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Disclaimer: This is AI-generated content. Validate details with reliable sources for important matters. Tire pressure sensors are essential components in modern vehicles, ensuring optimal tire performance and enhancing overall safety. By monitoring tire pressure in real-time, these sensors play a crucial role in preventing accidents caused by under-inflated tires. Understanding the various types and functions of tire pressure sensors can significantly impact vehicle maintenance and operating efficiency. Their integration into advanced driver assistance systems further underscores their importance in meeting contemporary vehicle safety standards. Significance of Tire Pressure SensorsTire pressure sensors are critical components in modern vehicles, designed to monitor the air pressure within tires. Accurate tire pressure management is vital for vehicle performance, safety, and fuel efficiency, making these sensors significant in automotive technology.Maintaining optimal tire pressure helps extend tire lifespan and enhances traction, contributing directly to vehicle handling and stability. This is particularly important in adverse weather conditions, where proper tire pressure can mitigate the risk of hydroplaning or loss of control. Furthermore, tire pressure sensors play a role in reducing environmental impact. Under-inflated tires lead to increased rolling resistance, thereby lowering fuel efficiency and increasing carbon emissions. By promoting appropriate tire pressure, these sensors contribute to more environmentally friendly driving practices.In addition to safety and environmental benefits, tire pressure sensors are often integrated into advanced driver assistance systems, enhancing features such as automatic tire pressure warnings and aiding proactive maintenance strategies. This integration reflects the growing significance of tire pressure sensors in automotive safety and technology.Types of Tire Pressure SensorsTire pressure sensors are categorized into two main types: direct and indirect. Direct tire pressure sensors measure the actual pressure within the tire by employing a pressure sensor located inside the tire. These sensors provide real-time data to the vehicles monitoring system, enabling immediate awareness of tire pressure fluctuations.In contrast, indirect tire pressure sensors do not measure tire pressure directly. Instead, they rely on the vehicles wheel speed sensors to identify discrepancies in rotational speed among the tires, which may indicate a loss of pressure. While this system is less precise, it can still alert drivers to potential issues.Both types of tire pressure sensors play vital roles in maintaining optimal tire performance. Direct sensors offer precise measurements, making them particularly beneficial for performance vehicles or those used in challenging driving conditions. Indirect sensors, being simpler and more cost-effective, are commonly found in many standard vehicles. Understanding these differences is essential for vehicle owners aiming to enhance driving safety and efficiency. Direct Tire Pressure SensorsDirect Tire Pressure Sensors measure the actual pressure within each tire, providing real-time data to the vehicles onboard system. These sensors are typically mounted on the valve stem or incorporated within the tire itself, offering precise readings that reflect tire conditions.Key features of Direct Tire Pressure Sensors include:Real-Time Monitoring: Continuous assessment of tire pressure allows for immediate detection of deviations from recommended levels.Improved Accuracy: These sensors provide precise pressure readings, minimizing the risks associated with under-inflation or over-inflation.Self-Contained Systems: Many models are equipped with batteries and communicate wirelessly with the vehicles computer.See also Understanding Tire Sizes: A Comprehensive Guide for Vehicle OwnersThe integration of Direct Tire Pressure Sensors enhances vehicle safety and fuel efficiency. By ensuring optimal tire pressure, these sensors contribute to better traction, handling, and tire longevity, ultimately benefiting overall vehicle performance.Indirect Tire Pressure SensorsIndirect Tire Pressure Sensors utilize the vehicles anti-lock braking system (ABS) or wheel speed sensors to monitor tire pressure. Unlike direct sensors that attach to each tire, these sensors calculate tire pressure based on the rotational speed of the tires. When a tire is under-inflated, it has a smaller diameter compared to properly inflated tires. Consequently, it rotates at a different speed than the other tires. The system detects this discrepancy and alerts the driver about potential tire pressure issues. While less accurate than their direct counterparts, indirect Tire Pressure Sensors are advantageous due to their lower cost and ease of installation. They do not require additional hardware, making them an accessible option for manufacturers and consumers alike. Regular calibration of the system is essential for optimal performance. When a tire is replaced, the indirect system should be recalibrated to ensure accurate readings. This integration of technology enhances overall vehicle safety while promoting efficient tire maintenance.How Tire Pressure Sensors WorkTire pressure sensors operate through the integration of specific technologies that monitor tire inflation levels. They utilize either direct or indirect methods to gauge the pressure within the tire, generating real-time data that aids in maintaining optimal tire conditions.Direct tire pressure sensors are installed within each tires valve stem and measure pressure using strain gauges. This data is transmitted wirelessly to the vehicles electronic control unit, alerting drivers when tire pressure falls below recommended levels. In contrast, indirect sensors rely on the vehicles existing wheel speed sensors to detect changes in tire pressure by monitoring rotational differences among tires.The information gathered by tire pressure sensors is crucial for ensuring vehicle safety and performance. When the system identifies abnormal pressure, it triggers a warning light on the dashboard, prompting the driver to address the situation promptly. Thus, regular monitoring facilitated by tire pressure sensors contributes significantly to safe driving practices and improved fuel efficiency. Benefits of Using Tire Pressure SensorsTire pressure sensors offer significant advantages that enhance vehicle safety and performance. One primary benefit is the timely detection of tire pressure changes, enabling drivers to address issues before they escalate. This proactive approach reduces the risk of blowouts and ensures optimal tire function.Another important advantage is the contribution to fuel efficiency. Properly inflated tires minimize rolling resistance, leading to better gas mileage. When tire pressure sensors alert drivers to low pressure, it helps maintain fuel economy, ultimately saving money over time.Tire pressure sensors also enhance overall driving comfort. By maintaining the correct tire pressure, these sensors improve vehicle handling and stability, particularly in adverse weather conditions. This leads to a smoother ride, increasing both driver and passenger satisfaction.Finally, the integration of tire pressure sensors within vehicles often corresponds with advancements in vehicle safety technology. This interconnection enhances the overall safety standards of modern vehicles, ensuring that tire health directly influences vehicle safety metrics.Common Issues with Tire Pressure SensorsOne common issue with tire pressure sensors is the occurrence of false readings, which can lead drivers to misinterpret the actual tire condition. This situation may arise from sensor malfunctions or interference from external factors, such as temperature fluctuations or electronic signals from other vehicle components. See also Understanding Run-Flat Technology: Benefits and MechanismsAnother frequent concern involves battery depletion, particularly in direct tire pressure sensors. Many of these sensors are equipped with batteries that have a limited lifespan. When the battery fails, the sensor may stop transmitting data, prompting warning lights on the dashboard.Physical damage to the sensors is also a significant issue. Debris from the road or impacts can compromise sensor integrity, leading to inaccurate readings or total failure. Regular inspections can help identify such damage before it results in more severe tire performance problems.Lastly, calibration errors can impact tire pressure sensors, particularly during tire rotations or replacements. Ensuring that the sensors are properly calibrated can mitigate the risk of erroneous alerts and maintain the integrity of the tire monitoring system.Maintenance Tips for Tire Pressure SensorsRoutine inspections of Tire Pressure Sensors should be conducted, particularly during tire rotations or seasonal changes. Ensure that the sensors are free of dirt and debris, as these can interfere with their functionality. A clean environment will promote accurate readings.Regularly check the battery life of direct Tire Pressure Sensors. These sensors often rely on batteries that may deplete over time. If sensor alerts become erratic or if the dashboard warning light activates, consider replacing the batteries or consulting a professional technician. Monitor tire pressure consistently, even if equipped with a Tire Pressure Monitoring System (TPMS). Regular manual checks can serve as a backup to sensor readings, providing an opportunity to identify potential discrepancies or sensor malfunctions early on.Seek professional help if you notice persistent issues with your Tire Pressure Sensors. Technicians can conduct comprehensive diagnostics and ensure that the sensors are calibrated correctly, maintaining optimal safety and vehicle performance.Integration of Tire Pressure Sensors in Modern VehiclesTire pressure sensors are increasingly being integrated into modern vehicles, contributing significantly to vehicle safety and performance. This integration is vital for monitoring tire health in real-time, preventing hazards associated with underinflated or overinflated tires.The role of tire pressure sensors extends to enhancing advanced driver assistance systems (ADAS). By supplying critical data to various vehicle systems, these sensors help regulate traction control, stability control, and even automated driving features, ensuring a comprehensive safety net for drivers.Integration of tire pressure sensors also impacts vehicle safety standards. They are now a fundamental requirement in many vehicles, established by regulatory bodies. This inclusion underscores the importance of maintaining optimal tire pressure for overall vehicle efficiency and accident prevention. As tire pressure technology evolves, manufacturers are increasingly focusing on seamless integration with vehicle infotainment systems. This allows drivers to easily access tire information, promoting proactive maintenance and enhancing the driving experience.Role in Advanced Driver Assistance SystemsTire pressure sensors significantly contribute to the functionality of advanced driver assistance systems (ADAS). They provide real-time data regarding tire conditions, which is critical for ensuring optimal vehicle performance and safety. Accurate tire pressure monitoring enhances the efficiency of other ADAS features, such as traction control and stability management.These sensors help in alerting drivers to potential issues, allowing for timely interventions. For instance, if tire pressure drops, the system may activate safety measures, adjusting braking or steering to mitigate risks. This integration exemplifies how tire pressure sensors play a vital role in maintaining vehicle stability and preventing accidents.In modern vehicles, tire pressure sensors work seamlessly with various electronic control units (ECUs). This synergy fosters a comprehensive approach to vehicle safety, contributing to improved overall performance. Consequently, reliable tire pressure sensing is indispensable for the efficacy of advanced driver assistance systems.See also Understanding Bias-Ply Tires: Advantages and ApplicationsImpact on Vehicle Safety StandardsTire pressure sensors significantly influence vehicle safety standards by ensuring optimal tire functionality. Accurate tire pressure monitoring plays a vital role in maintaining the integrity of a vehicle, directly affecting traction, handling, and braking performance. By providing real-time data on tire pressure, these sensors help prevent under-inflation and over-inflation. Compliance with established safety regulations necessitates the incorporation of tire pressure sensors in modern vehicles, ultimately reducing the risk of tire blowouts and accidents.Moreover, tire pressure sensors contribute to the overall safety of advanced driver assistance systems. Enhanced safety features, such as adaptive cruise control and electronic stability control, rely on accurate tire pressure data to operate effectively, promoting safer driving conditions.The integration of tire pressure sensors into vehicles has led to higher safety ratings in crash tests and consumer reports. As manufacturers adhere to evolving safety standards, the continued development and implementation of reliable tire pressure sensors will remain paramount in enhancing vehicle safety.Future Technologies in Tire Pressure SensorsEmerging technologies are set to revolutionize tire pressure sensors, enhancing their functionality and reliability. One significant advancement is the integration of wireless communication protocols, which allows real-time data transmission to drivers smartphones. This will enable greater accessibility and monitoring of tire conditions.Moreover, the incorporation of advanced materials and miniaturization techniques promises to improve the accuracy and longevity of tire pressure sensors. These sensors can be designed to withstand harsher environments while providing constant updates on tire performance, thereby increasing vehicle safety. Artificial intelligence is another area that holds promise for tire pressure monitoring systems. By analyzing data patterns, AI can predict tire maintenance needs, helping drivers anticipate issues before they escalate. This proactive approach could significantly extend tire lifespan and improve overall vehicle performance. In addition, the integration of tire pressure sensors with IoT technology will pave the way for connected vehicles. This development ensures a seamless flow of information between the vehicle and external entities, promoting safer roadways through enhanced data sharing regarding tire performance and maintenance needs.Selecting the Right Tire Pressure Sensors for Your VehicleSelecting the right tire pressure sensors for your vehicle involves a thorough understanding of your automobiles specifications and the various sensor options available. Vehicles typically utilize either direct or indirect tire pressure sensors, each offering unique functionalities.Direct tire pressure sensors measure the pressure in each tire and transmit this data to the vehicles onboard computer. When choosing these sensors, consider their compatibility with your vehicles make and model, as well as the sensors battery life and range. Indirect tire pressure sensors, on the other hand, estimate tire pressure using the vehicles ABS system, relying on algorithms that assess wheel speed. Ensure that your selection aligns with your driving habits, as indirect sensors may not provide real-time pressure readings.Evaluate the quality and reliability of the brand when selecting tire pressure sensors. Trusted manufacturers often offer enhanced durability and accuracy, reflecting in their warranty and customer support services. Additionally, consider the ease of installation, particularly if you prefer a DIY approach or anticipate professional assistance for setup. Price is another factor to weigh; while cheaper sensors may be tempting, investing in high-quality tire pressure sensors could save on potential tire damage and maintenance costs in the long run. Ultimately, choosing the right tire pressure sensors requires balancing compatibility, accuracy, and budget to enhance vehicle safety and performance. Tire pressure sensors are indispensable components in modern vehicles, significantly enhancing safety and performance. Their ability to accurately monitor tire health contributes to efficient fuel usage and improved vehicle handling.As technology advances, the integration of tire pressure sensors will become even more critical in automotive design. Embracing these innovations ensures that drivers remain informed and protected on the road for years to come. 2008 Dec 9;8(12):81238138. doi: 10.3390/s8128123This review discusses key technologies of intelligent tires focusing on sensors and wireless data transmission. Intelligent automobile tires, which monitor their pressure, deformation, wheel loading, friction, or tread wear, are expected to improve the reliability of tires and tire control systems. However, in installing sensors in a tire, many problems have to be considered, such as compatibility of the sensors with tire rubber, wireless transmission, and battery installments. As regards sensing, this review discusses indirect methods using existing sensors, such as that for wheel speed, and direct methods, such as surface acoustic wave sensors and piezoelectric sensors. For wireless transmission, passive wireless methods and energy harvesting are also discussed.Keywords: Intelligent tire, Wireless monitoring, Automobile tire, TPMS, Energy harvesting, Passive monitoringIntelligent tires, also known as smart tires, are equipped with sensors for monitoring quantities such as air pressure, applied strain, temperature, acceleration, wheel loading, friction, and tread wear, and are expected to improve the reliability of tires and tire control systems such as anti-lock braking systems (ABS). The stimulus for increased research into intelligent tires is attributed to the Bridgestone/Firestone recalls in 2000 [1]. As a result of the recalls, United States Transportation Recall Enhancement, Accountability, and Documentation (TREAD) legislation has mandated that every new automobile be equipped with a tire pressure monitoring system (TPMS) [2-8]. A TPMS employs pressure or other sensor types plus a reliable method for transferring data from inside a pneumatic tire to alert drivers when tires are under-inflated [9-18]. This legislation has given impetus to the development of advanced tire technologies for improved tire safety.Various reports [19-20] clearly show that adverse road conditions and tire defects play a major role in road traffic accidents. As a consequence, there is urgent need, from a traffic safety point-of-view, for intelligent tires with a warning system for road conditions, optimizing control on poor surfaces, and a tire defect detection system that measures tire deformation, in addition to a TPMS.The key technologies for the intelligent tires are sensors and data transmission methods. In the case of installing sensors to measure strain applied to a tire, many problems have to be considered. First, because the stiffness of the tire rubber is very low, the conventional foil strain gages designed for metal or plastic materials are not suitable. The high stiffness difference may cause debonding of sensors from tire rubber or degrading performance of the tire because sensors themselves inhibit the deformation of the tire. Second, it is spatially impossible that large-sized sensors are installed in a special environment like the interior space of the tire. Moreover, it is economically difficult to use expensive sensors because tires are comparatively inexpensive products.In terms of the data transmission, when sensors are installed inside the tire, wireless monitoring is indispensable. Although a slip ring can be used in measurements for rotating objects in laboratory testing, abrasion of the brush and rings may occur and the slip ring does not have a long operational life. Moreover, to activate the sensor, it is necessary to install a battery in the tire. The battery, however, has a limited life and it is difficult for tire users to replace the battery inside the tire. Therefore, energy harvesting or energy scavenging that converts mechanical vibration of tires to electric power has been researched to eliminate the need for battery replacement in recent years. Passive wireless sensors that do not require batteries have also been researched. The passive wireless sensor omits batteries and an energy harvesting system and thus downsizes the instruments installed in the tire. The sensor also has the advantages of decreasing fuel consumption and off-balance problems of the tire due to sensor installation.This review therefore discusses two key technologies of intelligent tires: 1) tire sensing technology that involves a TPMS and is used in developing an advanced intelligent tire with a tire deformation, wheel loading, or friction measurement system and 2) a system for wireless data transmission between tires and a vehicle that involves active and passive wireless methods and energy harvesting.A simple TPMS method is based on indirect measurements and fuses information from several different physical sensors to compute tire pressure. Persson et al. [9, 21] proposed an indirect TPMS using wheel-speed sensors and an electronic control unit (ECU) of ABSs based on vibration and wheel radius analysis. Kojima et al. [22] also developed an indirect TPMS using the signal from wheel speed sensors and focusing on the relationship between tire pressure and tire torsional stiffness.Although indirect systems use existing sensors and are easy to install, the degree of accuracy is not reliable. In particular, changes in road conditions affect indirectly calculated pressure. The combined pressure loss of more than two tires is also problematic. A calibration is often required when one or more tires are changed, or when the pressure is adjusted [16].TPMSs using direct measurements have been developed by many companies such as SmarTire System Inc. of Canada, whose system used clamp-on rim sensors, and Schrader Electronics Ltd. of the United Kingdom, who used valve-attached sensors. The clamp-on rim sensors are fixed on the well bed of the rim with a stainless steel clamp and this fixing method can be applied as an after-sales service. Bridgestone Corp. and Alps Electric Co., Ltd. developed valve-attached sensors, for which the sensor casing is attached to the bottom end of the tire valve.Conventional capacitive pressure sensors measure capacitance between two electrodes, which changes owing to applied pressure [23]. As the dielectric material for the capacitor, Arshak et al. [24] found Nb_2O_5 has good sensitivity to applied pressure. Since the sensitivity is related to particle size, small or nanosized particles are good candidate materials for high-sensitivity pressure sensors. This sensor is cost effective and can be produced as a film which is rugged in nature and can operate in many harsh environments.However, the output capacitance is usually nonlinear with respect to input pressure changes and the sensitivity in the near-linear region is not high enough to ignore many stray capacitance effects. To solve this problem, the touch-mode pressure sensors have been developed and are shown in Figure 1 [25-29]. This sensor operates at the instants of two electrodes coming into contact. When two electrodes touch, the contact area increases as the external pressure increases. The advantages of the touch mode operation are good linearity in contact range, mechanical robustness, and large overload protection. Structure of a touch-mode capacitive pressure sensor: (a) normal mode, (b) touch mode. The diagram is from Oh et al. [25] and is reprinted with permission from Elsevier.A number of advanced tire sensor systems are currently under development. Known as intelligent tires, they are equipped with sensors to monitor quantities such as strain [30, 31], temperature [32, 33], and acceleration [34] in addition to air pressure to improve automobile safety [35-42]. A European Union project, called APOLLO (20022005), has been set up for the purpose of developing intelligent tires that can monitor their deformation [20, 43-46]. Tire deformation or strain monitoring enables one to know the amount of friction between the tires and road surface, which can then be used for the optimization of automobile tire control systems, such as the ABS. The use of intelligent tires also benefits other advanced active safety systems, including traction control systems (TCSs), vehicle stability assist (VSA) systems, early detection of tire separation systems [37] and tire-burst prevention systems [47].There are two types of methods for estimating the friction coefficient: indirect and direct methods. The indirect method does not monitor tire deformation while the direct method does. In most indirect methods, the friction coefficient is determined based on sensing parameters such as the vehicle velocity, wheel angular speed, and normal and tractive forces applied to the tire, axis and wheel [48]. Since the relationships among tire parameters are very nonlinear and complex, quantitative relations are difficult to acquire. Therefore, algorithms such as a fuzzy logic controller [49, 50] or Kalman filter [16, 51-52] are used to estimate tire parameters. Yi et al. [53] used the wheel slip, vehicle velocity, and normal load on the tire to determine the friction coefficient and develop a control scheme for emergency braking maneuvers. Miyazaki et al. [54-55] measured the four-axis direction force by attaching strain gages to improve the ABS efficiency. Ohori et al. [56] and Kamada et al. [57] measured the strains applied to the wheel to estimate the six force components in the tire.These methods require extra sensors such as a strain sensor, yaw rate sensors, acceleration sensors, and steering angle sensors even though they are indirect methods. On the other hand, a reduction in installation cost is possible using only existing sensors. Umeno [58] used the frequency characteristics of the vibration of a wheel rotating at different speeds to estimate tireroad friction. This method requires only wheel speed sensors, which are already used in an ABS. Gustafsson et al. [51, 52] proposed a method for estimating the friction between tires and the road surface based on Kalman filtering using existing sensor signals such as individual wheel speeds and an engine torque indicator (injection time or manifold pressure indicator) referred to as a virtual sensor. Bevly et al. [59] estimated three key vehicle stateswheel slip, body sideslip angle and tire sideslip angleusing global positioning system (GPS) velocity data. Tireroad friction, effective radius and other tire parameters can also be estimated in real time using a GPS [60-64].As opposed to indirect measurements, the direct sensor allows a precise measurement of tire deformation or strain. For direct strain monitoring, a strain gage, based on polyimide film, is the best known and most widely used method. The sensor, however, has a very high degree of stiffness and low elongation compared with tire rubber. This large difference in stiffness may disturb the deformation and stress of tires, and may also cause the debonding of sensors and rubber over a long period of usage. Sensors with low elongation are also easily damaged by large abrupt deformations.Surface acoustic wave (SAW) sensors have been proposed for monitoring the deformation during road contact [35, 65-69]. SAW devices use metallic interdigital transducers arranged on the surface of a piezoelectric substrate. SAW devices operate as filters, resonators and delay lines in a growing number of applications. Palmer et al. [36] demonstrated the embedment of fiber optic sensors in an automobile tire for monitoring tire strain and captured and measured the onset of a skid. The transducer mechanism is based on an extrinsic FabryPerot interferometer (EFPI) using minute changes in the low-finesse FabryPerot air gaps. Brandt et al. [40, 70] proposed a tread deformation sensor, the Darmstadt tire sensor, which uses GaAs chips glued to thick-film ceramic carriers as shown in Figure 2. The tread element deformation is measured by the sensor as a position change of a magnet relative to four crosswisely arranged Hall sensors. Tjiu et al. [71] used microelectromechanical system (MEMS) sensors, including a pressure sensor, accelerometer and temperature sensor for a tire condition monitoring system. Yi [72] used polyvinylidene fluoride (PVDF)-based sensors to measure the tread deformation. Two PVDF deformation sensors are attached on the inner surface of the rubber tire. Savaresi et al. [73] embedded piezoresistive low-mass accelerometers mounted inside the tire, which measure the in-tire radial acceleration; the accelerometers are installed in the front-left and rear-left tires. The Darmstadt tire sensor using a Hall sensor for measurements of deformation of a tread element in the tire contact area. The diagram is from Gruber et al. [70] and is reprinted with permission from Elsevier.All these sensors, however, are made of high stiffness materials. Until now, flexible sensors have been developed based on thin technology. Although their flexural rigidity is low, allowing them to be bent, their tensile stiffness is high and elongation low [74, 75]. These sensors are only suitable for very short service periods and, therefore, more reliable sensors with sufficiently low stiffness and high elongation need to be developed.Matsuzaki et al. [76] proposed a flexible patch-type strain sensor made from flexible polyimide substrates and ultraflexible epoxy resin, which makes the sensor low in stiffness and high in elongation as a whole structure. Matsuzaki et al. [77] also proposed a rubber-based strain sensor fabricated using photolithography. The rubber base has the same mechanical properties as the tire surface; thereby the sensor does not interfere with the tire deformation and can accurately monitor the behavior of the tire using sensor capacitance change as shown in Figure 3. (a) Rubber-based sensor attached to the inner surface of a radial tire and (b) sensor capacitance change when the tire deforms. The diagram is from Matsuzaki [77] and is reprinted with permission from Elsevier.As a non-contact sensing technique for tire rubber, Magori et al. [31] presented an ultrasonic tire sensor mounted on the base of the wheel rim inside the tire. The sensor measures continuously the distance to the opposite inner wall of the tire providing highly significant information about the status of the tire. Since the sensor is not in contact with the tire rubber, the inconvenience associated with tire replacement is avoided.Without attaching sensors, Matsuzaki et al. [78-81] presented a self-sensing method using the tire structure itself as a parallel circuit of a capacitor and resistor as shown in Figure 4. Since the actual tire structure acts as a sensor, no additional sensor is required. Therefore, there is no debonding of the sensor, even during prolonged service, because there is no stiffness difference between the sensor and tire rubber. The measurement system could be small, lightweight and capable of withstanding harsh conditions. Moreover, the method allows for a more direct strain measurement than a method that uses a sensor attached to the inner surface does. Sergio et al. [30, 82] also developed a strain monitoring method that adopts the tire itself as a sensing element. The embedded grid of steel wires is used as the electrodes of a distributed array of passive impedances. Self-sensor modeling of a steel wire belt in a radial tire as an electric resistorcondenser parallel circuit. The diagram is from Matsuzaki et al. [79] and is reprinted with permission from Elsevier.Simple wireless data transmission uses the resonance of a capacitor and an inductor. Data can be converted to the resonance frequency or Q value. To enhance the function of data transmission, most wireless transmission uses an integrated circuit wireless transmitter. Most cases take advantage of the unlicensed ISM (industrial, scientific, and medical) bands, and use communication protocols such as Bluetooth, ZigBee, and IEEE 802.11 [20]. Basically, these wireless communications require a power supply to send a radio signal.Yi [72] developed piezo-sensor-based intelligent tire system, and used ZigBee wireless communication protocols between a sensor data processing module and a receiving unit. A small battery to power the circuits is located inside the wheel. The receiving unit with an antenna is connected to the onboard laptop. Savaresi et al. [73] developed a wireless data transmission of the intire acceleration signal made via a Datatel (Langenhagen, Germany) telemetry system. The transmitter and its battery are mounted on the wheel rim. The receiver antenna is placed on the car roof; the acquisition of the sensor signals is made by a DSpace Autobox (Michigan, USA) acquisition system. In most cases, wheel-sensor activities are autonomous of any central intelligence and typically require an accelerometer to control wake-up and sleep-mode switching to conserve battery life [83].Kolle et al. [84] developed a low-power sensor for tire pressure monitoring using low-power oscillators. It consists of four tire modules transmitting their data via an HF-link to a central receiver, the hardware of which is shared with the remote keyless entry receiver system. However, a battery limits the operation time of the sensor and wireless communication. To guarantee an effective lifetime of 510 years, the battery needs to have a capacity of several hundred mAh, which increases the weight and size of the sensing system.Instead of embedding batteries, mechanical vibration energy can be converted into electricity by capacitive [85], electromagnetic [86-88] and piezoelectric generators [89-90]. Harvesting energy from a rotating tire is a possible method of powering wireless devices implanted in the surface of the vehicle.Meninger et al. [85] proposed capacitive generators for converting ambient mechanical vibration into electrical energy using an MEMS variable capacitor. By placing charge on the capacitor plates and then moving the plates apart, mechanical energy can be converted into electrical energy, which can then be stored. The energy increases as more charge is loaded onto the capacitor. However, the capacitive generators need an initial voltage before they can produce power.Shearwood et al. [86] proposed an electromagnetic generator that consists of a magnet on a polyimide spring. When the generator is vibrated, there is a net movement between the magnet and housing. This relative displacement generates electrical energy by the interaction of the magnet with a planar pick-up coil.Elvin et al. [91] introduced a self-powered method of sensing and communicating using piezoelectric material. The power is generated solely from the conversion of mechanical strain energy into electrical energy, which is then used to power a wireless link to a receiver and data processing unit. Jeong et al. [89] developed bender-type piezoelectric devices for power generator as shown in Figure 5. To match the external vibration frequency with the device resonant frequency, the device consists of two different thick layers, with each layer having different resonant frequency. Snyder [92] also proposed a battery-less TPMS where piezoelectric reeds are included in the tire sensor units and generate electricity. Two-layered piezoelectric bender device for micropower generation. The figure is from Jeong et al. [89] and is reprinted with permission from Elsevier.As an example of other methods, Wang et al. [93-94] demonstrated nanowire generators that are driven by an ultrasonic wave to produce continuous direct-current output for harvesting local mechanical energy produced by high-frequency vibration. Qin et al. [95] proposed a low-cost approach that converts a low-frequency vibration energy into electricity using piezoelectric zinc oxide nanowires grown radially around textile fibers. By entangling two fibers and brushing the nanowires rooted on them with respect to each other, mechanical energy is converted into electricity owing to a coupled piezoelectricsemiconductor process.Although a battery has the advantage of a fixed and stable voltage supply, its disadvantages are its limited total energy available, temperature dependency and relatively short life span. To overcome these problems, a passive wireless system that does not require batteries in the sensor circuit has been developed. A passive wireless system usually involves electromagnetic coupling using two inductors such as a radio-frequency (RF) tag or radio-frequency identification [96, 97]. For passive intelligent tires, Matsuzaki et al. [81] used electromagnetic coupling between the two inductors of the antenna and sensor with an inductance capacitance (LC) resonant circuit. Tire deformation changes the sensor's capacitance; then it changes the resonant frequency of the LC circuit. This resonant frequency change is measured as a change in the phase angle for the antenna using electromagnetic induction. Nabipoor et al. [23] developed a passive pressure and temperature sensor optimized for a TPMS using an LC circuit and electromagnetic coupling of two inductors. In this passive telemetry LC pressure and temperature sensor, a pressure sensitive capacitor is used in parallel with a temperature sensitive inductor and together they make a LC tank circuit. Changing the applied pressure affects the resonant frequency of the circuit while the temperature affects the bandwidth and amplitude of the impedance at this frequency. However, the energy due to electromagnetic coupling is insufficient to activate the sensor system. This problem also causes the short wireless range.Without magnetic coupling, Matsuzaki et al. [79-80] proposed a battery-less sensor using frequency filtering by a tire sensor. The method comprises the sensor or tuning circuit, an external transmitter that emits white noise, and an external receiver as shown in Figure 6. Since the tuning circuit performs as a frequency filter, the tuning frequency of the sensor can be wirelessly measured without any batteries for the sensor circuit. Using spectral features of the tuning frequency and the peak power spectrum and quality factor, tire strain was estimated accurately using a response surface method. Schematic image of the wireless passive strain measurement system using a tuning circuit and frequency filtering. The diagram is from Matsuzaki et al. [79] and is reprinted with permission from Elsevier.SAW sensors are also powered by the energy of the RF field; thus no battery is required. The SAW device receives incident radio signals and it can reflect them into the air as shown in Figure 7. The reflected signals launching on the surface of the SAW radio transponder contain information such as the impedance and the loaded mass on the substrate. Schimetta et al. [33, 66] developed a SAW transponder tag with a capacitive pressure sensor that requires no batteries for a pressure-measurement system. They demonstrated the prototype of a tire pressure sensor unit with a typical accuracy of 15 kPa within a pressure range of 100400 kPa and an excess pressure stability of 600 kPa. Oh et al. [25] also developed a SAW transponder for passive wireless monitoring using the touch-mode pressure sensor. They showed that the maximum distance for detection is about 40 cm and the short range problem when using electromagnetic coupling is solved. (a) Schematic illustration of the SAW traveling wave in piezoelectric substrate and (b) a schematic diagram of the traveling wave launched at the SAW inter-digital transducer. The diagram is from Oh et al. [25] and is reprinted with permission from Elsevier.This review discussed two key technologies required for intelligent tires: sensing and wireless data transmission. Indirect and direct tire sensing technologies for TPMSs and advanced intelligent tires that measure tire deformation for friction estimation were introduced. Although the direct sensing using SAW, fiber optic, piezoelectric, and MEMS sensors have advantages in measurement accuracy compared with the indirect methods, the suitability for tire rubber is problematic. Direct tire monitoring that has better compatibility for tire rubber will be required for long-term service. The wireless transmission between tires and vehicle must be passive because of difficulties in battery installation. 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[Google Scholar] In today's rapidly advancing automotive industry, technology continues to play a pivotal role in improving vehicle safety, performance, and efficiency. One remarkable innovation that has gained significant traction is the integration of embedded sensors into tires for real-time monitoring. These intelligent tires have revolutionized the way we interact with our vehicles, offering a myriad of advantages that extend far beyond traditional rubber and tread.Tires with Embedded SensorsImagine a tire that can communicate its vital statistics directly to you, the driver, in real-time. Embedded sensors have made this vision a reality. Gone are the days of merely guessing the condition of your tires based on visual inspection or relying on outdated pressure gauges. With this cutting-edge technology, tire manufacturers have transformed tires into intelligent devices that continuously monitor and report critical data, ensuring optimal performance and safety.These sensors, typically placed inside the tire's structure, are equipped to measure various essential parameters, including tire pressure, temperature, tread depth, and even load distribution. The data collected is then transmitted to the vehicle's onboard computer, providing drivers with instant access to a wealth of information that can enhance their driving experience and keep them well-informed about their tire's condition.Understanding Real-time Monitoring in Tire TechnologyReal-time monitoring in tire technology is the cornerstone of the benefits offered by tires with embedded sensors. Traditional tires, without such smart capabilities, lack the means to alert drivers of potential hazards or problems that may arise during their journey. However, with embedded sensors, drivers are empowered with a comprehensive monitoring system that constantly evaluates tire health and performance.Tire pressure is a vital aspect of tire maintenance, as underinflated tires can lead to decreased fuel efficiency and a higher risk of blowouts. Real-time monitoring of tire pressure allows drivers to receive immediate alerts if pressure levels fall below the recommended threshold. This timely notification enables them to take proactive measures, such as

inflating the tires to the correct pressure, thus avoiding potential accidents and improving overall fuel economy.Moreover, these embedded sensors monitor tire temperature, which is crucial in preventing overheating. As tires heat up during extended drives or under heavy loads, their structural integrity may be compromised. Real-time temperature monitoring helps drivers recognize and address excessive heat buildup before it causes tire failure, extending the tire's lifespan and ensuring a safer journey.Furthermore, with the ability to assess tread depth, drivers can now gauge the level of wear on their tires accurately. Worn-out treads are a major safety concern, particularly on wet or slippery roads, where traction is critical. Real-time monitoring of tread depth enables drivers to schedule timely tire replacements, reducing the risk of accidents caused by inadequate grip on the road surface.Enhanced Safety and Accident Prevention with Sensor-equipped TiresOne of the most significant advantages of tires with embedded sensors is the enhanced safety they offer to drivers and passengers alike. With real-time monitoring of tire pressure, temperature, and tread depth, drivers can detect potential issues before they escalate into dangerous situations on the road.Imagine you're driving on a highway, and suddenly, your tire pressure drops significantly due to a slow leak. Without the embedded sensors, you might not notice the gradual loss of pressure until it's too late, and the tire fails completely. However, with the smart tire technology, you receive an immediate alert on your dashboard, notifying you of the pressure drop. This gives you the chance to safely pull over and address the problem, preventing a potential blowout that could lead to an accident.Moreover, smart tires can also help prevent accidents caused by hydroplaning. Hydroplaning occurs when a vehicle's tires lose contact with the road due to a thin layer of water between the tire and the road surface. This results in a loss of control over the vehicle, leading to potentially dangerous situations. With embedded sensors continuously monitoring tread depth, drivers can replace worn-out tires before the tread depth becomes insufficient for effectively dispersing water on wet roads, significantly reducing the risk of hydroplaning.Another crucial aspect of enhanced safety is load distribution monitoring. Overloading a vehicle can strain the tires beyond their capacity, leading to accelerated wear and potential tire failure. Smart tire sensors can track the load on each tire, providing real-time data on how much weight each tire is carrying. This information allows drivers to adjust the load distribution or remove excess weight to prevent tire damage and maintain optimal performance.Improving Fuel Efficiency through Real-time Tire DataBeyond safety benefits, tires with embedded sensors also contribute to improved fuel efficiency, a key consideration for environmentally-conscious drivers and those seeking to cut down on fuel expenses.Tire pressure has a direct impact on fuel efficiency. Underinflated tires cause increased rolling resistance, requiring the engine to work harder and consume more fuel to maintain speed. Real-time tire pressure monitoring ensures that tires are always inflated to the manufacturer's recommended levels, optimizing fuel efficiency and reducing greenhouse gas emissions.Additionally, tires with the right amount of tread can significantly impact fuel consumption. Worn-out treads lead to decreased traction and increased rolling resistance, resulting in higher fuel consumption. By monitoring tread depth in real-time, drivers can promptly replace tires before they become overly worn, maintaining optimal fuel efficiency and reducing their carbon footprint.Moreover, the data provided by these smart tires can also help drivers identify driving habits that impact fuel economy. For instance, rapid acceleration and hard braking can lead to unnecessary fuel consumption. By analyzing tire data alongside other vehicle performance metrics, drivers can make informed decisions to improve their driving habits and achieve better fuel efficiency.Extending Tire Lifespan with Continuous MonitoringSmart tires not only enhance safety and fuel efficiency but also contribute to extending the lifespan of the tires themselves. Traditional tires often suffer from premature wear and tear due to neglect or lack of timely maintenance. With embedded sensors providing continuous monitoring, drivers can take proactive steps to preserve the longevity of their tires.One critical factor that affects tire lifespan is proper inflation. Underinflated tires can cause uneven wear patterns, leading to premature tire degradation. On the other hand, overinflated tires can lead to a harsher ride and wear out the tire's center section quickly. Real-time tire pressure monitoring ensures that tires are always inflated to the recommended levels, thus promoting even wear and maximizing the tire's lifespan.Furthermore, tire temperature plays a significant role in tire health. High temperatures generated during long drives or heavy loads can cause the tire's rubber compound to deteriorate rapidly. Smart tire sensors continuously track temperature levels, alerting drivers if the tires are getting excessively hot. By addressing such situations promptly, drivers can prevent damage to the tire's internal structure and extend its overall lifespan.Additionally, smart tires monitor tread depth over time, providing drivers with insights into how quickly their tires are wearing down. Armed with this data, drivers can rotate their tires regularly to promote even wear across all tires, extending their usability and overall lifespan.By investing in tires with embedded sensors and utilizing the continuous monitoring capabilities, drivers can maximize their tire investment, reduce the frequency of replacements, and ultimately save money in the long run.Enhancing Vehicle Performance and Handling with Embedded SensorsBeyond safety and efficiency, smart tires equipped with embedded sensors play a vital role in enhancing the overall performance and handling of vehicles. These sensors provide real-time data that allows drivers to fine-tune their driving experience, especially in challenging road conditions.One aspect where embedded sensors make a significant difference is in traction control. By monitoring tire pressure and tread depth, smart tires can help optimize the tire's grip on the road. This becomes particularly valuable when driving on wet or slippery surfaces, as the sensors' data enables drivers to adjust their driving style and reduce the risk of skidding or loss of control.Moreover, real-time monitoring of tire temperature provides insights into the tires' performance during spirited driving or high-speed maneuvers. Overheating tires can result in reduced performance and handling capabilities, compromising the vehicle's stability and control. With smart tires, drivers can monitor tire temperature and make informed decisions about their driving speed and aggressiveness to prevent tire overheating and maintain peak performance.Furthermore, the data collected by embedded sensors can be integrated into the vehicle's onboard systems, allowing for dynamic adjustments based on the prevailing road conditions. Some advanced vehicles can automatically adapt their traction control systems, suspension settings, and braking systems based on the real-time tire data, creating a safer and more stable driving experience.In the pursuit of enhanced vehicle performance, smart tires also contribute to a smoother and quieter ride. By continuously monitoring tire condition, drivers can identify and rectify imbalances, vibrations, or irregularities that may affect the vehicle's comfort and smoothness on the road.Tire Pressure Monitoring Systems (TPMS) and BeyondTire Pressure Monitoring Systems (TPMS) have been a significant step forward in the automotive industry, and they are a fundamental component of tires with embedded sensors. TPMS technology has become mandatory in many regions due to its proven effectiveness in improving road safety. These systems continuously monitor tire pressure and provide real-time alerts to drivers when there is a significant deviation from the recommended pressure levels.The early versions of TPMS would only indicate a warning light on the dashboard when tire pressure dropped below a certain threshold. While this was a valuable improvement, modern TPMS integrated into smart tires takes monitoring to a whole new level. Drivers can now access precise tire pressure readings for each tire directly from their vehicle's dashboard, allowing them to take immediate action if any tire requires inflation.Beyond just detecting low tire pressure, advanced TPMS can also detect gradual leaks, which might not be immediately noticeable. This allows drivers to identify slow punctures or other issues that may affect tire performance over time, preventing unexpected flat tires and enhancing overall safety on the road.Looking ahead, the capabilities of embedded sensors in tires are poised to evolve further. We can anticipate even more sophisticated TPMS technologies that incorporate artificial intelligence and machine learning algorithms to predict tire issues before they become apparent. With such advancements, smart tires will undoubtedly play an even more critical role in keeping drivers informed and vehicles running at their peak performance.The Role of Embedded Sensors in Autonomous VehiclesAs we progress toward the era of autonomous vehicles, the importance of smart tire technology becomes increasingly evident. Autonomous vehicles rely heavily on real-time data from various sensors to navigate safely and efficiently. Smart tires equipped with embedded sensors provide an additional layer of crucial information that can significantly enhance the autonomous driving experience.Real-time tire data is essential for autonomous vehicles to make informed decisions regarding traction control, stability, and overall vehicle handling. Autonomous driving systems can utilize tire pressure, temperature, and tread depth information to optimize the vehicle's performance and adjust driving parameters according to road conditions, weather, and tire health.Moreover, smart tires contribute to the overall safety of autonomous vehicles. By continuously monitoring tire condition, the autonomous driving system can detect any abnormalities or potential hazards related to the tires. This data allows the system to alert the vehicle's occupants or even trigger precautionary measures to prevent tire-related incidents.Beyond safety, smart tires also play a role in optimizing energy efficiency in autonomous vehicles. By providing real-time data on tire health and inflation levels, the autonomous driving system can fine-tune its driving behavior to reduce energy consumption and extend the vehicle's range.As the development of autonomous vehicles progresses, smart tire technology will continue to evolve hand-in-hand, supporting the advancement of self-driving capabilities and ensuring that these vehicles operate safely and efficiently on our roads.In ConclusionThe future of tire sensor technology is bright and full of possibilities. As innovation continues to drive the automotive industry forward, smart tires with embedded sensors will play a pivotal role in reshaping how we interact with our vehicles. From ensuring safety and efficiency to promoting sustainability and adapting to autonomous driving, smart tires are poised to revolutionize the way we drive and experience mobility in the years to come.With 11 years of experience in a tire shop, Dave is a devoted family man and tire enthusiast. He shares his extensive knowledge on tire-related products, maintenance tips, and industry updates. His passion for automobile maintenance and in-depth understanding of tires make his posts a valuable resource. In the world of tires, Dave is an expert you can trust.JUL 14, 2025 | Understanding Tire Pressure Monitoring Systems (TPMS)As vehicles become more advanced, so too do the technologies designed to keep drivers safe. One such innovation is the Tire Pressure Monitoring System (TPMS), a crucial safety feature in modern vehicles. This article delves into the fundamentals of TPMS, exploring how these systems work, the types of sensors involved, and the signals they use to communicate crucial information to drivers.The Importance of Tire PressureBefore diving into TPMS specifics, it's vital to understand why maintaining proper tire pressure is so important. Incorrect tire pressure can lead to a host of problems, including reduced fuel efficiency, increased tire wear, and compromised vehicle handling. In extreme cases, it can even cause tire blowouts, leading to dangerous situations on the road. TPMS helps mitigate these risks by alerting drivers to any significant changes in tire pressure.Types of TPMSThere are generally two types of TPMS: Direct and Indirect systems. Each type has its own unique approach to monitoring tire pressure.Direct TPMSDirect TPMS uses sensors mounted inside each tire to directly measure air pressure. These sensors transmit data to a central control module, which then displays the information on the vehicle's dashboard. If the pressure in any tire falls below a certain threshold, the system triggers a warning light to alert the driver. Direct TPMS provides accurate, real-time tire pressure data, making it a reliable choice for monitoring tire condition.Indirect TPMSIndirect TPMS, on the other hand, does not measure air pressure directly. Instead, it uses data from the vehicle's anti-lock braking system (ABS) to monitor wheel speed. Since under-inflated tires rotate at a different speed compared to properly inflated ones, the system can infer potential pressure issues. While indirect TPMS can be less accurate than direct systems, it is generally more cost-effective and easier to maintain.How TPMS Sensors WorkThe heart of any TPMS is the sensor. In direct systems, each sensor is typically attached to the tire's valve stem or mounted inside the tire itself. These sensors are powered by small batteries and consist of a pressure sensor, a transmitter, and a microcontroller.The pressure sensor measures the tire's air pressure and converts this information into an electrical signal. The microcontroller processes this signal and sends it via radio frequency (RF) to the vehicle's central receiver. The receiver then interprets the data and communicates it to the driver through the dashboard display.In indirect systems, the sensors are part of the vehicles existing ABS, measuring wheel rotation speeds to detect discrepancies that may indicate pressure issues.Interpreting TPMS SignalsUnderstanding the signals sent by your TPMS is crucial for vehicle safety. When the TPMS warning light illuminates on your dashboard, its essential to confirm which tire is affected and address the issue promptly. Some systems provide additional information, such as the current pressure of each tire, allowing for more precise adjustments.Regular maintenance and timely replacement of TPMS components, especially the sensors, are necessary to ensure the system's accuracy and reliability. Over time, sensor batteries can deplete, and components may wear out, necessitating replacement to maintain optimal function.ConclusionTPMS is an invaluable tool for modern drivers, enhancing road safety and vehicle efficiency by keeping track of tire pressure. Whether through direct or indirect systems, TPMS offers critical real-time alerts that help prevent potential tire-related issues. Understanding how these systems work and the importance of maintaining them can make a significant difference in your driving experience, ensuring both safety and peace of mind every time you hit the road.From 5G NR to SDN and quantum-safe encryption, the digital communication landscape is evolving faster than ever. For R&D teams and IP professionals, tracking protocol shifts, understanding standards like 3GPP and IEEE 802, and monitoring the global patent race are now mission-critical.Patsnap Eureka, our intelligent AI assistant built for R&D professionals in high-tech sectors, empowers you with real-time expert-level analysis, technology roadmap exploration, and strategic mapping of core patentsall within a seamless, user-friendly interface. Experience Patsnap Eureka today and unlock next-gen insights into digital communication infrastructure, before your competitors do. Tire Pressure Monitoring Systems (TPMS) have come a long way since their original technology was introduced in the 1980s. At its inception, the system only went as far as turning on a warning light when tire pressure went outside of its recommended range. TPMS service was really limited to needing to stock dozens of different SKUs to offer coverage for all vehicle types equipped with TPMS. Today, TPMS service can be covered using a single programmable sensor and the technology has advanced through wireless auto location displays, detecting temperature and pressure, using Bluetooth capabilities and mechanically fitting into more applications than ever before. For the technology to truly advance, the sensor must be able to detect more than just the air. Today, the sensor is most often connected to the inside of a valve mounted in the rim where it is suspended in the air inside of the tire, limiting its sensing capabilities to what it is exposed to air. Increasing its capabilities is nearly impossible unless the sensor is mounted in a way that enables it to sense additional factors. By mounting the sensor to the inside wall of the tire, it is removing those limits and opens opportunities for new technologies to enter the mix. A tire-mounted sensor is surrounded by a rubber sleeve which enables it to be glued to the inside wall of the tire. The tire is the only part of the vehicle that touches the road, so by adhering a sensor to the tire wall, the sensor can sense the road. Tire-mounted sensors will still detect tire pressure and temperature, but the new surface placement will allow it to also detect factors like vehicle load, road terrain and unique tire identification. These are capabilities that will continue to rise in importance as legislations continue to tighten on gas mileage and EVs continue to enter the market. The ability to give necessary data to optimize these areas is going to continuously increase in importance to the driver. Honestly, its a bit too soon to tell what the repair side of tire-mounted sensors looks like. Will the sensor be removable from the protective case and a new sensor easily replaced? Will the whole protective case be detachable? Will the sensor last the entire life of the tire with no repairs necessary/possible between tire purchases? Stay tuned. There will likely be multiple types of tire-mounted sensors that enter the market that have various capabilities for repair. Staying on top of this trend and training at the shop level will be key to a shops ability to navigate this new technology and turn it into profit. Jacki Lutz is the Global Head of Communications, Training and E-Commerce for Schrader TPMS Solutions, a global leader in TPMS. She is a TIA ATS instructor and serves on a variety of industry boards. When it comes to tire safety, understanding TPMS sensors is crucial. These little devices play a big role in ensuring your tires are properly inflated, which can enhance fuel efficiency and improve handling. Ive noticed that many drivers arent fully aware of the different types of TPMS sensors available and how they function. TPMS, or Tire Pressure Monitoring System, consists of two primary types of sensors: direct sensors and indirect sensors. Understanding these types is essential for effective tire maintenance and safety. Direct TPMS sensors monitor tire pressure in real-time. These sensors are located inside each tire, typically attached to the valve stem. They measure air pressure directly using piezoelectric or capacitive technology. When tire pressure drops below a specified threshold, the sensor sends a signal to the vehicles onboard computer.Features of direct TPMS sensors:Real-time Monitoring: Provides immediate updates on tire pressure.Accurate Readings: Measures pressure changes directly.Battery Life: Lasts approximately 5 to 10 years, depending on usage. Indirect TPMS sensors dont measure tire pressure directly. Instead, they monitor the rotational speed of each tire through the vehicles ABS (Anti-lock Braking System). If a tires inflation level decreases, its rotation speed changes compared to the others. The system interprets these differences to identify under-inflation.Characteristics of indirect TPMS sensors:Cost-Effective: Typically less expensive than direct sensors.Integration: Utilizes existing vehicle systems for monitoring.Calibration: Requires recalibration after tire rotation or pressure change. Knowing the differences between direct and indirect TPMS sensors aids in selecting the right maintenance strategy for your vehicle. Each type serves a specific purpose, enhancing tire safety, fuel efficiency, and overall performance. By recognizing these functionalities, drivers can improve their vehicles reliability and safety on the road. Understanding the two main types of TPMS sensorsdirect and indirecthelps me maintain tire safety and efficiency. Direct TPMS sensors measure tire pressure in real-time from inside each tire. These sensors provide accurate pressure readings and communicate directly with the vehicles onboard computer. Most direct TPMS sensors integrate with the valve stem and typically last between 5 to 10 years. They require a simple battery replacement for continued operation. Manufacturers, such as Schrader and Huf, produce various models of direct TPMS sensors, ensuring compatibility with numerous vehicle makes and models. Indirect TPMS sensors operate differently, focusing on monitoring tire rotation speed using the vehicles Anti-lock Braking System (ABS). These sensors dont measure actual tire pressure; instead, they detect changes in tire circumference as pressure decreases. Indirect systems are often less expensive and dont require frequent maintenance, though they need recalibration after tire rotations or replacements. Commonly employed by manufacturers like GM and Ford, indirect TPMS sensors offer a cost-effective solution for maintaining tire safety without the need for complex installations. TPMS sensors come with distinct features that cater to different vehicle needs. Understanding these features helps in making informed choices regarding tire safety and maintenance. Direct TPMS sensors offer high accuracy by measuring tire pressure in real-time. They provide immediate feedback on tire conditions, reducing the risk of under-inflation or over-inflation. Their reliance on precise readings enhances overall vehicle safety and contributes to better fuel efficiency. In terms of performance, direct sensors typically last between 5 to 10 years, depending on usage and environmental factors.Indirect TPMS sensors excel in a different manner; they monitor tire rotation speed rather than direct pressure. While not as precise as direct sensors, they still signal potential issues by detecting changes in tire circumference. This approach allows for a more cost-effective solution but requires users to recalibrate the system after any tire alterations, making them slightly less reliable in real-time monitoring. Direct TPMS sensors integrate seamlessly with the valve stem and require minimal setup. Their battery replacement process is straightforward and generally doesnt necessitate professional assistance. Routine checks and maintenance ensure continued performance, vital for long-term reliability.Indirect TPMS sensors, on the other hand, are easier and quicker to install, as they rely on existing ABS data. However, they necessitate recalibration after new tires are fitted, which can complicate maintenance. Accessing the vehicles onboard diagnostics may be required, often involving a visit to the service center. Understanding the installation and maintenance needs helps optimize the performance of each TPMS type. Examining the differences between direct and indirect TPMS sensors reveals valuable insights into their respective advantages and disadvantages. Understanding these pros and cons aids in making informed decisions on tire safety solutions. Accuracy: Direct TPMS sensors deliver precise tire pressure readings, reducing risks associated with under-inflation or over-inflation.Immediate Feedback: Real-time data alerts drivers to pressure changes, facilitating prompt action to maintain optimal tire conditions.Easy Maintenance: Battery replacement for direct sensors is straightforward and usually requires minimal effort.Higher Cost: Initial purchase and installation costs for direct TPMS sensors tend to be higher than those for their indirect counterparts.Installation Complexity: While battery replacement is simple, initial installation may involve professional expertise, especially during comprehensive system integration.Lower Cost: Indirect TPMS sensors generally present a more budget-friendly option, both in terms of purchase and installation.Simple Installation: The installation process relies on existing vehicle systems and doesnt require additional components, making it quick and easy.Less Accuracy: Indirect sensors monitor tire rotation speed rather than direct pressure, which can lead to inaccurate readings during pressure loss.Recalibration Requirement: After any tire change or rotation, recalibration becomes necessary to maintain accurate monitoring, often needing professional assistance. Choosing the right TPMS sensor type can significantly impact tire safety and vehicle performance. Direct sensors offer precision and ease of maintenance while indirect sensors provide a more budget-friendly option.I believe understanding these differences empowers drivers to make informed choices that enhance their driving experience. By prioritizing proper tire inflation through the right TPMS solution, we can all enjoy better fuel efficiency and safer journeys on the road. C.Daimler, Apollo IST-2001-34372: intelligent tyre for accident-free traffic, Eur. Comm. Inform. Society Tec, vol.1, pp. 164, 2005. Google Scholar A.J. 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Google Scholar As a library, NLM provides access to scientific literature. Inclusion in an NLM database does not imply endorsement of, or agreement with, the contents by NLM or the National Institutes of Health. Learn more: PMC Disclaimer | PMC Copyright Notice . 2014 Jun 11;14(6):1030610345. doi: 10.3390/s140610306This article presents an overview on the state of the art of Tyre Pressure Monitoring System related technologies. This includes examining the latest pressure sensing methods and comparing different types of pressure transducers, particularly their power consumption and measuring range. Having the aim of this research to investigate possible means to obtain a tyre condition monitoring system (TCMS) powered by energy harvesting, various approaches of energy harvesting techniques were evaluated to determine which approach is the most applicable for generating energy within the pneumatic tyre domain and under rolling tyre dynamic conditions. This article starts with an historical review of pneumatic tyre development and demonstrates the reasons and explains the need for using a tyre condition monitoring system. Following this, different tyre pressure measurement approaches are compared in order to determine what type of pressure sensor is best to consider in the research proposal plan. Then possible energy harvesting means inside land vehicle pneumatic tyres are reviewed. Following this, state of the art battery-less tyre pressure monitoring systems developed by individual researchers or by world leading tyre manufacturers are presented. Finally conclusions are drawn based on the reviewed documents cited in this article and a research proposal plan is presented.Keywords: TPMS, pressure sensor, energy harvesting means, tyre structureThis article presents a research proposal plan on developing a functional tyre condition monitoring system (TCMS). The proposed device is planned for land vehicles, but can also be used for aircraft with limited modifications. A TCMS, also called a Tyre Pressure Monitoring System (TPMS), when it is primarily installed to monitor inflation pressure, is an electronic device by which tyre conditions, such as tyre inflation pressure, cavity air temperature, tyre belt stress and strain, normal load, traction force, acceleration, tyre wear, etc., are measured and transmitted to notify the vehicle driver about the values of the measured quantities, the status of the tyre, and to warn the driver if there is any unsafe change in any of the measured values, e.g., low inflation pressure. TCMS is usually installed inside the pneumatic tyre cavity, but it can also be designed to be tightened onto the tyre valve stem cap externally.Deflated tyres can cause several problems which may lead to insecurity; extra fuel consumption; excessive tyre wear; reduction in tyre lifetime; higher rolling resistance; noise emissions and escalation in CO_2 emissions. It is estimated that from the introduction of the TPMS to the EU-15 alone; reduction in CO_2 emissions can be 9.6 million tons per year by 2020. On average; it is estimated that maintaining the recommended tyre inflation pressure can reduce CO_2 emissions and fuel consumption by about 2.5%. In a passenger car tyre; the recommended inflation pressure lies within 1.92.2 bar pressure range. A decrease of 0.5 bar in the recommended inflation tyre pressure may increase that tyre rolling resistance by 10%; leading to an increase in fuel consumption of 2.5% [1]. According to Transense technologies plc; a company based in Bicester; UK; has developed a SAW based tyre pressure monitoring system which is supposed to be available on the market for motorsport applications [2]; a car that has tyres that are 20% underinflated has an increased rolling resistance of 12%; reducing tyre lifetime by up to 50% and leading to increased fuel consumption by 6% [3]. Existing TPMSs require a power supply; which is nearly always a battery; however; an external power supply is possible; e.g., electromagnetic coupling and/or RF power telemetry. Problems with batteries in TPMSs can be summarised into three main categories; safety issues due to battery finite life; environmental impact consequences primarily due to the disposing of toxic chemicals contained in depleted TPMS batteries (Spectrum Batteries Inc.: Flushear, TX, USA) [4]; and initial and then maintenance costs; the former is due to the need for specially made batteries for the TPMS environment; while the latter results from the need for the depleted batteries replacement. A TPMS battery is subjected to the tyre cavity's harsh environment which can significantly deteriorate its efficiency by the extreme climatic conditions inside the tyre; e.g., a wide operation temperature range and battery contacts' problems resulting from the extreme vibration conditions occurring within the tyre-rim assembly [5]. External TPMS powering; whether via electromagnetic coupling or through an RF powered system; relatively consume a high amount of power (Delta Electronics Inc.; Taipei; Taiwan) [6]; which therefore results in the consuming of more fuel. Furthermore; the reader part of these types of tyre monitoring systems has to be installed within a few centimetres of the sensor embedded inside the tyre. The TCMS developed in this research avoids the energy problem associated with conventional TPMSs by using an energy harvesting technique which converts a fraction of the strain energy dissipated throughout the pneumatic tyre cyclic deformation into electrical charge and stores it in an electrical capacitor in order to use it via the system circuitry. In this way; using batteries for powering the TCMS is eliminated and therefore obviates the disposal of a huge amount of depleted batteries; which is a contribution towards eco-driving.In order to obtain a long life vehicle tyre and to promote road traffic safety, research has been conducted by several researchers and by some of the biggest tyre manufacturers, e.g., Michelin, Continental, Pirelli and Dunlop [7] to produce a means to sustain road traffic safety by improving vehicle control system and tyre-road interaction, e.g., tyre contact patch area and pressure distribution within it , that is an intelligent tyre.Maintaining tyre pressure levels is particularly vital for avoiding traffic accidents and prevents wasting fuel caused by faulty tyre air pressure levels; which therefore helps the reduction of carbon emissions. In the US, the government has put in to place legislation in which all new vehicles since September 2007, except those with dual wheels on an axle, have to have a TPMS installed in all its tyres. This is enforced by the National Highways and Traffic Safety Administration (NHTSA)-(FMVSS No. 138) [815]. Likewise, in the EU from 1st November 2012, all new vehicles must have a TPMS installed (UNECE Vehicle Regulations (Regulation No. 64))[1517]. The next paragraph explains the problems associated with powering a tyre monitoring system.The problems associated with using batteries as the main power supply unit in TPMSs include limited life time, low energy density at extreme temperatures [18,19], energy capacity deterioration associated with high centrifugal loading, shocks and vibration exposure, and the need for frequent replacements [20,21]. The technique used in the proposed TCMS is a clean and perpetual solution to powering sensors by avoiding the use and the need for the toxic and corrosive thionyl chloride chemistry used in TPMS lithium batteries, and subsequently their resulted waste, in which special handling and disposal is required. However, the designed system is active only when the containing tyre is in motion. This property helps by saving energy from being wasted while the vehicle is stationary and accelerates waking up time after starting off.In general, a TCMS consists of three main units; the power supply unit, sensing unit, and readout circuitry unit as shown in Figure 1. The power supply unit comprises an energy source element which is primarily a battery, and a power monitoring and conditioning circuitry. The sensing unit includes different types of sensors with respect to the properties intended to be measured, e.g., pressure and temperature sensors. The third unit is a programmable element run by a microcontroller. Its function is summarised into handling the system sensors' input and output signals using an interface circuit, switching on and off the system components, and transmitting the measured quantities [2224]. General TCMS schematic diagram.The research is planned to address the power requirements and sensing mechanism issues related to the above mentioned three main TCMS units in such a way that an energy harvester is installed on the inner surface tyre linear. In addition, the overall power consumption of the system must be within the energy harvester power generation capacity in order to achieve an acceptable duty cycle. A duty cycle is the fraction of the time over which a device is active divided by the length of a certain period of time.Figure 2 shows the developed TCMS in this research. The main difference in this system, compared to the general TCMS components, is the power supply unit. This device is self-powered and therefore does not require using a battery or any other means of contact free powering methods, e.g., induction coupling. The research is intended to develop a TCMS that can be attached to the inside of a passenger vehicle pneumatic tyre. Having the system applied on that area allows the sensing of additional parameters rather than inflation pressure and tyre cavity air temperature, e.g., traction force, normal load, tyre strain, acceleration, etc. and promotes the intelligent tyre system. TCMS schematic diagram.The key feature of the TCMS developed in the research is its energy scavenging capability and wide speed range coverage. Instead of embedding batteries to power sensors and the transmitter, it converts tyre strain energy into electricity using a piezoelectric device. The developed TCMS has the advantages of minimal maintenance requirements, obviating the disposal of large quantities of batteries, and the compatibility of functioning over an automotive temperature range of a higher level than lithium batteries.The development of the energy harvesting based TCMS went through logical steps as follows. First, a micro tyre pressure sensor and several types of electronic circuits for both power management, and measuring and transmitting the embedded sensors data purposes were designed and tested. Then two energy harvesting units were studied. The harvesting unit of the higher energy density was then selected for pneumatic tyre application. This energy harvesting unit which can operate efficiently in the tyre cavity atmosphere conditions and generates sufficient energy for the TCMS circuitry was promoted by testing its performance via applying it inside a pneumatic tyre and observing its performance under different loading and speed conditions. Experiments were then conducted to examine the performance of the selected Piezo Fibre Composite (PFC) energy harvester in the School of Mechanical Engineering laboratory by using a tyre test rig, in which controlled loading and speed conditions were applied. Then the chosen energy harvester, coupled with the integrated TCMS circuitry including the pressure and temperature sensors, were tested on both the tyre test rig and on the road including motorways to validate the designed TCMS performance and to make it ready for application in passenger vehicle tyres.The article structure starts with a historical review of pneumatic tyres and means to measure tyre inflation pressure, followed by a comparison between major pressure sensing techniques. Then possible extractable energies and major energy extraction techniques within rolling tyres are illustrated in detail. A state of the art of useful energy harvesting techniques and ones developed by researchers for powering TPMS is presented. Following that power conditioning and TCMS design principles are explained. Finally conclusions and discussion in order to establish a research plan for designing a TCMS.The aim of the research proposal plan is to design and develop a competitive battery-free tyre condition monitoring system (TCMS) and to test its feasibility in the laboratory and on the road. The power source is aimed to be a robust and durable energy harvesting unit that can resist tyre cavity conditions and is able to perform up to standard over a wide range of vehicle speeds and loading conditions for the lifetime of the tyre. An additional aim is to design a novel low power micro pressure sensor as a part of the TCMS to reduce the overall system power requirement, particularly when tyre air pressure readings are being taken. It is also intended that the developed TCMS will have a miniature structure suited for installation on the inner tyre surface.This section summarises how the pneumatic tyre was developed over history and how different methods have been used to measure tyre inflation pressure.Tyre specification is always a matter of selecting the most appropriate design based on a number of inter-related and often conflicting properties. The first documented invention of the pneumatic tyre was in 1845 by Robert William Thomson, who called the invention the Aerial Wheel. This invention introduced three new advantages of the Aerial Wheel: reduced rolling resistance, better manoeuvrability, and decreased noise while in motion. At that time, Thomson first suggested that the new tyre would be inflated with air along with various solid substances of an elastic quality. A tyre with multiple tubes was first developed. Wired type tyre construction with a straight side rim appeared in 1922 made by Dunlop. Back in 1892, a tubeless tyre was predicted to be the future by W. H. Paull. It took approximately six decades until tubeless tyres became commercially available [25]. The next section summarises the development of air pressure sensors following the discovery of pressure phenomena by Galileo in 1594.Having pneumatic tyres filled with air, makes the air act as an ideal compressible elastic support for the tyre structure and the amount of air needed inside the tyre is directly determined by the vertical load capacity for which the tyre is designed. Friction coefficients, both static and kinetic, are mildly affected by inflation pressure on dry roads, while on wet surfaces inflation pressure is a crucial factor to improve both friction coefficients [26]. Having the correct tyre pressure benefits optimal performances in several land vehicle controls, e.g., braking distance and less tyre wear. It also saves fuel and reduces the possibility of having unexpected tyre break down and overheating, which can be a direct cause of fatal accidents [27,28]. Noise generated from rolling tyres increases when tyres are under low inflation pressure. These facts make measuring tyre air pressure vital and therefore different types of tyre pressure measurement have been developed. A detailed report by W. Reithmaier et al. [29] demonstrates and analyses tyre-related accident research data and summarises the main effects of under inflated tyres on their durability and overall vehicle performance. In addition, this report presents different techniques and methods to monitor, control and maintain tyre inflation pressure.Mechanical pressure gauges are the most common tyre pressure measurement tool and still the most widely used instrument for measuring pressure of different fluids. Originally they were invented for measuring atmospheric pressure, as the aneroid barometer by Lucien Vidie for low pressure in 1844, and 5 years later developing into the Bourdon tube pressure gauge for high pressures [3032]. These pressure sensors were the first ones that did not use liquids for the pressure measurement mechanism; instead they use mechanical linkages, springs, a diaphragm, and bellows to detect any applied pressure and result in corresponding movement.In 1856, Lord Kelvin discovered the piezoresistive effect in metals which was an essential factor in developing strain gauges [33]. Electrical pressure transducers were developed in the early 1930s by applying potentiometers or variable capacitors on a Bourdon tube. In the late 1930s, pressure transducers were developed using strain gauges by applying them on pressure sensitive diaphragms after the invention of independent bonded strain gauges by E. E. Simmons of the California Institute of Technology and AC. Ruge of Massachusetts Institute of Technology [34]. In the mid-1950s, the piezoresistive effect in semiconductors, which is comparatively much higher than its parallel in metals, was found by C. S. Smith, and since then, various kinds of micromachined sensors, including micro pressure sensors, have been widely produced [33,35]. Having strain gauges bonded to a pressure sensitive diaphragm causes inescapable hysteresis and instability. Thin-film transducers with good stability and low hysteresis were introduced in the 1960s by Statham. This technology is particularly useful for high pressure sensors' fabrication. As thin-film technology is more suitable for high pressure application, William R. Poyle applied for a patent for a capacitive transducer on glass or quartz basis in 1973, whereas Bob Bell of Kavlico did the same on ceramic basis in 1979 [36].The automotive industry has been using silicon micromachining since the mid-1970s where primarily pressure sensors were applied to monitor and control air-fuel ratio to improve fuel economy. Since the 1990s micro pressure sensors were applied to detect fuel vapour leak to reduce raw fuel emissions [37].Having MEMS pressure sensors mass produced with a relatively low unit cost, small weight, micro size and higher precession than conventional pressure sensors, opened a huge market in the automotive industry and made them practical for various pressure related automotive applications. In addition, technological advances in the fabrication of integrated circuits (IC) including doping, etching, and thin film deposition methods, have allowed significant improvements in piezoresistive device sensitivity, resolution, bandwidth, and miniaturization [38]. The relation between ICs and MEMS pressure sensors' micro fabrication evolution over virtually the second half of the 20th century is demonstrated in Figure 3. The next section compares different types of pressure sensing mechanisms within MEMS scale, among which some might be suited for tyre pressure monitoring systems. Technological advances in IC fabrication (above the horizontal line) and micromachining (below the horizontal line) [38].Macroscopic pressure sensors used for detecting pressure greater than atmospheric pressure share a common characteristic with deformable diaphragms, and they are also the case with their micro scale counterparts [35]. Diaphragms are the simplest mechanical structure for pressure sensing and have been employed in micro machined pressure sensors because of their compatibility with a range of bulk and surface silicon micromachining processes [39]. The deflection of the pressure sensitive diaphragm can be detected by either measuring the diaphragm deflection or by measuring the stresses produced in the diaphragm [39,40]. Diaphragms can take different geometries depending on their purpose and whether there is a stress or deformation limitation in that application [41,42]. Figure 4 shows the evolution of diaphragm-based MEMS pressure sensors. The evolution of diaphragm-based MEMS pressure sensor [38].Bossed diaphragms, as shown in Figure 5, are attractive in the case of a traditional bonded strain gauge pressure sensor as they offer mechanical stress amplification. (a) Bossed diaphragm geometry and (b) its associated displacement under uniform pressure [39].When pressure is applied on a bossed diaphragm, the developed stresses on the inner and the outer perimeters are the greatest and it is higher than the maximum which occurs in a flat diaphragm [39]. This type of diaphragm offers more sensitivity and linearity in pressure-capacitance response. However, they are more suited for low pressure detection sensors [35,39,43]. In addition, and particularly in TPMS application, having a bossed diaphragm causes considerable error in pressure measurement due to the high centrifugal force up to 3000 g [23], or shocks from the road up to 1000 g [27].In general, diaphragm-based micro machined pressure sensors can be classified, according to the pressure sensing principle, into piezoresistive, capacitive and resonant pressure sensors. These three most common types of MEMS pressure sensors in automotive application, particularly with tyre inflation pressure, are presented and compared in the following sections. Other types of pressure sensors like piezoelectric and optical pressure sensors are outside of the scope of this research due to the high cost and complexity of the measuring chain associated with handling these types of sensors [44], and also because of their high power consumption, which make them not well suited for TCMS application.A comparison between pressure sensors; piezoresistive, capacitive and resonant pressure sensors, the most used microsensors, is illustrated in Table 1.Performance Features of Resonant, Piezoresistive, and Capacitive Sensing [39,45].FeatureResonantPiezoresistiveCapacitiveOutput formFrequencyVoltageVoltageResolution1 part in 1081 part in 1051 part in 104105Accuracy1001000 ppm50010,000 ppm10010,000 ppmPower consumption0.110 mW10 mW