Retrofit Early-Warning Module for Battery Fire Risk in Existing Electric Two-Wheelers: A Conceptual Framework

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***Abstract*—The rapid adoption of electric two-wheelers (E2Ws) in India has been accompanied by recurring lithium-ion battery fire incidents, several fatal, particularly where charging occurs within domestic premises.**

Amendments to the AIS-156 safety standard now mandate thermal-propagation prevention and a thermal-event warning, but only for newly certified battery packs leaving the substantial existing E2W fleet, much of it reliant on passive cooling, without such protection. Battery-safety research has separately established that thermal runaway is preceded by measurable precursor signals gas venting, abnormal casing temperature and pressure rise, and late-stage voltage irregularities detectable minutes ahead of failure under laboratory conditions, with gas-based indicators emerging earliest.

However, such sensing principles remain confined to OEM-level integration and are increasingly patented at the battery-pack design stage; no low-cost, vehicle-mountable retrofit device translates them into an early-warning solution for vehicles already on the road, and commercial alarm accessories for E2Ws address theft rather than battery safety.

This paper does not propose a new sensing principle; it presents the conceptual design of a retrofit early-warning module that repackages established gas, thermal, and current-sensing techniques into a low-cost, aftermarket form factor to alert riders of an emerging thermal event. The system is intended to extend laboratory-validated precursor-detection principles to the existing E2W fleet, offering a low-cost pathway toward improved safety awareness without claiming to eliminate battery fire risk entirely.

***Index Terms*—Electric two-wheelers, lithium-ion battery, thermal runaway, early-warning system, retrofit device, IoT, embedded sensing, battery safety**

I. INTRODUCTION

India's rapid expansion of electric two-wheelers has made battery safety a practical engineering concern for a large and diverse in-service fleet. Lithium-ion battery thermal runaway is a progressive failure process rather than an instantaneous event: electrochemical and thermal changes can generate gases, mechanical deformation, heat and electrical abnormalities before a visible thermal event. This creates an opportunity for early warning, provided that the relevant precursor can be sensed with sufficient reliability and lead time.

Indian regulatory development has strengthened the safety expectations for newly approved rechargeable electrical energy storage systems (REESS). AIS-156 specifies an audio-visual warning associated with a thermal event and a five-minute advance-warning criterion within the applicable thermal-propagation acceptance framework for covered REESS type-approval requirements. [1] This regulatory direction is important, but it does not itself provide a retrofit pathway for vehicles already in service. The engineering problem addressed here is therefore different from designing a new battery pack: the sensing module must be added without opening, redesigning or electrically modifying the existing pack.

Research on thermal-runaway detection has produced evidence for several precursor domains. Gas evolution is particularly attractive because characteristic gases can appear before the temperature rise becomes an effective external indicator. Wang et al. identify H_2, CO, CO_2, C_2H_4 and CH_4 as important gases for early detection and review the associated sensor technologies. [2] More recent work continues to develop gas sensors with improved sensitivity and environmental robustness. [3], [4] Other studies have demonstrated warning through photoacoustic gas sensing, electrochemical impedance, mechanical stress and strain, and contactless sensing. [5]– [9]. The central difficulty is not whether precursor signals exist; it is whether they remain observable and reliable when the sensor is moved from the instrumented laboratory cell or pack to the outside of a sealed, heterogeneous battery enclosure on a moving vehicle. E2W-specific work also exists. Madugula et al. report an AI-based early-warning approach for E2W battery packs, demonstrating that the vehicle domain is receiving increasing attention. [10]

However, that work does not remove the distinct design question considered here: an aftermarket module that operates externally and does not depend on modifying the battery pack or assuming access to the OEM BMS. Accordingly, this paper develops a conceptual framework rather than claiming experimental validation. Its contribution is the structured translation of established sensing principles into a retrofit-oriented architecture, together with explicit treatment of placement, environmental robustness, signal fusion and embedded feasibility. The paper deliberately distinguishes evidence demonstrated in laboratory or integrated battery systems from functions that remain to be experimentally validated for retrofit E2Ws.

II. THERMAL-RUNAWAY PRECURSORS AND EARLY-WARNING SIGNALS

Thermal runaway involves coupled electrochemical, thermal and mechanical processes. Depending on cell chemistry, state of charge and abuse condition, gas generation and other measurable changes can precede rapid temperature escalation. For an early-warning system, the useful signal is therefore not necessarily the most obvious final symptom; it is the signal whose onset is sufficiently early, repeatable and measurable under the intended deployment conditions.

Gas sensing has one of the strongest evidence bases. Wang et al. organize the gas-detection literature around H_2, CO, CO_2, C_2H_4 and CH_4 and emphasize the potential of small, sensitive and integrable resistive sensors. [2] Deng et al. more recently identify gas sensing as a promising route while highlighting unresolved issues in selectivity, environmental robustness and practical deployment. [3] Hou et al. demonstrated a humidity-resistant Ce-doped MoS_2 hydrogen sensor using CALB 72-Ah lithium-iron-phosphate batteries and reported a 76-s improvement relative to temperature-based detection under the tested conditions. [4] This result is useful as evidence that gas sensing can precede conventional temperature-based warning, but it should not be interpreted as a 76-s performance guarantee for the proposed retrofit module.

Photoacoustic sensing provides another quantitative example. Liao et al. used C_2H_4, CH_4 and CO with a cantilever-enhanced photoacoustic spectrometer and reported average warning times of 7.3 min at 50% state of charge and 11.5 min at 100% state of charge for NCM cells. [5] The strong lead time demonstrates the potential of gas-based detection, while the specialized instrumentation also illustrates the cost and integration trade-off relevant to an aftermarket E2W module.

Temperature remains attractive because sensors are inexpensive, compact and mature. Its weakness is physical: heat generated within a cell must propagate toward an externally mounted sensor, creating thermal lag.

Temperature is therefore retained in the proposed framework as a corroborating signal rather than the sole early-warning channel.

Electrical measurements can provide early information without physically opening the pack. Dong et al. demonstrated an impedance-based approach for early warning of lithium-ion battery thermal runaway, while also identifying issues associated with practical measurement and deployment. [6] For a low-cost retrofit module, full electrochemical impedance spectroscopy is consequently treated as a secondary research option rather than the primary sensing channel.

Mechanical signals deserve particular attention because they can be measured at an external surface. She et al. reported an early-warning method based on mechanical stress using commercial square 280-Ah lithium-iron-phosphate batteries and obtained more than 30 min of lead time in their experimental setting. [7] Wu et al. subsequently investigated a strain-based method and reported warning ahead of conventional temperature-based confirmation in their model. [8] These results make mechanical sensing a promising candidate for future retrofit validation, although neither study establishes performance on a moving E2W with heterogeneous battery enclosures.

Acoustic and contactless sensing are also active research directions. Owen et al. demonstrated operando ultrasonic monitoring for thermal-runaway detection, while recent surveys identify wireless and contactless battery sensing as an emerging area rather than a solved deployment problem. [9], [11] For road-going E2Ws, however, vibration, motor noise and changing acoustic paths may confound acoustic measurements. Acoustic sensing is therefore not selected as an active primary channel in the present framework.

III. COMPARATIVE ASSESSMENT OF SENSING OPTIONS

The literature supports a comparative rather than single-sensor view. Table I summarizes the engineering implications for a retrofit application. The ratings are qualitative because the cited studies use different cells, trigger conditions, sensor locations and test environments; combining their numerical performance values into a single ranking would create a false precision.

TABLE I. QUALITATIVE COMPARISON OF CANDIDATE SIGNALS FOR A RETROFIT E2W MODULE.

Method	Early-stage potential	Retrofit practicality	Main advantage	Main concern	Role in framework
Gas	High	Moderate	Chemically specific precursor	Placement, humidity, cross-sensitivity	Primary
Temperature	Low–moderate	High	Low cost and mature	Thermal lag	Corroborating
Current	Moderate as context	High	Captures electrical-abuse context	Not a direct TR precursor	Context / false-alarm reduction
EIS	Potentially high	Low–moderate	Sensitive to internal state	Hardware/measurement complexity	Secondary research option
Mechanical strain	Potentially very high	Promising	External measurement	Unvalidated on E2W retrofit	Future/complementary
Acoustic/ultrasonic	High in lab	Uncertain	Non-invasive	Road/motor noise	Out of active design

IV. THE RETROFIT PLACEMENT PROBLEM

The principal engineering constraint is sensor access. Most quantitative early-warning demonstrations place the sensor close to the cell, inside a pack, in an instrumented enclosure, or in a controlled test environment. A retrofit module cannot assume any of these conditions. In an existing E2W, the battery enclosure may be sealed, the internal geometry may be unknown, vent paths may differ between manufacturers, and the module may have to tolerate vibration, weather and thermal cycling.

Gas sensing illustrates the problem most clearly. A gas sensor can only respond if a representative gas concentration reaches its sensing surface. Mounting the sensor outside an intact enclosure therefore does not automatically reproduce the performance demonstrated in an open or instrumented test cell. The proposed architecture consequently treats placement as a first-order design variable rather than a minor installation detail. Candidate locations include existing vents, seams or other manufacturer-defined interfaces where gas exchange may occur without opening the enclosure. The framework does not claim that every sealed pack will provide a usable external gas path; this is a key experimental question. The same reasoning applies to other modalities. External temperature is physically measurable but delayed. Surface strain is inherently compatible with external measurement but depends on enclosure mechanics and mounting conditions. Acoustic sensing is externally accessible but vulnerable to environmental noise. Thus, retrofit feasibility is not determined solely by the intrinsic sensitivity of a sensor; it depends on whether the physical signal survives the transfer path from the cell to the external mounting position.

V. PROPOSED CONCEPTUAL ARCHITECTURE

The proposed module is deliberately simple. Its objective is not to reproduce a complete OEM battery-management system, but to provide an independent rider-facing early-warning layer that can operate without modification of the battery pack.

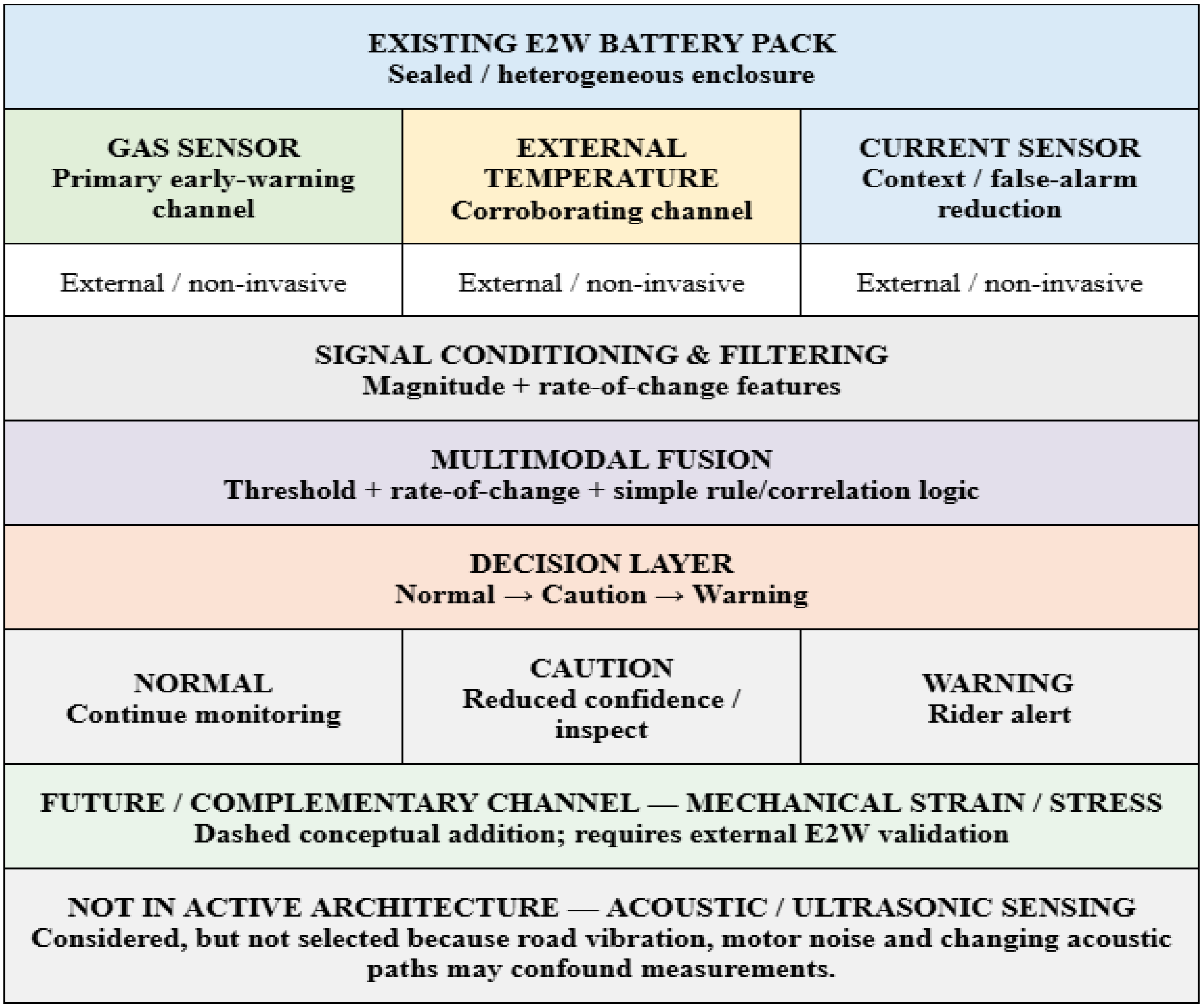

Fig. 1. Proposed conceptual architecture for an external, non-invasive, retrofit-compatible E2W thermal-runaway early-warning module.

Note: The architecture is conceptual and has not been experimentally validated as an integrated E2W retrofit system.

The primary channel is a compact gas sensor positioned as close as practicable to an existing vent or enclosure interface. CO_2 and/or H_2 are proposed as initial targets because the literature identifies them among characteristic thermal-runaway gases and recent experimental work demonstrates the usefulness of hydrogen sensing. [2], [4] Sensor technology may be selected according to cost, power and environmental requirements; the conceptual framework does not commit to one commercial sensor or claim a specific detection limit.

External surface temperature forms the second channel. It is not expected to provide the earliest indication by itself; instead, a temperature rise following a gas anomaly can increase confidence in the warning. A non-invasive current measurement forms a contextual channel. Abnormal current during charging or discharge can indicate electrical stress and can therefore modify the alert logic without being treated as proof of thermal runaway.

A lightweight embedded controller combines these signals using threshold and rate-of-change rules. A representative logic is: a gas anomaly establishes a preliminary warning state; corroborating temperature change raises confidence; an abnormal current condition increases risk context; persistent or rapidly increasing gas response escalates the alert. If the gas signal is unavailable or ambiguous, the module should report sensor fault or reduced confidence rather than silently treating absence of gas as evidence of safety.

This rule-based approach is intentional. Although machine-learning prediction is an active research direction, a retrofit safety accessory has limited computational, power and training-data budgets. A transparent rule-based layer is easier to audit, update and implement on a low-cost microcontroller. Machine learning can be considered later after field data are available across multiple E2W battery designs.

VI. EMBEDDED IMPLEMENTATION AND ALERT STRATEGY

A practical module can be organized into five functional blocks: sensing, signal conditioning, decision logic, alerting and power management. The sensing block acquires gas, temperature and current information. Signal conditioning removes obvious noise and converts sensor outputs into normalized values. The decision layer evaluates absolute thresholds together with rates of change over a short moving window. The alert block provides a local audio-visual warning to the rider, while the power block manages low-power operation and sensor warm-up requirements.

The decision logic should distinguish at least three states: normal, caution and high-risk warning. A sensor-fault state should be separate so that loss of sensing is not interpreted as a normal battery condition. The thresholds should not be copied directly from laboratory studies because enclosure geometry, sensor placement, ambient conditions and battery chemistry will alter the observed signal. Instead, threshold selection is an explicit future calibration task.

The design also favors modularity. A gas-sensor board, temperature interface and current-sensing interface can be replaced independently as evidence improves. This is particularly relevant to heterogeneous E2W packs, where a single universal mounting arrangement may not exist. The module should therefore be designed around configurable sensor channels rather than a fixed assumption about one battery enclosure.

VII. ANTICIPATED EVALUATION FRAMEWORK

Because this paper is conceptual, it does not report experimental accuracy or warning time for the proposed module. Instead, future validation should evaluate the following criteria.

- Detection lead time relative to an agreed thermal-propagation or failure reference event.
- False-alarm rate under normal riding, charging and parking conditions.
- Missed-event rate across representative failure triggers.
- Gas detectability at multiple external enclosure locations and vent configurations.
- Robustness to humidity, ambient temperature, vibration and road noise.
- Sensor drift and calibration stability over repeated thermal cycles.
- Power consumption and warm-up behavior under realistic duty cycles.
- Performance across heterogeneous E2W battery chemistries, capacities, enclosure geometries and vent arrangements.
- Alert latency and rider-perceivable warning reliability.

VIII. DISCUSSION

Three architectural directions emerge from the evidence. A gas-led design has the strongest direct experimental foundation and the clearest chemical link to thermal runaway, but external detectability through a sealed enclosure remains unproven. A mechanical/strain-led design may be more naturally compatible with external mounting and has produced striking lead-time results, but the evidence is not yet specific to small vehicle-mounted retrofit systems. A balanced multimodal design therefore provides the most defensible conceptual position: it retains the established gas evidence while using temperature and current to improve confidence and context, and it identifies strain as a priority channel for subsequent validation.

The comparison also changes how retrofit safety should be evaluated. A sensor that performs exceptionally well in a laboratory is not automatically the best aftermarket sensor. For a vehicle already in service, installation access, environmental exposure, enclosure diversity, maintenance requirements, power consumption and false-alarm behavior can be as important as nominal sensitivity. The proposed framework therefore treats deployment conditions as part of the sensing problem itself.

The E2W-specific literature reinforces the need for this distinction. Madugula et al. demonstrate an E2W early-warning approach using battery-related operating information and AI-based processing. [10] That work establishes the relevance of E2W-specific predictive monitoring, but it does not eliminate the separate opportunity for an independent external retrofit layer. The proposed framework is therefore complementary rather than a claim that existing E2W monitoring research is absent.

IX. LIMITATIONS AND FUTURE WORK

The most important limitation is that external gas detectability has not been experimentally demonstrated for the heterogeneous population of sealed E2W battery packs targeted here. A conceptual recommendation to mount a sensor near a vent cannot substitute for measured transfer characteristics. Future work should first characterize gas transport and signal attenuation at candidate external mounting points.

Second, battery enclosure designs are not standardized from the perspective of an aftermarket accessory. A practical product may require adaptable mounting, configurable thresholds or a small family of installation variants. Third, environmental conditions may alter gas-sensor response and mechanical/acoustic measurements. Long-duration testing is therefore required before any safety-performance claim can be made.

Future experimental work should proceed in stages: controlled cell/pack tests to establish external signal observability; enclosure-level tests to quantify transfer and attenuation; multi-pack tests across battery designs; and finally, vehicle-level tests under charging, stationery and riding conditions. Mechanical strain should be included as a parallel candidate channel because the available literature suggests that it may provide earlier external-compatible information than gas. Field data collected across these stages would also provide the basis for determining whether simple rules are sufficient or whether lightweight machine learning offers a meaningful improvement.

The module should ultimately be evaluated as an additional warning layer rather than a replacement for the battery manufacturer's protection systems or regulatory safety requirements. Its purpose is to improve awareness of a developing event, not to guarantee prevention or rider survival.

X. CONCLUSION

This paper has developed a conceptual framework for a low-cost early-warning module intended for existing electric two-wheelers. The literature establishes multiple measurable precursors to lithium-ion battery thermal runaway, with gas sensing providing the strongest direct evidence for early chemical detection. Temperature remains valuable as a corroborating signal, while current measurement can provide electrical context. Mechanical strain is identified as a particularly promising external-compatible research direction, although its retrofit performance remains to be established.

The central contribution is the reframing of thermal-runaway sensing as a retrofit deployment problem rather than solely a sensor-selection problem. A useful aftermarket module must address physical signal access, enclosure diversity, environmental robustness, embedded simplicity and transparent alert logic. The proposed gas–temperature–current architecture is therefore presented as a testable framework, not as a validated safety product. Experimental characterization of external signal transfer across heterogeneous E2W battery packs is the necessary next step toward determining whether this concept can provide a practical additional layer of rider warning.

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