Triboelectric nanogenerator as next-generation self-powered sensor for cooperative vehicle-infrastructure system

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A R T I C L E   I N F O

Keywords:
Triboelectric nanogenerator
Cooperative vehicle-infrastructure system
Human-vehicle-road-environment

A B S T R A C T

Triboelectric nanogenerators (TENG) have progressed over the years, bringing significant benefits to self-powered sensing owing to the compelling features of high sensitivity, low limitation, and high efficiency. Cooperative Vehicle Infrastructure System (CVIS) plays a vital role in realizing intelligent transportation systems (ITS). The use of various sensors for real-time monitoring of information about human, vehicles, roads, and the environment is necessary to achieve CVIS. Therefore, the development of TENG will promote the realization of CVIS, which means that TENG can be considered as a next-generation self-powered sensor for CVIS. With a comprehensive review of the technical architecture of CVIS and fundamental of TENG, the materials, structure designs and corresponding performance of TENG for CVIS among human (pedestrian and driver), vehicle (automobile, non-motorized vehicle and intelligent tire), road and environment are summarized to promote the triboelectric self-powered sensing application to ITS fields. Furthermore, the challenges and future perspective are emphasized for the development of self-powered CVIS. It is anticipated that TENG, as next-generation self-powered sensor for CVIS, will exhibit unique advantage of energy harvesting, traffic information monitoring, safety warning and environmental assessment.

1. Introduction

With the rapid developments in the Internet of things (IoTs) and artificial intelligence (AI) [1–4], the intelligent service has become inevitable. The research on Cooperative Vehicle Infrastructure System (CVIS) plays an irreplaceable role in the development of intelligent transportation systems (ITSs) [5,6]. In order to achieve the real-time interaction and sharing of information between vehicle to vehicle (V2V), vehicle to infrastructure (V2I), and vehicle to pedestrian (V2P) [7,8], CVIS emphasizes the coupling and coordination of the four elements of human-vehicle-road-environment relying upon onboard unit (OBU), roadside unit (RSU) and other data communication facilities in traffic system [9], which is the integration and improvement of Internet of Vehicles (IoVs), automatic driving and smart pavement. It is of great significance to address the four major problems of urban traffic congestion, high energy consumption, environmental pollution, and traffic accidents to achieve the ultimate goal of safety, smoothness, and efficiency of ITS.

CVIS usually requires various sensors for the real-time monitoring of information about humans, vehicles, roads, and the environment. However, supplying power to numerous sensors has always been a great challenge [10–13]. Therefore, there is an urgent demand for a sustainable and stable power source to realize self-powered sensing in the CVIS. Fortunately, there are abundant energy sources in the CVIS system, including mechanical energy [14], thermal energy [15], solar energy [16], and wind energy [17]. Several progressive techniques for extracting energy from the ambient environment have been developed, such as piezoelectric [18–21], pyroelectric [22–24], photovoltaic [25–28], thermoelectric [29,30], triboelectric [31–33], and hybrid effects [22,34,35]. The triboelectric nanogenerator (TENG) has become an attractive and promising energy harvesting technology, due to its high energy density, low cost, simple production, a wide range of material choices, and wide adjustability [36–38]. It can serve as not only an energy harvester but also an active sensor in self-powered sensing system [31]. Wang’s group [39–41] has first invented TENG based on triboelectric and electrostatic induction. Recently, TENGs have experienced rapid development, including the vertical contact separation mode [42–45], the sliding mode [46–48], the single electrode mode...
Generally, TENG is designed to harvest low-frequency and disordered energy in daily life, including mechanical energy, tire rotation, human activities, bridge vibration, wind energy, sound wave energy, water wave energy, etc. Meanwhile, under the premise that no external power supply is required, it is also used as a self-powered sensor or actuator in health monitoring, biological sensing, human-machine interface (HMI), environmental monitoring, infrastructure security, high-voltage actuation, and neural stimulation. In ITS, TENG has gradually been utilized for sensing, analyzing, and monitoring of driving behavior, vehicle operation, road conditions and environmental emissions, as summarized and shown in Fig. 1. It can be believed that TENGs are one of the foundation technologies for CVIS in the upcoming 5G era, and their integration with IoT will be considered as one of the most effective measures to solve current energy and sensing challenges in the future.

Based on the brief description of CVIS and TENG’s fundamental and structure, this review focuses on energy harvesting and self-powered technology in humans, vehicles, roads, and the environment to present comprehensive and systematic knowledge about TENGs for CVIS. It also includes pedestrian track, driving behavior, vehicle speed, tire pressure, road temperature, environmental emission, and real-time monitoring. Herein, a great emphasis is placed on the recent progress in practical applications for CVIS. Furthermore, perspectives and challenges for the future development of TENGs for CVIS are discussed. It is expected that this review can significantly promote the development of TENGs for CVIS and shed some light on providing a and sustainable energy solution to the CVIS in the upcoming era of the IoTs.

2. Cooperative vehicle-infrastructure system and triboelectric nanogenerator

2.1. Brief description of cooperative vehicle-infrastructure system

In the 1850s, the concept of CVIS was first proposed and is expected to be commercialized in 2030. CVIS is an efficient combination of IoT and intelligent vehicles, which relies on advanced roadside units (RSU), on-board units (OBU) and other sensors. It integrates modern communication and network technology to carry out intelligent information exchange and sharing among humans, vehicles, roads and environment, making them interact with each other and form a whole together, so as to improve vehicle safety, reliability and traffic efficiency.

CVIS can improve the ability of autonomous vehicles perception, decision-making and control execution via the visual information processing, reliable and low complexity communication, green wave control of traffic flow and other advanced technologies. The important elements of CVIS are divided into vehicle, human, road, and environment. The technical architecture of CVIS is shown in Fig. 2, which consists of two systems (a. vehicle-infrastructure cooperation system (RSU, OBU, etc.), b. network communication system) and two platforms (c. edge computing platform and d. central cloud control platform). The traffic information is monitored through the

![Fig. 1. Schematic diagram showing the typical research on CVIS using TENGs. Human- [73–75]; Vehicle- [79–81]; Road- [83–85]; Environment- [87,88,90]; triboelectric-layer mode [52–54].](image)

![Fig. 2. The technical architecture diagram of Cooperative Vehicle-Infrastructure System.](image)
vehicle-infrastructure collaborative system and then transferred to the network communication system and edge computing platform for intersection-level multi-dimensional fusion perception computing. The driving guidance and suggestions will be proposed by the central cloud control platform with reference to the computed results. Specifically, the RSUs detect real-time traffic environment information such as traffic flow, pedestrian information, and road conditions through video detection, radar, laser, and RFID, and sends the information to the roadside control unit for post-processing. Meanwhile, the traffic information is transferred to vehicles and other RSUs using V2I communication. The OBU collects positioning, acceleration, braking, steering wheel angle, road condition and pedestrians’ information through GPS, GIS, radar, CDD vision sensor, etc. Similarly, the information is transmitted to the on-board control unit for data processing and analyzing, and sent to RSUs and other vehicles using V2V communication. Finally, the central cloud control platform distributes the application data and management data to the vehicle-infrastructure cooperation system, which means that the information flow cycle of CVIS is completed.

In the future, CVIS will realize typical application scenarios such as blind area early warning, coordinated lane changing of multi-vehicle, intersection conflict avoidance, pedestrian and non-motorized vehicles collision, speed guidance, fleet control, etc. However, these scenarios all depend on advanced self-powered sensors, which promote the attempts of triboelectric nanogenerators as next-generation self-powered sensor for cooperative vehicle-infrastructure system.

### 2.2. Fundamental and structure of triboelectric nanogenerator

Triboelectric nanogenerator technology has been invented based on contact electrification and electrostatic induction. In order to meet the needs of different application scenarios, TENGs with four modes have been gradually invented, including vertical contact separation mode [42–45], the sliding mode [46–48], the single electrode mode [49–51], and the freestanding triboelectric-layer mode [52–54]. To get a superior performance and high efficiency, suitable modes should be selected considering different application scenarios.

#### 2.2.1. Triboelectric nanogenerators for human

When TENG is utilized as the key sensing element of smart shoes and smart insoles [74,94–96], the vertical contact separation mode is the most popular since the contact surface between pedestrians’ feet and shoes is almost parallel to the ground. TENG separated and contacted successively during the lifting and lowering of human feet, which generates periodic electrical signals. If TENG is integrated into the wrist, neck, arm, leg and other parts, it is generally designed as a textile structure similar to clothes, mainly including sliding of rotating structure and vertical contact separation modes [75,97]. It can not only monitor blood pressure, pulse and other physiological signals in real time, but also harvest the energy from human motion. Among of them, the linear-to-rotary hybrid nanogenerator (LRH-NG) [75] including a threaded rod, a rotator and a stator, is interesting. As a critical component, the disc with the peanut-shaped hole can transform the linear biomechanical motions into rotatory mechanical motions (Fig. 3(a)). The steering wheel and pedal are core operating device in the process of driving, which are the best positions for TENG with sliding mode. It is worth noting that a novel sweep-type triboelectric nanogenerator (ST-TENG) [98] designed to harvest the energy of random triggering motion and monitor driver habits. The ST-TENG is composed of a push rod, shells, two flywheels and a single freewheel. When the random triggering motion is applied to the push rod, the push rod and single freewheel transform the triggering motion into rotation motion of the shaft. Besides that, the ST-TENG can also monitor driver habits, analyze

![Fig. 3. Fundamental and structure of Triboelectric nanogenerator. (a) The linear-to-rotary hybrid nanogenerator (LRH-NG) [75]. (b) The sweep-type triboelectric nanogenerator (ST-TENG) [98]. (c) The disc-shaped TENG with non-contact mode [99]. (d) The textile-based tire cord triboelectric nanogenerator (TC-TENG) [81]. (e) The paint based triboelectric nanogenerator (PBT) [86]. (f) The self-powered triboelectric filter [101].](image-url)
road conditions, monitor driver habits, intelligent driving, and traffic safety (Fig. 3(b)).

2.2.2. Triboelectric nanogenerators for vehicle

Considering unsuitable acceleration and deceleration of vehicles is the main factor causing traffic accidents, TENG-based sensors are becoming attractive to be used in the pedal and tire. The TENG installed on the vehicle usually adopts the sliding mode, and rotating structure is an attractive strategy. As shown in Fig. 3(c), an innovative design is a disc-shaped TENG with non-contact mode [99]. It relies on electrostatic
induction for energy harvesting, and no material wear occurs during triboelectrification process. At the initial condition, the two surfaces are charged negative and positive since the negative and positive triboelectric layer have been in contact. Then, the positive triboelectric layer slides in parallel to the negative triboelectric layer with a small angle after the two surfaces have a distance d. The free electrons will flow to the positive layer to balance the non-mobile triboelectric charges in the negative layer, the free electrons in positive layer will flow back to the negative layer. This process continues until the charges rebalance in the two layers. In addition, a textile-based tire cord triboelectric nanogenerator (TC-TENG) [81] is well designed, which not only integrates TENG and tire, but also cleverly designs dual-mode, including (i) the vertical contact separation mode composed of road and tire tread, and (ii) the single electrode mode composed of tread and cord layer (Fig. 3(d)). This approach provides a framework for future energy harvesting technology in smart vehicles.

2.2.3. Triboelectric nanogenerators for road

The first TENG for road is installed in speed bump. Gradually, TENG is applied to the main pavement structure, including vertical contact separation mode, free sliding, single electrode modes. Among of them, the most innovative is paint based triboelectric nanogenerator (PBT) [86] by the facile spray deposition(Fig. 3(e)). The PBT consists of the spray paint as the dielectric layer, electrode layer with conductive spray adhesive tapes 3.5 × 2.75 cm and two parallel electrode plates are fixed on an elastomeric materials and a helix inner electrode sticking on a tub Top-down approachITO, PET, polyimide/Kapton adhesive tapes 3.5 × 2.75 cm rubber, 10 × 10 cm/15 × 10 cm/20 × 10 cm/25 × 10 cm/30 × 10 cm, which leads to triboelectric charges on the pellets surface. The electrons flow first from one electrode into PTFE pellets in the high electrostatic fields are formed by the applied vertical load on the chamber, which leads to triboelectric charges on the pellets surface. The electrons flow first from one electrode into PTFE pellets in the high electrostatic fields, which are used in self-powered air pollution control technology. Besides that, a serious of TENG for wind and rainfall energy harvesting have been developed, which includes freestanding flag-type mode [102], rotating-disk-based sliding mode [103], and water–solid contact electrification mode [104], which all focused on energy harvesting aspect.

3. Triboelectric nanogenerators for human

In the CVIS system, human factors dominate traffic safety, and it is also the most critical aspect in ITSs. Human factors account for a large proportion of traffic accidents. It is well known that the human factors in the CVIS system are composed of drivers and pedestrians. The pedestrians’ motion state and action intention are essential for road traffic safety. The driver’s fatigue state and other driving behavior directly affect the handling stability and safety of vehicles. Therefore, the following discussion mainly focuses on the self-powered system based on nanogenerators for human behavior detection, including drivers’ and pedestrians’.

3.1. Pedestrians

With the development of the vehicle to the Internet, pedestrians play an indispensable role in the traffic scenario. The real-time monitoring of pedestrians [105–109] is conducive to the realization of CVIS. Specifically, the current state of pedestrians (including status, walking, running and cycling) can be used to warn the approaching vehicles. Therefore, the triboelectric self-powered sensors gradually appear to recognize the activity state of pedestrians in the traffic environment, including position sensors and inertial sensors, which harvest the energy generated from walking, jumping, running, speaking, heartbeat, muscle contraction, and other movements to power sensors [110–114].

As shown in Fig. 4(a), a multilayered attached-electrode contact-
mode TENG [94] was first designed and optimized to harvest human biomechanical energy from human walking and running efficiently. This TENG can be integrated into a human-motion-driven self-powered system, including sensors, data processors, displays, and wireless transmitters to monitor human behavior dynamically. From the perspective of material and structural optimization, an as-fabricated TENG [115] was invented, having a symmetric helix-belt structure. Its significant advantages appear in two aspects: boosting the electrical performance via dividing the electrode into several small areas for more sufficient contact and having stable performance due to trigging from various directions. In addition to biomechanical energy harvesting, it can be used as a power source to drive other wearable electronic devices like fitness trackers (Fig. 4(h)). Similarly, the U-TENG [117], almost natural TENG [96], self-powered versatile shoes [116], novel corrosion-resistant copper-nickel based TENG (CN-TENG) [118], and TENG-based smart insole [74] were also reported to harvest energy and monitor pedestrian motion, such as walking, jumping, and running. The triboelectric smart insole [110] including a forefoot TENG and hindfoot tube-based TENGs, was the accounted foot pressure distribution design to maximize the energy conversion efficiency in harsh environments. Furthermore, the deep learning-enabled triboelectric smart sock [114] with textile structure was developed to deliver information, regarding the identity, health status, and activity of the users with the accuracy of 93.54%. TENG as a self-powered sensor to monitor human motion has been gradually used to detect pedestrian physiological information. Based on the excellent flexibility, stretchability, and high-sensing mechanoluminescent features of the TENG yarns, a self-powered body motion detector [97] was developed by using coil spring as the inner support layer and mechanoluminescent ZnS:Cu/PDMS composite as the outer friction layer. These TENGs were attached to the neck, finger, arm, wrist, elbow, knee, ankle, and sole to monitor the human-body physiological signals of the different parts, which are the most common body recovery sites for human. The human movement behaviors can be understood based on various electrical signals (Fig. 4(h)). In addition, the stretchable, multichannel respiratory sensor (BSG-RS) [119] inspired by the structure of shark gill cleft was reported, which can produce a graded electrical response to different tensile strains. Therefore, the BSG-RS can simultaneously monitor the breathing rate and breathing depth of the human body accurately, and realize the effective recognition of the different human body’s breathing state.

Fig. 5. The typical research on CVIS using TENGs for drivers. (a) The driver behavior monitoring of self-powered triboelectric sensors [123]. (b) Voltage signals of the APU-TENG under driver normal breathing and deep breathing [73]. (c) Monitoring of closed eyes, open mouth and, nod and twisting the neck by PL-TENG [124]. (d) Monitoring of driver habits based on sweep-type TENG [98]. (e) Structural design of the SSAS and monitoring and warning signals [72]. (f) Driving behavior monitoring via DT-TENG [125].
In order to further systematically understand above TENG's design ideas, Table 1 shows the name, materials and structure designing, output and functions and performance of TENG. It can be found that TENGs for pedestrians have developed through biomechanical energy harvesting, human motion monitoring, and real-time sensing of physiological information. In the future, it is not difficult to imagine that TENG will play a significant role in pedestrian trajectory tracking, gait monitoring, and action intention judging.

3.2. Drivers

In CVIS systems, research about drivers’ state is complicated due to the driving behavior. In addition, driving behavior [120–122] is the performance of each driving individual’s personality characteristics and driving habits. The driver is directly involved in the driving link of the road traffic system, which is the direct manipulator of vehicles. Therefore, driving status monitoring is highly desirable to ensure safety and prevent traffic accidents. Unsafe and inappropriate driving behaviors can be identified via monitoring the driver’s body motion.

In 2018, the Al-Kapton-based TENGs [123] were utilized as a self-powered sensor for monitoring the driver’s behavior in automobiles for the first time (Fig. 5(a)). The designed TENGs were mounted on the driver’s glass, accelerator, and brake of a driving simulator, respectively. Based on $V_{OC}$ signals, the TENG sensors can monitor driving behaviors, including pressing the accelerator, braking or poor concentration, impulse or drowsiness driving. As shown in Fig. 5(b), the APU-TENG and AS-TENG sensors [73] were arrayed onto a commercial safety belt to monitor driving status, including aggressive deceleration and turning actions. The APU-TENG was highly sensitive with $0.89 \text{ V/cm}^2$, and the $V_{OC}$ of the APU-TENG could capture the regular breathing and deep breathing of a driver. Recently, a stretchable polyacrylamide (PAAM)-LiCl-based TENG (PL-TENG) [124] is utilized for the first time to monitor driver fatigue and distraction by attaching them to the face and neck of a driver. These PL-TENG sensors can detect eye closure, mouth closure, and neck rotation with high accuracy, which has the characteristics of high voltage, high sensitivity, and good biocompatibility (Fig. 5(c)). In addition, a novel sweep-type TENG (ST-TENG) [98], including a push rod, shells, two flywheels, and a single freewheel, was mounted under the car’s pedals. According to the stepping signal of the driver, it can monitor driving habits, analyze road conditions after data processing, and record data to find different driving habits. Specifically, the driver habits were investigated for four volunteer drivers with legal licenses under different road conditions. They pointed out that the average speed of stepping indicates the stability of driving and

![Triboelectric Nanogenerators for Automobiles](image)

Fig. 6. The typical research on CVIS using TENGs for automobiles. (a) DIV-TENG integrated with the vehicle rear deck [132]. (b) The structure of the disc-based TENG [99], including a push rod, shells, two flywheels, and a single freewheel, was mounted under the car’s pedals. According to the stepping signal of the driver, it can monitor driving habits, analyze road conditions after data processing, and record data to find different driving habits. Specifically, the driver habits were investigated for four volunteer drivers with legal licenses under different road conditions. They pointed out that the average speed of stepping indicates the stability of driving and
may also reflect driving personality (Fig. 5(d)). Using three-phase electrodes, a self-powered steering-wheel angle sensor (SSAS) [51] based on TENG was developed to form a real-time monitoring system about automobile driver status and intelligent fatigue warning. The warning thresholds for four parameters (including steering wheel turns, averaged steering angle, standard deviation of the steering wheel angle and proportion of time spent with steering wheel remaining stationary) were calculated to determine the driver status, and a double turnable structure based TENG (DT-TENG) [125] was designed to detect high-speed turning, intense braking, rapid acceleration and frequent lane changes for monitoring safe driving behavior and aggressive driving behavior. Moreover, a simple algorithm was proposed to prove the feasibility of TENG as a sensor for monitoring driver’s driving behavior. A new TENG based method [76] for monitoring the driver’s steering action was reported for intelligent driving, with a statistically fast response and a high accuracy of 92.0% for the corresponding trained algorithm.

Table 2 systematically reviews the relevant materials, structures, output signals, and sensing parameters in detail. In short, the driving behavior sensing based on TENGs is essentially the driving action sensing, including turning angles, steering angle, and frequency. Combined with the research of TENGs for pedestrians, it can be determined that TENG will play an irreplaceable role in judging fatigue driving, driving habits and driving emotions.

4. Triboelectric nanogenerators for intelligent vehicles

Intelligent vehicle is an important means of delivering at the expressway, bridge, and tunnel, the safety, stability, and intelligence of vehicle operation directly affect the intelligent coordination and cooperation technology of V2I [126–128]. As the carrier of driving behavior manipulation, the essential dynamic performance of the vehicle, such as braking, steering, rolling, and the reliability of each system and component workshop, are closely related to its safety performance. If the vehicle safety system fails, even if the driver operates correctly, it may lead to a traffic accident. Therefore, running safety and stable dynamic performance are the basic condition for an intelligent vehicle; a self-powered system effectively achieves real-time sensing for vehicle operation state. Nanogenerators are gradually playing a critical role in energy harvesting, self-powered sensing, and safety monitoring to achieve vehicles’ intellectualization. Typical research on CVIS using TENGs for automobiles and bicycles is summarized as follows.

4.1. Automobiles

Automobiles are the main participants in road traffic. Vehicle performance has a substantial impact on driving safety. In the CVIS system, connected autonomous vehicles (CAV) [129–131] have been widely studied and tested as a near-future transportation system. It provides an opportunity for TENG as a self-powered on-board unit (OBU).

As shown in Fig. 6(a), a double-impact vibration TENG (DIV-TENG) [132] was developed to monitor the highly variable frequency of vehicle vibrations, which was installed on the rear deck and front dashboard, operating under a broad range of input frequencies. Therefore, the different stiffness springs were employed to DIV-TENG, and the results demonstrated its effective operation capacity from 5 to 25 Hz frequencies. It is worth noting that a common issue is the durability, life-time, and stability of traditional TENG due to the direct contact of the two triboelectric layers. Therefore, a disc shape TENG [99] was designed based on the practical situation of a disc-based braking system in an automobile, which can harvest energy in both contact (~540 V, 43 mA/m²) and non-contact modes (~ 65 V, 3.4 mA/m²), respectively. That method is innovative for harvesting energy from rotating machines, such as automobiles, bicycles, and trains (Fig. 6(b)). Moreover, a triboelectric sensor for a traffic monitoring system [133] was proposed, which can measure speed with more than 95% accuracy and estimate the weight of a vehicle with non-linear fitted curves for the voltages (Fig. 6(c)). In addition, oil-solid interacting TENG (O-TENG) [134] was designed via the contact electrification process of oil-solid contact, which can detect at least 1 mg/mL debris and 0.01 wt% water contaminants in real-time (Fig. 6(d)). Then, a self-powered Hall vehicle sensor (SPHVS) [79], integrating the TENG, the management circuit, the magnet, and the Hall element, was developed for the automobile safety system, which exhibits wide sensing range, great stability, and excellent sensitivity with 0.22 Hz/km and 0.08 mV⁻¹ for vehicle speed sensing and vehicle braking monitoring (Fig. 6(e)). An eye-shaped TENG device (EYE-TENG) [135] was designed using the reused plastic substrate for a vehicle security alert, tire motion signaling, and energy harvesting with good reliability and cheap manufacturing cost (Fig. 6(f)).

Table 3

<table>
<thead>
<tr>
<th>TENGs</th>
<th>Materials and Structure</th>
<th>Output</th>
<th>Functions and performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIV-TENG [132]</td>
<td>Acrylic plate, Cu plate, coil springs; 17 × 8 × 3 cm</td>
<td>−20 µA, 100 V</td>
<td>• Harvesting broadband vehicle vibrations • Broadband performance</td>
</tr>
<tr>
<td>Disc shape TENG [99]</td>
<td>PTFE, 100 µm-thick, 300 nm thick copper layer, PAMMA, 5 mm-thick, Non-contact mode</td>
<td>5.7 mW/m², 60 V</td>
<td>• Rotating speed sensing • Space sensing</td>
</tr>
<tr>
<td>Triboelectric sensor strip [133]</td>
<td>PTFE-Al, 20 × 5 cm</td>
<td>−243 V</td>
<td>• Vehicle speed measurement system • 95% accuracy</td>
</tr>
<tr>
<td>O-S TENG [134]</td>
<td>Dropper covered with copper foil, PTFE, LDPE, GLASS, copper layer, oil flows multilayered</td>
<td>0.8 V</td>
<td>• 1 mg/mL debris • 0.01 wt% water contaminants</td>
</tr>
<tr>
<td>Self-powered Hall vehicle sensor (SPHVS) [79]</td>
<td>Structure, acrylic sheets, Cu, PTFE, Hall element</td>
<td>4.2 mW, 140 V</td>
<td>• Speed sensing and braking monitoring</td>
</tr>
<tr>
<td>EYE-TENG [135]</td>
<td>Water bottles, Kapton film, Cu</td>
<td>25 µA, 250 V</td>
<td>• Vehicle security alarming</td>
</tr>
</tbody>
</table>

4.2. Non-motorized vehicles

Non-motorized vehicle is an essential part of green transportation, which realizes zero energy consumption and zero-emission. At the same time, non-motorized vehicle riding is convenient and flexible, realizing door-to-door travel. Therefore, in the face of traffic congestion and environmental pollution, non-motorized vehicles with environmentally friendly, convenient, and healthy features have an important strategic position, affecting the intelligent traffic system [136–138]. At present, the application of TENGs in non-motorized vehicles has been studied, and they can be seen in Fig. 7.

As shown in Fig. 7(a), a single-electrode-based rotating TENG (SR-TENG) [139] was reported for harvesting rotational energy, which also can serve as a self-powered speed sensor with a sensitivity of about 0.83 V/(m/s). Then, a rationally designed automatic transition TENG (AT-TENG) [140] was developed as a self-powered speedometer for real-time rotational speed and traveled distance measurement. It is worth noting that it can generate electricity both in contact and non-contact working state, which means that this structure significantly reduces the surface friction, improving device robustness (Fig. 7(b)).
Moreover, a hybridized nanogenerator coupling an electromagnetic generator (EMG), a TENG, and a thermoelectric generator (ThEG) [19] were reported for simultaneously harvesting mechanical and thermal energies in one process. The hybridized nanogenerator has been successfully installed in a commercial bicycle to scavenge biomechanical energy to lighten globe lights and charge up a cell phone (Fig. 7(c)). An elastic multi-unit TENG [82] was rationally designed to match the low-frequency external vibration, which can harvest energy from gentle road bumping within a distance of 90 m. Specifically, it can charge a 1mF Al electrolytic capacitor from 0 to 2.3 V (Fig. 7(d)). Besides that, the ambient temperature, humidity, and bike riding speed can be continuously monitored while riding a bicycle. A triboelectric-electromagnetic hybrid generator built on a freestanding magnet (FMHG) [141] was proposed to harvest low-frequency vibration...
energy from arbitrary in-plane directions. It was mounted on a bicycle wheel to light up commercial LEDs due to bicycle braking (Fig. 7(e)). A novel palette structure-based CFP-TENG [142] was constructed by commercial powder particulates (a cosmetic fixing powder) as triboelectric materials, which can harvest mechanical energy from bicycle motion as a self-powered bicycle speed sensor due to the approximately linear relationship between speed and output voltage (Fig. 7(f)).

Table 4 displays the basic information of TENGs for bicycles. It can be found that the non-contact working mode is proposed to improve sensing accuracy and device durability. In addition, most researchers show great interest in bicycle speed sensing, which is mainly due to the 70% fatality rate of non-motor vehicle accidents.

### 4.3. Intelligent tire

As the interface between vehicle and the road, tire plays an important role in ensuring safety, stability, maintenance, and performance. Damaged tires can cause vehicle instability and create potential traffic accidents [143,144]. Therefore, significant attention has been devoted to the utilization of new sensing technologies for tire health monitoring, such as accelerometer [145,146], piezoelectric sensor [147,148], electromagnetic sensor [149–151], and triboelectric sensor. Among many technologies, the triboelectric self-powered sensor is emerging owing to its wide materials, low cost, lightweight, and high energy conversion efficiency. Most focus on energy harvesting and tire parameter sensing, including tire pressure, tire speed, humidity, and temperature information.

In 2015, the multiple single-electrode TENGs (S-TENGs) [152] were first designed and implemented on the tire’s surface of a toy vehicle as energy harvesting, which can monitor speed for 0.1–0.5 m/s and tire weight load for 0–2.2 kg. It is worth noting that most road materials like silica, cement, and even metals are electron-donating materials [153], while the tire is rubber electron accepting materials. When the vehicle tires roll on the road surface, the road surface generates a positive charge, and the rubber loses electrons. In order to harvest vertical rotation energy in a broad frequency band, a hybrid nanogenerator [154], adopted cylinder-like fully-packaged structure, was developed, which mainly consists of two parts, eight contact-separation modes TENGs, and four EMG units. In addition to energy harvesting, it also acts as a wireless temperature, humidity, speed, or even tire pressure monitoring system (Fig. 8(a)). A TENG-based self-powered sensor [155] was reported as a tire pressure monitoring system (TPMS). The performance under different frequencies and stroke displacements was analyzed to demonstrate the capability for tire condition monitoring.

On the other hand, the best location of the tire inside for attaching the sensor was firstly pointed (Fig. 8(b)). An array of compressible hexagonal-structured TENGs (CH-TENGs) [156] were stacked in parallel connections like a honeycomb structure for harvesting the wasted mechanical energy (Fig. 8(c)). The harsh-environmental TENG (heTENG) [157], including a freestanding and single electrode, was integrated with the automobile’s self-powered smart braking system for safety monitoring, such as tire pressure and overloading and partial load. A porous conductive polymer (PCP)-TENG [158] with sponge structure was demonstrated for harvesting vibrational mechanical energy and operating a humidity sensor even under small deformation of the tire. An on-vehicle magnetically TENG (V-TENG) [159], including a flexible seessaw structure and an indurate metallic frame, was designed to power a commercial wireless sensor for TPMS. A large centrifugal force at a high operating speed can be overcome due to the unique seesaw balance structure and quadrupling the efficiency contact areas of a miniaturized device. Besides that, it can quadruple the efficiency contact areas of a miniaturized device. A rotary cylinder-based hybrid nanogenerator [160] was designed based on TENG and EMG as a sustainable power source for potential speed monitoring, and it is capable of triggering a transmitter-integrated tire pressure sensor for as TPMS in real-time (Fig. 8(d)). As the silica filler significantly decreases rolling resistance, a green energy tire [161] was first invented by coupling silica tread rubber with TENGs. Specifically, the treads are friction layers, and a sandwiched copper film between tread rubbers was the electrode. It is worth noting that the green energy tire can also measure tire pressure and road condition according to the change of electrical signals (Fig. 8(e)). A textile-based tire cord TENG(TC-TENG) [81] was integrated into the intelligent tire as an energy harvesting device, which mainly consists of tread and cord, including alarms, environmental monitoring, and friction between the road and the tire tread and friction between the tread and the tire cord via continuous contact/separation. A high-performance stretchable TENG [162] was developed comprising 100% amorphous commercial rubbers. The electrical output performance of different materials was characterized to demonstrate the feasibility of flexible rubber-based TENG for tire application (Fig. 8(f)).

Moreover, the performance of the TENGs for the intelligent tire is shown in Table 5. Energy harvesting is the basic function, and self-powered sensing is the key to ensuring its popularity and application in the intelligent tire. With research development, the range of speed, pressure, load and displacement sensing has been broadened. It is believed that TENGs integrated into intelligent tires will be commercially applied in the future.

### 5. Triboelectric nanogenerators for intelligent roads

An intelligent road is another crucial element besides intelligent vehicles in CVIS, composed of specific structural materials, perceptive networks, information centers, communication networks, and energy systems to provide services for humans, vehicles, and the environment. The development of intelligent pavement will help develop the road network potential and help it to adapt to future vehicles [163–165]. Now, more and more researchers contribute to intelligent road sensors and energy harvesting research. In 2012, the first generation of the mechanical roadway system [166] with total working efficiency of 41.03% was developed, composed of the piston plates and the instantaneous electric generating apparatus in connection with the potential energy storage. However, the larger size of the piston plate with L × W = 106 × 56 cm² and poor compatibility limits its practical application.

As shown in Fig. 9, a hybridized electromagnetic-triboelectric generator [167], including four units of freestanding TENG and four EMG for road traffic monitoring, was proposed, which can deliver

![Table 4](image-url)

The typical research on CVIS using TENGs for bicycles.

<table>
<thead>
<tr>
<th>TENGs</th>
<th>Materials</th>
<th>Output</th>
<th>Functions and performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR-TENG [139]</td>
<td>PTFE, Al electrode</td>
<td>30 pW, 55 V</td>
<td>• Mechanical energy harvesting and speed sensing</td>
</tr>
<tr>
<td>AT-TENG [140]</td>
<td>Aluminum, PTFE</td>
<td>250 μA, 500 V</td>
<td>• A self-powered speedometer with ultrahigh accuracy</td>
</tr>
<tr>
<td>Hybridized nanogenerator [19]</td>
<td>TENG, EMG, ThEg</td>
<td>3.6 mA, 58.7 V EMG, 4.5 mA, 26.5 V ThEg: 57.7 mA, 1.2 V</td>
<td>• Scavenge the biomechanical energy from bicycle</td>
</tr>
<tr>
<td>Elastic multunit TENG [82]</td>
<td>AL, ALuP</td>
<td>102 W m⁻³</td>
<td>• Harvested vibration energy as an exclusive power source</td>
</tr>
<tr>
<td>Hybrid generator (PMHEG) [141]</td>
<td>Copper, Kapton, magnets</td>
<td>TENG: 85.7 μJ, EMG: 3.29 mW</td>
<td>• Self-powered sensing systems including alarms, environmental monitor.</td>
</tr>
<tr>
<td>CFP-TENG [142]</td>
<td>novel palette</td>
<td>1141 V, 521 μA, 570.96 μW/cm²</td>
<td>• Self-powered bicycle speed sensor</td>
</tr>
</tbody>
</table>
output volume power density of 20.96 W/m³ and 50.81 W/m³ for TENG and EMG components in the frequency of 1 Hz, respectively. Then, an origami tessellation-based TENG (OT-TENGs) [83] integrated with different origami tessellation patterns bases was designed for energy harvesting, which was embedded into a tracking board to simulate the pavement deformation by moving vehicles. The periodic output current 0.05 μA can be obtained due to energy upon the moving wheel. A practical speed bump TENG (SB-TENG) [84] was proposed by a commercial PVC speed bump as a body substrate and six copper electrodes. It can act as a self-powered velocity sensor by analyzing the time at which peaks were generated in ITSs. Besides, a fully self-powered TENG-based wireless traffic monitoring system [168] was designed for real-time monitoring of illegally entered electric motorbikes on the footpaths, flow rates of pedestrians and motorbikes, and speed and driving
direction of electric bikes on non-motorized lanes. That system can identify pedestrians and motorbikes, check the illegally entered direction of electric motorbikes on non-motorized lanes. That system

The typical research on CVIS using TENGs to intelligent tire.

<table>
<thead>
<tr>
<th>TENGs</th>
<th>Materials and Structure</th>
<th>Output</th>
<th>Functions and Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-TENG [152]</td>
<td>PDMS, single-electrode mode 1 cm × 1 cm× 120 µm</td>
<td>~2.0 µA, 2.3 V</td>
<td>• Energy Harvesting</td>
</tr>
<tr>
<td>Hybridized generator [154]</td>
<td>Acrylic cylinder (200 mm diameter, 48 mm width, 2 mm thickness), magnet rod (30 mm diameter, 42 mm length)</td>
<td>TENG:~100 mC,240 V; EMG:~7 mA,2 V</td>
<td>• Speed-sensing for 0.1–0.5 m/s</td>
</tr>
<tr>
<td>Flexible TENG [155]</td>
<td>100 µm temperature resistant Kapton,1.5 mm thick polyurethane single-electrode mode</td>
<td>~243 V</td>
<td>• Power source</td>
</tr>
<tr>
<td>CH-TENGs [156]</td>
<td>FEP film (50 µm thick, 30 ×50 mm in area), Cu</td>
<td>1.9 mW</td>
<td>• Temperature sensing</td>
</tr>
<tr>
<td>heTENG [157]</td>
<td>single electrode mode copper, PTFE film, AI balls, Q235 steel</td>
<td>27.9 µA cm −2, 33.4 µC cm −2, 221 V,</td>
<td>• Humidity sensing</td>
</tr>
<tr>
<td>PCP-TENG [158]</td>
<td>sponge structure PTFE- Al wires</td>
<td>60 mC 2</td>
<td>• Speed-sensing</td>
</tr>
<tr>
<td>V-TENG [159]</td>
<td>Seenas balance structure 60 µm thick Al film, 80 µm thick PTFE film 56 × 38 × 24 mm</td>
<td>25 µA,70 V</td>
<td>• Power source for 0.4–2.8 m/s</td>
</tr>
<tr>
<td>Green energy tire by TENG and silica filler [161]</td>
<td>Sandwiched copper film, Kapton, rubber</td>
<td>21.3 µA,150 V</td>
<td>• Velocity sensing for 0-5 m/s</td>
</tr>
<tr>
<td>Hybrid rotary nanogenerator [160]</td>
<td>4 mm thick acrylic sheets, 4 mm × 5 cm PTFE strips, 110 µm thick Al foils</td>
<td>0.1 mA, 1.8 mW,16 V</td>
<td>• Rotational speed for 0-5 r/min</td>
</tr>
<tr>
<td>TC-TENG [162]</td>
<td>PDMS-Ag textile, woven nylon textile; 5 × 3 cm</td>
<td>42 µA,0.5 mW,225 V</td>
<td>• Self-powered smart braking device</td>
</tr>
</tbody>
</table>

Most previous studies show that an inclément road environment increases traffic accidents [169–171]. For example, air pollution affects driver visibility; high temperature reduces driving comfort, and inclement weather such as strong wind or rain challenges driving safety. Therefore, the sensing of the road environment is the key technology of the CVIS system and the foundation of vehicle judgment and decision. At present, the research of nanogenerators for road environment has been developed to improve air quality [62,87,90,101,172] and harvest environmental energy such as rain energy [89,104,173–175], water wave energy [176,177] and wind energy [35,88,102,103]. As shown in Fig. 10(a), a self-powered triboelectric filter [101] was invented to remove PMs from automobile exhaust fumes, with a mass collection efficiency of ~95.5% for PM2.5 in actual automobile exhaust fumes. Then, a stable and reliable self-powered chemical-sensing system [87] was proposed by coupling triboelectric and chemoresistive effect, which can monitor NO2 content change by parallel connection with commercial LEDs. The LEDs were lighted due to the injection of NO2 gas, whereas they cannot be lighted up without NO2 (Fig. 10(b)), and the captured carbon was used as the electrode of supercapacitor in the self-powered system [90], which collected regular graininess particles closed to 100 nm. The supercapacitor exhibits areal specific capacitance of 1.11 mFcm−2 at 0.1 mA/cm2 and displays excellent cycling stability retaining its capacitance even after 100,000 continuous cycles (Fig. 10(c)). In order to harvest the mechanical energy and simultaneously detect CO2 gas, the hybrid piezoelectric micromachined ultrasonic transducer (pMUT) array and TENG sensor [178] was developed, which possessed a good CO2-sensing response from below 700 ppm to over 12,000 ppm. Meanwhile, it can act as a active humidity sensor with extremely high sensitivity (748 Hz/% RH) and relatively sensitivity (290 ppm/% RH), rapid response and recovery (<2 s/53 s at 90%), small hysteresis (3.07% RH), excellent linearity over a wide range of 20–90% RH (0.9951 for R2) and good stability. A water-air triboelectric nanogenerator (WATENG) [179] was presented for detecting CO2, the sensing range can be up to 6000 ppm. For dynamic CO2 sensing, the sensing range of dynamic situation can be broadened to 30,000 ppm due to the fast recovery of PEI surface reaction. A washable multilayer triboelectric air filter (TAF) [180], including multipieces of nylon fabrics and polytetrafluoroethylene (PTFE) fabrics, can be charged via contact electrification. Its removal efficiency of PM0.5 and PM2.5 were increased from 26.3% to 84.7% and 69.1–96.0%, respectively. The rotating triboelectric nanogenerator (R-TENG) enhanced multilayered antibacterial polyimide (PI) nanofiber air filters[181,182] was designed to remove ultrafine particulate matter (PM) from ambient atmosphere, which can work on all of the particles with diameters larger than 0.54 µm. The highest removal efficiency was 94.1% at the diameter of 53.3 nm and the average removal efficiency reaches 89.9% owing to the connecting with the R-TENG.

In addition, an integrated multi-unit transparent TENG [173] was developed to harvest water energy in an ambient environment, which can be integrated with vehicle glasses for harvesting clean energy from raindrops (Fig. 10(d)). A hybrid energy harvesting nanogenerator [104] based on water/solid-solid coupling contact was reported, which can improve the energy harvesting efficiency by 30 times during rainfall (Fig. 10(e)). The first single waterproof and fabric-based multifunctional TENG (WPF-MTENG) [89] was developed, which can produce
electricity from tiny natural impacts (rain and wind) and body movements and act as a self-powered, active, fabric-based sensor (Fig. 10(f)). An innovative freestanding woven TENG flag (WTENG-flag) [102] was developed for harvesting high-altitude wind energy from arbitrary directions, which had the temperature/humidity sensing capability (Fig. 10(g)). A self-powered active wireless traffic volume sensor [103] coupling rotating-disk-based hybridized nanogenerator of TENG and EMG as the sustainable power source was designed, which demonstrated effective wind energy harvesting by moving vehicles (Fig. 10(h)). Besides that, a smart self-powered sensing network based on a hybrid nanogenerator (NG) [35] was developed, which can harvest wind energy and solar energy simultaneously or individually and serve as a sustainable power source. If these devices were installed along the roads, the wind energy induced via moving vehicles and solar energy could be harvested simultaneously or individually. When a vehicle is going across the smart network sensing node, the induced electrical signals can be utilized to light up streetlights or traffic signal lamps and monitor the traffic volume, moving speed, and others (Fig. 10(i)). The near-zero power triboelectric wake-up system [184] was proposed to monitor autonomous Beaufort scale of wind force, which can be judged according to the electric energy and the signal is sent out wirelessly. In standby mode, when there is no wind, the power consumption of the system is only 14 nW. When the wind scale reaches or exceeds light air, the system can switch to active mode within one second and accurately

Table 6
The typical research on CVIS using TENGs for intelligent roads.

<table>
<thead>
<tr>
<th>TENGs</th>
<th>Materials and Structure</th>
<th>Output</th>
<th>Functions and Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybridized nanogenerator [167]</td>
<td>PM, Steel, coil, rubber, Teflon, PTFE, Al</td>
<td>TENG : 20.96 W/m², EMG: 50.81 W/m²</td>
<td>• Speed bump</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Vehicle velocities sensing for 0–60 km/h</td>
</tr>
<tr>
<td>OT-TENG [83]</td>
<td>Arc pattern, 30 µm copper foils, 100 µm nylon film, 50 µm PTFE film</td>
<td>0.75 µA, 37.5 V, 25 µW</td>
<td>• Miura pattern</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Energy harvesting</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Tracking board test</td>
</tr>
<tr>
<td>SB-TENG [84]</td>
<td>single-electrode and freestanding modes; PVC speed bump, PTFE six copper electrodes</td>
<td>12.6 µA, 69.2 V</td>
<td>• Self-powered automobile warning sensor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Self-powered velocity sensor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Monitoring speed with ~94% accuracy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Monitoring driving direction on non-motorized lanes</td>
</tr>
<tr>
<td>self-powered spontaneous traffic monitoring system [168]</td>
<td>TPG, Al, PAA, Rubber, FEP, Spring</td>
<td>−200 V</td>
<td>• Monitoring driving direction on non-motorized lanes</td>
</tr>
</tbody>
</table>

Fig. 9. The typical research on CVIS using TENGs for intelligent roads. (a) Schematic representation of hybridized nano generator and car passing over a speed bumper [167]. (b) A sketch of the developed Miura pattern OT-TENGs in application of pavement [83]. (c) Schematic illustration and electric electrical signal SB-TENG [84]. (d) The Ni-PBT©cement based self-sustainable intrusion detection system (NSIDS) [86].
Fig. 10. The typical research on CVIS using TENGs for Environments. (a) The collection efficiency of self-powered triboelectric filter [101]. (b) The triboelectric self-powered vehicle emission system [87]. (c) The collecting mechanism of the captured carbon [90]. (d) The layer structure and Working mechanism of WATENG [179]. (e) Schematics of TWMAT with wind-driven fluttering triboelectric ribbons [104]. (f) Fabrication process of WPF-MTENG and its applications [89]. (g) WTENG-flag and equivalent electric circuit of the self-powered sensor [102]. (h) Sketch of the sensor and its working in the tunnel [103]. (i) The hybrid NG used in the intelligent traffic system [35]. (j) The WEH used as a supplementary power source for wind-solar complementary circuit [183]. (k) Sketch of the NP-TWS for Beaufort scale of wind force monitoring [184].
judging the Beaufort scale of wind force within 10 s. The triboelectric-electromagnetic hybrid wind energy harvester (WEH) [183] was proposed, which can work as a sustainable power source and a self-powered wind speed sensor. The testing results demonstrated its ability to monitor calm wind (<3.5 m/s), light breeze wind (3.5–6 m/s), gentle breeze wind (6–9 m/s), fresh breeze wind (9–12 m/s), and gale (>12 m/s) wind. When the wind speed is 12 m/s, the peak open-circuit voltages reach 47.4 V and 683 V by the EMG and TENG, respectively, corresponding to the high-power outputs of 62 mW and 1.8 mW. Further, the development of a wind-driven TENG [88] was reviewed (Fig. 10(j)), which focuses on triboelectric materials optimization, structure improvement, and hybridization with other types of energy harvesting techniques.

In summary, the TENGs for road environments can be divided into three types, including vehicle emission detection, rainfall, and others. Their corresponding key performance characteristics are shown in Table 7. It can be found that the strategy of vehicle emission detection consists of air quality monitoring and air purification, and the purified particle size can reach 100 nm to prevent air pollution. Moreover, TENGs for environments are not only used to harvest ambient energy, but also to realize the perception of wind speed, temperature and humidity to reach the self-powered sensing of the weather environment.

### 7. Challenges and future perspective

The full utilization of TENGs in CVIS faces a few challenges. In summary, the human-vehicle-road-environment is a complicated system, and each part is interrelated but independent. Although the TENG as a new energy technology for self-powered ITS was summarized in 2019 [69], its research in CVIS is only in the initial stage, most of which still stay in the indoor experiments, and there is still a long way to go towards practical application. For example, the standard vehicle axle load is 100 kN and the number of standard axle load actions usually exceeds 3000,000 times in the design service life. The large contact between vehicles and roads leads to sufficient friction in the road traffic system, but meanwhile it brings higher requirements for the durability of TENG. How to ensure that TENG can bear the repeated loading is one of the key challenges. Besides, as the TENGs for CVIS would affect by the surrounding factors including temperature, humidity, pressure, ultraviolet ray, etc., the excessive traffic loading and harsh environmental condition may cause instability of TENGs, resulting error monitoring and abnormal operation of ITS. The design of the fully-packaged structure is an effective solution, but the compatibility between the packaged structure and the road structure should be considered. Poor compatibility not only affects the TENGs’ electrical performance, but also leads to serious reduction of road service life. Therefore, to guarantee the durability of TENGs is still a critical challenge.

As the world marches into the era of Cooperative Vehicle-Infrastructure, it is time to develop a pervasive technology to realize zero casualties, delay, maintenance, emission, and reliable ITS. Drawing on the research of smart organisms, the CVIS will have the capability of self-sensing, automatic analyzing, self-adaptation, information interacting, and continuous energy supply. For future field development of TENG as a next-generation self-powered sensor for CVIS, research directions can be implemented in the following aspects (Fig. 11):

#### 7.1. Human

Triboelectric wearable electronic devices are utilized to detect the characteristics of pedestrian physiological and psychological (i.e., heart rate, blood pressure, pulse, and blink rate) in real-time based on the harvesting of biomechanical energy in the human body. They further predict pedestrian action intention, improve pedestrian crossing safety, and reduce conflict between pedestrian-vehicle. Besides, real-time perception of driving behavior can prevent safety accidents caused by fatigue and emotions.

#### 7.2. Vehicle

As an essential element of the transportation system, several attempts have been recently made to demonstrate the possibility of TENGs for vehicles. Most of them are installed on the vehicle steering or braking system for speed, tire pressure, monitoring of oil consumption, and safety.

#### 7.3. Road

It is believed that TENG will make outstanding contributions to building smart roads due to the large amount of low-frequency and disordered mechanical energy in the road system. The function characteristics, including energy harvesting (i.e., mechanical energy, thermal energy), self-powered sensing (i.e., stress, strain, and displacement), and self-adaptation (crack repair, automatic snow melting, and aging degradation), developed and applied gradually.

#### 7.4. Environment

It is composed of the external environment and traffic environment. Through the energy harvesting and information monitoring of air,
temperature, rain, fog, ice, wind, and snow, the impact of bad weather on traffic safety can be warned in time. In terms of traffic environment, speed limit control, signal adaptation, and variable lane control will be adjusted in time according to traffic congestion. In summary, CVIS is composed of intelligent roadside and vehicle systems. The roadside self-powered sensor and onboard unit (OBU) can obtain the road condition, vehicle position, speed, acceleration, and traffic flow information and monitor the environment information such as ambient weather in real-time. Wireless communication transmits it to the roadside unit (RSU) node and traffic supervision.

TENG has rapidly developed in self-powered sensing due to its high sensitivity and low limitation, and the pace of development of CVIS is also brisk. The active fusion sensing technology based on TENG would substantially impact CVIS. It plays an irreplaceable role in improving pedestrian and vehicle safety, monitoring fatigue driving, estimating traffic environment, and prolonging road service life.

**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.

**Acknowledgments**

The work described in this paper is supported by the National Natural Science Foundation of China (Nos. 51922079 and 61911530160), “Shuguang Program” supported by Shanghai Education Development Foundation and Shanghai Municipal Education Commission (No. 21SG24), Key Research Project from Shanxi Transportation Holdings Group (No. 19-JKKJ-1), and the Fundamental Research Funds for the Central Universities.


Y. Pang et al.

Nano Energy 97 (2022) 107219