to enhance safety protection. In addition, Matilainen and Tuononen[(3)] stated that when a tire comes into contact with a water film on the road, the tread contact length changes significantly. These changes can be rapidly and effectively fed back to the computer, transmitting signals to the ABS for vehicle control. The method involved mounting a three-axis acceleration sensor on the wheel rim's inner wall to monitor the tire surface's contact length when passing on slippery roads. The results revealed that the contact length can be measured effectively on dry or wet roads. The contact length hardly varied with the vehicle speed on dry roads, while it decreased functionally with the vehicle speed (owing to the smaller contact length) on wet roads. The tires play a crucial role in ensuring safety in these environments. However, most technologies developed over the years focused on in-vehicle systems, with limited attention to tire-mounted sensor technologies. It was not until the term "smart tires" emerged in 2013 that major tire manufacturers became fully devoted to this issue. There are various methods of embedding sensors in tires. In this study, we aim to develop a low-cost and easy-to-manufacture strain gauge. Most of these commercially available products are unsuitable for the interior of tires with high strain rates.

2. Research Method

2.1 Literature review

According to Lee and Taheri[(4)], installing a three-axis accelerometer in the tire assists in measuring vibrations in each axial direction. Figure 1 shows the installation diagram.

The accelerometer was installed on the tire's inner rubber to record the rolling tire's vibration data. The experimental results suggest that road recognition can be implemented, as shown in Fig. 2. This development is valuable for judging the automatic systems of the vehicle.

Lee and Taheri[(4)] also pointed out the possibility of installing the strain gauge in the tire. Figure 3 shows that the front and rear wheels' experimental results differed. The road and vehicle dynamics can be identified on the basis of these characteristics, which benefits the development of smart tires.

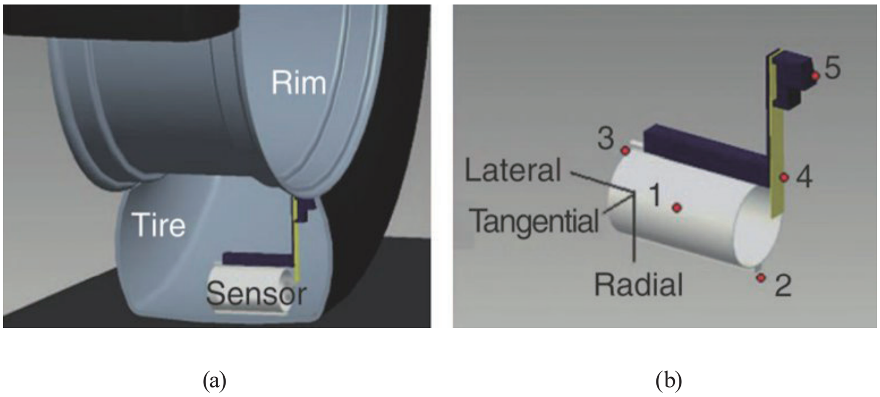

Fig. 1. (Color online) Schematic of accelerometer installation in the tire.

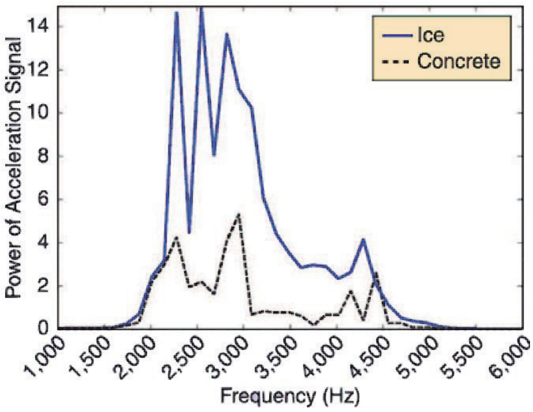

Fig. 2. (Color online) Vibration characteristics of different roads.

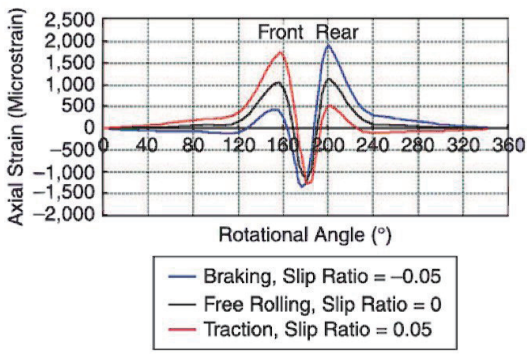

Fig. 3. (Color online) Strain rate characteristics of front and rear wheels.

Daniel *et al.*[5] discussed the changes in the tire speed and vertical load of the strain gauge under different tire pressures. They also introduced an approach to exploring the slip angle and employed fuzzy logic to develop a prediction method, which can be used to identify the current state of the tires. In their study, tire testing was conducted on an indoor tire testing machine under multiple conditions. Three strain gauges were attached to the inner surface of the tire, two of which were in the same cross-sectional area, while the third strain gauge was installed on the inner side of the tread at an angle of 123.75°. The resistance of the strain gauges used in their study was 120 Ω, while the resolution of the strain measurement was 0.001 με. The changes in strain values under different experimental conditions are shown in Fig. 4.

On the basis of the experimental results, when the vertical load is 250 N, the strain peak measures approximately 1250 με, while with a vertical load of 500 N, the strain peak increases to about 2000 με. Therefore, the strain gauge can be used to measure the vertical load of the tire (i.e., to check whether the vehicle is overloaded; a non-compliant load will reduce the tire life).

Figure 5 shows the changes in strain values at different tire speeds. The experimental data reveal that at a speed of 30 km/h, the faster the tire rotates, the shorter the period T1 of the strain

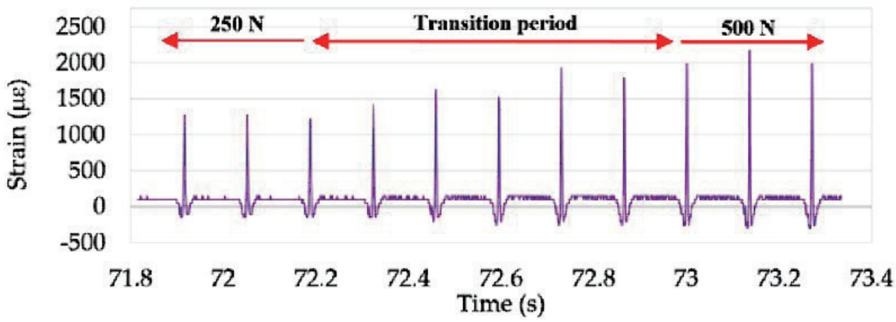

Fig. 4. (Color online) Strain values of different loads.

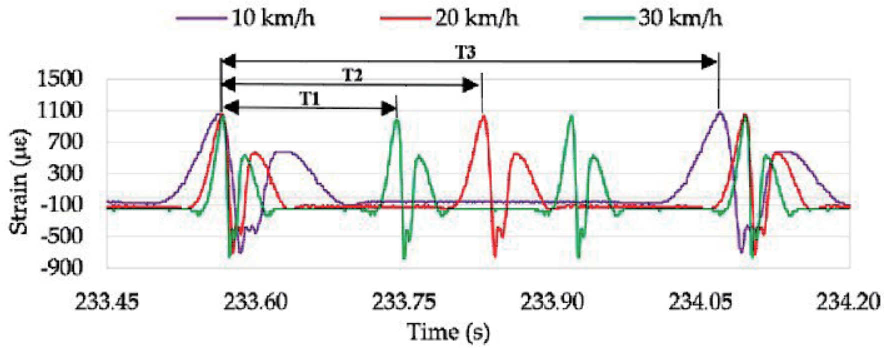

Fig. 5. (Color online) Strain values of different tire speeds.

value (the distance from peak to peak). As the speed decreases to 10 km/h, the T3 period becomes larger. In this paper, we also show the strain gauge used to explore the lateral movement changes of tires. The experimental results indicated a connection between the lateral force and the deflection angle during tire motion. Slip angles were analyzed under basic operating conditions to explore the relationship between the lateral force and the deflection angle.

In Fig. 6, when the tire deflection angle is 10°, the longitudinal strain value begins to decline significantly, while the lateral strain value begins to rise. Changes were observed under different tire pressures, particularly when the deflection angle reached 10°. These findings show that the tire slips when the deflection angle reaches 10°. This will help detect whether the tire is at the critical value of overcontrol. Additionally, in most experiments, tin foil strain gauges (common types on the market) were directly attached to the inner rubber of the tires. Since the tires are rubber, the stiffness differs significantly from the strain gauge, affecting the experimental measurement. In addition, Pasterkamp and Pacejka(6) conducted a study involving the installation of sensors in tires. They developed a method of identifying tire friction and indicated that the lateral force between the tire and the road can be measured using the air pressure flow trajectory. Moreover, the moment was automatically aligned with the vertical load of the tire. Their approach allows for calculating the longitudinal and transverse forces affecting the vehicle's friction force. A simulated car system was built in the test part. The experimental

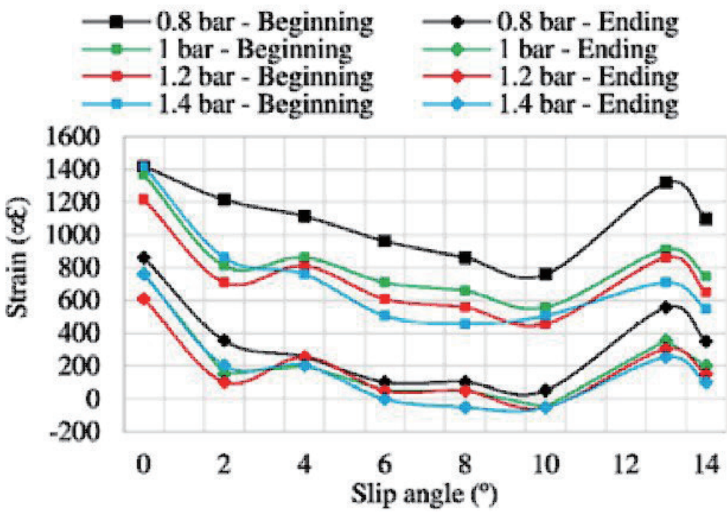

Fig. 6. (Color online) Strain values of different slip angles.

results revealed that the friction monitoring vehicle test results were consistent with the researchers' expectations. Xu *et al.*(7) employed an intelligent tire system and machine learning (ML) algorithm to simulate the slip ratio of the tires. Their study utilized ML to develop a novel slip ratio estimation model. The acceleration value of the tire when it contacted the ground was measured using a three-axis accelerometer installed in the tire. The findings revealed that the ML technology holds significant potential in estimating tire slip ratios. The study demonstrates that combining the intelligent tire system and ML algorithm represents great research value in tire slip ratio simulation. Notably, the measured tire speed in most previous studies was relatively low, implying that the vehicles were running at lower speeds, lower than the typical range between 60 and 120 kph. Upon implementing the experimental methods disclosed in the literature, the researchers of this study discovered that most commercially available strain gauges cannot withstand speeds above 60 kph. As a result, we designed and developed a strain gauge suitable for tire applications.

2.2 Design and production of in-tire strain gauge

Figure 7 shows the production process for the strain gauge. The required line length and thickness of the 350 Ω circuit board were first calculated using the PCB simulation software, while the required circuit diagram was designed using AutoCAD, as shown in Fig. 8. Figure 9 shows the fabrication of the required mask.

The wafer was repeatedly washed with deionized water and acetone, and baked on a baking tray until the wafer glass was dry. Then, it was placed on a spin coater to coat the photoresist. After the even coating, it was placed on the baking tray to remove the excess organic solvent, while the wafer glass was placed on the spin coater to coat the photoresist. The next step involved covering the wafer glass with a mask bearing the circuit design and placing it in the exposure machine to perform the exposure process, which effectively finalized the photoresist. Afterward,

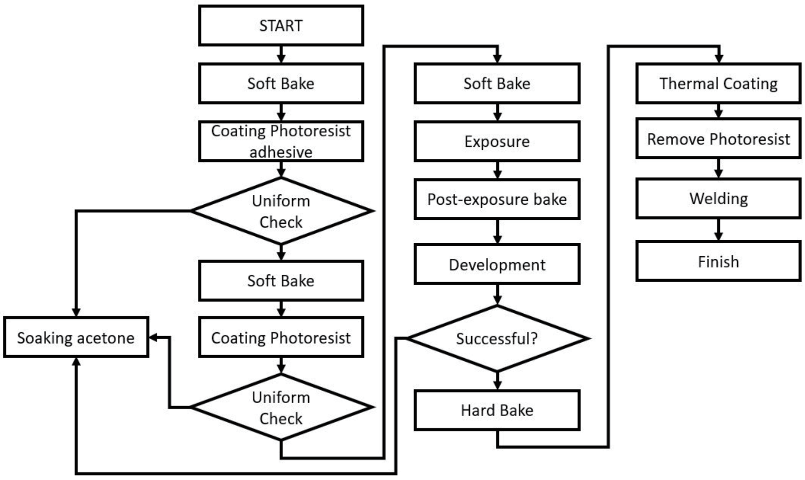

Fig. 7. Production process for strain gauge.

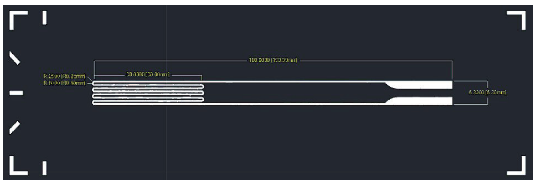

Fig. 8. (Color online) Circuit design drawing.

Fig. 9. (Color online) End product of mask.

the wafer glass was further placed on the baking tray for post-exposure baking. Once the pattern was visually confirmed, the wafer was submerged in the developer to reveal the photoresist pattern. Then, the wafer was again placed on the baking tray for hard baking to complete the production of the photoresist layer until the pattern matching the expected design was confirmed. The glass wafer, featuring the photoresist pattern, was placed in the evaporator to perform the thermal evaporation and coat the surface of the glass wafer with the required metal copper. After cooling, the glass wafer was soaked in acetone to remove the unnecessary photoresist layer and complete the copper circuit, as shown in Fig. 10. This marks the conclusion of the basic process verification of the strain gauge.

The strain gauge completed above cannot be applied to the tires' interior because the substrate to which the copper circuit was attached is still the glass wafer used in the traditional

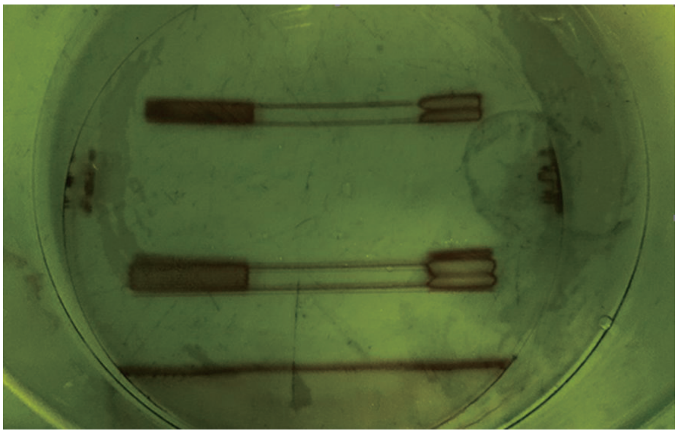

Fig. 10. (Color online) Copper circuit for strain gauge.

MEMS process. This glass wafer lacks the necessary flexibility, making the production process for the strain gauge slightly modified. Figure 11 shows the semifinished product using a flexible circuit board as the substrate, with the photoresist pattern of the circuit design on the surface.

The required metal material was deposited on the surface of the flexible circuit board bearing the circuit design using the evaporator. This process results in a semifinished product, as shown in Fig. 12. Lastly, the photoresist from the circuit design was removed using acetone to complete the soft strain gauge, as shown in Fig. 13.

2.3 Real vehicle testing method and discussion

To determine whether the tire is under the critical effect of overcontrol, the strain gauge was embedded into the tire, and the dynamic performance of the real vehicle was tested. This process not only verifies whether the developed strain gauge is effective but also explores the strain value of the tire during the actual control process. The line of the strain gauge was extended to the wireless data transmitter installed on the wheel frame. Figure 14 shows that the wheel frame was modified to implement an external connection of the line. The figure also shows that the soft strain gauge developed in this study was installed in the tire.

Figure 15 depicts that the wireless data transmitter was installed after the tire was prepared. The cable was connected to the wireless data transmitter, and the signals were subsequently transmitted to the vehicle receiver via radio. This process allowed the recording of actual vehicle driving data, as depicted in the waveform shown in Fig. 16.

3. Results and Discussion

In this study, we utilized an in-tire strain gauge to detect the critical characteristics of tire overcontrol. Therefore, the conditions for the actual vehicle test involve maintaining a constant vehicle speed while the tire executes an S-turn without deceleration to observe the numerical changes of the in-tire strain gauge. Figures 17 and 18 illustrate the vehicle test results.

Fig. 11. (Color online) Semifinished product of strain gauge with a soft substrate.

Fig. 12. (Color online) Coating the required metal material on the flexible circuit board.

Fig. 13. (Color online) End product of strain gauge with a soft substrate.

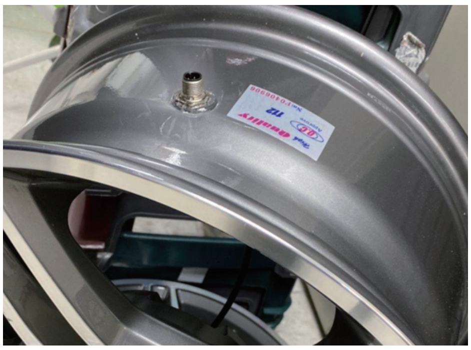

Fig. 14. (Color online) Special wheel frame for the experiment.

Fig. 15. (Color online) Wireless data transmitter outside the tire.

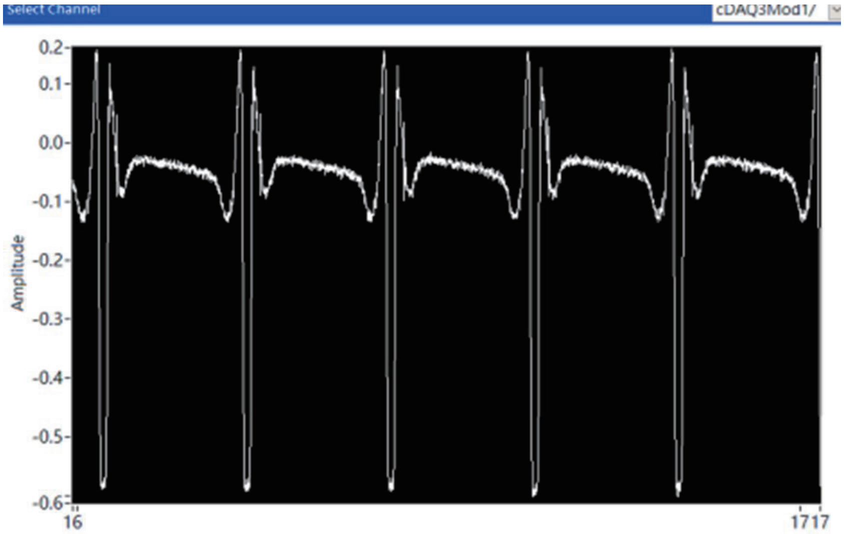

Fig. 16. (Color online) In-tire strain gauge waveform recorded using a wireless recorder.

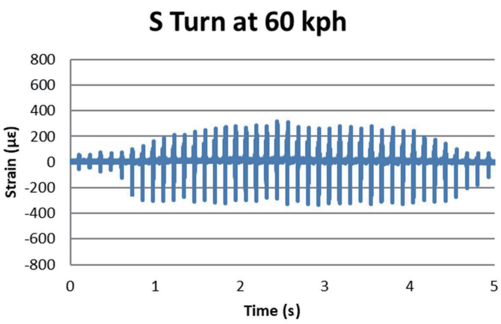

Fig. 17. (Color online) Strain rate on S-route at 60 kph driving speed.

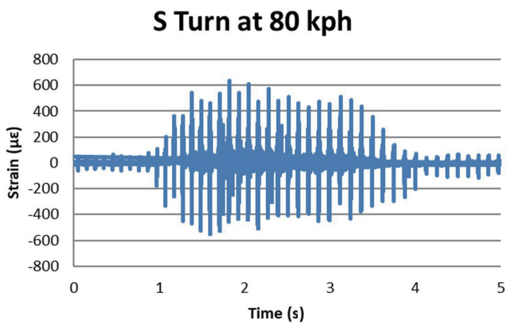

Fig. 18. Strain rate on S-route at 80 kph driving speed.

The experimental results reveal that the tire undergoes a clear deformation when navigating sharp turns, resulting in a spring-like effect. This deformation is essential to maintaining grip during a sharp turn. When the vehicle is moving at a low speed, the tire's grip is enough to support the vehicle, preventing oversteering and ensuring a relatively stable strain gauge waveform. As the vehicle speed increases to 80 kph, the inertial forces of the vehicle surpass the tire's support force capacity. Consequently, the grip required for steering is compromised, leading to a relatively unstable strain gauge waveform. Thus, it can detect tire oversteering, reduce the need for early tire replacement caused by tire oversteering, and minimize the environmental impact.

4. Conclusion

Embedding a strain gauge in tires presents a unique challenge owing to the significantly greater deformation they undergo compared with general rubber products. Therefore, most academic articles published in international journals focused on speeds below 60 kph. The yield of the strain gauge process was addressed during the development process to develop a suitable strain gauge. The process selection of the metal conductive layer was time-consuming. After finalizing this process, the substrate to which the metal conductive layer was attached should be replaced to develop a strain gauge suitable for tires. The strain gauge developed in this study was embedded into the tire and remained connected even as the vehicle speed was increased to 100 kph. The real vehicle test on the S-route without deceleration showed that as the vehicle speed increased, the waveform displayed by the strain gauge became increasingly unstable. Therefore, the special strain gauge for tires developed in this study is valuable for detecting tire overcontrol. This information can alert the driver to slow down, thus mitigating the potential tire wear and minimizing environmental impact.

Acknowledgments

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