

Article

A Rack-Shaped Self-Powered Triboelectric Sensor for Online Monitoring of Vehicle Speed and Load

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Abstract

Strict control of vehicle speed and load is crucial for driving safety. However, existing methods for monitoring vehicle speed and load heavily rely on power supply, limiting their application in remote areas. In this work, a low-cost rack-shaped triboelectric self-powered sensor was developed, which is capable of accurately monitoring vehicle speed and load due to its precise structure, overcoming the challenge of low accuracy in traditional triboelectric sensors when monitoring multiple parameters. It can generate an output voltage exceeding 96.3 V under a speed of 30 m/s and a pressure of 30 kPa. Based on the excellent output performance of the triboelectric sensor, a vehicle speed and load online monitoring system was developed and validated through outdoor experiments, demonstrating that the error in speed and load measurements is within 5%. This work provides a promising paradigm for the construction of smart transportation cities and intelligent traffic monitoring.

Keywords: triboelectric sensor; rack-shaped; vehicle speed; vehicle load

1. Introduction

Strict regulation and monitoring of vehicle speed and load are crucial measures to ensure traffic safety and extend road lifespan [1,2]. Research indicates that approximately 30% of traffic accidents are directly caused by speeding [3,4], while excessively overloaded vehicles can accelerate road damage by several tens of times [5,6]. Therefore, it has significant practical value for safe driving to monitor vehicle speed and load. Currently, Quartz-based weigh-in-motion sensors have been widely used for vehicle-load monitoring because of their high sensitivity and relatively mature engineering implementation [7–12]. However, these systems usually require external power supply, embedded installation, regular calibration, and relatively high maintenance cost, which may limit their use in remote or low-cost road-monitoring scenarios. Radar-based systems can effectively measure vehicle speed without direct contact, but they are generally unable to directly obtain vehicle load information and still require a stable power supply and signal-processing unit [13–15].

In recent years, triboelectric nanogenerator-based self-powered sensors have provided a promising route for traffic monitoring because they can convert mechanical energy into electrical signals. TENGs have been widely investigated in terms of device structure, working mechanism, energy harvesting, and self-powered sensing applications [16–18]. These studies demonstrate that TENGs are suitable for converting low-frequency mechanical excitation into electrical signals, which provides an important basis for developing



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self-powered sensing systems. Based on this principle, TENG-based sensors have been further applied to dynamic motion and flow-related sensing. For example, self-powered wind-speed sensors driven by moving trains and unmanned aerial vehicles have been reported, showing that the frequency or temporal characteristics of TENG output signals can be used for speed-related monitoring [19–21]. These studies confirm the feasibility of using TENG signals for dynamic parameter detection. However, their sensing targets are mainly related to wind speed or motion-induced flow, rather than direct vehicle load monitoring.

For road-traffic applications, several TENG-based systems have been explored for tire-friction energy harvesting and traffic monitoring. Mao et al. reported a single-electrode TENG for harvesting friction energy from rolling tires, demonstrating the possibility of utilizing tire–road interaction as a mechanical excitation source [22]. Li et al. developed an all-weather self-powered intelligent traffic monitoring system by combining self-healable piezoresistive sensors with TENGs, which improved environmental adaptability for traffic sensing [23]. Sarkar et al. further discussed TENGs as a next-generation traffic monitoring system from the perspective of concept and modeling [24]. These studies provide important references for self-powered traffic monitoring. Nevertheless, many existing TENG-based traffic sensors mainly focus on vehicle passage detection, traffic-flow monitoring, energy harvesting, or single-parameter sensing. When vehicle speed and load simultaneously affect the output signal, the coupling between frequency-related and amplitude-related information still makes high-precision multi-parameter monitoring difficult. In addition, many studies have focused on improving TENG output performance and environmental stability through material and structural optimization. MOF-derived nanoporous carbon incorporated nanofibers have been used to improve output performance and pressure-sensing capability [25]. High-thermal-stability polymers, composition-tailored PVDF, and microdome-patterned polyimide have been developed to improve TENG performance under high-temperature or harsh operating conditions [26–28]. Humidity-resisting structures and oleic-acid-enhanced triboelectric materials have also been reported to improve humidity resistance, output stability, and wear resistance [29,30]. These studies indicate that environmental adaptability and long-term stability are critical issues for practical TENG-based sensors. However, material optimization alone cannot fully solve the signal-coupling problem in simultaneous vehicle speed and load monitoring.

Therefore, a structural strategy that can decouple speed-related and load-related sensing information is still required. In this work, inspired by the meshing of gears and racks, a rack-shaped self-powered triboelectric sensor is proposed for simultaneous vehicle speed and load monitoring. The vehicle speed is determined from the fixed rack spacing and the time interval between adjacent voltage peaks, while the vehicle load is estimated from the compensated voltage amplitude after speed determination. This design reduces the coupling effect between speed and load and provides a simple but effective approach for improving the accuracy of multi-parameter triboelectric traffic sensing under outdoor conditions. To further clarify the novelty of the proposed sensor, a brief comparison of representative TENG-based traffic sensors is summarized in Table 1.

Table 1. Brief comparison of representative TENG-based traffic sensors.

Type	Main Target	Main Feature	Limitation
Speed-related TENG sensors	Speed/traffic-flow detection	Time or frequency signal analysis	Load information is difficult to obtain
Load-related TENG sensors	Pressure/weight sensing	Voltage amplitude response	Affected by speed and environment
Multi-parameter traffic sensors	Multiple traffic parameters	Combined sensing functions	Signal coupling remains challenging
This work	Speed and load monitoring	Rack spacing for speed; compensated voltage for load	Long-term field validation still needed

In this work, a rack-shaped self-powered triboelectric sensor is proposed for simultaneous vehicle speed and load monitoring. Different from conventional triboelectric sensors whose output is simultaneously affected by speed and pressure, the rack-shaped structure enables vehicle speed to be determined from the fixed rack spacing and the time interval between adjacent voltage peaks, while vehicle load is estimated from the compensated voltage amplitude. This structural design provides a simple but effective strategy for improving the accuracy of multi-parameter triboelectric sensing. Combined with environmental compensation and outdoor vehicle experiments, the proposed system demonstrates good potential for low-cost, self-powered traffic monitoring in intelligent transportation applications.

2. Materials and Methods

A hydrophobic microstructured surface was fabricated using a solution-based gelation and silane modification method. First, a 4 wt% NaCl solution (sodium chloride, Sinopharm Chemical Reagent Co., Ltd., Shanghai, China) and a saturated sodium silicate solution (Sinopharm Chemical Reagent Co., Ltd., Shanghai, China) were mixed at room temperature under magnetic stirring. Subsequently, 10 wt% dilute H₂SO₄ (sulfuric acid, Sinopharm Chemical Reagent Co., Ltd., Shanghai, China) was added dropwise until the formation of a silica hydrogel. The as-prepared hydrogel was immersed in a mixed solution of n-hexane (Sinopharm Chemical Reagent Co., Ltd., Shanghai, China), anhydrous ethanol (Sinopharm Chemical Reagent Co., Ltd., Shanghai, China), and propyltriethoxysilane (Shanghai Aladdin Biochemical Technology Co., Ltd., Shanghai, China) for 1 h to reduce the surface energy of the silica network. Finally, the modified hydrogel was taken out and dried in an electrothermal constant-temperature drying oven (Shanghai Yiheng Scientific Instrument Co., Ltd., Shanghai, China) at 100 °C for 12 h. The resulting hydrophobic layer possessed a micro/nanostructured surface, which is beneficial for maintaining an air layer at the solid–liquid interface and improving the water repellency of the silicone rubber surface.

The PLA base was directly formed by a 3D printing (SHINING 3D Tech Co., Ltd., Hangzhou, China). PLA filament (Shenzhen Esun Industrial Co., Ltd., Shenzhen, China), aluminum electrodes (Sinopharm Chemical Reagent Co., Ltd., Shanghai, China), and springs (Shanghai Yihui Precision Spring Co., Ltd., Shanghai, China) were used to assemble the rack-shaped triboelectric sensor. The voltage was recorded by an electrometer (Keithley 6514, Keithley Instruments/Tektronix, Solon, OH, USA), and a linear motor (NTI AG LinMot, Spreitenbach, Switzerland) was employed to conduct the cyclic press of the sensor.

Outdoor experiments were conducted on closed road sections with strict safety conditions. The outdoor vehicle-monitoring experiments were conducted using two representative vehicles with different vehicle masses and tire-contact characteristics. The first vehicle was a Honda Accord 9th-generation sedan (Honda Motor Co., Ltd., Tokyo, Japan), with an approximate vehicle mass of 1.52–1.56 t and a factory tire specification of 225/50 R17. The second vehicle was a Yutong ZK6609D51 bus (Yutong Bus Co., Ltd., Zhengzhou, China), with an approximate vehicle mass of 4.75–5.18 t and a factory tire specification of 215/75 R17.5. During the test, the vehicles passed over the rack-shaped triboelectric sensor at controlled speeds and loading conditions. The main components, materials/modules, and functions of the proposed rack-shaped self-powered triboelectric sensor are summarized in Table 2. The output voltage signals were recorded and analyzed for vehicle speed and load estimation. Finite element simulations were performed using COMSOL Multiphysics 6.2 (COMSOL AB, Stockholm, Sweden). Data processing and plotting were performed using OriginPro 2021 (OriginLab Corporation, Northampton, MA,

USA). The upper-computer monitoring interface was developed using LabVIEW software (National Instruments, Austin, TX, USA) for real-time data display, storage, and analysis.

Table 2. Main components of the proposed rack-shaped self-powered triboelectric sensor.

Component	Material/Module	Function
Triboelectric layer	Silicone rubber	Generates triboelectric charges
Base structure	3D-printed PLA	Supports the rack-shaped structure
Electrode	Aluminum	Collects electrical signals
Elastic component	Spring	Provides restoring force
Environmental sensor	Temperature–humidity sensor	Records environmental parameters for compensation
Signal-processing circuit	Amplification/filtering/data acquisition module	Processes voltage signals
Wireless/monitoring module	MCU/wireless module/upper computer	Displays and transmits speed/load data

3. Results

Figure 1a shows a schematic diagram of the rack-shaped self-powered triboelectric sensor for vehicle speed and load monitoring. As shown in Figure 1b and Supporting Information Figure S1, the sensor consists of silicone rubber, a polylactic acid (PLA) base, aluminum electrodes, and springs. The silicone rubber serves as the triboelectric layer, while the PLA base provides mechanical support for the rack-shaped structure. The aluminum layer acts as the electrode, and the spring provides the restoring force for repeated contact–separation motion. When a vehicle passes over the sensor, the tire pressure drives the contact–separation process and generates electrical signals. These signals are then used for vehicle speed and load estimation. To improve outdoor adaptability, hydrophobic modification was applied to the silicone rubber surface. Figure 1c shows that the modified silicone rubber surface changes from hydrophilic to hydrophobic, with its contact angle increasing from 52° to 102° . The surface morphology of the modified silicone rubber is shown in Figure 1d. The micrometer-sized folded structure makes it highly hydrophobic, while its porous structure increases the contact area between the silicone rubber and the aluminum electrode, further enhancing the output performance of the sensor. The speed and load parameter signals obtained by the sensor can be wirelessly transmitted to an upper computer through a developed circuit module and displayed and stored in real-time by the online monitoring system (Figure 1e), ultimately achieving passive monitoring of vehicle speed and load.

The working mechanism of the triboelectric sensor is based on the combination of the contact electrification and electrostatic induction [31], converting mechanical signals into electrical signals. The contact electrification process can be described using the electron cloud potential well model [32], as shown in Figure 2a. Al and silicone rubber serve as the positive and negative materials, respectively. Before the silicone rubber contacts the Al, the potential well tightly confines the electrons in specific orbits, preventing them from escaping freely (Figure 2(aI)). When the silicone rubber approaches and contacts the Al, the energy barrier between them decreases, causing electrons to transfer from the Al to the silicone rubber (Figure 2(aII)). As the silicone rubber separates from the Al, the transferred electrons remain as static charges on the silicone rubber (Figure 2(aIII)). Consequently, the resulting potential difference drives electrons to flow from the Al to the ground, forming a periodic alternating current of positive and negative charges (Figure 2b,c). The working process of the triboelectric sensor was simulated using finite element simulation software. When the silicone rubber is subjected to pressure, it deforms, causing contact charges to be generated between the silicone rubber and the Al (Figure 2d). When the pressure is removed, the silicone rubber gradually separates from the Al, generating an induced potential (Figure 2e). The finite element simulation results indicate that the output voltage

of the designed triboelectric sensor is highly sensitive to the pressure applied to the silicone rubber (Figure 2f), further demonstrating the rationality of the sensor.

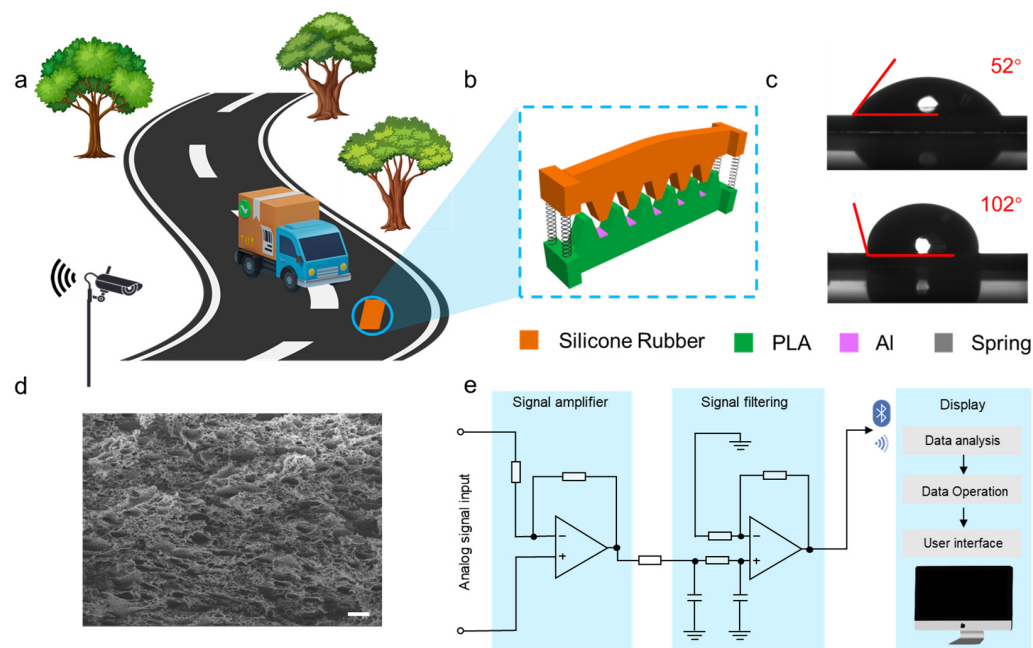


Figure 1. Design of a rack-shaped self-powered triboelectric sensor for monitoring vehicle speed and load. (a) Illustration of the triboelectric sensor for vehicle speed and load monitoring. (b) Schematic diagram of the rack-shaped triboelectric sensor. (c) Water contact angle measurement of ordinary and hydrophobic modified silicone rubber. (d) SEM surface morphology of silicone rubber. Scale bar, 20 μm . (e) A schematic diagram of the triboelectric sensor for real-time vehicle speed and load monitoring system.

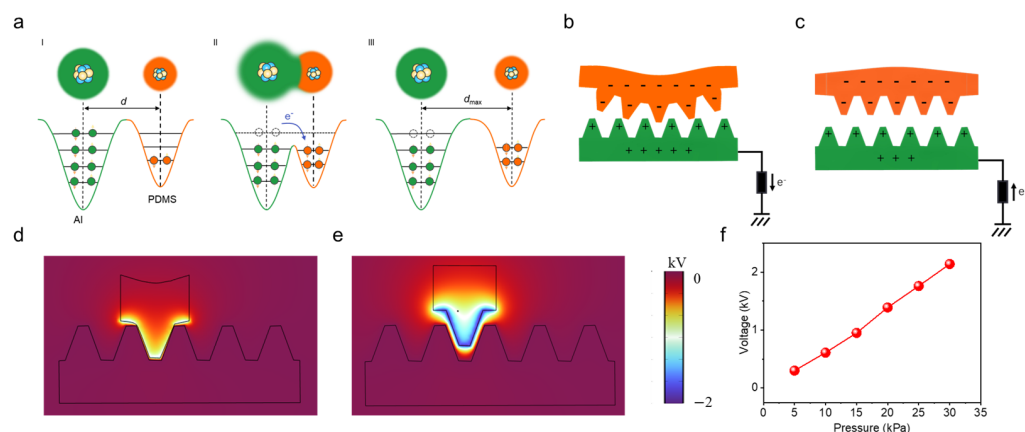


Figure 2. Working mechanism of the rack-shaped triboelectric sensor. (a) Electron-cloud-potential-well model between silicone rubber and Al: (I) before contact; (II) contact; (III) separation. (b,c) Working mechanism of the triboelectric sensor. (d,e) Simulated potential distribution at a pressure of 30 kPa. (f) Simulated output voltage with different pressure from 5 kPa to 30 kPa.

The mechanical–electrical output performance of the triboelectric sensor was systematically studied. First, the response to pressure of the sensor was experimentally verified, as shown in Figure 3a. When the pressure increased from 5 kPa to 30 kPa, the output voltage of the sensor rose from 34.1 V to 96.3 V. This is because greater pressure causes more significant deformation of the silicone rubber, enhancing the contact and separation with the Al. Additionally, higher pressure can cause a more substantial overlap of the electron clouds between the silicone rubber and Al, thereby inducing more charges. Similarly, as the

moving speed increases, the sensor's output voltage also shows an upward trend because higher frequencies can generate stronger charge flows (Figure 3b). The experimental results indicate that the triboelectric sensor has excellent linearity in response to both pressure and speed, which is beneficial for accurately monitoring vehicle speed and load. Figure 3c shows the impact of spring stiffness on the sensor's output performance, demonstrating that a spring stiffness of 10.69 yields the maximum output voltage. When the sensor is placed outdoors, environmental factors such as rain and temperature changes can affect its output performance. Experiments investigated the effects of humidity and temperature changes on the sensor's output performance, as shown in Figure 3d,e. Both increased humidity and temperature lead to a decrease in the sensor's output voltage. Increased humidity directly reduces the number of induced charges, while higher temperatures increase the energy of the induced charges, causing them to escape from the silicone rubber surface. Therefore, when used outdoors, compensation circuits must be employed to mitigate the interference of environmental factors like temperature and humidity on the sensor's measurement accuracy. Considering that the output performance of the triboelectric sensor is affected by ambient temperature and humidity, an environmental compensation algorithm was applied during the outdoor vehicle monitoring tests. A commercial low-power temperature and humidity sensor was integrated into the testing system to intermittently record the ambient temperature and relative humidity. The recorded environmental parameters were then used to correct the output voltage according to the fitted temperature–voltage and humidity–voltage calibration curves (Supporting Information Figures S2 and S3). The temperature-dependent compensation and humidity-dependent compensation equation is expressed as Equations (1) and (2):

$$\Delta V_C = 110.92 + a_1 C + a_2 C^2 \quad (1)$$

where C is the ambient temperature, $a_1 = -0.25$, and $a_2 = 6.97 \times 10^{-4}$.

$$\Delta V_H = 100.41 + b_1 H + b_2 H^2 \quad (2)$$

where H is the relative humidity, $b_1 = -1.49$, and $b_2 = 7.84 \times 10^{-3}$.

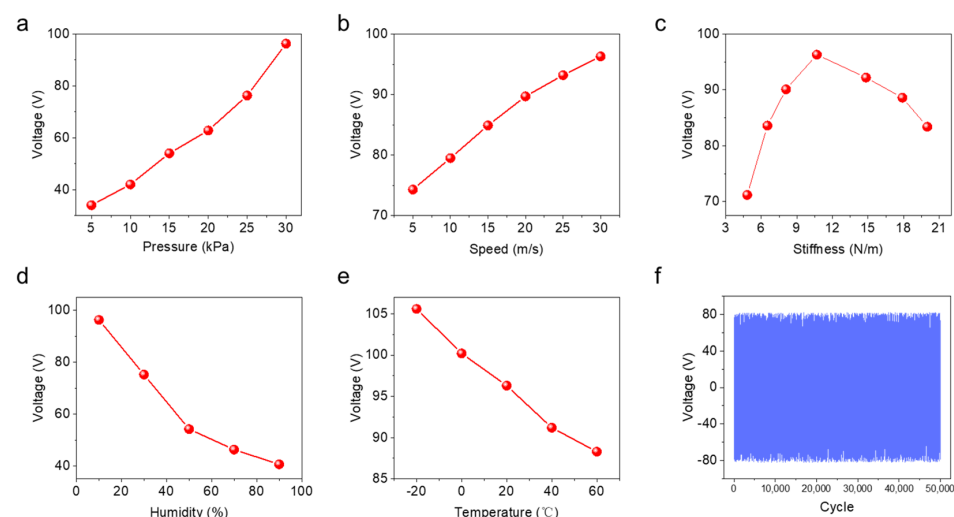


Figure 3. Electrical characterization of the triboelectric sensor. (a–e) Output voltage of the triboelectric sensor with different pressures, speeds, spring stiffness, humidity, and temperature. (f) Electrical output stability of the triboelectric sensor over 50,000 cycles.

The environmental compensation considering both temperature and relative humidity is given by Equations (1) and (2). Equation (1) describes the temperature-dependent

voltage correction, where C is the ambient temperature, and a_1 and a_2 are the first-order and second-order temperature-related fitting coefficients, respectively. Equation (2) describes the humidity-dependent voltage correction, where H is the relative humidity, and b_1 and b_2 are the first-order and second-order humidity-related fitting coefficients, respectively.

Based on these calibration equations, the measured voltage signals were corrected before being used for vehicle speed and load monitoring. This compensation strategy reduced the deviation caused by environmental fluctuations and improved the reliability of the outdoor monitoring results. To verify the effectiveness of the compensation strategy, the output voltages before and after compensation were compared under the same speed and load conditions. The compensated voltage values were much closer to the reference value, confirming that the compensation algorithm can effectively reduce the influence of high temperature and high humidity on the sensor output (Supporting Information Table S1).

To further evaluate the durability of the rack-shaped triboelectric sensor, the cycling stability test was extended to 50,000 repeated loading–unloading cycles. The output signal remained stable without obvious degradation, demonstrating the good mechanical and electrical stability of the sensor (Figure 3f, Supporting Information Figure S4). However, practical traffic-monitoring applications may involve millions of repeated tire loads during long-term service. Therefore, more rigorous durability evaluation under real road environments and high-load repeated impact conditions is still necessary. For practical deployment, the proposed sensor can be designed as a modular sensing unit. Under long-term operation, local degradation may occur due to repeated mechanical loading, surface wear, contamination, or environmental aging. If an individual sensing unit is damaged or its output signal significantly decreases, the degraded unit can be replaced independently without replacing the entire monitoring system. This modular replacement strategy is beneficial for reducing maintenance cost and improving the long-term feasibility of the sensor in traffic-monitoring applications. Future works need to focus on extended cycling tests under higher loading cycles and real road conditions to further clarify the operational lifespan and failure mechanisms of the sensor.

Traditional speed and pressure sensors based on TENG often struggle to simultaneously monitor speed and pressure parameters accurately. The fundamental reason is that the sensors are simultaneously affected by both factors, along with interference from external environmental parameters, making it difficult for the triboelectric sensors to accurately identify the excitation source. However, the developed triboelectric sensor in this work effectively addresses this issue. When a vehicle tire compresses the silicone rubber, the first rack of silicone rubber meshes with the PLA substrate and contacts the Al, generating an electrical signal. As the tire moves forward, the first rack of the silicone rubber gradually separates from the PLA while the second rack begins to mesh with the PLA (Figure 4a). Therefore, the vehicle's running speed V can be accurately calculated using Equation (3):

$$V = \Delta h / \Delta t \quad (3)$$

where Δh is the rack tooth spacing between adjacent sensing units, with a unit of meter (m); Δt is the time interval between successive tooth engagements, with a unit of second (s); and V is the calculated vehicle speed, with a unit of meter per second ($\text{m}\cdot\text{s}^{-1}$). This design allows for precise monitoring of both speed and pressure parameters, significantly improving the accuracy of the triboelectric sensor in complex environments. When the pressure is constant, increasing the driving speed will raise the output voltage of the triboelectric sensor (Figure 4b), but it does not affect the accuracy of the sensor in monitoring vehicle speed. By averaging the vehicle speed measurements, calculation errors can be further reduced, thereby improving the accuracy of speed parameter monitoring. Once the speed parameters are accurately obtained, the triboelectric sensor can more precisely monitor the vehicle's

pressure parameters. The speed can be determined by the time interval Δt , and then the vehicle's load can be accurately calculated based on the pressure–voltage characteristic curve at a specific speed (Figure 4c). To achieve complex parameter calculations and data transmission, an online monitoring system for measuring vehicle speed and load was developed (Figure 4d). This system can perform functions such as signal filtering, amplification, computation, transmission (Figure 4e). For practical deployment, the rack-shaped sensor can be embedded into a shallow groove or fixed onto the road surface using a supporting substrate. The sensing units should be arranged perpendicular to the driving direction to ensure sequential tire contact, allowing the vehicle speed to be calculated from the time interval between adjacent voltage peaks. Prior to measurement, calibration of the rack spacing, voltage–load relationship, and environmental compensation coefficients is required. Road surface irregularities may influence the tire–sensor contact state and cause output fluctuations; therefore, installation on relatively flat road sections or the use of a leveling/protective layer is recommended. Signal averaging and repeated peak detection can also be used to reduce random errors. The effectiveness of the online monitoring system was validated through outdoor experiments. To evaluate the reproducibility of the proposed traffic-monitoring system, 30 repeated outdoor tests were performed. The measured vehicle speed and load were analyzed statistically, and the results are presented as mean values with standard deviations. The measurement errors of both speed and load remained within 5%, indicating good repeatability and reliability under the tested conditions. (Figure 4f, Supporting Information Table S2). To evaluate the applicability of the proposed sensor under different vehicle conditions, an additional vehicle type was introduced in the outdoor test (Supporting Information Table S3). The results indicate that the vehicle type has a limited influence on speed measurement, since the speed is mainly calculated from the fixed rack spacing and the time interval between adjacent voltage peaks. For load estimation, although tire-related factors may affect the contact state, the small effective contact area of the rack-shaped sensor ensures full contact between the tire and the sensing unit within the tested range. In addition, considering the possible influence of vehicle center-of-gravity deviation, the signals generated by the front and rear tires were averaged to obtain a more reliable estimation of vehicle load.

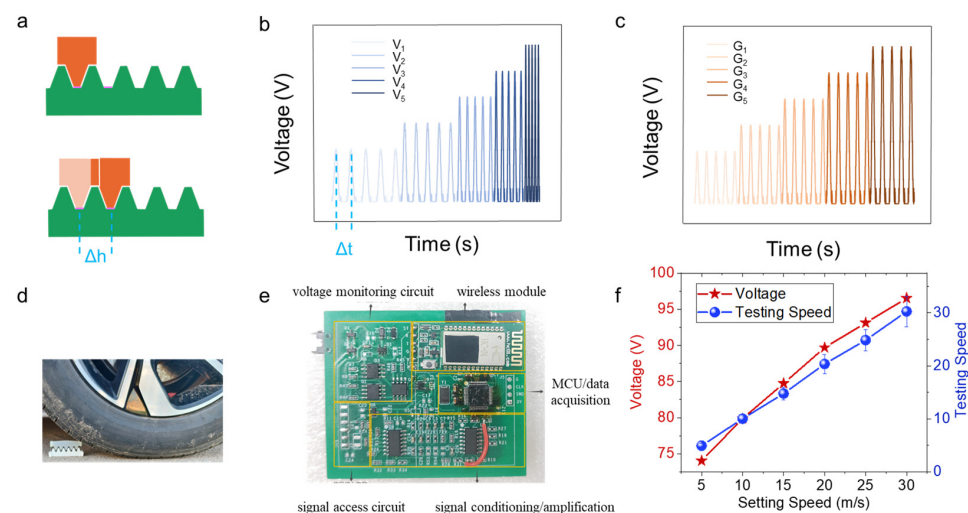


Figure 4. Design of a vehicle speed and load monitoring system. (a) Schematic diagram of precise monitoring of vehicle speed by the triboelectric sensor. (b) Output voltage wave form of the triboelectric sensor with five different speeds. (c) Output voltage wave form of the triboelectric sensor with five different pressures. (d) Outdoor experiment for vehicle speed and load monitoring. (e) Signal-processing circuit board with labeled functional modules. (f) Error statistics for speed testing.

In practical measurements, the vehicle speed was not determined from a single voltage peak pair. Instead, multiple adjacent voltage peaks were extracted from the filtered output waveform, and the vehicle speed was calculated by averaging the instantaneous speeds obtained from consecutive rack engagements:

$$V_i = \frac{\Delta h}{t_{i+1} - t_i} \quad (4)$$

$$\bar{V} = \frac{1}{N-1} \sum_{i=1}^{N-1} \frac{\Delta h}{t_{i+1} - t_i} \quad (5)$$

where t_i and t_{i+1} are the occurrence times of two adjacent voltage peaks, N is the number of detected peaks, and $\bar{V}$ is the averaged vehicle speed. Since the speed is determined by the fixed structural spacing and the peak-time interval, the speed estimation is mainly affected by the peak-timing accuracy rather than the voltage amplitude. Therefore, moderate voltage fluctuation caused by environmental noise or tire-contact variation has limited influence on speed estimation as long as adjacent peaks can be clearly identified.

After the vehicle speed was obtained, the load-related pressure was estimated from the calibrated voltage–pressure relationship under the corresponding speed condition. Before load estimation, the measured voltage was corrected using the temperature- and humidity-dependent compensation equations. The corrected voltage can be expressed as:

$$V_c = V_m - [F_T(C) - F_T(C_0)] - [F_H(H) - F_H(H_0)] \quad (6)$$

where V_m is the measured voltage, V_c is the compensated voltage, C and H are the measured ambient temperature and relative humidity, respectively, and C_0 and H_0 are the reference temperature and relative humidity. $F_T(C)$ and $F_H(H)$ represent the fitted temperature–voltage and humidity–voltage calibration functions, respectively. The vehicle load was then estimated from the calibrated relationship between compensated voltage and applied pressure. Compared with speed estimation, load estimation is more sensitive to voltage-amplitude fluctuation. Therefore, signal filtering, environmental compensation, repeated peak detection, and averaging of the front- and rear-tire signals were applied to improve the robustness of load estimation.

4. Discussion

At the current stage, the proposed system is most suitable for controlled road sections, highways with relatively flat pavement, parking lots, campus roads, industrial parks, and low-to-medium-speed traffic-monitoring scenarios where the vehicle trajectory can be guided to pass over the sensing area. Additional tests and analysis indicate that moderate tire offset and tire-pressure variation have limited influence on speed measurement, because the speed is mainly calculated from the fixed rack spacing and the time interval between adjacent voltage peaks. For load estimation, tire-related factors may affect the output amplitude, but the small effective contact area of the rack-shaped sensing unit helps ensure sufficient tire–sensor contact within the tested range.

Severe off-center tire passes, very wide tires, abnormal tire pressure, or highly uneven road surfaces may change the tire–sensor contact state and introduce output fluctuations. Therefore, installation on relatively flat road sections, the use of a leveling/protective layer, signal averaging, repeated peak detection, and sensor-array design can be adopted to improve measurement stability.

In terms of durability and maintenance, the cycling stability test was extended to 50,000 repeated loading–unloading cycles, and the output signal remained stable without obvious degradation. Nevertheless, practical traffic-monitoring applications may involve

much larger numbers of repeated tire loads during long-term service. Therefore, million-level accelerated durability tests and long-term field validation are still necessary in future work. Owing to its simple structure, low material cost, and convenient installation, the proposed sensor can be designed as a modular sensing unit, allowing locally degraded units to be replaced independently without replacing the entire monitoring system.

In terms of manufacturing scalability, the hydrophobic silicone rubber with microstructured surfaces was prepared through a solution-based gelation and silane modification process, which is simple, low-cost, and potentially scalable for batch preparation. Further optimization of fabrication uniformity, device packaging, installation reliability, and long-term road durability will be carried out in future work.

To further clarify the practical applicability and limitations of the proposed system, Table 3 summarizes the current status, remaining limitations, and future optimization directions from the perspectives of application scenarios, installation conditions, environmental adaptability, durability, non-ideal tire contact, and manufacturing scalability. Although the present results demonstrate the feasibility of the rack-shaped self-powered sensor for vehicle speed and load monitoring, further work is still required to improve long-term durability, installation reliability, large-area fabrication uniformity, and robustness under complex road conditions.

Table 3. Summary of practical applicability, limitations, and future optimization of the proposed system.

Aspect	Current Status	Limitation	Future Optimization
Practical applicability	Controlled roads; flat highways; parking lots; industrial parks	Guided tire trajectory required	Wider sensing modules; sensor arrays
Installation condition	Shallow-groove embedding; surface mounting	Uneven installation; contact fluctuation	Leveling/protective layer; standardized installation
Environmental adaptability	Temperature/humidity compensation	Long-term environmental drift	Aging tests; adaptive compensation
Durability	Stable output after cycling tests	Million-level validation needed	Accelerated durability tests; field tests
Non-ideal tire contact	Moderate offset/tire-pressure variation acceptable	Severe offset; wide tires; uneven roads	Peak detection; signal averaging; sensor arrays
Manufacturing scalability	Simple gelation and silane modification	Large-area uniformity; packaging reliability	Batch fabrication; packaging optimization; modular replacement

5. Conclusions

In summary, a low-cost rack-shaped triboelectric sensor was developed for simultaneous vehicle speed and load monitoring. The sensor exhibited good electrical output performance, generating an output voltage of 96.3 V under a pressure of 30 kPa and a speed of 30 m/s. Owing to the rack-shaped structural design, vehicle speed can be estimated from the fixed rack spacing and peak-time interval, while vehicle load can be obtained from the compensated voltage amplitude. The outdoor experiments demonstrated that the measurement errors of both speed and load were within 5%, indicating good feasibility for self-powered traffic monitoring.

In future work, the proposed system will be further optimized toward practical industrial applications, such as smart highways, logistics parks, industrial parks, overload-warning systems, and low-power IoT-based traffic-monitoring networks. From the scientific perspective, further studies will focus on million-level accelerated durability tests, long-term field validation, adaptive environmental compensation, sensor-array design for

complex tire trajectories, and improved packaging for harsh road environments. These efforts are expected to promote the practical deployment of self-powered triboelectric sensors in intelligent transportation systems.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/electronics15153304/s1>, Figure S1: Image of the rack-shaped self-powered triboelectric sensor. Scale bar, 1 cm; Figure S2: Fitted curve of the triboelectric sensor with various humidity; Figure S3: Fitted curve of the triboelectric sensor with various temperature; Figure S4: Electrical output stability of the triboelectric sensor over 50,000 cycles; Table S1: Comparison of output voltage before and after environmental compensation under the same speed and load; Table S2: Outdoor speed test results of vehicle 1; Table S3: Outdoor speed test results of vehicle 2.

Author Contributions: F.Z.: conceptualization, methodology, formal analysis, writing—original draft, writing—review & editing. S.C.: conceptualization, formal analysis, writing—original draft, writing—review & editing. Z.S.: conceptualization, methodology, formal analysis. R.Z.: conceptualization, funding acquisition, writing—review & editing, visualization, supervision. R.G.: writing—review & editing, supervision. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The key datasets supporting the main conclusions of this study, including environmental calibration data, vehicle speed/load monitoring data, repeated-test statistical data, and cycling-stability data, are provided in the Supporting Information. Additional raw data are available from the corresponding author upon reasonable request.

Conflicts of Interest: Author Fang Zheng was employed by the company Shanxi Jiaoke Highway Survey and Design Institute Co., Ltd. Author Zhuxing Shi was employed by the company Shanxi Provincial Transportation Planning Survey and Design Institute Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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