Intelligent Systems

# Tire Condition Monitoring and Intelligent Tires Using Nanogenerators Based on Piezoelectric, Electromagnetic, and Triboelectric Effects

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The quest to utilize intelligent tires has prompted substantial multidisciplinary research including vehicle dynamics, control, estimation, energy harvesting, and even nanotechnology. This review article presents the progress in the area of tire condition monitoring systems (TCMS) and intelligent tires using devices fabricated based on piezoelectric, electromagnetic, and triboelectric effects. Three main branches of the research in this area are presented, including estimation techniques, sensing, and energy harvesting approaches. The authors delineate the importance of TCMS for vehicle active safety systems, its importance for transportation safety, and also its remarkable economic and environmental impacts on the development of intelligent transportation systems. The historical evolution and the perspective of research in the area of intelligent tires and TCMS are also reviewed. In addition, it is discussed how nanogenerators would be effective on the future of intelligent tires.

# 1. Introduction

Tires are the interface between a vehicle and the ground providing forces and isolation to the vehicle. For vehicle safety, stability, maintenance, and performance, it is vital to estimate or measure tire forces, inflation pressure, and contact friction coefficient. Estimation methods can predict tire forces to some extent, however, they fail in harsh maneuvers and are dependent on road surface conditions for which there is no robust estimation method. Measurement devices for tire forces exist for vehicle testing but at the cost of hundreds of thousands of dollars.<sup>[1,2]</sup>

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With the prospect of autonomous driving on roads in near future, it is paramount to make the vehicles safe on any driving and road condition. This is only possible by additional sensors to make up for the driver's cognitive and sensory system. Measuring road condition and tire forces especially in autonomous vehicles are vital in their safety, reliability, and public confidence in automated driving. Real time measurement of road condition and tire forces in buses and trucks can significantly improve the safety of road transportation system, and in miming/construction and off-road vehicles can improve performance, tire life, and reduce operational costs.

There are three particular branches of research in the area of tire condition monitoring systems (TCMS) including estimation, sensing, and power harvesting.

The main focus of this review article would be on progress in estimation techniques, energy harvesting, and also sensing approaches for TCMS based on piezoelectric, electromagnetic, and triboelectric nanogenerators (TENGs). Indeed, the fusion of these three areas in a singular package leads to designing future intelligent tires. The implementation of intelligent tires is highly advantageous for reduction of disastrous accidents,  $CO_2$ , and noise emissions, and also fuel consumption. **Figure 1** depicts an intelligent tire with its basic parts, its crucial applications, and advantages. In Figure 1, NGs, PEGs, and EMGs refer to nanogenerators, piezoelectric nanogenerators, and electromagnetic generators, respectively.

Advances in applications of sensor technologies, sensor fusion, and cooperative estimation in intelligent transportation systems facilitate having reliable tire forces. Consequently, developing a flexible estimation structure to operate the available sensor data in production vehicles is a preeminent objective of the car manufacturers. In this direction, reliable estimation of tire forces at a reasonable cost is necessary for proper functioning of active safety systems in current vehicles. Longitudinal, lateral, and vertical tire forces make major contributions to velocity estimation,<sup>[3]</sup> traction and stability control,<sup>[4,5]</sup> and obstacle avoidance systems.<sup>[6,7]</sup>

This article provides a comprehensive review on intelligent tire and TCMS. The first part of the article describes tire models, techniques for tire force, and tire-road friction



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estimation. The focus of the second section of the paper is on principal sensing and energy harvesting approaches including piezoelectricity, electromagnetism, and nanogenerators. The last section of the paper illustrates a general overview on TCMS and intelligent tires in addition to concluding remarks on the perspective of this area of research. In addition, the high potential of nanotechnology for developing a reliable and durable sensing and energy harvesting technique in tires is discussed.

# 2. Tire Models and Force Estimation

Tire-road forces have played a vital role in state of the art developments in the field of vehicle state estimation and control. They are incorporated into the lateral dynamics to estimate vehicle states and analyze the vehicle stability on different roads (see refs. [5,8–10]). Tire curves are represented by three regions including linear, transient, and nonlinear defined by road friction coefficient, normal forces, and cornering stiffness. The generated lateral and longitudinal forces during cornering, acceleration, and brake scenarios are realized to depend on the road surface friction, slip ratio/angle, and vertical forces.

#### 2.1. Tire Model

The most widely used static tire model, known as the Magic Formula, was proposed by Pacejka et al.<sup>[11]</sup> and Uil.<sup>[12]</sup> This model is obtained by using specific experimental data that allow independent linear and angular velocity modulation in longitudinal and lateral directions. One advantage of this model is that it does not have differential equations in each form of partial or ordinary, making it an appropriate choice for real-time simulations. This model focuses on the steadystate response of the tires versus slip and is generated based on empirical data. Steady-state assumption in the aforementioned model will not lead to precise outcomes during transient acceleration/barking maneuvers. Therefore, dynamic models seem more reliable for transient regions as examined in refs. [13-15]. Canudas-de-Wit et al. proposed a dynamic friction model, known as the LuGre, in refs. [16-18], and introduced tire deflection as a state. Pre-sliding and hysteresis loops as well as combined friction characteristics are considered in their model.<sup>[19]</sup>

Compared to other conventional approaches, e.g., Pacejka, the LuGre model utilizes relative velocities  $v_{rx} = R_e \omega - v_{xt}$  and  $v_{ry} = -v_{yt}$  rather than slip ratio  $\lambda = \frac{v_{rx}}{\max\{R_e \omega, v_{xt}\}}$  and slip angle  $\alpha = \tan^{-1} \frac{v_{pt}}{v_{xt}}$  where  $\omega$  is the wheel speed and  $R_e$  is the tire's effective rolling radius. Longitudinal and lateral velocities in the tire coordinates are denoted by  $v_{xt}$  and  $v_{yt}$ . The passivity of the transient LuGre makes it a bounded and stable model and prohibits the divergence of both internal tire states and consequent forces.<sup>[20]</sup> Accurate tire forces will be calculated by implementing vertical force distributions over the contact patch and multiple bristle contact points. The average lumped LuGre model<sup>[21]</sup> represents average deflection of the tire bristles. In



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this model, the tire internal state  $\overline{z}_q$  for longitudinal and lateral directions (i.e.,  $q \in \{x, y\}$ ) is related to the relative velocities  $v_{rq}$  and tire parameters as  $\dot{\overline{z}}_q = v_{rq} - \left(\kappa_q R_e |\omega| + \frac{\sigma_{0q} |v_{rq}|}{\theta g(v_{rq})}\right) \overline{z}_q$ ,







Figure 1. An intelligent tire: estimation, measurement, energy harvesting, data fusion, advantages, and applications.

in which  $\sigma_{0q}$ ,  $\sigma_{1q}$ ,  $\sigma_{2q}$  are the stiffness, damping, and relative viscous damping in longitudinal/lateral directions, respectively, and  $\kappa_q$  represents force distribution along the tire patch. The pure-slip LuGre model's normalized forces is shown by  $\mu_q$ . The friction transition function  $g(\nu_{rq})$  is defined by  $g(\nu_{rq}) = \mu_{cq} + (\mu_{sq} - \mu_{cq})e^{-\frac{\nu_{rq}\pi}{V_c}}$ , in which  $\mu_{cq}$ ,  $\mu_{sq}$  are the normalized Coulomb friction and static friction, respectively. The Stribeck velocity  $V_s$  shows the transition between these

two friction states. The relative velocities  $\nu_{rx}$ ,  $\nu_{ry}$  of the LuGre model resemble slip ratio  $\lambda$  and slip angle  $\alpha$  in the mostly used tire models such as Pacejka.<sup>[11]</sup> The parameter  $0 < \theta \le 1$  represents the road friction coefficient. To identify this road friction condition parameter, Chen and Wang developed an adaptive controller and a recursive least square (RLS) estimator in ref. [22]. A sliding mode observer is designed in ref. [23] for the maximum transmissible torque estimation, wheel slip, and identification of the road classification parameter. Steady-state



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Figure 2. Pure-slip LuGre tire model, normalized forces: a) longitudinal, b) lateral.<sup>[43]</sup>

normalized longitudinal and lateral pure-slip LuGre tire forces are shown in **Figure 2** for an acceleration driving scenario on roads with friction coefficients ( $0.2 < \theta < 0.97$ ).

The pure-slip condition cannot address the issue of decreasing lateral (or longitudinal) tire capacities due to the longitudinal (or lateral) slip. The combined-slip, i.e., direct correlation between the lateral and longitudinal slips, LuGre model is proposed by Velenis<sup>[19]</sup> in which the internal state  $\overline{z}_q$  for each direction is described as  $\dot{\overline{z}}_q = v_{rq} - C_{0q}\overline{z}_q - \kappa R_e |\omega| \overline{z}_q$ , where  $C_{0j} = \frac{||M_e^2 \mathbf{v}_r|| \sigma_{0q}}{g(\mathbf{v}_r)\mu_{eq}^2}$  and  $M_c = [\mu_{cx} 0; 0 \mu_{cy}]$ . The transition between the Coulomb and static friction in the combined-slip tire model is shown by  $g(\mathbf{v}_r) = \frac{||M_e^2 \mathbf{v}_r||}{||M_e \mathbf{v}_r||} + \left(\frac{||M_s^2 \mathbf{v}_r||}{||M_s \mathbf{v}_r||} - \frac{||M_e^2 \mathbf{v}_r||}{||M_e \mathbf{v}_r||}\right) e^{-\frac{||\mathbf{v}_r||_{0.5}}{V_c}}$ where  $M_s = [\mu_{sx} 0; 0 \mu_{sy}]$  and  $\mathbf{v}_r = [v_{rx} \ v_{ry}]^T$ . The final form of the normalized friction force  $\left(\mu_j = \frac{F_j}{F_{zj}}\right)$  of the averaged lumped LuGre model with  $\overline{\mathbf{z}} = [\overline{z}_{\gamma} \ \overline{z}_x]^T$  yields  $\mu = \sigma_0 \overline{\mathbf{z}} + \sigma_1 \overline{\mathbf{z}} + \sigma_2 \mathbf{v}_r^{[19]}$ in which  $\mu_r \overline{\mathbf{z}}, \mathbf{v}_r \in \mathbb{R}^2$  and can be described both in longitudinal

and lateral directions in the combined or unidirectional-slip models. **Figure 3** illustrates the effect of slip angle on the normalized longitudinal forces and the effect of longitudinal slip on the normalized lateral forces. It corroborates the decreased tire capacity especially for the lateral direction in case of employing the combined-slip model, which is close to real behavior of the tire.

These pure and combined-slip models can be used in roadindependent state estimation approaches<sup>[24,25]</sup> or incorporated in the lateral dynamics for road classification.

#### 2.2. Tire Force Estimation

Sensors mounted on the wheel hub can be used to measure longitudinal, lateral, and vertical tire forces, but available wheel transducers are expensive, hard to calibrate, and require large space; thus, they are not used for production vehicles. The longitudinal and lateral tire forces by static/dynamic tire models need information on road surface friction; thus, even accurate slip information by from the GPS is not sufficient to calculate tire forces. Therefore, tire force estimation using available measurements on production vehicles has been recently addressed in related literature and is discussed in this section.

A high gain observer with input–output linearization is proposed by Gao et al.<sup>[26]</sup> to estimate the lateral states. A cascaded force and side-slip angle estimation structure is provided in ref. [27] by using a sliding mode observer and extended Kalman filter (EKF). Steering torque measurement is implemented in refs. [28,29] for force estimation. In refs. [30,31], tire forces are estimated by using vehicle lateral dynamics, EKF, and unscented Kalman filter (UKF).<sup>[32]</sup> In their



Figure 3. Combined-slip LuGre model, normalized tire forces: a) longitudinal b) lateral.<sup>[43]</sup>





**Figure 4.** Estimated forces for a) steering on wet road,  $\mu \approx 0.5$  and b) brake-in-turn & acceleration on snow. Reproduced with permission.<sup>[38]</sup> Copyright 2017, Elsevier.

approach, longitudinal and lateral force evolution is modeled with a random walk model.

Lateral tire forces are estimated in ref. <sup>[33]</sup> by using lateral dynamics and a random-walk Kalman filter. A Kalman-based unknown input observer is developed by Wang et al.<sup>[34,35]</sup> for tire force estimation with the vehicle lateral dynamics and wheel dynamics. Nam et al.<sup>[36]</sup> used real-time lateral tire force measurements, obtained from the multisensing hub units, and designed on RLS-based observer and a Kalman filter for estimating vehicle side slip and roll angles.

A robust Kalman-based observer is designed in ref. [37] for tire force estimation in longitudinal direction with the presence of uncertainties in the road surface friction, inflation pressure, and wheel effective radius. A nonlinear observer is designed in ref. [38] for the longitudinal force estimation. An arduous steering maneuver on a slippery surface ( $\mu \approx 0.5$ ) is done to evaluate the force estimator in combined-slip conditions and results are shown in Figure 4a for the front-right tire. A brake-in-turn driving scenario accompanied by driver traction request (at the end) is done on the packed snow ( $\mu \approx 0.3$ ) and results are shown in Figure 4b.

The robust tire force estimator developed in refs. [37,38] is tested in a lane-change maneuver on dry asphalt and results are demonstrated in **Figure 5** for the all-wheel drive case. The yaw rate, r, and longitudinal/lateral accelerations (i.e.,  $a_x$ ,  $a_y$ ) measured by inertial measurement unit (IMU) at vehicle center of gravity (CG) are also shown in Figure 5 to show lateral response of the vehicle during this maneuver.

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Experimental results of a fast steering maneuver on an icy (ended up on packed snow) surface are demonstrated in **Figure 6** for the front-left tire. The fluctuations in the forces measured by the wheel hub sensors are due to the low-stick nature of the surface.

Sun et al.,<sup>[39]</sup>, proposed a nonlinear observer for estimation of the longitudinal slip and tire force by using UKF during brake maneuvers. Albinsson et al. designed a tire force estimator in ref. [40] using recursive least square and known driving wheel torque with direct application to electric vehicles. They have also studied the case with torque estimation from internal combustion engines in gasoline cars. Hamann et al.<sup>[41]</sup> designed a robust observer using a UKF and standard vehicle sensors to estimate tire forces for a passenger vehicle without knowledge of tire and road properties. The developed observer uses the bicycle model and a random walk tire force model and its robustness is tested in the presence of disturbances such as changes in tire-road friction.

Corner-based longitudinal, lateral, and vertical force estimation methodologies are provided in refs. [42,43] using a



**Figure 5.** Lateral and vertical force estimates, LC on a dry surface. Reproduced with permission.<sup>[38]</sup> Copyright 2017, Elsevier.







**Figure 6.** Force estimates, steering on ice then packed snow. Reproduced with permission.<sup>[38]</sup> Copyright 2017, Elsevier.

nonlinear observer on the wheel dynamics, an adaptive UKF on vehicle kinetics, and linear observer on the roll and pitch dynamics of the vehicle sprung mass. Yu et al. developed a modular nonlinear observer for estimation of vehicle velocities and longitudinal tire forces in ref. [44]. They used known traction and brake torques for longitudinal force estimation and information on tire cornering stiffness for the velocity estimation. A delayed interconnected cascade-observer structure is proposed in ref. [45] to estimate tire-ground forces in all directions using an EKF. The proposed structure is designed based on nonlinear vehicle dynamics and eliminates mutual dependence between longitudinal, lateral, and vertical estimators.

Farhat et al.<sup>[46]</sup> proposed a method for detecting critical stability conditions in the lateral vehicle dynamics by estimating the nonlinear part of the tire forces using a robust fault detection, which minimize uncertainties, and a proportional integral observer. A linear matrix inequality feasibility approach is employed to generate a set of switched robust observers for uncertain switched systems. A longitudinal tire force estimator is introduced in ref. [47] using the Youla controller output observer on the wheel dynamics, which implements wheel torques and wheel speed measurements. A simple drivetrain model of the system is also provided using bond graphs and their algorithm is tested for a rear-wheel-drive electric vehicle on high, low, and split- $\mu$  road surfaces.

#### 2.3. Tire-Road Friction Estimation

Identification of tire parameters and road surface friction is generally suggested to have longitudinal and lateral tire forces and dedicate appropriate control input at each corner in vehicle traction and stability control systems. A linear regression model is developed in ref. [48] to estimate the tire-road friction during normal drive using only the wheel slip. They also designed an adaptive estimator for a model linear in parameters, to work for simultaneous slow and fast parameter drifts, uncertainties in the model parameters, poor-excitation cases, and abrupt changes. Ray proposed an extended Kalman-Bucy filtering and Bayesian hypothesis selection approach in ref. [49] to estimate tire forces and road friction coefficient. Resulting force and slip ratio/angle estimates were compared statistically with those from a nominal analytic tire model to select the most likely friction coefficient from a set of hypothesized values. An observer-based least square method and a filtered-regressor-based methods are proposed in ref. [50] to estimate tire-road friction coefficient, tire parameters, and longitudinal slip. They evaluated the proposed methods on a nonlinear vehicle dynamic and transmission model using the Bakker-Paceika's tire model.

A slip-based approach is proposed and experimentally verified in ref. [51] for the low-slip and low- $\mu$ parts of the slip curve by using linear and nonlinear observers. They have tested the performance of this approach to estimate the maximum tire-road friction coefficient during normal driving, which is challenging because of close slopes for various road surface friction conditions. A real-time tire-road friction is developed in ref. [52] by using differential GPS, a nonlinear longitudinal tire force model, and a recursive least square method, for acceleration and braking maneuvers during high- and lowslip cases. Lee at al.<sup>[53]</sup> designed and experimentally verified a real-time maximum road friction coefficient estimator method based on the relationship between the wheel slip ratio and the friction coefficient. The proposed approach implemented typical vehicle sensors (carrier speed, engine speed, throttle position, and brake pressure sensors), a fifth wheel, a tire normal force linear observer, and a tire rolling radius observer to deal with uncertainties in the longitudinal slip ratio and friction models.

A parameter adaptation approach is used and a Lyapunovbased observer is designed in ref. [54] to estimate vehicle states and identify road surface friction during an emergency brake by implementing the dynamic LuGre model.<sup>[21]</sup> An EKF is employed in ref. [55] to estimate tire forces and road friction condition simultaneously. Patel et al. designed sliding mode observer by using the equivalent output error injection, pseudostatic LuGre,<sup>[17]</sup> and parameter-based friction<sup>[56]</sup> in ref. [57] to identify the friction coefficient and estimate tire longitudinal forces in brake maneuvers. A road friction estimator together with a tire force estimation structure is developed in ref. [58] based on an iterative quadratic optimization by using the Dugoff tire model.

Hsu et al.,<sup>[59]</sup>, designed a nonlinear observer to identify the road friction and estimate tire slip angles by using steering torque measurement. A recursive least square estimator and a nonlinear observer is used in ref. [60] to identify the surface friction and estimated longitudinal forces, respectively, by implementing wheel torques and longitudinal slip information from a GPS. These methods deal with time-varying model parameters and simultaneously identify the road friction and estimate tire forces. Choi et al. identified the tire-road friction coefficient in real-time for a combined-slip brushed tire model in ref. [61] by linearized recursive least squares methods and measurements related to both vehicle lateral and longitudinal dynamics. Their method requires estimated vehicle velocities in longitudinal and lateral directions.

Using steering torque measurement and combining the vehicle, tire, and steering models, Ahn et al. designed a robust nonlinear observer for road friction estimation in ref. [62]. They also estimated slip angle at each corner (tires) and guaranteed the stability and convergence of the observer in a given region of attraction. In ref. [63], lateral tire forces are directly measured by load-sensing hub bearings and are used for estimation of vehicle lateral velocity and tire cornering stiffness (tire-road friction) employing a recursive least square algorithm. Utilizing the estimated lateral vehicle velocity, tire-road friction is estimated and the algorithm is verified in road experiments.

The vertical and longitudinal dynamics of a quarter wheel is integrated to form a nonlinear model in ref. [64] and the timevarying random road profile and the tire friction are treated as unknown inputs. A combination of Lipschitz observer and modified super-twisting algorithm is used to simultaneously estimate such unknown inputs and states. Chen et al.<sup>[65]</sup> proposed and verified a resonance frequency-based tire-road friction coefficient estimator by considering the dynamics performance of the in-wheel motor drive system and a recursive least squares filter. An adaptive observer is designed in ref. [66] for estimation of the tire-road friction condition based on a recursive least squares algorithm, without adding any extra sensor on a production vehicle. The front biased braking characteristic is also studied and longitudinal vehicle velocity is identified during the tire-road friction estimation process. A nonlinear observer is designed in ref. [67] for the estimation of tire-road friction coefficient and vehicle velocity using a longitudinal tire force observer and a lateral tire friction model.

A combination of a diagnosis module and filtered derivative signal is proposed and verified in ref. [68] by utilizing extended braking stiffness. A weighted Dugoff tire model is also used during specific intervals to estimate the maximum tire-road friction force. **Table 1** summarizes various approaches and related literature for tire force estimation and tire-road friction identification.

Table 1. Tire force estimation and tire-road friction identification.

Туре	Methodology	Illustration/references
Tire force estimation	Linear observers	Switching: [46]
		Steering torque Meas.:[28,29]
	RLS-based observers	[36,40]
	Sliding mode observers	[27]
	Nonlinear observers	[38,43,44,47,60]
	Unknown input observers	[34,35]
	Kalman-based estimation	Random-walk KF: <sup>[33]</sup>
		UKF on wheel/vehicle dynamics: <sup>[37,39,41]</sup>
		KF and EKF: <sup>[30,31,42,45]</sup>
Road friction estimation	Nonlinear observers	[51,54,67]
	Unknown input observers	[64]
	Sliding mode observers	[57]
	Linear observers	[53,56,58,60,68]
	RLS-based Est.:	[48,50,52,61,63,65,66]
	Steering torque Meas.	[59,62]
	Kalman-based estimation	Extended Kalman filter <sup>[55]</sup>
		EKFBucy and Bayesian hypothesis <sup>[49]</sup>

# 3. Techniques for Sensing and Energy Harvesting in Tire

Smart tires equipped with different sensors for the sake of tire condition monitoring are highly in demand to improve vehicle control and safety. The idea of using self-powered sensors for TCMS is a hot topic among researchers. It is a new quest for researchers to exert wasted kinetic energy sources for energyscavenging applications. Plenty of innovative approaches have been proposed so far to extract clean useful energy from accessible ambient sources that would be otherwise dissipated. The proposed energy harvesting techniques have the potential to be used for sustainable powering of wireless sensor nodes (WSN). Employing new methods for energy harvesting results in smaller and more efficient devices. The significance and high influence of tires in providing safety for passengers have prompted researchers to furnish advanced vehicles with a smart tire/wheel system. Implementing of the smart tire/ wheel system leads to increasing traffic safety.<sup>[69]</sup> In addition, it is highly significant in improving chassis/vehicle control systems, and Advanced Driver Assistance Systems. In order to reach the above-mentioned aims, numerous sensory technologies have been proposed and implemented so far for collecting strain and deflection related data from tires.<sup>[70]</sup> A few examples are piezoelectric sensors, surface acoustic wave sensors,<sup>[71]</sup> capacitance based strain sensors,<sup>[72,73]</sup> fiber Bragg grating, and resistance based strain sensors,<sup>[74]</sup> segmented capacitance ring.<sup>[75]</sup> With implementing the aforesaid sensory technologies, a fully functional smart tire is capable of providing information about longitudinal force, lateral force, normal force,<sup>[76]</sup> friction coefficient,<sup>[77]</sup> inflation pressure,<sup>[78]</sup> and aligning moment. Furthermore, we can have online information about tire tread





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Figure 7. A fully functional smart tire. Reproduced with permission.<sup>[80]</sup> Copyright 2017, Wiley.

deformation with implementation of TCMS.<sup>[79]</sup> Figure 7 represents a fully functional smart tire system.<sup>[74]</sup>

In fact, a smart tire contains a TCMS, which is capable of online extracting all the aforesaid parameters. In spite of recent developments in the reduction of power supplying of minuscule micro electromechanical systems, it is desperately needed to have power sources for the autonomous and continuous operation of such tiny and low-energy consumption electronic devices.<sup>[81]</sup>

The fusion of sensory systems and energy harvesters results in improvements in our daily life, and leads to emerging new devices. There are plenty of different energy sources in our environment such as thermal, light, acoustical noises, and also kinetic. Among the above-mentioned available sources, the kinetic type is ubiquitous, which makes it as a potent option to provide power for self-powered smart systems, especially sensors.<sup>[82–84]</sup> This section provides information about the principal techniques for energy harvesting and sensing in tires. Section 3.1 presents the published articles in the area of TCMS using piezoelectric mechanisms. The focus of Section 3.2 is on electromagnetism and its applications in TCMS. Section 3.3 reviews the application of nanogenerators in development of TCMS. The last section of this part presents other methods, which have been already implemented by researchers in TCMS.

#### 3.1. Piezoelectricity

The presence of an electric field engenders physical deformation in piezoelectric materials, or on the other hand, generates an electrical charge when mechanically deformed. In fact, the spontaneous separation of charge within certain crystal structures under the right conditions leads to the generation of an electric dipole.<sup>[85]</sup> The most significant advantage of piezoelectricity is the direct conversion of mechanical strain, stress, or deformation into electrical charge and vice versa.<sup>[86]</sup> These superior characteristics of piezoelectric materials have been fascinating for researchers to utilize them in energy harvesting devices and sensors.<sup>[85,87,88]</sup> They have been exploited to scavenge energy for number of systems in bio-engineering, the detection of pollutants, programmable paper, vibration detection and vehicle monitoring. In addition, the generated voltage by the piezoelectric based device not only can be used for energy harvesting applications, but also, it can be utilized for sensing in different systems including tires.<sup>[89–93]</sup>

Recently, piezoelectric materials have been considered by a number of companies including Piezotag, Siemens, and Michelin Research et Technique SA to develop energy harvesters and sensing instruments. A few teams have dedicated research efforts on the development of piezoelectric generators for TCMS. In a novel research work, Marian Keck developed an energy harvester using piezoelectric materials to provide power for embedded sensors in a tire. The fabricated power harvesting device is capable of generating average power of 40 µW over 30-180 km h<sup>-1</sup> velocity range.<sup>[94]</sup> The energy harvesting device contains a beam with support on both ends and also nonlinear spring stiffness. In another work, Zheng et al. proposed a piezoelectric energy harvesting device, which should be installed on the wheel up-side-down, and it works in compression mode. The radial vibrations of the air-spaced cantilever were used to generate the peak power at the resonant frequency. The fabricated device can scavenge 47 µW power at approximately 80 km  $h^{-1}$ . The only shortcoming of their energy harvester is its size, which made its practical application impossible for TCMS.<sup>[95]</sup> Tang et al. designed piezoelectric cantilevers excited by magnetic repulsive force, and effectively generated an average power of 10  $\mu$ W in frequency range of [10–22] Hz. The harvester is mounted on the rim inside the tire cavity.<sup>[92]</sup> Gu and Livermore proposed a self-tuning power harvesting mechanism, which encompasses a pendulum-driven system. With implementing tangential vibrations, the device is capable of generating a maximum power density about 30.83 µW cm<sup>-3</sup>.<sup>[96,97]</sup> Their energy harvesting device was designed for a tire with a 572 mm outer diameter. The speed range of considered tires spans 25 miles per hour mph to 65 mph. The considered speed range corresponds to a rotational frequency range from 6.2 Hz to 16.2 Hz. Figure 8 depicts the self-tuning energy harvester.<sup>[98]</sup>

A piezoelectric bender generator, which directly harvests energy exerted by the tire speed, was developed by Pinna in 2010. The generator was attached to the tire wall from the outside in the tangential direction at 16 *cm* distance from the wheel center. It has been represented that their energy harvesting device is capable of generating power around 2.99  $\mu$ W at 80 km h<sup>-1</sup> velocity.<sup>[99]</sup>

Roundy and Tola developed a power harvesting system, which uses the earth's gravitational field.<sup>[100,101]</sup> In order to have a better operational bandwidth in their designed system, they combined the unique dynamics of an offset pendulum with a nonlinear bistable restoring spring. The ball inside of the harvester rolls back and forth in the curved track between the two end stops. As it passes through the center of the track, the piezoelectric beams are excited. The device can generate 10  $\mu$ W power at 10 *kph*, which is more than the required power for transmitting the signal in each minute.<sup>[100]</sup>





Figure 8. A harvester prototype mounted on an electrical fan. Reproduced with permission.<sup>[98]</sup> Copyright 2010, AIP.

The feasibility of implementing an inertial vibrating energy harvester unit to provide electrical power for the sensor module inside the tire was investigated by Singh et al.<sup>[102]</sup> They showed that due to high acceleration levels associated with a tire result in certain issues in designing a harvester system for tires. These issues include broad-band operation, low weight, and small volume. Therefore, they designed a piezoelectric bimorph transducer considering all of these design issues. Also, in order to optimize the frequency band of operation, they developed a novel artificial neural network (ANN) based feedback loop control.<sup>[102]</sup>

A new ring piezoelectric harvester excited by magnetic forces was developed by Xie et al. for power harvesting in tires. The harvester includes an outer ring stator and an inner ring rotor. The stator ring is fabricated by a series of discrete piezoelectric patches with a rectangular shape surface mounted by magnetic ring slabs with the same size. **Figure 9** shows the schematic of the proposed energy harvester. The proposed ring can generate up to 5274.8W power with considering l = 0.4 m, w = 0.005 m,  $t_m = t_p = 0.01 m$ ,  $r_1 = 0.5 m$ ,  $r_2 = 0.499 m$ , and  $B_r = 1.48T$ .<sup>[103]</sup> All of the aforesaid parameters are defined in Figure 9. Following

this work, Xie and Wang proposed a mathematical model for piezoelectric ring energy harvesting technology in tire. The model was developed based on an iteration method to obtain the energy harvested from excitations of vehicle tires by rough roads. In their conceptual design, they supposed a piezoelectric ring harvester, which consists of a series of discrete PZT4 patches in a square shape. The results of the paper show that implementation of this ring in tires not only is capable of powering tire sensors, but also, it can power other appliances in vehicles as the RMS of the power for each ring can reach 42.08 W.<sup>[104]</sup>

Makki and Pop-Iliev designed and developed a functional automotive TPMS using very low cost and highly flexible piezoceramic (PZT) bender elements. Based on the results of their research, the fabricated TPMS can be implemented as both a battery-less and wireless device inside a tire.<sup>[105]</sup>

Lee and Choi<sup>[106]</sup> used piezoelectric materials to design a power harvesting patch, which can generate 34.5  $\mu$ J. The fabricated power harvesting patch uses the strain energy of the deformation in a tire to generate electrical voltage. They also proposed an efficient method to enhance generation efficiency of the piezoelectric patch. the dimension of the fabricated piezoelectric patch is (60 × 10 × 0.3 mm<sup>3</sup>).

Eshghi et al. designed an optimized piezoelectric energy harvester, which is capable of powering TPMS under uncertainty and speed variability. A piezoelectric energy harvester was tested for an automotive wheel using stochastic resonance. Their results demonstrates that stochastic resonance can be used to optimize the performance of the power harvester with a sustainable power density of 0.76  $\mu W \ cm^{-3}.^{[107]}$ 

In our research group, Mechatronics Vehicle System lab (MVS-lab), we have used piezoelectric sensors for finding tire forces. Using the Finite Element Analysis, we first obtained the best location for attaching the piezoelectric sensors, and then, with employing a trained neural network, different forces in tires have been obtained.<sup>[74]</sup> Although, the electrical output of the piezoelectric sensor was enough for both power harvesting and sensing, but we realized that it cannot be used for real tire system due to its low thermal and mechanical durability.<sup>[108]</sup> An instrumented system for smart tire application was fabricated in MVS-lab using piezoelectric sensors.<sup>[108]</sup> To develop the smart tire sensory system, four sensors were located in different places of the smart tire. Two of them were attached to the sidewalls of tire, and the other sensors were located at the tread center-line. This pattern of sensors attachment provides the required measurement for different forces in a tire.



Figure 9. Schematic diagram and geometries of the piezoelectric energy harvester. Reproduced with permission.<sup>[103]</sup> Copyright 2014, Elsevier.



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**Figure 10.** Nonlinear suspended energy harvester (NSEH) used in a wheel. a) Schematic representation of a rolling wheel, b) schematic of the NSEH. Reproduced with permission.<sup>[19]</sup> Copyright 2015, MDPI.

A scrutiny of literature about the piezoelectric energy harvesting and sensing devices in TCMS indicates that there are a few drawbacks and limitations in their designs:

- a) In most cases, it is essential to design a harvester which is capable of tuning the frequency.
- b) In the case of utilizing beam-mass model, the developed devices must have an overload protection.
- c) Generally, the considered resonant frequency for the different developed piezoelectric harvesting devices is not realistic.
- d) The piezoelectric ceramics commonly used in energy harvesting devices which are brittle.

#### 3.2. Electromagnetism

The second practical and principal approach for energy harvesting and sensing performs based on the electromagnetic mechanism.<sup>[109–111]</sup> Electromagnetic transducers typically work based on the relative motion of an electrical conductor in a magnetic field. In most cases, the conductor is wound in a coil to make an inductor.<sup>[112]</sup> In fact, the relative motion between the coil and magnetic field causes a current to flow in the coil.<sup>[113–115]</sup> Electromagnetic transducers have two interesting features. First, there is no need for having a separate voltage source to start the energy conversion process as with the electrostatic type. Second, no mechanical contact is needed for designing the device.

Owing to low-cost of the electromagnetic approach, it has been considered as a viable platform for TCMS.[116] There are two different types of electromagnetic power harvesting in tires including inertial electromagnetic and relative displacement electromagnetic transducers. The first type of electromagnetic transducers is utilized to generate electrical output for different applications such as TCMS. As an example of inertial devices, we can refer to an energy harvesting design by Lee and Kim, which contains coil strap attached to the circumferential face of a rim, and a permanent magnet located on the brake caliper system.<sup>[117]</sup> The fabricated device harvests rotational energy and alters it into electricity utilizing electromagnetic induction via the coil strap located inside the wheel rim.<sup>[117]</sup> Inertial harvesters that are installed in the inner side of the tire have also been illustrated by Tornincasa et al.<sup>[118]</sup> It is suggested that the inertial harvesting device to be mounted on the inner liner of a tire. The harvester operates based on magnetic levitation. Because of tire and road interaction, the permanent magnet would have relative motion with respect to the coil. A novel design was proposed by Wang et al. to harvest power from a rotating wheel. The fabricated power harvesting device includes two springs along with a coil, magnet and an electrical circuit.<sup>[119]</sup>

The centrifugal force, and the push-pull forces by two springs are the main dynamical parameters of their proposed energy harvester. An energy harvesting device embedded in a rotating wheel is shown in **Figure 10**.<sup>[119]</sup> The proposed energy harvesting device can generate 30 to 4200  $\mu$ W power for a range of speed between 200 to 900 rpm. Their work also reports a non-linear mathematical model for the developed fabricated energy harvesting device. The obtained nonlinear differential equation of their system has relativistic form,<sup>[120]</sup> and its approximated form can be presented by the Duffing equation.<sup>[121–123]</sup>

Considering the tangential accelerations faced by a rolling wheel, the fabricated power harvester can generate an output power of 0.4 mW for a resistance load of a 100  $\Omega$  at 15g peak-to-peak amplitude.<sup>[124,125]</sup> Figure 11 represents an assembled



**Figure 11.** a) Assembled FR4 energy scavenger design with spacer, b) assembled structure with an oversized magnet. Reproduced with permission.<sup>[125]</sup> Copyright 2009, Elsevier.



Figure 12. a) An assembled energy harvester. Reproduced with permission.<sup>[126]</sup> Copyright 2012, Elsevier.

FR4 energy scavenger design with spacer and components of a scavenger design. The implemented magnet in the fabricated energy harvester has a radius of 10 mm and a height of 2 mm.

Oscillations induced by Karman Vortex Street in the flow channel can be effectively used for energy scavenging. Based on this idea, Wang et al. designed an electromagnetic power harvester which utilizes the pressure oscillations because of the Karman vortex street to generate electrical voltage. This results in a periodical relative motion between the magnet and coil, and therefore inducing electrical current.<sup>[126]</sup> **Figure 12** represents their developed model. The volume of proposed energy harvesting device is 37.9 cm<sup>3</sup>, and it can generate an instantaneous power of 1.77  $\mu$ W at the pressure fluctuation frequency of 62 Hz and a pressure amplitude of 0.3 kPa.<sup>[126]</sup>

Tang and Zuo derived closed-form of the output power of dual-mass harvesters considering random excitations such as displacement, velocity, and acceleration. Then, they compared the results with the performance of the single-mass configuration. With developing single- and dual-mass vibration harvesters, they presented two different applications for them including: large-scale vibration energy harvesting from the regenerative suspensions of vehicles, and the regenerative TMDs of tall buildings.<sup>[127]</sup> Hybrid piezoelectric and electromagnetic energy harvesting from random vibrations have been developed by Li et al.,<sup>[128]</sup> who proposed a hybrid energy harvester integrated with piezoelectric and electromagnetic conversion mechanisms, as shown in Figure 13. Their paper reports a comprehensive analytical and experimental results based on the proposed hybrid energy harvesting device considering random vibrations. Dimension of the piezoelectric layer of their device is  $10 \times 8 \times 2$  mm. The electromagnetic component of the

energy harvester consists of a radial magnet with radius and thickness of 15 and 40 mm, respectively. The designed coil for the energy harvester has a diameter of 15 mm with 360 number of turns.<sup>[128]</sup> Wang et al. designed a well-weighted pendulum to harvest energy from a rotating wheel using electromagnetic induction technique. The fabricated device includes a pendulum and one or more weights, and it is capable of converting kinetic energy into electricity using electromagnetic approach. The proposed device can generate several milliwatts, which is enough for powering sensors inside a tire.<sup>[129]</sup> A similar design can be found in ref. [130] in which Wang et al. proposed a weighted pendulum-type electromagnetic generator for harvesting energy from a rotating wheel. Results of their paper illustrate that the fabricated energy harvester is capable of generating the electrical power of 200–300  $\mu W$  at about 200-400 r min<sup>-1.[130]</sup>

After a broad survey about the use of electromagnetic transducers in TCMS, we find that this mechanism is not suitable for this application, as any design based on this technique results in a bulky system. This leads to a high centrifugal force in a tire, which can be effective on tire dynamics. In addition, it is difficult to have a flexible system using electromagnetic technique.

#### 3.3. Nanogenerators

Since their discovery in 2006,<sup>[131]</sup> nanogenerators<sup>[132]</sup> have fascinated researchers to use them in different applications including wave,<sup>[133–141]</sup> and wind energy harvesting,<sup>[110,142–145]</sup> traffic monitoring,<sup>[146]</sup> harsh environments such as turbines and tires<sup>[80]</sup>



Figure 13. a) Designed hybrid PE and EM energy harvester. b) SDOF model of hybrid PE and EM energy harvester. Reproduced with permission.<sup>[128]</sup> Copyright 2015, Springer.





**Figure 14.** a) Shape change of the tire in the contact patch, b) a sketch of the nanogenerator, c) simulating the tire's deformation, and d) the location of the nanogenerator in tire. Reproduced with permission.<sup>[186]</sup> Copyright 2011, Wiley.

and wearable electronics and also portable devices.<sup>[111,147–152]</sup> Generally, a nanogenerator can convert mechanical/thermal energy as generated by a tiny physical variation, into electricity. There are three main categories of nanogenerators including piezoelectric,<sup>[153–155]</sup> triboelectric,<sup>[156–160]</sup> and pyroelectric.<sup>[161–163]</sup> The piezoelectric and triboelectric nanogenerators are used for converting wasted kinetic energy into electricity,<sup>[150,156,164–184]</sup> and pyroelectric nanogenerators<sup>[185]</sup> can scavenge thermal energy from a time-dependent temperature fluctuation.

The focus of this part of the present review article is on recent progress in tire condition monitoring using both piezoelectric and triboelectric nanogenerators. One of the pioneering works in this area is a paper by Hu et al. in which they used piezoelectric nanogenerators for self-powered sensing in tire. When a bending load is applied to the fabricated piezoelectric

nanogenerator, a transient flow of electrons is generated across an external electrical load.<sup>[186]</sup> In accordance with the working area of the device, a maximum power output density of 70  $\mu$ W cm<sup>3</sup> was obtained. They reported that the fabricated NGs can generate an output voltage about 1.5 V and output current around 25 nA with a travel distance of 12 mm and an acceleration of 30 ms<sup>-2</sup>. Also, the effective working area of the NGs is about 1.5 cm  $\times$  0.5 cm.<sup>[186]</sup> Figure 14 represents the shape change of the tire in the contact patch, a sketch of the nanogenerator, simulating the tire's deformation, and the location of the nanogenerator in the tire  $^{\left[ 186\right] }$ 

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As another earliest attempt of implementation of nanogenerators in a tire system, we can refer to a paper by Mao et al.<sup>[187]</sup> For the first time, they utilized single-electrode triboelectric nanogenerator for scavenging friction energy from rolling tires. With design and implementation of a PDMS S-TENG on a rubber wheel, they provided a systematical analysis on the potential of triboelectric nanogenerators in tires. Results of their work show that the fabricated device is capable of generating maximum instantaneous power of 1.79 mW at a load resistance of 10 M $\Omega$ . **Figure 15** schematically represents their TENG self-powered device for tire systems.<sup>[187]</sup> The experimental setup includes 6 PDMS S-TENGs (1.5 × 3.5 cm<sup>2</sup> each), which were located on the tire surface of a toy car. They showed that the highest efficiency is 10.4% when it is shunted to 10 M $\Omega$  load resistance.<sup>[187]</sup>

Chen et al. proposed a fully packaged hybridized nanogenerator to scavenge rotation energy. The proposed device is a cylinder-like fully-packaged hybrid nanogenerator, which can scavenge vertical rotation energy. It implements a magnet rod to trigger the TENG. The hybridized generator includes eight TENG units which have been uniformly located on the inner surface of an acrylic cylinder with dimension of  $200 \times 48 \times 2$  mm<sup>3</sup>. The magnetic component of the device operates based on electromagnetic concepts, and it is triggered by coupling magnet rod with copper coils.<sup>[188]</sup> The magnet rod has a diameter of 30 mm and length of 42 mm, and it is used as a rolling trigger for TENG and magnetic source for EMG unit of the hybridized device. The copper coil of the EMG unit has 1500 laps, and its wire's diameter is 0.015 mm. Figure 16 schematically depicts the designed hybridized generator and an installed device in an automobile tire.

In another recent published paper, Guo et al. proposed compressible hexagonal-structured triboelectric nanogenerators (CH-TENGs) for harvesting mechanical energy from rolling tire. The proposed sensory device consists of a fluorinated ethylene propylene film and copper electrodes. It shows a good structural stability when it is installed in a tire. Results of the paper show that the proposed device is capable of generating at least 1.2 W for a standard tire at the speed of 100 km h<sup>-1</sup> when a tire is equipped by 500 units of CH-TENG.<sup>[189]</sup>

In our group, Mechatronic Vehicle Systems lab (MVS-lab), we have designed, fabricated and tested a few sensory devices based on triboelectric and electromagnetism concepts. Figure 18 shows different types of the sensors that have been developed in the MVS-lab so far. We have developed 6 types of



**Figure 15.** Schematic setup for characterizing the friction energy scavenging ability of the S-TENG from a rolling wheel. Reproduced with permission.<sup>[187]</sup> Copyright 2015, Elsevier.





Figure 16. a) Schematic diagram of the designed hybridized generator, b) schematic of the WSN charged by the proposed nanogenerator used in a tire. Reproduced with permission.<sup>[188]</sup> Copyright 2017, Elsevier.

sensors for tire condition monitoring. The first one is presented in **Figure 17**. As shown in Figure 17, we proposed a triboelectric based self-powered sensor for tire condition monitoring which uses highly flexible and thermally durable material. The fabricated sensor has a sandwich form, and it contains a rectangular 1.5mm thick Polyurethane layer and a 100mm temperature resistant Kapton. Experimental results illustrate that TENG based sensor has the potential to directly measure tire forces. Figure 17 represents the fabricated sensor and also an installed one in tire sidewall.<sup>[80]</sup> The fabricated sensor shows a promising potential in terms of durability for tire condition monitoring.

The rest of developed sensors are presented in **Figure 18**.<sup>[190]</sup> Figure 18a presents a single electrode TENG sensor, which has been tested for finding the normal force of tire. This sensor works based on contact and separation mode, and its dimensions are 70 mm  $\times$  10 mm  $\times$  7 mm. Figure 18b shows a hybridized TENG-EMG sensor, which has been also tested for tire condition monitoring and finding tire forces. It was shown that this device has the potential to be used as a self-powered sensor for tire condition monitoring. The electromagnetic component of the sensor generates sufficient electrical output for powering a wireless node. This sensor not only can be used for TCMS, but also, it can be utilized for joint rehabilitation assessment and vibration monitoring. The EMG unit of the fabricated hybridized device has a round coil with dimension of 10 mm  $\times$  4 mm, an iron core with a diameter of 6.35 mm, and 73 turns. TENG component of the proposed device was fabricated by Kapton and Polyurethane, and Copper layers.<sup>[191]</sup> Figure 18c represents



Figure 17. The proposed single electrode TENG based sensor developed in MVS lab: a) sidewall of the tire equipped with as-fabricated sensor (top-view), b) the sidewall of the tire equipped with as-fabricated sensor, c) schematic representation of the attached sensor in a tire, d) roughness of sensor polymers before and after sanding with grit#2000. Reproduced with permission.<sup>[80]</sup> Copyright 2017, Wiley.







(e)

**Figure 18.** Designed, optimized, and fabricated sensors by MVS-lab: a) single electrode vertical contact separation mode-TENG, b) hybridized TENG-EMG sensor. Reproduced with permission.<sup>[191]</sup> Copyright 2018, Elsevier. c) Flexible single electrode TENG, d) self-powered hybridized EMG-TENG sensor. c,d) Reproduced with permission.<sup>[190]</sup> Copyright 2018, Elsevier. e) Thermally and mechanically durable TENG sensor.

a single electrode TENG sensor, which was developed in MVSlab, and has been used for tire force measurement. The proposed sensor is made of highly flexible, mechanically and thermally durable, and cost-effective polymeric materials, and its dimensions are 75 mm  $\times$  7 mm  $\times$  2 mm. This sensor is also a single electrode based TENG, and can be attached into inner liner of tires for TCMS. Figure 18d depicts another MVS-lab sensor for tire condition monitoring. This sensor has also a promising potential for tire condition monitoring. Moreover, it can be used for other applications such as pressure sensing and human motion energy harvesting. The sensor comprises two different units for energy harvesting. The first one is the EMG unit, which contains a magnet and a coil with an iron core. In addition, an optimization analysis was provided to design, and also compare square and round coils for the considered applications. The second part of this sensor is a single electrode TENG unit, which works based on the contact-separation mode.

The last fabricated sensor is a double electrode TENG, which has been implemented in a real car testing, and has shown a high potential for finding the tire forces. This sensor

was attached into the inner surface of the tire, and has been tested on road application to find different forces in the tire. All of these developed sensors not only can be used for tire condition monitoring, but also, have the potential to be used in other sensing and energy harvesting applications. Among all of these developed sensors, the last one which is presented in Figure 18e, has the highest potential for implementation in real tires in terms of mechanical and thermal durability, required flexibility, and also electrical output. This sensor can generate electrical output under different mechanical loads including torsion, pressure, and bending.

#### 3.4. Other Approaches

The above-mentioned approaches are in fact the principal methods for energy harvesting and sensing in tires. There are a few other approaches, which have been used by researchers to develop a sensing or energy harvesting system for tires. These approaches include surface acoustic wave (SAW), electrostatic, piezoresistive, and optical fiber sensing. Table 2 illustrates these approaches for TCMS.

# 4. General View and Perspective

Force calculation at each corner (tire) based on a tire model requires road friction information and accurate tire parameters. Thereby, even accurate slip ratio/angle information from a high precision GPS does not result in

forces at each tire. Estimation of longitudinal, lateral, and vertical tire forces is therefore required whenever affordable and practical measurement solution is not available. Tire force estimation independent from the road friction condition is classified on the basis of wheel dynamics and planar kinetics into the linear, nonlinear, sliding mode, Kalman-based, and unknown input observers as discussed and summarized in Table 1. Road friction estimation is also required for advanced vehicle active safety systems and falls into two main categories: i) Estimation in the linear and low-excitation region (slip-slope) and ii) Estimation around saturation area. These two main categories utilize Kalman-based, RLS-based, and linear/nonlinear methods to estimate road friction conditions. Connectivity in inter-and intravehicular networks provide information such as nearby sudden braking events, road conditions, and road topographic data. Using this approach, a distributed diagnosis method robust to disturbances, and communication failure could be devised such as done in ref. [195]. Based on the comprehensive review in this paper, it can be concluded that additional sensory information (such as steering torque, TCMS, and sound/vision-based

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Table 2. Other techniques for sensing and energy harvesting in tires.

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Technique	Illustration-example
Surface acoustic wave (SAW)	SAW elements have been used in TPMS by Stack. SAW will re-transmit a particular RF frequency, in response to the pressure and tempera- ture inside the tire. In addition, there is a central module in TPMS of each tire, which interrogates each wheel sensor by transmitting RF signal. <sup>[7]</sup>
Electrostatic	<b>Example 1</b> : a microscale electret based energy harvester for TPMS systems was developed by Westby and Halvorsen. It is capable of generating 4.5 $\mu$ W power in speed of 50 km h <sup>-1</sup> which is enough for TPMS. <sup>[192]</sup>
	<b>Example 2</b> : Löhndorf et al. developed an MEMS-based electrostatic vibration power harvesters, which can generate up to 10 μW electrical power for a TPMS.
Piezoresistive Sensors	Example: a flexible piezoresistive pressure sensor for measuring force magnitude and location and was proposed by Emon and Choi. <sup>[193]</sup>
Optical fiber sensors	<b>Example</b> : Coppo et al. have used optical fiber sensors to measure the internal tire strain during the tire rolling in real operating conditions. They have used the measured data for identification the dynamics of contact patch. <sup>[194]</sup>

systems) and data provided by connectivity from IoT (infrastructure and inter-vehicular networks) are enhancing the reliability of the tire force and road friction estimation and have high potential to be used is all production vehicles in near future.

In accordance with the approaches discussed in Section 3, there are four main subcategories for energy harvesting and sensing devices in tires, which have been developed so far by researchers in this area. Table 3 represents four subcategories of the developed devices in TCMS. In accordance with these four categories, plenty of devices have been fabricated for sensing and energy harvesting in tires.

Based on our comprehensive review on tire condition monitoring, we can conclude that nanogenerators have a high potential to provide a reliable solution for this application comparing with other techniques. As we discussed before, nanogenerators can be fabricated based on a highly flexible and thermally durable polymeric materials. These two features make them an excellent candidate for TCMS. Furthermore, NGs have a higher power density and also open circuit voltage comparing with other techniques for energy harvesting and sensing. These two features of NGs accentuate their potential for implementation in an inaccessible and harsh environment of a tire. We expect that NGs attracts attention of both academic and industrial researchers to use them for TCMS. In fact, due to their high durability, flexibility and electrical output of NGs, they are an ideal candidate for implementation in tires. Figure 19 illustrate the evolution of intelligent tire and our prediction for future TCMS technology.

### 5. Conclusion

A comprehensive review was provided about intelligent tires and tire condition monitoring. The main three branches of research in tire condition monitoring were fully described, and a detailed survey of these branches was presented. The impact of TCMS and intelligent tires on the transportation systems was briefly illustrated. Different tire models based on the recent published articles were reviewed.

Road-independent tire force estimation methods utilize linear, sliding mode, and Kalman-based observers to deal with model uncertainties. The Kalman-based force estimation methods augmented by adaptive schemes can handle harsh maneuver and more specifically combined-slip cases. Sliding mode, nonlinear, and linear observer-based tire force estimation approaches provide reliable results in pure-slip condition; they can be enhanced by robust observer design to cope with disturbances due to friction-varying surfaces and high-slip cases. For the road friction identification, slip-slope and identification around saturation point are major methods practiced in the literature. Estimation in low-excitation region (slip-slope) is appealing because of timely road identification (compared to the second one) and taking proper action in vehicle stability/ traction control systems. However, it is challenging because of close slopes of tire curves on various surface friction conditions in the linear region.

Robust vehicular force estimation methods could be augmented with affordable and commercialized tire force measurement technologies to provide accurate, fault-tolerant, and reliable tire forces for autonomous driving as well as advanced Electronic Stability Control and Driver Assistance systems.

Sensing and energy harvesting in tire are another important part of the research in the area of intelligent tires. As we reviewed, a number of researchers have focused on these two branches to find a reliable and durable technique for both sensing and energy harvesting in a tire. As we discussed, trend and results of the published works show that nanotechnology might provide an ideal solution for tire condition monitoring.

 Table 3. Categories of developed self-powered devices.

Technique	Illustration
Relative motion devices	Example: A magnetic harvester which is mounted on a rim and it rotates around a stationary coil which is installed on the brake caliper.[117]
Strain-driven devices	Example: Employ the longitudinal strain of a tire when it deforms in its contact patch, [196-198]
Fluid flow devices	Example: Pressure fluctuations and air flow inside the tire cavity. <sup>[199]</sup>
Inertial devices	Example: Using the concept of time varying acceleration of different points on a rolling tire. <sup>[200]</sup>



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Figure 19. Evolution of intelligent tire and our prediction for future TCMS technology.

Triboelectric nanogenerators have shown a promising potential for both sensing and energy harvesting in tires in compassion with other techniques such as electromagnetism, piezoelectrictity, and electrostatics. But, there are still a few open challenges that must be addressed in future research works. The first challenge is related to the thermal durability of sensors in tires. Based on existing data, the sensor functions well at temperature between -50 and  $200 \, ^\circ C.^{[201]}$  The decaying of triboelectric effect at high temperature is due to the electron thermionic emission effect.<sup>[202]</sup>

The second challenge is the durability of the sensor materials. This can be solved by choosing the right materials as well as a coupling of the operation mode of the nanogenerator. Another research direction is in correlating the sensor data to tire states and tire contact patch forces, which can be solved by comprehensively measuring and simulating the tire operation conditions. Extensive research is necessary to address these issues so that the nanogenerator can be integrated into future tires.

#### Keywords

energy harvesting, nanogenerators, tire condition monitoring, tire force estimation

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