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A Comprehensive Review of On-Board Weighing Systems (OBWS) In Heavy Vehicles

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ABSTRACT

Onboard weighing systems (OBWS) offer several advantages over traditional (stationary) weigh stations and weigh-in-motion (WIM) systems and allow for real-time monitoring of heavy vehicle loads. OBWS do not require any external infrastructure and are embedded within the vehicles to measure loads continuously while the vehicle is moving. Most studies conducted in the review have focused on WIM technologies, but there are limited comprehensive studies on vehicle-mounted OBWS. This gap is addressed with a structured literature review and a comparative discussion of available OBWS technologies, sensor configurations, placement strategies and signal processing techniques. This review covers the most popular sensors, such as load cells, strain gauges, piezoelectric sensors, fibre Bragg gratings (FBG), and novel emerging sensors. The results indicate that load cells have high accuracy but are difficult to install and cost more to implement. Less expensive and more popular, strain gauges are sensitive to environmental conditions and to signal drift. Optical sensors, such as FBG, however, are more accurate and durable but more expensive for large-scale applications. Noise, drift and nonlinearity can be minimized using signal processing techniques, such as chopper stabilization, digital filtering, compensation techniques and machine learning, but at the cost of increased complexity and computation load. Future studies are recommended to focus on the integration of sensors in a simpler manner, optimization of sensor placement using finite element analysis and metaheuristic optimization algorithms, and integration of sensor with AI for better performance in terms of accuracy, reliability and operational efficiency in OBWS.

Keywords: Finite Element Analysis (FEA); load sensing; on-board weighing system (OBWS); optimization algorithm; signal processing; strain gauge

INTRODUCTION

Challenges in transport mobility have led to innovations to improve safety and efficiency in transportation (Akram Nawaz & Rajesh 2020). Accurate vehicle weight measurements are increasingly in demand due to factors such as safety, operations and regulatory requirements. Road infrastructure is damaged by overloaded vehicles, as well as reduced vehicle lifespan and increase accident rates. This effect is worse in countries with weaker infrastructure such as Indonesia, where over 60% of trucks exceed the legal load limit, compared to 2.15% in Malaysia, which indirectly has a negative impact on road safety and infrastructure. (Agape et al. 2019; Ryguła et al. 2020).

Technologies such as Weight-in-Motion (WIM) have had a significant impact on vehicle weight monitoring because they can measure the gross and axle weights of vehicles while they are in motion, eliminating the need to stop at weigh stations (Prakoso et al. 2022a). This technology is widely used for applications such as traffic data collection, weight regulation enforcement, pavement design and overload protection. These systems utilize sensors embedded directly in the road such as piezoelectric,

flexure plate and load cell sensors and operate in real time to detect dynamic wheel loads, process the data and calculate accurate weight values (Stawska et al. 2021). These systems enable traffic monitoring and enforcement. However, they cannot perform onboard measurements. On the other hand, weighing stations create operational constraints as trucks are required to stop for inspection at these stations.

Due to the above constraints, on-board weighing systems (OBWS) have been designed and optimized for real-time weight monitoring (Hoogvelt 2004; Fernando 2006; Pan 2016; Patel & Khatod 2020; Srinivasan et al. 2019). The OBWS employs the direct attachment of weight sensors such as load cells, strain gauges and piezoelectric sensors to the vehicle, enabling continuous weight measurements. These systems improve efficiency by reducing downtime, optimizing payloads and ensuring regulatory compliance. Developments in technologies such as sensors, data analytics and wireless communications have led to the advancement of OBWS, making them essential in the logistics, mining and construction industries (Patel & Khatod, 2020).

To the best of our knowledge, a comprehensive review of On-Board Weighing Systems (OBWS) for heavy vehicles has not been conducted. Existing studies (Bistak et al. 2017; Rocheti et al. 2024) have extensively examined infrastructure-based Weigh-In-Motion (WIM) systems, focusing on sensor technologies and calibration standards (e.g., ASTM E1318-09) (Al-Qadi et al. 2016; Prakoso et al. 2022), These studies mainly address stationary installations and ignore the specific challenges of vehicle-mounted solutions. To fill this gap, our study systematically analyzes OBWS, where sensors such as load cells, strain gauges and piezoelectric are integrated into vehicles to monitor real-time weight using suitable signal processing methods. OBWS faces unique challenges that differ from those of WIM: (i) real-time calibration without relying on static weighing stations, (ii) dynamic compensation for vehicle-specific factors (e.g., suspension movement, tire pressure variations), and (iii) operation in unpredictable environments (e.g., uneven terrain, temperature fluctuations).

Although previous studies have demonstrated the feasibility of OBWS using different sensing approaches, there is still limited consensus regarding the optimal trade-off between sensor accuracy, installation complexity, environmental robustness, and long-term stability. Existing studies often evaluate individual sensing technologies under different operating conditions, making direct performance comparisons difficult. Furthermore, most studies focus on hardware implementation, whereas comparatively fewer studies critically examine the interaction between sensor placement, structural dynamics, and signal processing strategies. As a result, important design considerations for practical large-scale deployment remain insufficiently addressed.

The current reviews primarily address the development of infrastructure-based WIM systems, and do not cover vehicle-mounted systems. This review will address this by discussing the types of OBWS sensors, installation techniques and signal processing methods. This paper is organized as follows: Section 2 presents a description of a typical OBWS, Section 3 reviews the previous applications, Section 4 discusses the trade-offs between the sensors and signal processing methods, and Section 5 presents the future directions and conclusions.

COMPONENTS OF OBWS

An on-board weighing system (OBWS) is a technology that measures the vehicle load in real time under static or dynamic conditions. OBWS combines mechanical, electronic and computational functions, thus removing the need for external weighing stations and allowing direct monitoring during operation. This capability not only contributes to weight adherence but also plays a role in safer driving conditions and effective fleet management. The next few subsections detail the structure and components of the OBWS, beginning with an overview diagram of the system.

OVERVIEW OF OBWS ARCHITECTURE

Real-time truck load measurement is accomplished using an OBWS, as shown in Figure 1. This system consists of several important parts which will measure, process and present weight data:

1. Truck:The OBWS is directly mounted onto the truck, and sensors are mounted on parts of the truck such as the axle, suspension or the chassis. Sensors are used to measure the strain or force variations that occur when a load is applied.
2. Sensors: Loads are measured by various types of sensors such as load cells, strain gauges, piezoelectric and capacitive sensors. These sensors translate mechanical stress into analog electrical signals in proportion to the load on the truck.

3. Signal Conditioning Unit (SCU): The signals from the sensor are weak and noisy, so the SCU plays a vital role in amplifying and filtering these raw signals. It also digitizes the data for easier processing.
4. Signal Processing Unit (SPU): Embedded algorithms, artificial intelligence (AI) techniques and calibration data are used in the SPU, which is usually a microcontroller (MCU), to process digitized signals. It determines the weight and performs system functions based on the real-time data inputs.
5. Data Visualization: The processed data are then presented to the driver or operator on an LCD screen in easily understood terms (such as kilograms or tons) so that they can check the truck loading at any given time.

All components play a critical role in the accuracy of the measurements, speed of the system, and real-time monitoring. This system can ensure the load is not overloaded, conforms to weight limits, and acts as a measure to promote load distribution and fleet efficiency.

LITERATURE REVIEW

INTEGRATION OF LOAD CELLS IN OBWS

Various OBWS have been developed over the past decade based on the framework shown in Figure 1. These OBWSs were developed using different sensors and signal processing technologies. Patel & Khatod (2020) implemented strain-gauge-based shear beam load cells beneath a trailer platform (Figure 2). The signals were amplified, digitized, and processed using an embedded processor to obtain readable weight measurements. Moisture sealing and corrosion-resistant electroplating improved durability and enabled reliable operation under varying environmental conditions.

Pletts (2009) installed load cells on sugarcane transport vehicles to measure the gross vehicle weight and payload of sugarcane during transport. Both bending and shear beam designs were analyzed to ensure high precision in the weight measurement. In addition, pneumatic pressure transducers were incorporated to monitor the air suspension pressure, with the fused sensor readings enhancing overall measurement accuracy.

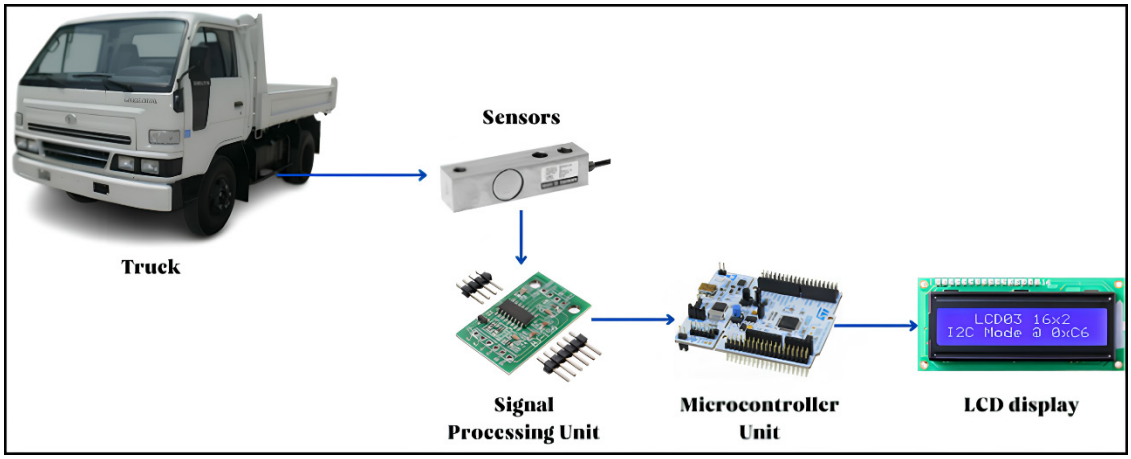


FIGURE 1. General architecture of an on-board weighing system (OBWS)

Safdar (2015) weighed municipal solid waste on vehicle collection using a custom load cell system designed with durability, waterproofing, and shock-absorbing features to withstand harsh operating conditions. The load cells were installed between the vehicle's chassis and suspension springs, connected to a compression spring and a voltage conversion unit that transformed resistance changes into voltage signals. These signals were sent to an Automatic Vehicle Location (AVL) system, which combined the weight data with GPS-based position and speed information before transmitting it wirelessly to a central server. The integrated system enabled real-time monitoring of the vehicle load and location. Real-time data transmission and tracking can be achieved by integrating weight sensor systems with Internet of Things (IoT) and navigation technologies.

Srinivasan et al. (2019) developed a six-cell shielded load cell system mounted at the base of a container to measure the cargo weight. The load cell outputs were processed by an Arduino microcontroller, which not only converted the signals into readable weight values but also transmitted the data in real time via cloud-based IoT platforms. The system also supports real-time weight monitoring and location tracking during transport (Srinivasan et al. 2019).

The authors (Singh & Srivastava 2022) utilized encapsulated load cells to improve the OBWS precision and system durability under intense conditions. As part of the design, the load cells were positioned underneath the truck axles to measure the loads applied, which were then amplified by the HX711 24-bit ADC before being converted into digital data. The Arduino UNO processed the HX711 output and triggered overload protection when an excessive load was detected (Singh & Srivastava 2022).

In another work, Maniar (2019) demonstrated a high-performance OBWS for heavy-goods vehicles, using load cells strategically installed at the axles to capture the dynamic load distribution and total vehicle weight. The system employed an automotive-grade ADS1261-Q1 24-bit delta-sigma ADC (see Figure 3), integrated into each load cell module, to ensure high-resolution and stable processing under harsh environmental conditions. A low-noise programmable gain amplifier (PGA) amplified the small millivolt-level bridge outputs from the load cells, using chopper stabilization to minimize the offset voltage drift over time and temperature. The implementation also featured precision external filtering to suppress high-frequency interference and careful component matching to prevent common-mode noise from converting into differential errors.

Notably, Maniar (Maniar 2019) employed two distinct methods to mitigate offset drift: (1) the PGA's chop mode, which continuously modulates and cancels the residual offset within the ADC signal chain, and (2) the ADS1261-Q1's AC bridge excitation, which alternates the bridge polarity between measurements to calibrate and remove system-level offset errors from the resistive bridge. These techniques improve the long-term measurement stability for direct weight enforcement applications.

Table 1 provides key findings on representative load-cell-based OBWS. OBWS utilizing load cells consistently demonstrates superior measurement linearity and long-term stability as it relies on direct force measurement rather than indirect structural deformation. However, the reviewed studies reveal a trade-off between the measurement performance and practical implementation complexity. Customed fitting is required to attach load cells to heavy vehicles structures to obtain direct force measurements from trailer platforms or chassis.

Systems employing high-end ADCs such as ADS1261-Q1 achieved better drift suppression and higher resolution than lower-cost HX711, but at the expense of increased power consumption, circuit complexity, and implementation cost. Similarly, axle-mounted configurations generally produce more stable measurements than suspension-mounted systems because they are less sensitive to transient suspension dynamics, although installation and maintenance become more difficult. Studies integrating multiple sensing modalities, such as load cells with pneumatic pressure transducers, further improved measurement accuracy under dynamic conditions, indicating that hybrid sensing approaches may be more suitable for real-world heavy vehicle environments than single-sensor systems alone.

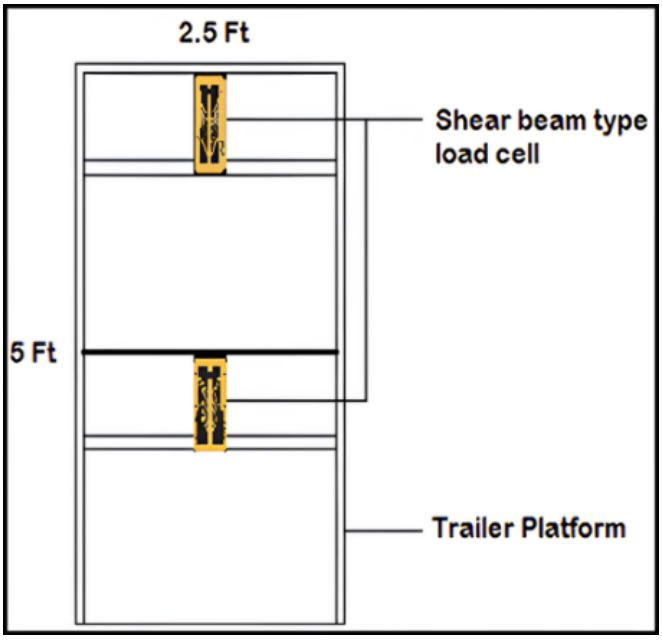


FIGURE 2. Installation of shear beam load cells beneath a trailer platform for real-time load measurement (Patel & Khatod 2020).

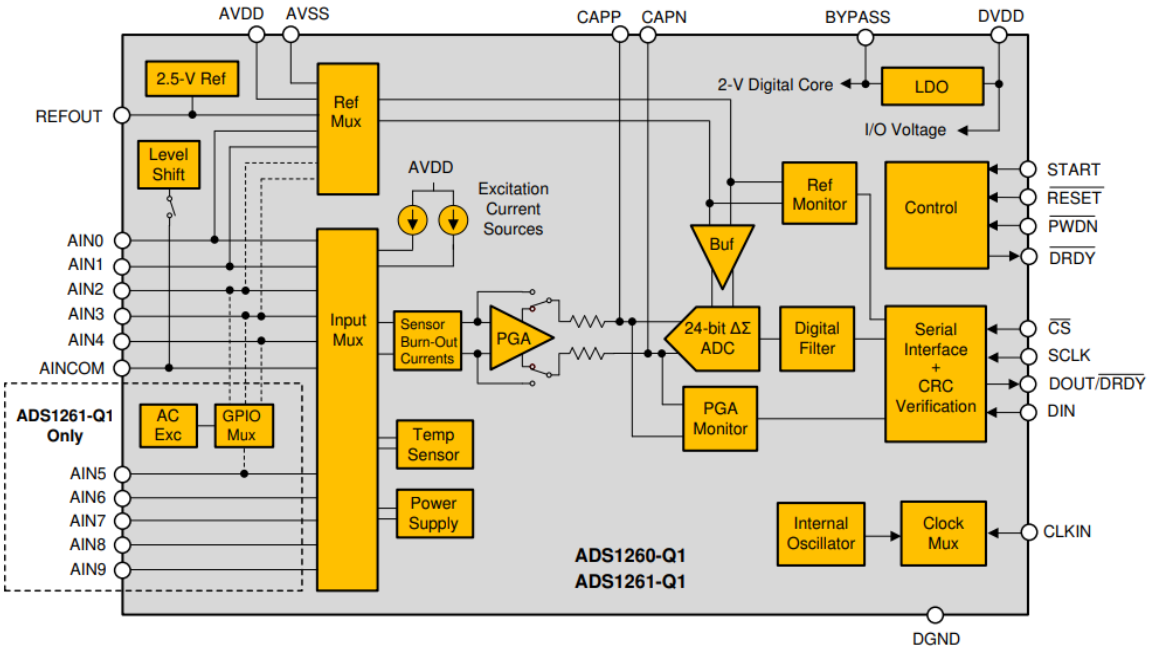


FIGURE 3. Internal architecture of the ADS1260-Q1/ADS1261-Q1 ADC used in OBWS applications (Maniar 2019).

TABLE 1. Comparative summary of load cell-based OBWS studies

Author	Installation Method	Key Findings
(Safdar 2015)	Between vehicle chassis and suspension springs	Overload prevention using pre-calibrated thresholds with ± 1.2% error margin
(Patel & Khatod, 2020), (Srinivasan et al. 2019)	Under trailer platform, bottom of container	High sensitivity under dynamic conditions (accuracy/error margin of ±1.5%), real-time weight and location tracking with ±2% error (Srinivasan et al. 2019). Introduced method to prevent moisture and corrosion (Patel & Khatod 2020).
(Maniar, 2019), (Singh & Srivastava, 2022a)	Vehicle axles	High-resolution (18-bit), noise-free performance; offset drift mitigated via chop mode and AC excitation for long-term stability (Maniar, 2019). Real-time remote monitoring capabilities using IoT; initiated engine locking upon overload detection (Singh & Srivastava 2022a)
(Pletts 2009)	Air suspension	Enhanced durability with waterproofing; fused reading enhanced overall measurement accuracy.

INTEGRATION OF STRAIN GAUGE IN OBWS

Besides load cells, strain gauges are widely used in OBWS to measure the deformation caused by mechanical stress. These sensors detect strain by measuring changes in electrical resistance as materials stretch or compress. They offer durability and good accuracy (1–2% error) in both static and dynamic applications (Todts et al. 2013). When a truck structure experiences strain under a load, the strain gauges detect proportional resistance changes (Tokyo Measuring Instruments Laboratory Co, 2023). Fernando et al. (2006) developed a dynamic load measurement system using shear strain gauges in a full-bridge Wheatstone circuit to enhance sensitivity and accuracy. The gauges were mounted between the suspension and tires, and their outputs were processed through a signal conditioner to amplify and filter the data (Fernando et al. 2006). A 16-bit data acquisition module sampled the signals at 4 kHz, ensuring high-resolution capture of dynamic loads. Thermocouples were integrated to monitor temperature variations, compensating for potential self-heating effects (Fernando et al. 2006).

Rahimov et al. (2023) developed a strain-gauge-based measurement system to determine the vertical and lateral forces acting on a subway car bogie frame during operation. Strain gauges were installed at the critical load-bearing

sections of the side beam and crossbeam locations identified through finite element analysis (FEA) as having the highest stress concentrations under simulated service loads (refer to locations A, B, C, and D on Figure 4) (Rahimov et al. 2023). Rather than being intended for direct weight measurement, the system was designed to monitor the dynamic interaction forces between the bogie and the track, providing real-time data for evaluating bogie structural performance and detecting abnormal load patterns. The system enabled real-time monitoring of bogie interaction forces for structural assessment under operational conditions (Rahimov et al. 2023).

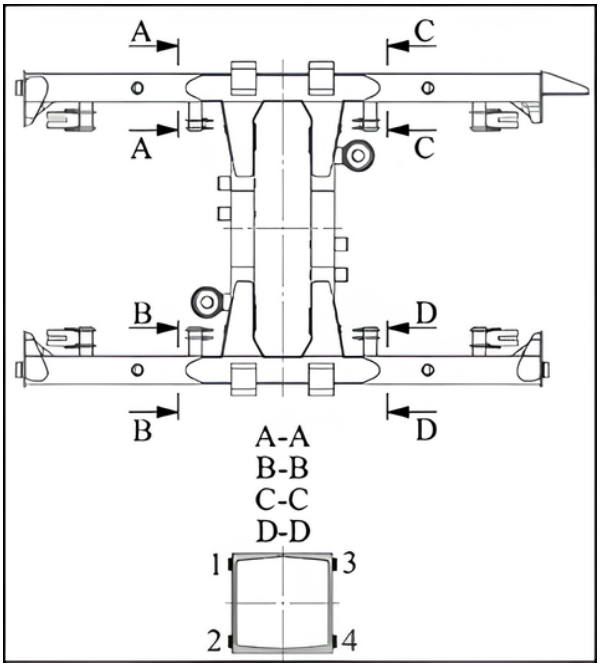


FIGURE 4. Finite element-analysis-based placement of strain gauges on the bogie frame (Rahimov et al. 2023).

Nieminen et al. (2023) employed strain gauges on the bogie frame of a railway vehicle to estimate individual wheel loads. Strain gauges were installed at FEA-identified high-stress regions on the bogie frame and calibrated using a hydraulic test rig to improve wheel-load estimation accuracy. This calibration process reduced measurement bias and compensated for installation-related variations, thereby improving the accuracy of wheel load estimation for subsequent fatigue analysis and structural inspection (Nieminen et al. 2023).

El Makkaoui et al. (2022) developed an IoT-based axle load monitoring system by bonding monoaxial strain gauges (Kimax WA series, 350Ω, constantan alloy) longitudinally onto parabolic leaf springs to measure deflection underloading. The millivolt-level signals were conditioned using a Kimax 2 data logger for calibration, with a gain of 0.0034 mA/kg, and processed by a custom Arduino board equipped with WiFi. The system achieved an accuracy of ±1.3 kg under static tests, whereas dynamic conditions (e.g., road inclination) introduced errors up to 2 kg. The system enabled real-time axle-load monitoring through wireless IoT-based data transmission (El Makkaoui et al. 2022). Y. Zhang et al. (2021) designed a truck-mounted scale system that used strain gauges installed on the truck's frame rails to detect strain changes caused by loading. The strain signals were amplified and digitized using an HX711 ADC before processing by an STM32F103 microcontroller for overload detection. The system was powered by an AMS1117 voltage regulator, providing stable 3.3 V and 5 V outputs. All measurement results were displayed in real time on a cabin-mounted display, with an alarm triggered in cases of overloading, load imbalance, or cargo displacement.

Pan et al. (2016) developed a dynamic truck overload monitoring system that utilized strain gauges on the leaf springs to measure deflection underloading. The system combined Beidou satellite positioning data with measurements from an MPU6050 attitude sensor to determine the vehicle's slope, allowing the correction of the load calculation for improved accuracy on inclined roads or uneven terrain. This slope compensation is important because vehicle inclination can cause load readings to deviate from the true weight. The STM32F103 microcontroller was interfaced with a CAN communication module to ensure a reliable data transfer. High-performance ADCs, namely ADS1256 and ADS1260-Q1/ADS1261-Q1, were used with AC bridge excitation, global chopping, and a low-noise design to minimize drifting and enhance weight measurement stability (Pan et al. 2016).

Thanigaivelan et al. (2015) developed an OBWS by bonding four strain gauges to the chassis of a static truck. Two strain gauges were attached to the chassis near the front wheels, and another two near the rear wheels, to measure the deflection under load. The PIC16F870 processed the signals and displayed the weight on an LCD. The system achieved improved accuracy (±1% full-scale) compared to traditional weighbridge measurements, as validated by experimental calibration using Macaulay's method to map the chassis deflection to the weight values (Thanigaivelan et al. 2015).

Tosoongnoen et al. (2017) proposed a strategic Wheatstone bridge configuration to improve the strain measurement accuracy for truck chassis monitoring by detecting resistance changes in strain gauges. Their method emphasized the importance of calibrating strain gauges through compression testing before deploying them in a full-bridge Wheatstone circuit, which enhances the measurement precision (Tosoongnoen et al. 2017). Zod et al. (2022) developed an OBWS in which four strain gauges were bonded to different points on the truck chassis to

measure the deflection underloading. The processed signals were calibrated to estimate the vehicle load and display the results in real time. The system's accuracy was achieved through the integration of correctly configured hardware (strain gauges, Wheatstone bridge, amplification, and ADC) with tailored software for calibration and weight computation (Zod et al. 2022).

The calibration vehicle described by (Hoogvelt 2004) verifies the Multiple Sensor Weigh-In-Motion (MSWIM) system, which enforces axle load regulations by measuring dynamic wheel loads. Strain gauges on the semi-trailer's first axle record wheel loads, while accelerometers correct for the inertia effects from the wheel-hub assembly. A GPS time generator (Datum ET6000) synchronizes data acquisition (National Instruments PXI-1010/LabVIEW) with the MSWIM system (Hoogvelt 2004). Static calibration uses hydraulic actuators with load cells, and dynamic tests employ sinusoidal excitations to validate accuracy. The INA2126 amplifier ensures precise conditioning of the strain gauge signals. The system achieves >95% accuracy for wheel loads of 25–75 kN, meeting regulatory standards.

Yang et al. (2008) developed an OBWS for heavy vehicles using strain gauges bonded to leaf springs in the truck suspension. The conditioned strain signals were processed using a neural-network-based approach to compensate for nonlinearities caused by hysteresis and payload distribution (Yang et al. 2008). A feedforward-backpropagation neural network was trained using experimental data (truck tires and car as payloads) to address the nonlinearities caused by leaf spring hysteresis and payload distribution, reducing the average error to 8%. The system demonstrated viability, but wind-induced vibrations disrupted signal stability, highlighting the need for further improvements (Yang et al. 2008).

In another work, Kheiralla & Eltigani (2014) developed strain gauge-based load pins for industrial wheel loaders, achieving measurement accuracies of ±0.7% (static) and ±1% (dynamic) under calibrated conditions. These pins replaced the existing mechanical hinge pins connecting the wheel loader's arms to its bucket, which lacked load-sensing capabilities. By integrating Kyowa KFG-10-120-C1-11 strain gauges into a full Wheatstone bridge configuration, the load pins converted the mechanical strain from bucket forces (up to 2,000 kg) into electrical signals while maintaining structural functionality (Kheiralla & Eltigani, 2014). The system provided environmental protection using SG280 epoxy coating to shield gauges from moisture, dust, and mechanical abrasion in harsh mining environments. A Campbell Scientific CR1000 data logger processed analog inputs (0–5 V) from the pins, enabling real-time payload monitoring with a linear correlation of $R^2 = 0.996$ between applied and measured loads (Kheiralla & Eltigani 2014).

The study by (Sirovatka et al. 2020) implemented an on-board weight control system in a mixer-distributor using strain gauges mounted between the trailer chassis and mixer frame to measure load-induced deformations. To address dosing inaccuracies (ranging from 2.57% to 29.8% error), the author proposed augmenting the system with loader boom sensors (Sirovatka et al. 2020). These sensors, integrated into the hydraulic system, convert hydraulic pressure data into real-time weight measurements, enabling faster operator response and reducing errors, particularly for smaller material batches (Sirovatka et al. 2020). On another note, the placement of strain gauges by (Chang et al. 2006) on truck axles enabled vertical wheel-load monitoring through the measurement of shear strain. This wheel deflection monitoring system also employed capacitance displacement sensors, while half-bridge strain gauges installed on the left axle side measured axle shear strain. Real-time data logging was implemented using a 16-bit ADC interfaced to a desktop computer to display wheel-load (Chang et al. 2006).

Sessions Hill (2012) developed a hybrid sensing system for the Prowler ATV, combining strain gauges mounted on suspension A-arms with deflection potentiometers installed parallel to coil-spring assemblies. The strain gauges, configured in Wheatstone bridge circuits and amplified using an INA2126 instrumentation amplifier (gain: 233–805), measured the lateral and vertical forces by detecting A-arm deformations, while the linear potentiometers (Celesco MLP-125) directly tracked the suspension displacement to calculate vertical forces via spring stiffness (65,000 N/m). The hybrid sensing approach improved multi-axis force estimation and suspension load validation under off-road conditions. The strain gauges resolved multi-axis forces while deflection data validated vertical load distribution, mitigating unmodeled effects due to chamber thrust, critical for off-road terrain adaptability (Sessions Hill 2012).

Jakukore et al. (2017) developed a go-kart frame monitoring system using wire-type strain gauges mounted at three critical locations: two on the main longitudinal chassis beams (locations 1 and 2) and one at the high-stress rear axle junction (location 3). A strain indicator connected to a quarter-bridge circuit provided real-time structural deformation measurements, with experimental results confirming the frame's safety under a 130 kg static load (maximum stress: 17 N/mm², well below the yield strength of mild steel) (Jakukore et al. 2017).

Gücüyener (2018) demonstrated a weight detection system for school buses using strain gauge sensors embedded in passenger seats. The sensors were strategically positioned based on a pressure map, a spatial representation

of force distribution, to maximize sensitivity to a seated child's weight. This design ensured reliable detection even with small occupants (e.g., children as light as 20 kg) by aligning sensors with high-pressure zones (Gücüyener 2018). The analog signals from the strain gauges were processed by an STM32F105 microcontroller. The system's primary purpose was to enhance safety in school transport services (i.e., school buses) by triggering alarms if a child was left unattended or unbuckled, addressing critical risks such as children being forgotten in vehicles (Gücüyener 2018).

Leppänen et al. (2020) employed strain gauges in a weight measurement system for timber trucks. The system utilized a Kyowa signal amplifier and an NI CompactDAQ microcontroller to process signals from strain gauges installed at critical locations identified through Finite Element Analysis (FEA), including U-bolts, transverse beams, and axle brackets. The NI CompactDAQ LabVIEW user interface provided real-time weight measurements by applying dynamic "compensation codes". These codes were designed to account for sensor nonlinearities caused by vehicle motion and road-induced vibrations, ensuring accurate measurements despite dynamic conditions.

Table 2 presents the key findings from the literature reviewed in this section. These studies demonstrate how these technologies improve accuracy, durability, and real-time monitoring in OBWS.

TABLE 2. Comparative summary of strain-gauge-based OBWS studies

Author	Installation Method	Key Findings
(Thanigaivelan et al. 2007), (Tosoongnoen et al. 2017), and (Zod et al. 2022), (Y. Zhang et al. 2021a), (Jakukore et al. 2017), (Sirovatka et al. 2020)	Truck chassis at maximum deflection points	The authors attached strain gauges to truck chassis at maximum deflection point achieving accuracy better accuracy compared to traditional weighbridge measurements. The authors implemented calibration on the signals using compression and Macaulay's method Thanigaivelan et al. (2007
(Rahimov et al. 2023) and (Nieminen et al. 2023), (Leppänen et al. 2020)	Cross beam, bogie frame, U-bolts, transverse beams, and axle brackets	Strain gauges were placed at high stress region such as crossbeam, bogie frame, U-bolts, transverse beams and axle brackets identified using FEA
(Kheiralla & Eltigani 2014), (Chang et al. 2006)	Mechanical hinge pin, axle and wheel	Strain gauge-based load pins for industrial wheel loaders were developed to replace mechanical hinge pin (Kheiralla & Eltigani, 2014); wheel deflection detected by a capacitance displacement sensor was integrated with axle strain to estimate wheel load (Chang et al. 2006).
(Yang et al. 2008),(Pan et al. 2016), (El Makkaoui et al. 2022)	Leaf spring	Strain gauges were placed on the leaf spring to harvest strain under loading. Compensation for vehicle inclination with Beidou/MPU6050 for improved accuracy on inclined roads in (Pan et al. 2016). Neural network was employed to address nonlinearities (hysteresis, distribution) in (Yang et al. 2008)
(Fernando et al. 2006), (Sessions Hill, 2012)	Between suspension and tires, suspension A-arms	Improved sensitivity in dynamic load monitoring with ±1.5% error margin (Fernando et al. 2006). Adopted hybrid sensing approach through advanced signal processing and compensation to estimate multi-axis forces.

Compared with load-cell-based systems, strain-gauge-based OBWS offer significantly greater installation flexibility because sensors can be bonded directly onto existing vehicle structures such as leaf springs, bogie frames, chassis members, and axles. However, the reviewed studies demonstrate that measurement performance is highly dependent on sensor placement strategy and compensation techniques. Studies employing finite element analysis (FEA) generally achieved better stability and repeatability because sensor locations were selected based on stress concentration behavior rather than empirical placement alone. Furthermore, systems combining strain gauges with compensation methods such as neural networks, temperature correction, inclination compensation, and digital filtering achieved substantially lower measurement error under dynamic operating conditions. Despite these improvements, strain gauges remain vulnerable to hysteresis, vibration-induced noise, and environmental drift, particularly during long-term outdoor operations. This suggests that strain-gauge-based OBWS require more sophisticated calibration and signal processing strategies than load-cell-based systems to maintain comparable accuracy. Nevertheless, their lower cost and easier structural integration continue to make them attractive for large-scale commercial deployment.

OBWS BASED ON OTHER SENSING TECHNOLOGIES

Researchers investigated other weight-sensing technologies beyond strain gauges and load cells, which include Fiber Bragg grating (FBG) (Hsieh et al. 2014), fiber optic (Luna Innovations Incorporated, 2019), angular displacement sensor (M. K. Seo 2021), piezoelectric sensor (Radoicic et al. 2016) and air pressure transducers (Todts et al. 2013). Hsieh et al. (2014) demonstrated that fiber Bragg grating (FBG) sensors embedded in composite leaf springs provided high-precision strain measurements with environmental resilience, using corrugated long-period fiber grating (CLPFG) filters, optical components that selectively attenuate wavelengths to isolate strain-induced Bragg wavelength shifts, analyzed via an optical spectrum analyzer (OSA). The system enabled dynamic vehicle load monitoring through temperature compensation (using a secondary FBG sensor) and real-time signal processing validated by static and thermal experiments (Hsieh et al. 2014).

Luna Innovations Incorporated (2019) developed fiber optic sensing for real-time monitoring of strain on vehicle control arms, which are the load-bearing suspension components that connect wheels to chassis. Two 5-meter sensors were precision-bonded along the inner curvature surfaces of each control arm and support beam to measure dynamic strain patterns during operation. The system employed Luna's ODISI 6000 interrogators to process wavelength shifts in the optical signal, achieving a 50με resolution with complete signal integrity even under severe -14g vibration loads.

Angular displacement sensors developed by M. K. Seo (2021) directly measured leaf spring deflection to determine vehicle weight. An ARM Cortex M4 microprocessor executed signal processing and calibration tasks to convert angular measurements into weight values (M. K. Seo 2021). Radoicic et al. (2016) investigated piezoelectric sensors in OBWS using HBM CLP/62 kN force washers mounted between suspension components and drive bridges. When mechanical forces deform the piezoelectric quartz elements, they generate a high-impedance charge output (unit: pC/N) proportional to the applied force. This charge signal was converted to a low-impedance voltage (0-10V range) by the HBM CMD-600P digital charge amplifier, which also performed signal filtering and was subsequently scaled linearly to weight values (kN) by a CatmanAP data acquisition system (Radoicic et al. 2016).

In another example, (Technoton 2020) developed axle load sensors using magnetoresistive and tensoresistive transducers to measure axle displacement and air suspension pressure, respectively. The sensor outputs were processed by ARM Cortex-M3 microcontroller. This approach enabled real-time axle load estimation with acceptable measurement accuracy for vehicle telematics applications. The microcontroller's performance handled input voltages ranging from 0.25–3.80 V with an error margin of ±2.5% or less, as specified by the industry standards for vehicle telematics (Technoton 2020).

A truck load measurement system developed by (Liu et al. 2018) uses load sensors installed above the gearbox on the central axis to monitor leaf spring deformations. These sensors convert positional changes of the leaf springs into voltage signals, which are then calibrated against actual load values. The system employs Bayesian filtering and iterative averaging to refine data accuracy, enabling precise detection of loading and unloading activities. This method achieves relative errors below 13.33% while reducing costs, making it viable for large-scale truck-load monitoring.

On another note, an air pressure transducer (APT) has been explored as a cost-effective alternative for weight estimation (Todts et al. 2013). The author proposed the integration of air pressure transducers (APT), load cells, and strain gauge sensors for on-board weighing systems (OBWS). APT sensors estimate axle loads from suspension air pressure, while load cells and strain gauge sensors measure structural deformation caused by vehicle loading. The sensor outputs were processed to estimate the gross vehicle weight (GVW) and axle load distribution.

Table 3 lists the key characteristics and findings of these alternative sensor technologies in the context of their application in OBWS. Overall, it was found that FBG and fiber optic sensors were more robust to electromagnetic interference, environmental degradation and mechanical fatigue than traditional electrical sensors. These properties make them especially suitable for long-term structural monitoring in extreme operating environments. However, they require sophisticated optical interrogation systems and more complex calculations, making them more expensive and less likely to be widely used in commercial applications. Piezoelectric sensors have a good dynamic response capability, and are very good for monitoring transients, however, their long-term stability with continuous heavy-duty operation has not been sufficiently investigated. Likewise, the angular displacement and air-pressure based methods provide simpler installations at the expense of precision. The literature reviewed in this study indicates that other sensing technologies would be technically viable but still have their trade-offs between accuracy, robustness, and cost.

TABLE 3. Comparative summary of other sensor-based OBWS studies

Author	Sensor	Installation Method	Key Findings
(Hsieh et al. 2014)	FBG (Fiber Bragg Grating) Sensor	Embedded in composite leaf springs	High resistance to environmental degradation, precise strain-induced wavelength shift measurement
(Radoicic et al. 2016)	Piezoelectric Sensor	Between suspension components and drive bridges	High impedance charge of the piezoelectric sensor could be converted to low impedance voltage through state-of-the-art signal processing.
(Liu et al. 2018)	Position Sensor	Above gearbox (converts leaf spring deformation)	Bayesian filtering refined load accuracy with 20% error reduction
(Todts et al. 2013), (Technoton, 2020)	APT Magnetoresistive + tensoresistive	Axle and suspension	Improved measurement reliability, multi-sensor integration could produce better accuracy
(Luna Innovations Incorporated, 2019)	Fiber Optic Sensors	On curved surfaces of control arms and support beams	High strain resolution (50με), superior noise resistance and dynamic strain analysis vs. conventional gauges (2 to 4 times improvement). Stable under severe vibration (-14g).
(M. K. Seo, 2021)	Angular Displacement Sensors	On leaf springs	2% error in weight estimation by directly measuring leaf spring deflection.

DISCUSSION

SENSOR AND INSTALLATION METHOD

Choosing the technology for sensing requires compromises between accuracy, installation complexity, durability and cost. The table below (Table 4) summarizes the pros and cons of each type of sensor reviewed.

The reviewed studies have shown that no sensor technology meets all the requirements for an OBWS at the same time, such as accuracy, durability, low cost and ease of installation. (Todts et al. 2013) identified three main sensor technologies for on-board weighing systems: load cells, air pressure transducers (APT) and strain gauges. Load cells are the most accurate (greater than 1%), but strain gauge sensors achieve a satisfactory balance of accuracy (1–2%) and ease of installation, with the benefit of a lower cost (0.5–1%) which makes them suitable for vehicles with steel or leaf spring suspension.

Rather, the appropriateness of each sensing method is highly application and environment specific. Load cells are typically the most stable type of measurement because they measure the force being applied, but they are less flexible for installation than strain gauges, which, however, tend to be more sensitive to environmental conditions and must be compensated for to ensure stability in the measurement. Other sensing techniques like FBG and fiber optic sensors offer greater noise and environmental immunity but are not economically practical due to high implementation costs.

Referring to Table 4, several environmental and operational considerations that impact sensor stability and calibration such as temperature fluctuations, vibration, humidity, and long-term material fatigue. These need to be addressed to ensure the accuracy and longevity of the OBWS.

The way sensors are installed on truck structures has direct consequences on measurement errors. (Chang et al. 2006) proposed better strain gauge setups for axle installations to improve shear strain-based weight measurements. The proper placement of strain gauges on leaf springs (Nieminen et al. 2023) and bogie frames (El Makkaoui et al. 2022) allow effective load distribution surveillance. OBWS requires load cells to be installed on trailer platforms and truck axles to achieve stable and accurate measurements (Patel & Khatod, 2020). Sensors were attached to the truck chassis to measure the frame mechanical deformations while monitoring load variations (Zod et al. 2022). An essential aspect of this monitoring system is its ability to deliver immediate structural stress feedback during real-time operations, especially when performance relies heavily on deformation changes caused by loads. Hence, sensors should be installed on the truck structure that allow direct measurement of load variations to achieve a linear correlation between the sensor input and output.

The measurement accuracy of certain sensors can be enhanced by integrating them with complementary sensing technologies. Strain gauges were integrated with thermocouples for temperature monitoring to prevent strain measurement variations due to self-heating (Fernando et al. 2006). The nonlinear measurement of the leaf spring's deflection based on strain gauges for suspension load measurement was integrated with the vehicle slope and

elasticity compensation (Fernando et al. 2006). On another note, sensor durability was improved using a hermetically sealed load cell (Singh & Srivastava, 2022a) and embedded FBG sensors in composite materials (Hsieh et al. 2014). These technological advances have implemented environmental compensation using insulation and sustainable materials to achieve accurate and precise measurements in OBWS systems.

Proper installation and integration of sensors on truck structures enables direct correlation of mechanical parameters with the loads applied. However, signals from sensors are also greatly affected by noise and interference. Sensors installed on the chassis can detect weight proportionately while experiencing interference from mechanical vibrations. U-bolt and axle sensors follow direct force pathways but can encounter environmental variations and mechanical operational degradation. Suspension-mounted sensors respond quickly to load shifts but are affected by transient effects. Thus, state-of-the-art signal conditioning and processing are crucial for optimizing performance. The next section will further explore this topic.

TABLE 4. Advantages and Disadvantages of Sensors

Sensor Type	Advantages	Disadvantages
Load Cell	High accuracy, proven reliability, applicable for static and dynamic measurements	Requires proper installation and calibration, expensive
Strain Gauge	Cost-effective, adaptable for various vehicle structures	Sensitive to temperature and environmental variations
Piezoelectric Sensor	High dynamic response, suitable for WIM applications	Limited durability, affected by temperature and humidity
Air Pressure Transducer (APT)	Cost-effective, easy to install	Requires frequent recalibration, lower accuracy (3-5% error)
Fiber Bragg Grating (FBG)	High accuracy, resistance to environmental factors	Expensive, complex signal processing is required

SIGNAL CONDITIONING AND PROCESSING

The signal conditioning and processing system is a critical component of OBWS application as it reduces output drift, suppresses system noise, and boosts the accuracy and precision of weight measurement. This section discusses the hardware and software aspects of the signal conditioning and processing of OBWS. Table 5 summarizes the signal conditioning and processing methods based on the literature review.

One commonly used signal conditioning hardware in weighing systems is the HX711 24-bit analog-to-digital converter (ADC), which has been shown to provide stable and low-noise digitization of load cell outputs (Singh & Srivastava, 2022; Y. Zhang et al. 2021). The HX711 integrates a low-noise programmable gain amplifier (PGA) with selectable gains of 32, 64, and 128 that amplifies millivolt-level signals from strain-gauge-based load cells without the need for external amplification circuitry. Its 24-bit resolution allows fine discrimination of small weight changes, contributing to improved measurement accuracy. However, the HX711 operates at a relatively low sampling frequency of 10 to 80 samples per second, which may limit its effectiveness in applications requiring high-speed weight measurements. Hence, low-cost processing platforms such as HX711 and basic microcontrollers are sufficient for static or low-speed applications but may struggle under highly dynamic loading conditions due to limited sampling rates and filtering capabilities.

In contrast, high-performance ADCs combined with advanced compensation algorithms significantly improve measurement stability but increase power consumption, software complexity, and implementation cost. For example, the 24-bit delta-sigma ADC family called ADS1261-Q1 achieves a noise-free measurement quality exceeding 18 bits (Maniar 2019). The Internal features of digital filtering and chopper stabilization in this ADC help minimize performance drift during weight measurement operations. Its ability to produce a stable and high-resolution signal with minimal offset errors makes ADS1261-Q1 a suitable choice for OBWS applications.

A Wheatstone bridge system connected to the STM32F103 microcontroller system provided enhanced signal stability and reduced drift effects (Y. Zhang et al. 2021). The STM32 series microcontrollers can offer speed and power efficiency due to their ARM Cortex-M3 architecture design. In contrast, the signal processing capabilities of the affordable PIC16F870 microcontroller are restricted because it does not feature sufficient built-in filters (Thanigaivelan et al. 2015). The system described in (Pan, 2016) achieved a reduction in long-term drift effects by applying AC bridge excitation to its high-end ADS1261-Q1 ADCs and STM32F103 microcontrollers.

The OBWS also encounters substantial noise

disturbances from electrical disturbances, temperature fluctuations, and mechanical vibrations. Researchers have implemented several filtering procedures to handle the problems encountered. Digital filtering methods for weight measurement enhancement in real-time applications have become the focus of research by (Todts et al. 2013). The method of using ratio metric measurements with chopper stabilization enabled the reduction of voltage drift while suppressing noise interference (Maniar 2019). The method enhances measurement precision using a signal modulation technique to remove low-frequency noise. In another work, the computer-based data acquisition system, based on LabVIEW, effectively merges numerous sensor inputs with automated signal adjustment while providing interactive data visualization (Hoogvelt et al. 2004)

Measurement accuracy of OBWS is also affected by the nonlinearity phenomenon. Various solutions exist for tackling this problem. A microcontroller incorporates a neural network model developed by (Yang et al. 2008) to refine data from strain gauges for effectively addressing the nonlinear behavior of the leaf spring. Detection methods presented by (Maniar 2019) allow the system to adjust for sensor and analog-to-digital converter inaccuracies through advanced calibration, resulting in improved long-term system reliability. The algorithm maintains weight reading accuracy by dynamically modifying offset values in conjunction with gain parameters during extended usage.

As summarized in Table 5, signal conditioning and processing techniques significantly affect OBWS measurement stability and reliability. There are solutions that are less expensive for basic implementations. In contrast, high-performance ADCs and complex processing techniques provide better measurement accuracy but do come with higher computational complexity, power consumption, and cost of implementation.

For the future development of OBWS, intelligent calibration, adaptive filtering and artificial intelligence techniques should be considered to increase long-term measurement reliability when the operating conditions change. The literature reviewed also points out the need to consider the computational complexity versus the robustness of measurements. Future development will aim to achieve a balance between accuracy and computing time depending on the operating conditions in real time.

TABLE 5. Advantages and Limitations of Signal Conditioning and Processing Methods

Signal processing method	Authors	Advantages	Disadvantages
HX711 24-bit ADC	(Singh & Srivastava, 2022), (Y. Zhang et al. 2021)	Low-cost, integrated PGA	Limited sampling rate
ADS1261-Q1 ADC	(Maniar, 2019), (Pan, 2016)	High resolution, AC bridge excitation	Higher power consumption
STM32 Microcontroller	(Pan, 2016)	Fast processing, low drift	Requires advanced coding
Chopper Stabilization	(Maniar, 2019)	Reduces voltage drift	Slightly increases response time
Neural Networks	(Yang et al. 2008)	Adaptively compensates for nonlinearity	Requires a training dataset
Digital Filtering	(Todts et al. 2013)	Removes high-frequency noise	May introduce delays in real-time systems
Computer-based DAQ (LabVIEW)	(Hoogvelt et al. 2004)	Merges multiple sensors, auto adjustment, interactive visualization	Needs dedicated setup

FUTURE DEVELOPMENT

This review identified that load cells and strain gauges are preferred in OBWS because of their inexpensive, accurate and sensitive measuring ability. But their installation is a complex process. The load cells need to be fitted with special fixtures to be mounted on the truck structure. Attaching the strain gauge is a tedious process and it is important to clean the surface correctly before attaching the strain gauge on the surface, using suitable adhesives. For future applications in trucks, customized strain-gauge-based sensing devices must be developed, that can be mounted on the truck structure within a reasonable time without significant modification of the truck components. For instance, weldable strain gauges housed in protective stainless-steel carriers can be welded onto any structural member like leaf springs, chassis beams or axle housing providing easy installation and durability in harsh operating conditions. On another note, load cells can be easily integrated into custom mounting brackets, bolted between suspension parts, or mounted directly into the axle seats, providing an easy way to install and replace. These

customized mechanisms not only reduce downtime during installation but also improve sensor durability and signal stability, making them well-suited for fleet-scale deployment.

The sensor placement process should include the identification of an ideal placement area for the weight-sensing device. Previous researchers conducted Finite Element Analysis (FEA) (Cortivo et al. 2022; Kumar et al. 2012; Manuel Gago Tripero et al. 2012). FEA can also be considered to optimize strain-gauge-based sensor devices. The application of FEA made power generation sensors more sensitive in (Kumar et al. 2012). FEA with Geometric and Sensitivity Matrix Methods was used to optimize automotive suspension strain gauge arrangements (Cortivo et al. 2022). The merger of FEA with Shear Bridge Optimization yielded better sensor detection results on aircraft landing gear weight-on-wheel detection (Manuel Gago Tripero et al. 2012). A three-dimensional FEA analysis of L-shaped load cells was implemented to enhance cycling performance accuracy (Bibbo 2018). These studies have shown the viability of using FEA to study the placement of weight sensors on strain-sensitive areas. Future research can apply FEA and experimentation methods to identify a truck structure that yields a strain that linearly correlates with loads applied. To date, investigation of the strain versus load behavior has not been comprehensively conducted on truck structures. This limitation represents a major research gap because many existing OBWS studies rely heavily on empirical calibration without fully understanding the structural mechanics governing strain distribution under dynamic loading. Consequently, sensor performance often becomes highly vehicle-specific, reducing the scalability and transferability of proposed solutions across different truck configurations.

Multi-objective optimization (MOO) can offer an optimization technique in sensor development through meta-heuristic search. Research has shown that genetic algorithms (GAs) have delivered successful MOO outcomes for determining the best locations of strain gauges on a customized sensor. NSGA-II functioned as a GA algorithm to enhance signal precision through reduced sensitivity of sensor response to bending conditions (Gavrilenkov 2020). Research applied GA to optimize strain measurements in civil structures through Strain Difference Coverage and Strain Contribution Coverage (K. Zhou & Wu, 2017). The combination of Greedy Hill Climbing and Tabu Search optimized blade vibration testing sensors through robust placement, but at a high computational expense (Teufel & Poland, 2015). D-Optimality Criterion was used for strain gauge optimization on circular shafts in (Iriarte et al. 2021) while the Effective Independence (EI) method was applied to truss structures for sensor placement optimization based on precise mode shape data (Kyung & Eun, 2023). The integration of EI and noise normalization allows for structural health monitoring applications (X. H. Zhang et al. n.d.). Other heuristic methods that could be referred to are the Forward Sequential Placement Algorithm (Loutas & Bourikas 2017), Performance-Based Seismic Design (PBSD) (Vafaei & Alih 2015) binocular vision (C. Zhou et al. 2024) and numerical optimization (Xiao et al. 2017). These optimization approaches can be used to optimize sensor placement on the truck structure or sensor placement on the customized sensing mechanism/device.

Single-sensor system caused measurement consistency issues because of nonlinearity, environmental drift and noise interference. The accuracy and reliability of measurement using the single-sensor can be improved using sensor fusion techniques and advanced processing algorithms. Methods to implement sensor fusion include the Kalman filter, Extended Kalman filter, particle filter, or complementary filter, as well as data-level fusion via statistical weighting or feature-level fusion via combining strain, displacement, and acceleration data. These methods allow for combining different sensors in order to overcome the limitations of each sensor and enhance the system's robustness in varying operating conditions. However, this approach can incur higher development costs.

Processing algorithms may needs further enhancement to process non-linear strain measurements from strain gauges. Machine learning methods like adaptive filtering algorithms for weight estimation, support vector regression (SVR), convolutional neural networks (CNN), and artificial neural networks (ANN) can be employed to compensate for the sensor response due to nonlinearity. Alternatively, new techniques such as recurrent neural networks (RNN) for time-series load forecasting, or hybrid neuro-fuzzy systems can be considered. Although machine learning techniques have potential, these techniques is limited by the requirement for significant training data especially for niche vehicle category. AC Bridge excitation techniques and dynamic recalibration algorithms can be used to stabilize sensors that drift as a result of temperature changes and gradual aging of the sensors. Noise caused by mechanical vibration and electromagnetic interference (EMI) can be mitigated using digital filtering and chopper stabilization technologies to ensure signal integrity. Edge computing for real-time processing, digital twins for predictive modelling of structural responses, and energy-harvesting sensors for maintenance-free operation are some of the other future systems that can be developed.

In OBWS systems, sensors are linked to processing algorithms to automatically adapt to each possible vehicle weight condition and/or environmental and/or road surface type. Real-time GPS based data transmission allows the

OBWS to transmit weight monitoring and location tracking using IoT technology. Future work could integrate live data transfer with analytics in a cloud environment to provide predictive asset and fleet management capabilities. These new technological innovations will allow continous monitoring to ensure operational safety and weight-based adherence authentication.

In summary, future research should focus on developing easy-to-install customized load cells and strain gauge sensors. Optimization methods can be introduced to optimize sensor placement and refine sensor signal calibration. Sensor fusion can be considered, but the development cost should be minimized to render it practical for applications. Signal processing techniques employing state-of-the-art signal conditioners and processors should be further explored. While signal processing using machine learning can be considered, its universal application to all types of trucks should be attained. To avoid the processing of these nonlinearities, sensing methods to harvest linear strains should be investigated. These proposed advancements in OBWS will contribute to highly accurate and efficient solutions tailored to diverse applications in construction, logistics, and quarries. It is desired that OBWS should achieve an accuracy of at least ±2% to ensure accurate and precise weight measurement while maintaining operational efficiency on par with some existing commercial grades of OBWS (Loadsense, n.d.), (Outset Pacinotti, n.d.), (Aptella n.d.; Topcon Corporation 2020), (RDS Technology Ltd, n.d.; Topcon Corporation 2024).

CONCLUSION

The weight monitoring in heavy vehicles is enhanced through OBWS. This review examines various weight sensors such as load cells, strain gauges, piezoelectric sensors, FBG, fiber optic, etc., and their installation methods. These sensors demonstrate operational advantages and drawbacks. Load cell systems typically give us top-notch accuracy and stability since they directly measure the applied forces. However, setting them up is complex and pricey. Strain gauge systems are more flexible and affordable but need advanced methods to handle nonlinear issues, temperature shifts, and vibrations. Other sensing technologies like FBG and piezoelectric sensors do well in rough conditions. However, extensive commercial uses are limited due to their high costs and complicated processes. Installation methods include mounting sensors on the vehicle chassis, axle, and suspension. Sensors installed on the chassis require vibration-stabilizing procedures, axle-based load cells require regular calibration and periodic adjustments, and suspension-based monitoring systems require dynamic movement adjustments. Current signal processing methods can reduce sensors drifting, system noise, non-linearities, and environmental effects. However, there is still much room for further research and improvement in the OBWS. These limitations can be addressed by the development of optimized sensors that are low-cost and simple to install, coupled with state-of-the-art signal processing methods. In addition, OBWS should be enhanced by incorporating live data transfer capabilities with analytics functions in cloud environments to deliver predictive asset management solutions and fleet-administration capabilities.

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DECLARATION OF COMPETING INTEREST

None.

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