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Design and Laboratory Evaluation of a Real-Time Onboard Load-Monitoring Prototype for Heavy-Truck Overload Prevention: Implications for Road and Environmental Sustainability in Tanzania

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Abstract: Heavy-truck overloading accelerates pavement deterioration, increases stress on vehicle components, complicates road-safety enforcement and may increase the life-cycle environmental burden of road freight through additional pavement rehabilitation, material consumption and vehicle emissions. This study designed and evaluated a laboratory prototype of an onboard system intended to provide drivers with continuous load information and an immediate overload warning. The prototype integrated a 500-kg S-beam strain-gauge load cell, an HX711 24-bit analogue-to-digital interface, an Arduino microcontroller, a liquid-crystal display, visual and audible alarms, and a SIM900 cellular module. A steel mounting concept was modelled for installation between a chassis cross-member and differential housing. Laboratory evaluation comprised sensor-output characterization (0–45 kg), calibration (0–100 kg), minimum-increment, hysteresis, repeatability and threshold-classification tests; dynamic and vibration behavior were assessed qualitatively. The reported sensor output increased from 0.000 to 0.900 mV over 0–45 kg, corresponding to a nominal sensitivity of 0.020 mV kg^{-1}. Across five non-zero calibration points, mean absolute percentage error was 0.226%, maximum absolute error was 0.18 kg and maximum percentage error was 0.30%. The maximum loading–unloading difference was 0.10 kg (0.10% of the 100-kg laboratory test span). Ten repeated applications of 50 kg produced a displayed value of 49.9 kg, indicating a −0.10 kg bias and no observable dispersion at the recorded 0.1-kg resolution. The alarm logic correctly classified all seven reported test points relative to a 100-kg laboratory threshold. These results demonstrate functional feasibility and good bench-scale agreement with reference masses. If validated at vehicle scale, preventive load information could support pavement preservation and more environmentally responsible freight management. However, the study did not measure pavement damage, fuel consumption, greenhouse-gas emissions, air pollutants, non-exhaust particle emissions or life-cycle impacts. Full-scale calibration against traceable axle-load references, controlled environmental and durability testing, uncertainty analysis, environmental-performance assessment and regulatory conformity evaluation are therefore required before field deployment.

Keywords: onboard weighing; truck overloading; load cell; axle-load monitoring; pavement sustainability; life-cycle assessment; freight emissions; laboratory validation; Tanzania

I. INTRODUCTION

Freight vehicles are essential to regional trade (East African Community, 2016). However, loads exceeding authorized axle or gross-vehicle limits impose disproportionate costs on road infrastructure and can undermine vehicle stability, braking performance and component durability (International Transport Forum, 2011; Jacob & Feypell-de La Beaumelle, 2010). Weigh-in-motion (WIM) technologies can improve screening and enforcement efficiency, while onboard weighing can provide information before a vehicle reaches a roadside control point (International Transport Forum, 2011). In East Africa, the Vehicle Load Control Act establishes a harmonized legal basis for controlling vehicle loads on the regional trunk-road network (East African Community, 2016).

The environmental significance of overload control arises through several linked pathways. Premature pavement deterioration can bring forward maintenance and rehabilitation, increasing demand for aggregates, asphalt binders, energy, construction transport and end-of-life management. Pavement life-cycle assessment therefore considers material production, construction, use, maintenance and rehabilitation, and end-of-life stages rather than maintenance cost alone (Harvey et al., 2016; Santero et al., 2011). Vehicle loading also affects the operating emissions of heavy-duty diesel

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trucks, while vehicle mass is among the factors associated with tyre, brake and road-wear particulate emissions (Organisation for Economic Co-operation and Development [OECD], 2020; Wang et al., 2021). These relationships make preventive load management potentially relevant to Tanzania's commitment to climate-resilient, lower-emission development under its updated Nationally Determined Contribution (United Republic of Tanzania, 2021).

Conventional static weighbridges provide a recognized reference but measure vehicles only at fixed locations. Roadside WIM systems extend coverage, yet their performance depends on sensor type, pavement condition, installation, speed, temperature, vehicle dynamics and sustained calibration. FHWA guidance therefore defines calibration as comparison of system outputs with known static axle weights and recommends sufficient repeated test runs to characterize error with statistical confidence (Federal Highway Administration [FHWA], 2018c). OIML R 134 similarly treats accuracy, influence factors, disturbances and in-motion testing as integral parts of metrological evaluation (International Organization of Legal Metrology [OIML], 2006).

Onboard weighing offers a complementary prevention strategy: measurement is available to the driver during loading and can be connected to alarms or remote reporting. Previous heavy-vehicle work has shown that onboard systems can be built from strain- or force-sensitive elements, but practical accuracy depends on the mechanical load path, sensor installation, temperature compensation, suspension geometry and vehicle-specific calibration (Radoičić et al., 2016). Regulatory approaches to onboard weighing also emphasize interoperability, compatibility, data integrity and periodic verification rather than sensor output alone (European Commission, 2019).

The present study addresses the design and bench-scale evaluation of a low-cost prototype intended for heavy-truck overload prevention in Tanzania. Its objectives were to: (i) characterize the selected load sensor; (ii) develop the electronic acquisition, display, alarm and communication architecture; (iii) develop a mechanical mounting concept; (iv) quantify laboratory calibration error, sensitivity, hysteresis, repeatability and threshold response; and (v) interpret the potential environmental relevance of preventive load monitoring using a transparent impact-pathway framework. Because the available experiments used laboratory masses rather than a loaded truck, the study is explicitly framed as prototype feasibility rather than full vehicle or environmental-impact validation.

II. MATERIALS AND METHODS

A. Study design and system architecture

An engineering design-and-test approach was used. The measurement chain comprised an S-beam strain-gauge load cell, an HX711 24-bit converter and amplifier, an Arduino-based control unit, an LCD, green and red status LEDs, a buzzer and a SIM900 GSM module. In the intended vehicle configuration, the load sensor and bracket would form a load-transfer path between the differential housing and a chassis cross-member. The microcontroller converted digitized bridge output into mass, displayed the estimate and compared it with a programmable limit. Loads at or below the laboratory threshold remained in the normal state; loads above the threshold activated the red LED and buzzer. The GSM module was included for remote alerts. The GSM communication module is intended to transmit vehicle-mass measurements generated by the onboard system and displayed on the LCD to authorized fleet managers and relevant regulatory authorities in real time. This functionality is consistent with modern onboard-weighing frameworks that support the transmission of vehicle-weight data to competent authorities for compliance monitoring. Remote access to these data can facilitate timely intervention when an overload condition is detected (European Commission, 2019).

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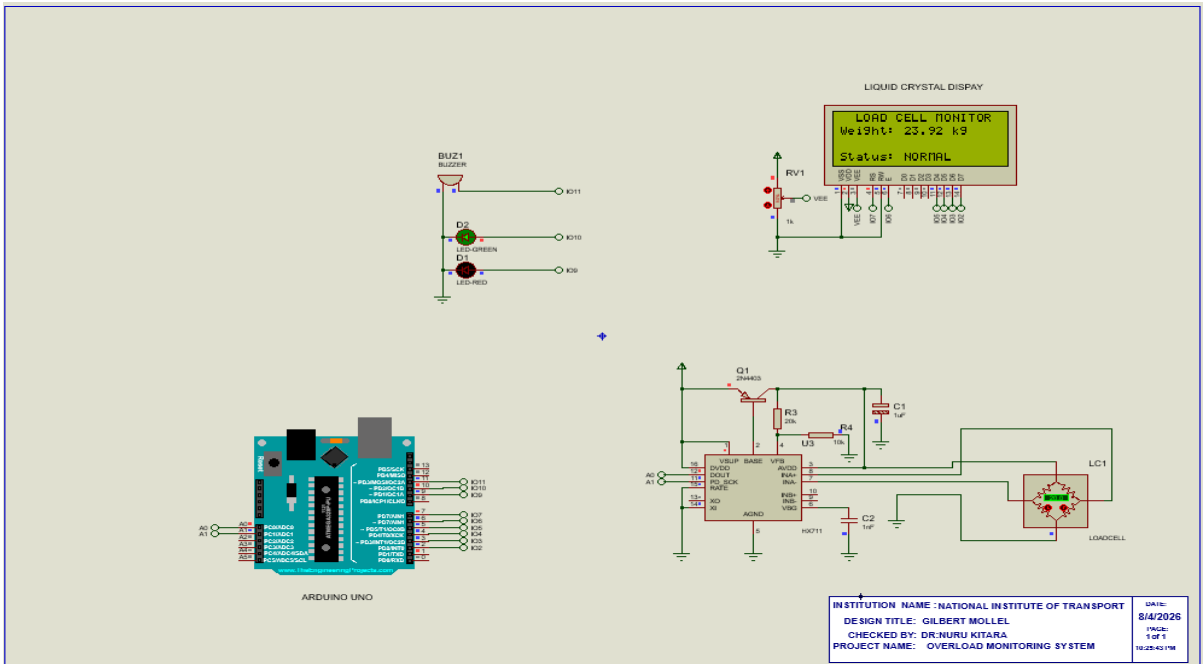


Figure 1. Proteus representation of the prototype measurement and display circuit supplied in the source study.

B. Sensor principle and laboratory calibration

The S-beam sensor used bonded strain gauges in a Wheatstone-bridge arrangement. Applied force produces elastic strain and a differential millivolt signal, which the HX711 amplifies and digitizes. Sensor-output characterization used masses from 0 to 45 kg in 5-kg increments. System calibration used reference masses from 0 to 100 kg in 20-kg increments. The source study described these as standard calibration weights but did not report their traceability class or calibration certificates.

For each non-zero reference load W_i, signed error was $e_i = M_i - W_i$, where M_i is the displayed mass. Percentage error was $|e_i|/W_i \times 100$. Mean absolute percentage error (MAPE) was calculated over the five non-zero calibration points; the zero point was excluded because percentage error is undefined at zero. Maximum absolute error and maximum reported percentage error were also calculated.

C. Performance tests

Sensitivity was assessed by applying 1-kg increments and observing whether the display responded. Hysteresis was assessed by comparing readings during increasing and decreasing load sequences at nominal loads of 20–100 kg. Repeatability was assessed by applying a 50-kg mass ten times under nominally identical conditions. Overload logic was tested at 20, 50, 80, 100, 110, 120 and 150 kg with a 100-kg laboratory threshold. Dynamic-load and vibration checks were descriptive: loads were varied manually and the assembly was subjected to unspecified ‘moderate’ vibration while display stability was observed.

D. Mechanical design and simulation

A bracket concept was developed in SOLIDWORKS using ASTM A36 mild-steel properties reported as Young’s modulus 200 GPa, Poisson’s ratio 0.30, yield strength 250 MPa, ultimate tensile strength 400–550 MPa and density 7,850 kg m^{-3}. The bracket was fixed at bolt locations and loaded at the sensor connection. During the SolidWorks simulation the maximum yield stress was obtained

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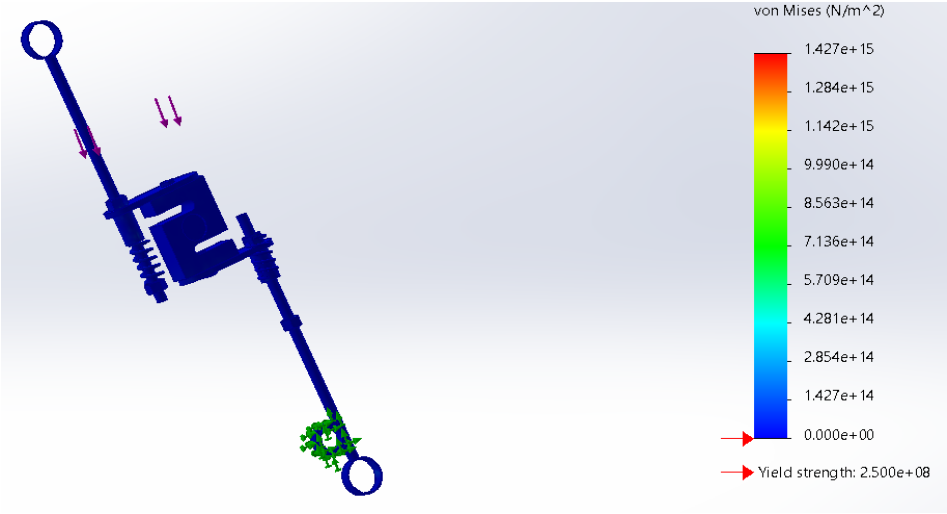


Figure 2. Solid works simulation on load cell sensor mounting bracket.

E. Data-analysis scope

The analysis was performed using the data from the digital oscilloscope (TEXA UNIProbe) only; this data was collected during testing of the on-board system for monitoring overload in heavy trucks in the Automotive Electronic lab. In the process of testing, the oscilloscope was utilized to capture and analyze the electric signals that were produced by the load cell, HX711 signal conditioning module, and Arduino microcontroller in the process of different loads application.

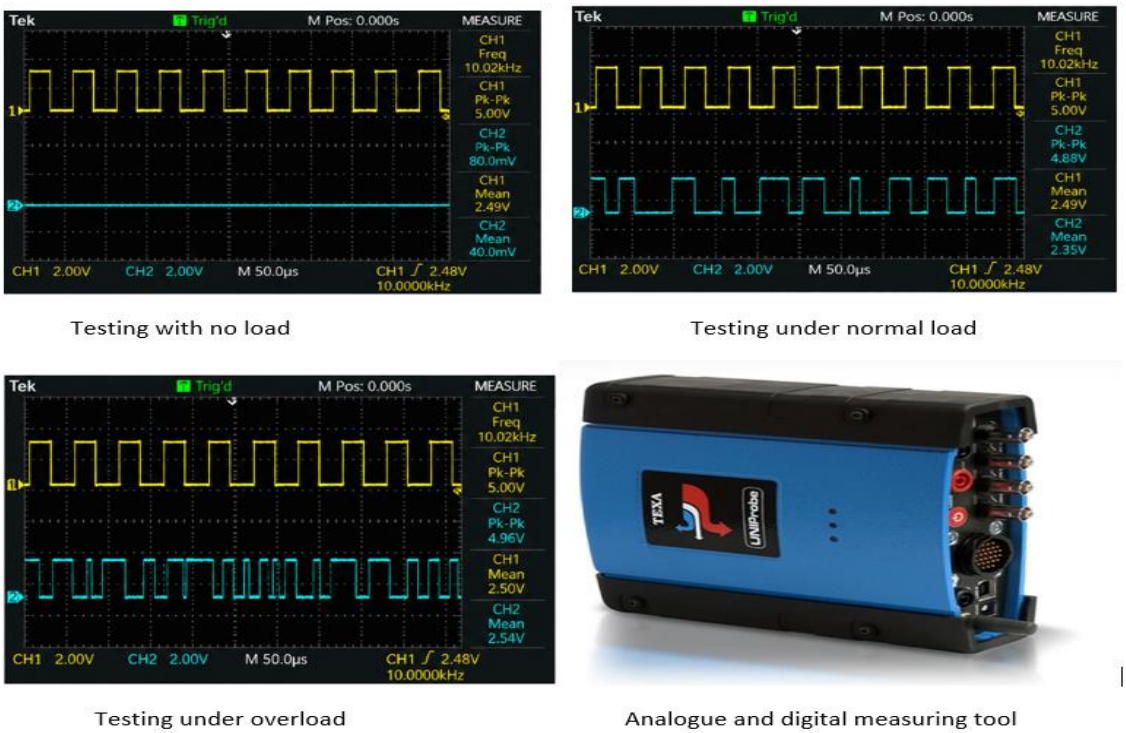


Figure 3: Electronic signal measurements

F. Environmental significance framework

Environmental significance was evaluated conceptually rather than experimentally using four literature-supported pathways: (i) avoided or delayed pavement maintenance and the associated material, energy and construction burdens (Harvey et al., 2016; Santero et al., 2011); (ii) load-related fuel consumption and exhaust emissions during freight operations (Wang et al., 2021); (iii) particulate emissions arising from tyre, brake and road-surface wear (Organisation

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for Economic Co-operation and Development [OECD], 2020); and (iv) the energy consumption, durability, repairability and end-of-life management of the monitoring equipment itself (International Organization for Standardization [ISO], 2006; International Telecommunication Union [ITU] & United Nations Institute for Training and Research [UNITAR], 2024). The prototype generated no primary data for these environmental indicators. Consequently, the discussion identifies plausible environmental mechanisms, trade-offs and variables for future measurement but does not estimate avoided emissions or claim a net life-cycle environmental benefit.

III. RESULTS

A. Sensor-output characterization

The reported output rose in uniform 0.100-mV steps for each 5-kg increase, from 0.000 mV at zero load to 0.900 mV at 45 kg (Table 1). The resulting nominal slope was 0.020 mV kg^{-1}. The table is exactly linear at the reported three-decimal voltage resolution. In the absence of repeated voltage readings and unrounded raw data, this pattern demonstrates the reported transfer relationship but does not permit independent estimation of residual non-linearity, noise or confidence bounds.

Table 1. Reported load-cell output characterization.

Applied load (kg)	Output (mV)	Applied load (kg)	Output (mV)
0	0.000	25	0.500
5	0.100	30	0.600
10	0.200	35	0.700
15	0.300	40	0.800
20	0.400	45	0.900

B. Calibration accuracy

Displayed masses closely followed the reference masses over 0–100 kg (Table 2; Figure 2). Signed error ranged from −0.18 to +0.15 kg. Across the five non-zero points, MAPE was 0.226% (rounded to 0.23%). Maximum absolute error was 0.18 kg at 80 kg, and the largest percentage error was 0.30% at 40 kg. The mean signed error across the five non-zero points was −0.02 kg, suggesting little aggregate bias in this small calibration set, although the number of observations was insufficient to characterize drift or uncertainty.

Table 2. Laboratory calibration results and recalculated summary metrics.

Reference (kg)	Measured (kg)	Signed error (kg)	Absolute error (%)
0	0.00	0.00	—
20	19.95	−0.05	0.25
40	39.88	−0.12	0.30
60	60.15	+0.15	0.25
80	79.82	−0.18	0.23
100	100.10	+0.10	0.10
Summary	MAPE = 0.226%	Max |error| = 0.18 kg	Max = 0.30%

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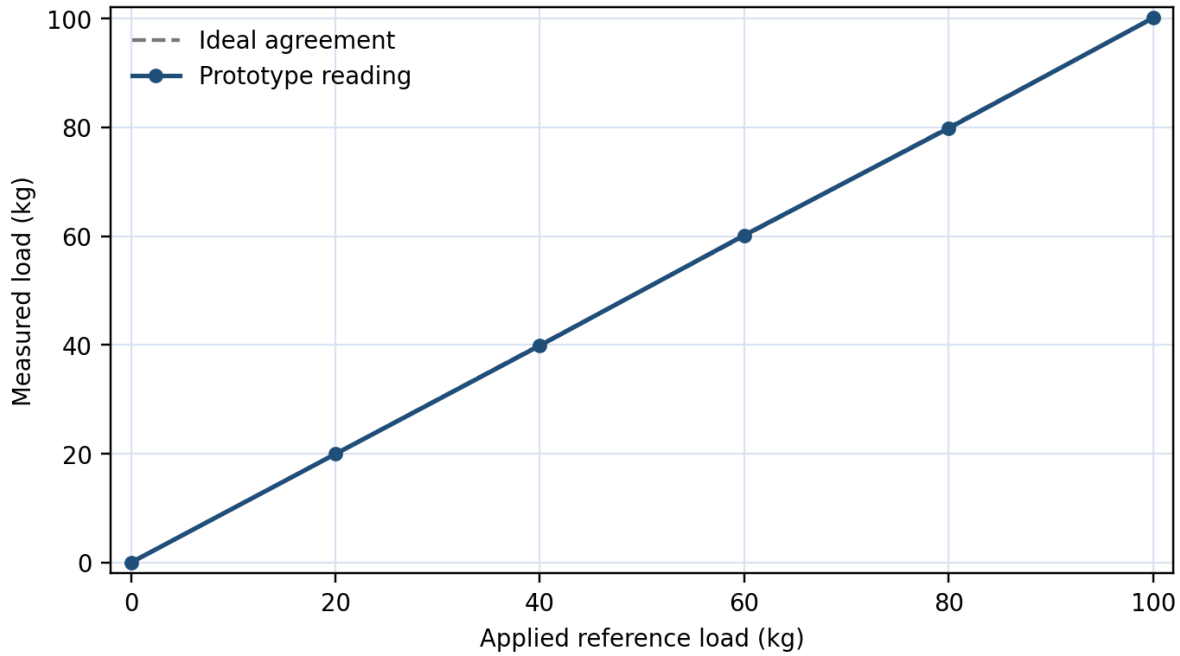


Figure 4. Agreement between applied reference loads and prototype readings during laboratory calibration.

C. Sensitivity, hysteresis and repeatability

The minimum applied increment reported as consistently detectable was 1 kg. This is a test increment, not a metrologically established resolution or detection limit, because smaller increments, noise distributions and decision criteria were not reported. Loading–unloading differences ranged from 0.07 to 0.10 kg, with a maximum of 0.10 kg, equal to 0.10% of the 100-kg laboratory test span (Table 3; Figure 3).

Table 3. Reported hysteresis test.

Nominal load (kg)	Loading (kg)	Unloading (kg)	Difference (kg)
20	19.95	20.02	0.07
40	39.88	39.95	0.07
60	60.15	60.08	0.07
80	79.82	79.90	0.08
100	100.10	100.00	0.10

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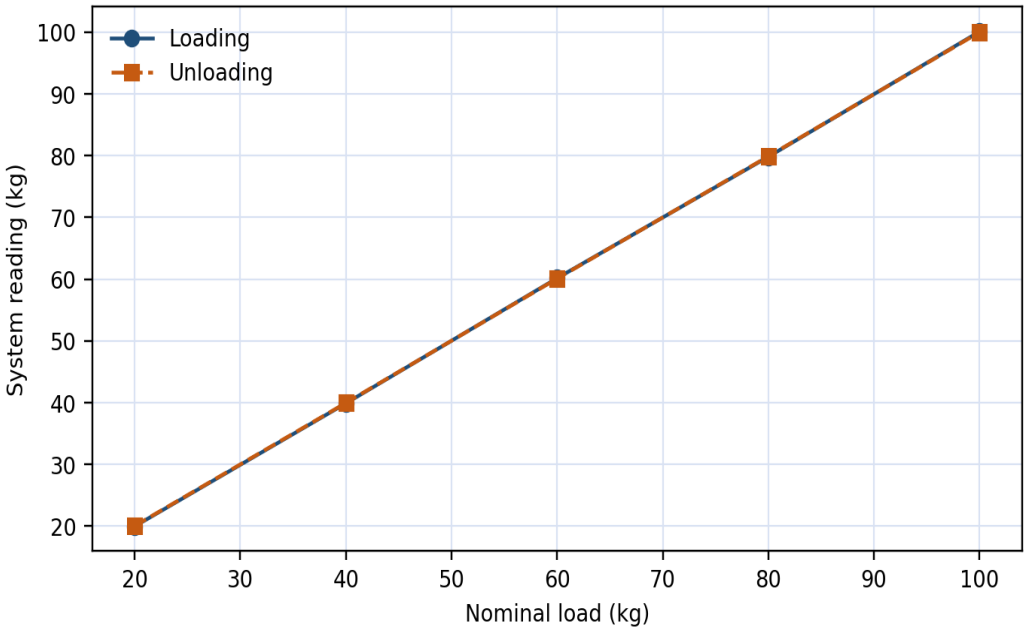


Figure 5. Loading and unloading readings. The largest reported separation was 0.10 kg.

All ten repeated applications of a nominal 50-kg load produced a displayed value of 49.9 kg. At the recorded 0.1-kg resolution, the mean was 49.9 kg, bias was −0.10 kg (−0.20%) and observed standard deviation was 0.00 kg. The zero observed dispersion should not be interpreted as perfect repeatability; variation smaller than the display or reporting resolution may have been masked.

D. Overload classification and functional response

The programmed decision rule behaved consistently at the seven reported test points (Table 4). Loads of 20–80 kg were classified as normal, 100 kg was treated as the threshold, and 110–150 kg activated the red LED and buzzer. Thus, seven of seven observations agreed with the programmed rule. This is a functional test of threshold logic rather than a diagnostic-accuracy study: there were no repeated observations close to the threshold, no induced noise and no independent blinded classification.

Table 4. Laboratory overload-threshold test (threshold = 100 kg).

Applied load (kg)	Green LED	Red LED	Buzzer	Classification
20	On	Off	Off	Normal
50	On	Off	Off	Normal
80	On	Off	Off	Normal
100	On	Off	Off	Threshold
110	Off	On	On	Overload
120	Off	On	On	Overload
150	Off	On	On	Overload

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Figure 6. Prototype display and green normal-load indicator during a bench test.

E. Qualitative dynamic, vibration and electronic observations

During manual load changes, the display was reported to update without a perceptible delay and to stabilize shortly after each change. Under unspecified moderate vibration, only slight display fluctuation was reported, with HX711 filtering and software averaging used to reduce noise. Oscilloscope screenshots showed continued SCK/DOUT digital activity at zero, normal and overload states, supporting functional communication between the HX711 and microcontroller. Because sampling rate, latency, vibration amplitude, vibration frequency, temperature and waveform statistics were not recorded, these observations cannot quantify dynamic accuracy or robustness.

IV. DISCUSSION

A. Principal findings

The prototype achieved its primary bench-scale engineering objective: it converted strain-gauge output into a readable load estimate and executed a programmable overload warning. The 0.23% MAPE, 0.18-kg maximum absolute error and 0.10-kg maximum loading–unloading difference are encouraging within the reported 0–100 kg calibration range. The symmetric occurrence of small positive and negative errors suggests that the calibration factor was generally well centred. The successful normal/overload state changes also show that the acquisition, decision and alarm subsystems were integrated correctly.

These outcomes are consistent with the feasibility of strain-based onboard weighing described by Radoičić et al. (2016), but the comparison must remain qualitative because sensor location, rated load, vehicle architecture and test conditions differ. The reported laboratory error is also not directly comparable with WIM accuracy classes: WIM performance is assessed using repeated vehicle passes, known axle loads, defined operating conditions and statistical tolerances (FHWA, 2018c; OIML, 2006).

B. Interpretation of calibration and repeatability

The near-unity calibration relationship indicates that the microcontroller scaling factor was effective over the bench range. Nevertheless, six calibration levels with one reported reading per level do not separate systematic error, random error, non-linearity, creep, zero return or drift. A rigorous calibration should use traceable masses, replicate ascending and descending cycles, randomized intermediate points and raw ADC observations. An uncertainty budget should include reference-mass uncertainty, load-cell non-linearity and hysteresis, amplifier noise, quantization, mounting effects, temperature and repeatability.

The repeated 49.9-kg display value is evidence of stability only at the reported 0.1-kg resolution. Reporting a standard deviation of zero would overstate precision if raw values fluctuated below that resolution. Future testing should store unrounded ADC counts and use control charts or repeated-measures statistics. Likewise, the 1-kg minimum test increment should be described as demonstrated responsiveness, not a detection limit, until smaller increments and a noise-based criterion are evaluated.

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C. Scale-up to a heavy-truck installation

The central engineering challenge is not the bench conversion of force to mass, but transfer of the vehicle's wheel and axle loads through a measurable, repeatable mechanical path. A 500-kg laboratory sensor and a 100-kg test span do not reproduce the magnitude, multi-axis loading or dynamic amplification experienced by a heavy-truck suspension. Side loading, bending, suspension articulation and chassis twist can introduce cross-sensitivity. Multiple sensors would normally be required to infer axle or gross mass, and each vehicle configuration would require a calibration model linking sensor outputs to traceable static axle weights.

Road operation also introduces temperature gradients, moisture, electromagnetic interference, connector degradation, shock, vibration, creep and fatigue. FHWA guidance highlights the influence of speed, temperature, site condition and vehicle type in WIM calibration, while OIML R 134 requires defined influence-factor, disturbance and in-motion tests (FHWA, 2018c; OIML, 2006). Although those documents concern road-based WIM instruments, the measurement principles illustrate why laboratory agreement alone cannot demonstrate enforcement-grade performance.

D. Mechanical and communication subsystems

The A36 bracket concept is plausible as an early prototype, but the evidence provided is insufficient for fabrication approval on a road vehicle. A factor of safety merely greater than one is generally inadequate for a safety-relevant component exposed to shock and fatigue, and no numerical result was available for audit. The model should be rerun with documented geometry, load cases, constraints, contact assumptions, mesh convergence, peak von Mises stress, displacement, buckling where relevant and fatigue life. Physical proof-load and fatigue tests should then verify the model.

The GSM module could support fleet alerts, but communication success rate, latency, coverage loss, message authentication and data governance were not evaluated. If remote reporting is developed, it should fail safely: local indication must remain available when cellular service is absent, and transmitted measurements should include timestamps, sensor health and calibration status. The European onboard-weighing framework provides a useful example of treating compatibility, secure information exchange and periodic inspection as system requirements rather than optional additions (European Commission, 2019).

E. Relevance to Tanzania and the East African region

A validated onboard warning device could complement, rather than replace, statutory weighbridges and enforcement systems. Its most immediate value would be preventive: helping drivers and fleet operators correct loading before entering the road network. The East African Community's harmonized vehicle-load-control framework makes consistent axle and gross-load information particularly relevant to regional freight operations (East African Community, 2016). However, any use for legal enforcement would require approval by the responsible metrology and transport authorities, traceable calibration and evidence that the complete installed system meets applicable legal and technical requirements.

F. Environmental significance and sustainability implications

The most direct potential environmental contribution is pavement preservation. When illegal axle loading accelerates structural deterioration, maintenance and rehabilitation may occur earlier or more frequently. Those activities require extraction and processing of aggregates and binders, movement of materials, operation of construction equipment and management of removed pavement. Pavement LCA frameworks show that these stages can contribute to energy demand, greenhouse-gas emissions and other environmental burdens (Harvey et al., 2016; Santero et al., 2011). A validated onboard warning system could therefore have an indirect environmental benefit if it measurably reduces overload events and extends pavement service life. This benefit was not quantified in the present laboratory study.

A second pathway concerns vehicle operation. Real-world evidence indicates that heavy-duty diesel emission factors vary with vehicle load, driving condition and speed (Wang et al., 2021). Preventing excess loads may reduce engine demand and emissions per vehicle trip, but the system-level outcome is not automatically favourable: carrying less freight per trip can increase the number of trips if logistics are poorly managed. Environmental evaluation should therefore report fuel use and emissions per tonne-kilometre as well as per vehicle-kilometre, and should distinguish illegal overloading from efficient loading within legal limits. This functional-unit approach would prevent an overly simple assumption that lower payload always produces lower freight emissions.

A third pathway is non-exhaust pollution. Tyre, brake and road-surface wear and the resuspension of road dust are important sources of traffic-related particulate matter, and vehicle weight is one of several determinants of these emissions (OECD, 2020). Load monitoring could potentially reduce wear associated with excessive mass, but this hypothesis requires field measurements that control for tyre condition, inflation pressure, braking behaviour, speed, pavement texture and weather. No tyre-wear, brake-wear or particulate data were collected in this study.

Finally, the monitoring system has its own footprint. Sensors, electronics, wiring, GSM communication, protective housings and replacement components require materials and energy and will eventually enter an end-of-life stream. Future design should therefore prioritize durability, low standby power, repairable modular components, replaceable

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sensors and responsible electronic-waste management. A comparative life-cycle assessment should evaluate the device against a baseline without onboard monitoring and include any changes in pavement maintenance, vehicle operations, enforcement travel and electronic equipment. Such an assessment would show whether the prototype provides a net environmental benefit under Tanzanian operating conditions and would align the technology with national climate objectives (United Republic of Tanzania, 2021).

V. STUDY LIMITATIONS

- The prototype was not installed and tested on a full-scale heavy truck; no comparison with a certified static weighbridge was reported.
- The 500-kg sensor and 0–100 kg calibration span do not represent heavy-truck axle-load magnitude or multi-sensor load distribution.
- Most calibration levels had one reported observation, and raw ADC values, unrounded readings and reference-weight certificates were unavailable.
- Dynamic-load and vibration tests lacked controlled inputs, timestamps, response-time measurements and quantified vibration conditions.
- Temperature, humidity, electromagnetic compatibility, creep, long-term drift, shock, ingress protection and durability were not evaluated.
- The finite-element account omitted numerical load cases, stress, displacement, factor-of-safety and fatigue results; the supplied image was a mesh-quality plot.
- GSM alert delivery, latency, failure modes, security and data management were not quantitatively tested.
- The overload decision test used only seven deterministic points and did not estimate false-alarm or missed-detection rates near the threshold.
- Environmental benefits were inferred from literature-based pathways; the study did not measure pavement-life extension, maintenance materials, fuel consumption, exhaust emissions, tyre or brake wear, particulate matter, energy use or electronic-waste impacts.

VI. RECOMMENDED FULL-SCALE VALIDATION PROGRAMME

Table 5. Minimum evidence recommended before field or regulatory use.

Stage	Recommended test	Primary output
1. Bench metrology	Traceable reference masses; ≥3 cycles; randomized intermediate points; raw ADC logging	Calibration function, linearity, hysteresis, repeatability and uncertainty
2. Environmental	Temperature and humidity sweep; zero/span drift; electromagnetic and power-supply variation	Compensation model and operating limits
3. Mechanical	Documented FEA; proof load; fatigue, shock and vibration; sensor misalignment tests	Structural margin, fatigue life and cross-sensitivity
4. Vehicle calibration	Instrumented truck; certified static axle and gross weights; multiple loading patterns	Vehicle-specific calibration and axle/gross-load error
5. Road trials	Repeated runs across speed, pavement, manoeuvre, gradient and temperature conditions	Bias, precision and 95% error intervals under use conditions
6. System assurance	Alarm boundary testing; fault injection; GSM loss/recovery; data integrity and cybersecurity	Fail-safe behaviour and reliable alert performance
7. Conformity	Assessment with Tanzanian/EAC authorities and relevant metrology standards	Defined legal status, verification procedure and recalibration interval
8. Environmental performance	Compare legal-load and overload scenarios using fuel and emission measurements, tonne-kilometre activity, pavement-deterioration modelling, maintenance LCA, non-exhaust wear indicators and device energy/end-of-life data	Net environmental effects per tonne-kilometre and road-service year, with trade-offs and uncertainty

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The road-trial design should compare each sensor-derived axle and gross weight with a traceable static reference before and after repeated passes. FHWA guidance indicates that repeated runs are necessary to characterize error with confidence; the exact sample size should be set from the desired accuracy class, expected variability and statistical power (FHWA, 2018c). Results should be stratified by axle group, gross mass, speed, loading pattern and environmental condition. In parallel, an environmental study should measure fuel use and emissions using both vehicle-kilometre and tonne-kilometre functional units, model changes in pavement maintenance demand, and document tyre, brake and road-wear indicators. This would establish whether overload prevention produces a net life-cycle benefit rather than shifting impacts between freight operations, infrastructure maintenance and electronic equipment.

VII. CONCLUSION

A low-cost onboard load-monitoring prototype was successfully integrated and evaluated under laboratory conditions. The reported data showed a nominal sensor sensitivity of 0.020 mV kg^{-1}, 0.226% mean absolute percentage error over five non-zero calibration points, a 0.18-kg maximum absolute calibration error, a 0.10-kg maximum loading–unloading difference and correct execution of the programmed overload rule at seven test points. These findings support the feasibility of the sensing, display and alarm concept.

The evidence does not yet validate a heavy-truck weighing system or demonstrate environmental improvement. No full-scale vehicle, certified weighbridge comparison, quantified road-dynamic test, environmental-exposure evaluation, auditable structural qualification or life-cycle environmental assessment was reported. The appropriate scientific conclusion is therefore that the prototype is ready for a staged full-scale validation programme, not operational deployment or enforcement use. If the technology reliably prevents illegal loading, it may help preserve pavement service life and reduce some maintenance-related material, energy and emission burdens. Those benefits must be tested against possible changes in trip frequency, fuel use per tonne-kilometre, exhaust and non-exhaust emissions, and the monitoring equipment's own energy and end-of-life impacts. Demonstrating traceable weighing accuracy together with a net environmental benefit under realistic Tanzanian operating conditions will determine whether the concept can support safer and more sustainable freight transport.

Declarations

Funding: No funding was received for this work.

Conflict of interest: The authors declare that they have no competing interests.

Ethics approval: Not applicable.

About the authors

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Data availability statement

The tabulated data supporting the findings are contained in this article. Environmental-performance data were not available for the present analysis. Any additional non-confidential technical data may be requested from the corresponding author.

Author contributions

CRediT author statement: Gilbert M. Mollel—Conceptualization; methodology; engineering design and prototype development; mechanical and electronic system integration; component selection and hardware fabrication; software development and programming; investigation; calibration and validation; formal analysis; data curation; visualization; project administration; writing—original draft; and writing—review and editing. Dr. Nuru N. Kitara—conceptualization, supervision, environmental interpretation, validation, and writing—review and editing.

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