Textile-inspired triboelectric nanogenerator as intelligent pavement energy harvester and self-powered skid resistance sensor

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HIGHLIGHTS

• A textile-inspired triboelectric nanogenerator (TENG) was designed and integrated to the intelligent tire to harvest the wasted energy.
• The output electrical signal waveform of the intelligent tires was firstly adopted to distinguish the difference of the pavement skid resistance.
• A lightweight data processing system was developed to warn the poor pavement skid resistance risk.

ABSTRACT

Triboelectric nanogenerator (TENG) provides a new idea for harvesting low-frequency energy tire-road interaction and self-powered sensors. A real-time assessment of skid resistance provides valuable information to deliver appropriate driving manner to ensure safety in all weather conditions. However, there is no mature perception technology in the previous study due to the complexity of tire-road interaction. Inventing appropriate devices and solutions for harvesting wasted energy and obtaining skid resistance information in real-time is essential. Here, a textile-inspired TENG is developed, which was integrated into the tire cord for energy harvesting and self-powered skid resistance monitoring. As the theoretical basis, the capability of the proposed textile-inspired TENG for energy harvesting and skid-resistance monitoring was demonstrated based on the coupling of vehicle-road dynamics and the electrodynamics. Consequently, the average power density reaches to 4.219 mW/m² (output power with 82.7 μW). Besides, the short-circuit current waveform of the intelligent tires...
1. Introduction

Energy dissipation and traffic safety is a common challenge facing road engineering. Securing renewable energy source in tire-road interactions is essential for long-term environmental sustainability [1]. The National Transportation Safety Board (NTSB) and the Federal Highway Administration (FHWA) report that 70% of traffic accidents can be avoided by improving the skid resistance of pavement [2]. Accordingly, skid resistance plays a vital role in evaluating tire-road interaction and is the primary factor in improving the safety of driving [3,4]. The force is generated when the tire is prevented from rotating and sliding along the road [5]. Recently, tire-road friction models that help to characterize the pavement skid resistance were widely investigated to simulate the real pavement conditions [6-8]. Meanwhile, numerous detecting devices for pavement skid resistance have been developed, including equipment for friction testing, texture testing, computer vision testing, etc. [9]. The detection of pavement skid resistance includes pavement friction coefficient detection and road surface texture detection. However, most existing equipment only manually detects pavement skid resistance information at specific conditions, which cannot conduct real-time monitoring. Insufficient rapid evaluation of pavement skid resistance may lead to traffic accidents. Therefore, providing a reliable strategy is significant to actively monitoring pavement skid resistance in real-time. In the past decade, triboelectric nanogenerators (TENG), coupling triboelectrification and electrostatic induction, have presented great potential in mechanical energy harvesting and self-powered sensing [10-14]. The electrification mechanism of TENG can be further described. When two materials with distinct electron affinity come into contact, electrons transfer, which is triboelectrification. Moreover, when the two materials are separated at a small distance, the electrode layers at both ends of the material will produce potential difference, that is, electrostatic induction phenomenon [15-17]. On the one hand, TENG can harvest mechanical energy from the road environment and convert it into electrical energy due to its high energy harvesting efficiency [14,18,19]. On the other hand, as an active sensor, TENGs have been gradually applied to the monitoring of speed/frequency [20,21], acceleration [18,22], pressure [23], strain [24], temperature [25], humidity [26], etc., which has great advantages given that its lightweight, wide adjustability, easy fabrication, and energy harvesting capability [19,27-30]. The versatile nature of TENG enables it to sense many parameters related to the factors affecting traffic safety. Therefore, it is interesting and attractive to develop a self-powered skid resistance monitoring system via TENG approaches.

As the only contact between vehicle and road, tires provide friction to the vehicles [31]. It is essential to monitor tire loadings, inflation pressure, and friction coefficient for optimal driving safety, reliability, and comfort. The self-powered intelligent tires with a built-in monitor may be the most direct and effective way to monitor vehicle and road information. Some single-electrode based TENGs were first applied to distinguish the difference of the pavement skid resistance caused by the roughness characters of the pavement structure. The open-circuit voltage amplitude was adopted to evaluate the correlation quantitatively between pavement skid resistance and the TENG’s output signal, and the accuracy of this system can reach 96%. This work innovatively proposes a new idea for simultaneously harvesting wasted energy from tire-road interaction and improving the level of traffic safety and expands the application of triboelectric nanogenerators for automatic driving technology.
PTFE and PA66 films with a thickness of 100 μm were cut into 2 cm × 10 cm. The conductive sponge electrodes of the same size were sandwiched between the PTFE and PA66 films. The prepared triboelectric layer stripes were woven into a triboelectric textile nanogenerator, which was integrated into the intelligent tire.

2.3. Indoor and outdoor tests and applications

The self-developed indoor tire-road testing machine was applied to demonstrate the feasibility of the proposed textile-inspired TENG for pavement skid resistance sensing. The open circuit voltage and short circuit current were collected at the pavements with different roughness and driving speeds. In the outdoor tests, a test vehicle with an integrated, TENG-based intelligent tire was driven for about ~4.5 km on four types of road sections at a speed of 12–20 km/h.

3. Results and discussions

3.1. Theoretical analysis of skid resistance monitoring

Vehicle and road are interactively coupled. However, there are barriers between vehicle dynamics and road dynamics. Vehicle dynamics takes the road surface as an excitation to study the handling, comfort and safety of vehicles, while road dynamics take the vehicle as a moving load to investigate the response, life and pavement damage [39,40]. Fortunately, the tire is the only component coupling the vehicle and the road. A tire-road coupling dynamic model is necessary to effectively combine the tire, vehicle, and road models, involving the pavement roughness and vibration field. In this study, a mechanical-electrical coupling system based on the intelligent triboelectric tire-road system is established to investigate the role of TENG in evaluating pavement roughness and skid resistance, as shown in Fig. 2.

In theory, the dynamic differential equation of the 1/4 vehicle model can be defined as:

\[ M_k \ddot{Z}_b + C_k (Z_b - Z_t) + k_r (Z_b - Z_t) = 0 \]  

(1)

\[ M_r \ddot{Z}_t + k_t (Z_t - q) = C_t (Z_t - Z_b) + (Z_b - Z_t) \]  

(2)

where the wheel part is simulated by the elastic element with a stiffness coefficient of \( k_t \) and the mass block with a mass of \( M_r \). \( M_k \) is the vehicle body mass. \( C_k \) and \( k_r \) are the stiffness of the spring and the damping of vehicle suspension systems, respectively. \( Z_b \) and \( Z_t \) are the displacement of vehicle body and the wheel. \( q \) is the road roughness excitation [41].

The compression at the contact point between the tire and road is

\[ \Delta Z(x, y) = \begin{cases} \omega(x, y) + q(x, y) + \sqrt{r_0^2 - x^2} - r_0 - Z_2(x) & \Delta z \geq 0 \\ \Delta z \leq 0 & \end{cases} \]  

(3)

where \( r_0 \) is tire radius. \( \omega \) is the vertical vibration due to pavement displacement. \( x \) is the longitudinal displacement of the tire centre, and \( y \) is the local longitudinal coordinates in the tire contact footprint with \( -r_0 \leq x \leq r_0 \). \( Z_2 \) is the vertical displacement of the tire centre.

Therefore, the relative speed between vehicles and roads can be written as

\[ \Delta z(x, y) = \begin{cases} \frac{\partial \omega(x, y)}{\partial t} + \frac{\partial q(x, y)}{\partial t} + \frac{\partial \omega(x, y)}{\partial t} \sqrt{r_0^2 - x^2} - \frac{\partial Z_2(x)}{\partial t} & \Delta z \geq 0 \\ \Delta z \leq 0 & \end{cases} \]  

(4)

where \( \nu \) is the vehicle speed.

The interaction force between vehicles and roads can be written

\[ F_i(x, t) = \int k_i(x) \cdot \Delta z(x, y) + C_i(t) \cdot \Delta z(x, y) \ dx \]  

(5)

where \( k_i \) is the vertical distribution of tire stiffness, and \( C_i \) is the vertical distribution of tire damping.

Fig. 1. Construction drawing of the energy harvesting and skid resistance monitoring system, including an intelligent tire, a light-weight algorithm and a warning terminal.
In addition, according to the theoretical model for TENG with the displacement for contact-separation \cite{42}, the displacement current, as the direct source of the triboelectric generator, depends on materials permittivity, triboelectric charge density and surface morphology.

\[ I = A \sigma T \frac{dH}{dt} \cdot \frac{d_1 \epsilon_{0}/\epsilon_1 + d_2 \epsilon_{0}/\epsilon_2}{d_1 \epsilon_{0}/\epsilon_1 + d_2 \epsilon_{0}/\epsilon_2 + d(t)} \]  

(6)

where \( A \) is the surface structure area of triboelectric materials, \( \sigma T \) is the triboelectric surface charge density, \( \epsilon \) is the dielectric property, \( d(t), d_1 \) and \( d_2 \) are the distance and the thicknesses of positive and negative materials, respectively. The transferred charge (\( Q_{sc} \)) can be expressed as:

\[ Q_{sc} = \frac{A \sigma T d(t)}{d_1/\epsilon_1 + d_2/\epsilon_2 + d(t)} \]  

(7)

and the corresponding short-circuit current (\( I_{sc} \)) can be written as \cite{43}:

\[ I_{sc} = \frac{dQ_{sc}}{dt} = \frac{dA}{dt} \]  

(8)

The interaction force between from tire-road is extracted to evaluate the skid resistance of pavement. The increased interaction force will lead to the expansion of the actual contact area due to deformation \cite{44}. Assume the surface structure area of triboelectric materials (\( A \)) is proportional to the interaction force (\( F_a \)), defined as \( F_a = k A (k > 1) \). Therefore, the, \( I, Q_{sc} \) and \( I_{sc} \) can be rewritten as:

\[ I = \frac{A \sigma T F_a}{K} \frac{dH}{dt} \cdot \frac{d_1 \epsilon_{0}/\epsilon_1 + d_2 \epsilon_{0}/\epsilon_2}{d_1 \epsilon_{0}/\epsilon_1 + d_2 \epsilon_{0}/\epsilon_2 + d(t)} \]  

(9)

\[ Q_{sc} = \frac{A \sigma T F_a}{K} d(t) \]  

(10)

\[ I_{sc} = \frac{dQ_{sc}}{dt} = \frac{dF_a}{dt} \]  

(11)

Thus, the displacement current (\( I \)) and the transferred charge (\( Q_{sc} \)) are positively correlated with the interaction force (\( F_a \)) of different skid resistance, while the short-circuit current (\( I_{sc} \)) is also positively correlated with the differentiation of the applied force relative to time (\( dF_a/dt \)). Since better pavement roughness means an increased tire-road contact area and the applied force, the output electrical signal of TENG can be adopted to evaluate the pavement skid resistance. Detailed analysis of tire-road coupling dynamics can be found in refs. \cite{45-47}.

### 3.2. Configuration and working mechanism of textile-inspired TENG

Textile-inspired intelligent tire triboelectric nanogenerator works on the combination of contact triboelectrification and electrostatic induction. A schematic illustration of the proposed textile-inspired TENG is revealed in Fig. 3a-c. Many triboelectric layer strips (\( N = 7 \)) were woven in longitude and latitude lines to maximize the contact area. For the durability and flexibility of the TENG device, an omnidirectional aligned conductive sponge (1 mm thickness) made from polyurethane (PU) foam was used. The PU sponge was treated by PVD and electrodeposition technique to make it conductive in all directions. In addition, the PET film was covered on the surface of the textile structure as a package structure to improve the reliability, wear resistance, and waterproof performance of the TENG device. 0.01 mm thick Nylon 66 and polytetrafluoroethylene (PTFE) films were pasted on the conductive sponge on both sides to form the positive and negative electrodes, respectively. A lithography machine (PLS 6.75, Universal laser systems) was utilized to cut electrode and triboelectric layer strips. The specific fabrication process of the textile-inspired TENG triboelectric layer strips can be seen in Supplementary Note 1 and Fig. S1 (Supplementary Information).

The textile-inspired TENG operates with a vertical contact-separation mode for generating electricity, illustrated in Fig. 3d. Each tire rotation cycle has a full cycle of the electricity generation process. Specifically, with the rotation of the intelligent tire, the textile-inspired TENG is continuously pressed and released to generate an alternating current. When the vehicle tire contacts roads, the triboelectric layers also contact each other. With the electrostatic induction between the surfaces, the Nylon 66 and PTFE film surfaces generate equivalent positive and negative charges, respectively. Once a relative separation occurs between two triboelectric friction layers, the positive charges will induce on the inner electrode, driving free electrons to flow from the inner electrode to the outer electrode. Once the electrical equilibrium is achieved, no output electrical signal is produced. When Nylon 66 approaches PTFE films, the induced positive charges on the inner electrode decrease, which leads to a reversed output signal. It is worth noting that the textile-inspired TENG not only acts as an active sensor but also as a cord layer of the tire tread to improve the tire’s structural strength. Hence, the textile-inspired TENG could be fully packaged in the tire’s inner liner to prevent water erosion. Based on the above process, the textile-inspired TENG device is designed, as shown in Fig. 3e, which contains seven excitation electrode strips in parallel to increase the performance.

### 3.3. Theory and performance of textile-inspired TENG

The textile-inspired TENG structure consists of two equal-length positive and negative triboelectric contact areas. To compare the output performance of two strips with different size and distance configurations, the finite element models were built and calculated by COMSOL Multiphysics software, as shown in Fig. 4a. In this model, the Nylon 66 stripe has a length of 100 mm. For PTFE strips, there are four choices of lengths: 50, 25, 20, and 10 mm, in which the triboelectric
layers are fabricated with distances of 2, 4, 6, and 8 mm, respectively. It can be found that the output voltage decreased with the PTFE stripes’ length decreased. This is mainly because, under the condition of charge conservation, the capacitance of the textile-inspired TENG increased with the decrease of the PTFE length. In addition, since the voltage is equal to the ratio of charge to capacitance, when the charge is constant and the capacitance increases, the voltage will naturally decrease. On the other hand, the textile-inspired TENG can be considered a grating structured TENG, and its theoretical investigation of the electrical performance is similar to the relevant theoretical study of grating structured TENG [48].

Fig. 4b shows the evolution trend of voltage depending on the distance of positive and negative triboelectric layers. The output voltage gradually increased with the increase of the distance. This is because, in the constant electric field region, the larger the distance, the larger the voltage. With the above analysis, the energy density was calculated and shown in Fig. 4c, representing the energy harvesting capacity of the proposed textile-inspired TENG. When the PTFE strip length is 10, 20, and 25 mm, the energy density first decreases, then increases, and then decreases with the distance increase. However, for the 50 mm PTFE film,
the energy density shows the trend of decreasing first and then increasing with the distance. The maximum energy density is mainly located at the sharp corners of the structure rather than on the surface. The reason for this phenomenon is that the length of the tribo-layer is much larger than the thickness, resulting in energy density concentration (1.90 J/m$^2$) at the material sharp corners and relatively high energy density (1.39 J/m$^2$) at the tribo-layer surface. This shows that if there is no energy density concentration at sharp corners, the energy density of the tribo-layer surface is relatively low. The result indicates that a balanced optimal choice between the triboelectric layer stripes’ length, thickness and the distance between the positive-negative triboelectric layers based on the energy density index.

The excellent electrical performance of the textile-inspired TENG is the foundation of this practical application. Here, a function generator (YE1311E), a power amplifier (YE5871A), and an electrodynamic shaker (JZK-5) composed the external powered system. The electrometer (Keithley 6517) and a data acquisition system were applied to collect electrical signals. Fig. 5a shows the output open-circuit voltage as a function of frequency. It can be found that the voltage is almost independent of frequency at about 20–25 V, which confirms that the open circuit voltage is only related to the electrode amplitudes but is not affected by the excitation speed and frequency. Moreover, the dependence of measured $I_{sc}$ on the frequency and amplitude is presented in Fig. 5b. The output current increases with the frequency and amplitude due to the increased charge transfer. The phenomenon also demonstrates that the open-circuit voltage is suitable for static monitoring, while the short-circuit current is suitable for the dynamic measurement of mechanical motion.

In order to understand the matching load resistance of the textile-inspired TENG, the peak open-circuit voltage and short-circuit current can be shown in Fig. 5c. It can be seen that the peak current decreases from $\sim$21.79 to $\sim$0.44 $\mu$A with the increasing load resistance from 10 k$\Omega$ ~ 1G$\Omega$, while the peak voltage exhibits an opposite trend and increases from $\sim$0.21 to 43.82 V. Through calculation, the peak power of 82.7 $\mu$W was obtained at 2.502 M$\Omega$ (corresponding the average power density with 4.219 mW/m$^2$). It means that this load resistance matches the internal resistance of the textile-inspired TENG, which is also about 2.5 M$\Omega$. Meanwhile, the output power is sufficient to light up 50 LEDs, as shown in Fig. S2c (Supplementary Information). In order to evaluate the reliability and durability of the textile-inspired TENG, Fig. 5d demonstrates the continuous operation for 20,000 cycles without any decrease in performance. Such excellent stability is essential for the practical application of the textile-inspired TENG.

3.4. Real-time detection of pavement skid resistance

To develop the textile-based TENG as the in situ sensor for real-time monitoring the pavement skid resistance, the TENG was mounted on the rim inside the vehicle tire, as shown in Fig. 6a and Fig. S3 (Supplementary Information). Compared with mounting on the outside of the tire, the internal mounting can avoid the interference of temperature, humidity and large load to improve the device durability. Generally, an
open-graded friction course (OGFC) is applied on top of the traditional dense-graded asphalt pavement to provide a higher degree of friction and permeability to the pavement surface of the pavement [49,50]. Specifically, since the textile-inspired triboelectric intelligent tire is fixed, the monitoring process of the pavement skid resistance includes 1) determining the friction coefficient of different pavement structures by the pendulum friction coefficient measuring instrument (BM-III), 2) collecting the electrical signals under different pavement structures at different speeds, and finally, 3) modelling the math correlation between the pavement friction coefficient and the electrical signal. The process is illustrated in Fig. 6a i-iv. The friction coefficient is calculated from the obtained BPN value. Here, the OGFC pavement specimens with 150 × 150 × 50 mm³ were prepared, and their friction coefficients were measured to be 88 ± 1 and 65 ± 1 for rough and smooth pavement samples, respectively (Fig. 6b and c). The friction coefficient was tested on dry pavement specimens. The output voltage and current signals textile-inspired from the intelligent tire with a triboelectric nano-generator sensor were collected to monitor pavement skid resistance.

Fig. 6b and c are the typically received voltage waveforms at 5 Hz frequency at the rough and smooth pavement specimens, respectively. Their voltage amplitudes are almost identical, about ~160 V. However, the samples presented different voltage waveforms. For the rough pavement specimen, the “half waveform” signal output was obtained, while for the smooth pavement specimen, the “full waveform” signal...
output was achieved, recognized from the insets in Fig. 6b and c due to the much higher friction resistance of the rough pavement specimen. As a result, only part of the textile-inspired TENG can effectively act on the rough surface specimen, while the rest leaves the pavement surface before it produces signals, forming a “half waveform” signal. The low friction resistance on a smooth pavement can ensure that the textile-inspired TENG plays the role more smoothly with the “full waveform” signal. The results show that it is possible to develop an intelligent tire capable of monitoring the pavement skid resistance by identifying the waveform of the TENG signal.

The output current was also investigated to demonstrate its feasibility for monitoring the pavement skid resistance. Four typical pavement surfaces, including grooved cement pavement, asphalt pavement, grooved marble pavement and smooth marble pavement, are selected as the test samples. Their friction coefficient values measured by the pendulum friction coefficient tester are 0.73, 0.65, 0.51 and 0.32 ± 0.01, respectively. According to the 2010 guidance from the Federal Highway Administration (FHWA 2010), the friction coefficient value must be >0.32 for old pavements or >0.45 for new pavements. Therefore, the four typical pavement samples are all within the FHWA 2010 specification. The pavement samples can be considered in the order of the rougher, rough, smooth and smoother types, respectively, determined by their friction coefficients. Then, a driver weighing 70 kg drove the test vehicle with an integrated TENG-based intelligent tire for about ~4.5 km on four typical road sections at a constant speed of 12 km/h. As shown in Fig. 6d and e, the peak current of the four pavements is significantly different. Compared to the dry condition, the current considerably decreases in the wet condition, but which still keep a same trend of increasing with the increase of roughness (friction coefficient). Moreover, the correlation between the peak current and the friction coefficient is quantitatively fitted in Fig. 6e with a linear relationship at the R² of 96% in dry condition. Fortunately, R² can reach to ~95% even

![Intelligent Analysis System for Skid Resistance](image)

**Fig. 7.** The Verification of Intelligent Analysis System for Skid Resistance. (a) The Intelligent Analysis System for real-time monitoring skid resistance. (b) WT results for the rough pavement with the friction coefficient of 0.88 ± 0.01. (c) WT results for the smooth pavement with a friction coefficient of 0.65 ± 0.01. (d) Traffic information perception principle based on the intelligent tire. (e) The workflow diagram of the lightweight data processing and analysis platform.
in wet condition. Therefore, the textile-inspired TENG-based intelligent tire can offer the perception signal representing the pavement skid resistance.

Despite the numerical and computational advantages of the machine-learning algorithms, Fourier transformation is still the most powerful when analyzing oscillating signals due to its simple principle, easily applied and rapid processing. Wavelet transform (WT), an extension of fast Fourier transform (FFT), plays a crucial role in successfully implementing the sensor signal analysis due to its ability to simultaneously deal with both the frequency and the temporal information contained within time series data \[51,52\]. The above work demonstrated that the proposed textile-inspired TENG-based intelligent tire could monitor the pavement skid resistance through pressure, speed and other information. In order to further quantitatively analyze the triboelectric output electrical signals, the current and voltage signals obtained from textile-inspired TENG in the intelligent tire were processed by FFT or WT. A lightweight data processing and analysis platform, Intelligent Analysis System for Skid Resistance (IAS-SR), is built through Python software to obtain a more intuitive and quantifiable electric signal waveform visualization (Fig. 7a).

Using the above data processing system, Fig. 7b and c show the WT results of rough and smooth pavements, respectively. The characteristic frequencies for the rough and smooth pavements are different in the wavelet time-frequency plots. More FFT and WT results can be seen in Supplementary Note 4 and Fig. S4–9 (Supplementary Information). The maximum DC component values from the rough rutting specimen, smooth rutting specimen, wet smooth rutting specimen and acrylic specimen are 55.50, 31.88, 29.41 and 27.65, respectively. Moreover, traffic monitoring can be realized using the intelligent tire to calculate the skid resistance, vehicle speed, and tire pressure from the time intervals and the electrical signal amplitude of the waveform. The skid resistance is determined through an iterative optimization, presented in Fig. 7d. Finally, the workflow diagram of the lightweight TENG data processing and analysis platform is illustrated in Fig. 7e. Initially, the noise reduction is carried out on the collected TENG signal, followed by calculating the wave number and peak value of the original signal. If there are significant differences, the characteristic indicators will be extracted. Otherwise, fast Fourier transform (FFT) and wavelet transform (WT) will be used to evaluate the pavement skid resistance performance with the DC and harmonic components.

3.5. Application demonstration of textile-inspired TENG in intelligent pavement

The energy harvesting ability of the textile-inspired TENG makes it possible to develop a self-powered sensor. That is to say the developed textile-inspired TENG can actively self-aware road surface information without additional energy sources. As shown in Fig. 8a, an energy management circuit is designed containing the TENG in the tire, a rectifier bridge, a capacitor, an inductor, an ultra-low power energy harvesting and a management chip (BQ25570). The 16-bit ADC converts the TENG analogue signal into a digital signal, which is transferred by the low-power Bluetooth BLE4.2 with only 3 V power supply protocol to the lightweight data processing platform in real time. Through this energy management circuit, the power generation efficiency of the textile-inspired TENG in the intelligent tire was further investigated. It can be

![Fig. 8. The self-powered skid resistance evaluation system. (a) The energy management circuit for textile-inspired TENG. (b) The power generation efficiency of the textile-inspired TENG-enabled intelligent tire. (c) The rapid warning terminal for self-powered pavement skid resistance monitoring.](image-url)
seen that the TENG intelligent tire can generate about 0.2 mV and 0.5 mV before and after impedance matching, respectively, at the applied force of 20 N, which provides 0.05 mW peak power (Fig. 8b). This phenomenon implies that when the vehicle equipped with this textile-inspired TENG-enabled intelligent tire runs at a speed of 60 km/h, it can power the ADC converter for 1 s every 248 s of driving. In literature [53], a planetary rolling triboelectric nanogenerator (PR-TENG) was able to power and autonomously transmit wind speed data in the range of 10 min every 120 s. Therefore, the proposed textile-inspired TENG-enabled intelligent tire technology has great potential in vibration mechanical energy harvesting. In fact, the contribution of energy management circuits is to improve the efficiency of converting mechanical energy into electrical energy. In fact, the strategies to improve TENG’s energy harvesting efficiency also include improving the efficiency of mechanical energy collection from the environment [54,55]. How to capture more waste mechanical energy and solve this problem requires considering from device design. Therefore, an elastic hemisphere is adopted to be installed between two opposing tribo-layer strips. By introducing the spacer structure of elastic hemisphere, more mechanical energy can be harvested and transmitted to TENG. The detailed structure can be observed in Supplementary Fig. S10.

In addition, insufficient pavement skid resistance is a potential danger, which results in many fatal traffic accidents. The ultimate goal of pavement skid resistance monitoring is to improve driving safety and reduce traffic accidents. Therefore, a rapid warning system is a supplement and upgrade to the self-powered pavement skid resistance monitoring system, which can send live information to the driver and road management department to avoid traffic accidents effectively. Hence, a rapid warning terminal was invented using Python software, which plays an important role in the rapid reporting of warning signals integrated with signal detection, wireless data transmission, and real-time data processing. The warning terminal is illustrated in Fig. 8c.

In order to ensure the timely warning of pavement skid resistance failure, it is significant to build an early warning system using multifunctional sensing. Here, the strategy for evaluating the skid resistance level based on the self-powered skid resistance monitoring system is proposed. Specifically, the timer of MCU saves 1024 voltage data points collected by ADC as a group. The Hamming window processing was added to reduce the spectrum leakage in the FFT. Then, the FFT was performed through the floating-point onboard DSP hardware. After calculating the frequency and amplitude of the wave signal and the first harmonic, the vehicle speed, tire pressure and other tire-road interaction information were obtained according to Eq. (12)–(14) to further evaluate the pavement skid resistance.

\begin{equation}
\nu = 2\pi R \times 3.6 \times \frac{\left(f_s + 1\right) \times f_w}{N}
\end{equation}

\begin{equation}
P = 1.867 \times \frac{a_0}{N}
\end{equation}

\begin{equation}
\partial = \left|\frac{2a_0}{N} \times c - 4.5\right|
\end{equation}

where \(N\) and \(f_w\) represent the sampling number and frequency, and \(a_0\) and \(c\) are the fundamental voltage and the ADC resistance partial voltage coefficient. \(a_1\) is the measured voltage. \(\partial\) is the skid resistance level.

According to literature [56] and the FHWA 2010, the friction coefficient value must be >0.32 for old pavements and >0.45 for new pavements. Based on these criteria, a pavement skid resistance failure early warning platform is developed in Fig. 8c. The pavement skid resistance is divided into three levels. When the friction coefficient value >0.45 (\(\partial = 2\)), the warning terminal will remind the driver that “the current road condition is good, and you can drive with confidence”. When the friction coefficient value <0.45 (\(\partial = 1\)), the warning terminal will send a warning of the low skid resistance through the vocal warning. When the friction coefficient value <0.32 (\(\partial = 0\)), the warning terminal will send a warning signal through a pop-up window, system vibration, in addition to the vocal warning. Therefore, Eq. (14) describes the calculation strategy for determining the safety level of the pavement. The change of the \(\partial\) value from 0 to 2 represents the transition from a smooth to a rough pavement. The larger the \(\partial\) value, the better the pavement skid resistance.

Meanwhile, an interactive data collection and processing system was also built, which can transmit and display the data through low-power Bluetooth in a self-developed warning terminal and realize the real-time display of vehicle speed and tire pressure, as well as the early warning of pavement skid resistance performance. Moreover, it can be confirmed that the feedback from the tires can control the power output of the car. Specifically, for autonomous vehicles, the feedback information from tires can be transmitted to the onboard unit (OBU) terminal, which can be connected to the onboard service to communicate with the autonomous vehicle in collaboration. Through the reminder of the warning terminal, commands can be issued to the autonomous vehicle to achieve more stable and safe driving.

4. Conclusion

In summary, the proposed textile-inspired TENG-enabled intelligent tire plays an unprecedented role in real-time monitoring of pavement skid resistance. The theoretical analysis of pavement skid resistance based on the triboelectric nanogenerator is reported for the first time in order to understand the mechanical-electrical coupling effect between pavement structure and TENG electronic devices. The designed textile-inspired TENG can produce electrical energy to power >50 LEDs, with a peak power output of 82.7 μW at 2.5 MΩ. Furthermore, the “half waveform” voltage signal on a rough rutting specimen and the “full waveform” voltage signal on a smooth rutting specimen demonstrates the feasibility of using the textile-inspired TENG for monitoring pavement skid resistance. A lightweight data processing and analysis platform, Intelligent Analysis System for Skid Resistance, is developed to quantitatively evaluate the correlation between pavement skid resistance and electrical signals. FFT and WT results show different characteristic frequencies due to the influence of pavement roughness. Finally, the textile-inspired TENG-based intelligent skid resistance evaluation system is proposed for self-powered pavement skid resistance monitoring, which can also display in real-time and give timely warning of skid resistance information. Based on the classification of the skid resistance lever, the rapid warning accuracy of this system can reach 96%. This study provides a promising strategy for real-time evaluation and rapid warning of pavement skid resistance properties.

CRediT authorship contribution statement

Yafeng Pang: Conceptualization, Formal analysis, Writing – original draft, Data curation, Methodology. Xingyi Zhu: Funding acquisition, Investigation, Methodology, Supervision, Writing - review & editing.


Lingjie Shen: Data curation, Methodology. Xinhong Li: Data curation, Investigation, Methodology. Chengkuo Lee: Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.
Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2023.121515.

References


