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Structural design of roof-mounted battery packs for thermal and vibration safety

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Abstract

Roof-mounted battery packs have attracted increasing interest in the design of electric buses, specialty vehicles, and heavy-duty vehicles because roof placement can preserve passenger space, reduce underfloor design constraints and enable modular service access. Meanwhile, roof location poses serious structural and safety demands. The increased mass alters modal behaviour, increases inertial loading during road-induced vibration and increases design challenges of rollover resistance, enclosure retention, thermal control, venting, and thermal-runaway containment. This review is concerned with the structural design of roof-mounted battery packs with a particular focus on thermal safety and vibration safety. Major themes include enclosure design, roof-frame reinforcement, modal and fatigue design, cell-to-module packaging, passive and active thermal control, thermal-runaway propagation barriers, and regulatory or scenario-based validation mechanisms. The reviewed literature suggests that safe roof-mounted integration depends on combined optimization of stiffness, mass, damping, cooling strategy, spacing, insulation, and pack-to-body interfaces, indicating that optimizing a single parameter in isolation is insufficient. However, persistent weaknesses remain in coupled thermo-mechanical modelling, vibration-based thermal design and roof-specific testing under rollover, fatigue, and abuse conditions. This area is also highly important because electrified public transit and heavy-duty platforms to have structurally efficient, thermally resilient, and structurally robust battery systems that can be used over long service lives under harsh dynamic loading.

Keywords*:* Battery Enclosure; Electric Buses; Roof-Mounted Battery Pack; Thermal Runaway; Vibration Safety

1. Introduction

Battery-pack location is one of the first-order structural choices in the design of an electric vehicle since the location of the packaging in the structure determines stiffness pathways, crash and rollover behaviour, thermal routing, ease of maintenance, and distribution of mass. Roof mounting has become an effective approach when underfloor space is limited by low-floor design, axle packaging, passenger access, or driver positioning. In electric buses, as well as some heavy-duty electrified systems, roof mounting has become a viable solution when underfloor space is limited by low-floor architecture, axle packaging, passenger access, or driver placement. However, roof integration is not merely a relocation of a traditional enclosure. A roof-mounted pack raises the centre of mass resulting in changes in body-mode participation and more demand placed on roof members, pillar joints, cross-bearers and pack retention interfaces. This design issue extends beyond enclosure strength to the structural dynamics of the entire body in vibration, manoeuvre, rollover, and thermal abuse [1].

The second complexity concerns thermal safety. Lithium-ion battery systems exhibit susceptibility to local overheating, uneven temperature gradients, accelerated aging, gaseous release, and thermal runaway propagation. After relocating the battery pack to the roof, any possible cooling strategies, vent paths, location of insulation, drainage facilities and service clearances could vary significantly. It may also change the solar loading, ambient exchange, contamination pathways and maintenance conditions caused by roof exposure. Recent review literature on battery pack safety always

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points to thermal runaway mitigation and hotspot control as the key pack-level issues, whereas pack design studies indicate that thermal architecture remains a package-level question, not only a cooling issue [2][3]. This requirement becomes even stronger when the installation is placed on the roof as the enclosure should also be a structural component, environmental shield, thermal shield, and a retention system.

Vibration safety is also highly significant, although it has historically been less thoroughly addressed than thermal abuse and crash scenarios. Broadband excitation in high-voltage battery systems is caused by road roughness, suspension response, braking events, steering inputs, body flexure, and powertrain-induced vibration. Experimental characterization of in-vehicle battery vibration has revealed that pack inputs vary to the point of significant difference compared with simplified laboratory models, and review studies on dynamic loads have shown that the relationship between vibration and battery degradation has yet to be fully established [6][18]. In the case of roof-mounted systems, the problem may be more severe as the pack will be much further out of the vehicle roll centre and may experience greater local displacements during vehicle motion. In practice, vibration safety extends beyond simple resonance avoidance. It also encompasses upholding clamping stability, avoiding fretting and connector fatigue, maintaining coolant-line integrity and limiting cumulative effects in brackets, welds, fasteners and cell supports [18][19][20].

Another challenge is that roof-mounted battery design lies at the boundary of several fields of study, which tend to be examined separately. The literature on structural optimization normally revolves around mass of the enclosures, static deformation, natural frequency, and crashworthiness. Thermal studies are often focused on cell temperature, cooling space, separation or propagation space. Body-frame lightweighting and rollover integrity are typically examined in bus-specific studies. Very few studies combine these concerns into a single roof-based design model. Recent electric-bus research reveals that the mass of battery mounted on a roof can alter deformation behaviour in the roof structure, and rollover oriented work indicates that it is important to retain battery mass and structural clearance in the event of severe events [5][9][17]. Such a set of constraints makes roof-mounted battery packs a specific design issue as opposed to a variant of battery integration under the floor.

This review addresses that gap by analysing the structural design methodologies relevant to roof-mounted battery packs, and the two areas that were especially of interest concerned thermal and vibrational safety. The review includes the evolution of the related literature, comparison of modelling and validation approaches, the reported findings analysis of the roof structures, enclosures, the vibration-response, thermal-control and thermal-runaway resistances, as well as the major research needs of the next-generation heavy-duty electrified vehicles. The following sections present the thematic literature review, conceptual design methodology, comparative discussion of reported results, future research directions, and conclusion in relation to the current scholarly evidence [4][5].

2. Literature Review

The literature applicable to roof-mounted battery packs may be categorized into four interconnected themes: the strategic placement and packaging logic, structural enclosure and roof-frame optimization, thermal safety and runaway control, and the vibration-based durability. Early work on robust EV battery packs developed a broad design rationale where the spatial location of the pack, restraint approach, thermal isolation, and vibration seclusion were considered fundamental determinants of safety. That work was not limited to buses; however, it laid the conceptual foundations of subsequent development of roof-mounted implementations by demonstrating that location yields direct impacts on exposure to thermal, mechanical and impact risks [1]. Other more recent bus-specific safety inspections build upon this argument by determining battery location, body integration, and regulatory compliance to be key safety factors in battery electric buses [5]. Roof mounting is not inherently superior; it offers underfloor packaging benefits at the cost of higher demands and places higher demands of the upper structure and pack attachment system.

The second stream of literature is related to roof and enclosure structure. Experiments into the optimization of electric-bus roofs reveal that the large mass of the battery pack mounted on the roof can significantly increase deformation and increase deformation demand and reduce safety margins unless the roof frame is redesigned to accommodate it. It has been indicated that multi-material topology optimization of bus roof structures makes lightweight redesign possible, which must be achieved through careful control of stiffness distribution and load paths [9]. Related studies on bus body-frame optimization indicate that the additional mass associated with battery systems necessitates multi-objective optimization approaches that balance rollover resistance, stiffness, and weight [10]. On the enclosure side, research on EV battery pack enclosures has produced optimization frameworks that integrate mass minimization and deformation control with improved natural frequencies, which suggests that enclosure design is a modal and fatigue issue in addition to a weight issue [7][8]. In the case of roof mounted systems, this literature suggests that the enclosure cannot be developed without regard to the supporting roof structure.

The third theme is concerned with thermal safety. Battery-pack design analyses consistently show that thermal management and abuse tolerance depend on battery spacing, cooling architecture, thermal interface design, and material choice [3]. The propagation of thermal runaway is better understood in primary research on the subject. Low-order and coarse models indicate that the distance between cells, the configurations of modules, the activation temperature and thermal conduction pathways determine whether thermal events remain localized or propagate across a pack [4][12][14]. Experimental work on passive thermal protection using phase change composite barriers has also established that propagation can be slowed or even prevented under nail-penetration abuse [11]. Recent comparative studies of automotive packs using NMC-811 and LFP cathodes incorporate a system-integration aspect since they show how safer chemistries or additional mitigation measures can affect energy density and packaging efficiency [15]. In the case of roof-mounted battery packs, this piece of evidence is significant since the enclosure is often located close to structural components of a lightweight body and passenger areas, propagation control and controlled venting are particularly important.

A fourth body of research analyses the effect of vibrations on cells and packs. Measurements from real vehicles have demonstrated that battery packs are not subjected to simple sinusoidal loading, but a complex vibration input [6]. It has been reported in review studies on dynamic loads and vibrations that the unresolved mechanical-electrochemical coupling is present, in regard to fatigue, contact degradation, seal wear, and long-term safety risk [18]. Statistically significant changes have been observed in experimental results on lithium-ion cells with reduced capacity and increased direct-current resistance following exposure to vibration [19] and other cathode materials also exhibit performance loss and temperature sensitivity under vibration [20]. At the pack level, based on an emerging body of machine-learning-assisted and finite-element-based research examining vibration stress and fatigue-life prediction, results indicate that structural thickness, bracket geometry, and state-of-charge-dependent stress fields can strongly influence predicted fatigue life [16]. These data indicate that the design of roof-mounted packs must be based on the consideration of vibrations during structural design rather than only during late-stage validation.

There is evident improvement in these thematic streams, but there is still disintegration. The structural studies normally terminate at mass, deformation or mode shape. Thermal analyses frequently make enclosure assumptions as opposed to determining those enclosure assumptions by realistic vehicle-body integration. Bus specific studies usually pay attention to rollover or roof strengthening without a description of thermal propagation. The literature then confirms that there is a clear need for a common design approach that integrates roof-frame design, enclosure optimization, thermal barrier, cooling plan and vibration stability.

Table 1 Summary of key findings

Ref	Focus	Key Findings
[6]	In-vehicle battery vibration characterization	Real driving inputs showed complex vibration environments at pack level, indicating that laboratory simplifications may underrepresent service loading severity.
[7]	EV battery enclosure optimization	Multi-objective optimization improved mass, deformation, and minimum natural frequency simultaneously, supporting resonance-aware enclosure design.
[8]	Lightweight battery-pack enclosure with AHSS	Size optimization with advanced high-strength steels improved structural efficiency and crashworthiness-related performance while reducing enclosure mass.
[9]	Electric bus roof structure topology optimization	Roof-mounted battery mass was shown to increase deformation demand, while multi-material topology optimization produced lighter yet safer roof designs.
[10]	Electric bus body-frame lightweight optimization	Collaborative optimization improved body-frame efficiency under strength and rollover considerations, highlighting system-level design trade-offs in battery-electric buses.
[11]	Passive thermal barrier against propagation	Phase change composite material reduced or delayed thermal runaway propagation, offering low-complexity pack-level mitigation.
[12]	18650 pack thermal runaway modelling	Ambient temperature, spacing, and stacking arrangement strongly affected propagation speed and risk.

[13]	NMC pack thermal runaway after fast charging	Higher spacing and triggering temperature reduced propagation risk; fast-charging history altered propagation behaviour.
[14]	Reduced-order thermal runaway pack model	Reduced-order modelling captured module and pack propagation behaviour with major speed gains relative to detailed simulation.
[15]	NMC-811 versus LFP automotive propagation behaviour	Safety measures influenced system integration and energy-density trade-offs, showing chemistry choice is inseparable from packaging design.
[16]	Pack-level vibration stress and fatigue-life prediction	Deep-learning-assisted modelling identified critical structural members and accelerated durability-oriented design evaluation.
[17]	Electric bus battery behaviour in rollover	Finite-element assessment demonstrated the importance of battery retention, deformation control, and regulatory compliance under rollover loading.

Table 1 reflects that the field has developed over time out of general design advice to specific structural, thermal, and vibration models. Nevertheless, explicit roof-mounted design frameworks remain fairly scarce, and many of the resulting insights have not yet been integrated across neighbouring sub-disciplines.

3. Methodology

The reviewed literature draws on vehicle-body structural analysis, battery-enclosure optimization, thermal optimization, and durability testing. Finite-element analysis is the most prevalent tool in roof structures and pack housings since it can account for static loading, modal response, stress concentrations around local areas and severe-event deformation in a single modelling chain [7][8][9]. As seen with bus structures, this is generally shell based body modelling with concentrated or diffuse battery mass, which is followed by stiffness, modal analysis, rollover simulation, or rather topology optimization. These methods are good in terms of geometric and structural details, whereas pack thermal properties and interface degradation processes are often simplified.

A different pattern appears in thermal modelling. Many studies use lumped or reduced-order models of module- and pack-scale propagation, whereas others use experimentally calibrated thermal networks or abuse-driven numerical simulations [4][12][14]. The significant advantage of a reduced-order method is the ability to run computations at high speed and explore multiple scenarios, as well as when rapid screening of the design space is needed in the initial stages. An obvious weakness is that enclosure geometry, vent-flow complexity, and local contact conditions can only be represented approximately. In the case of roof-mounted battery packs, this approximation may be significant since the wall thickness of an enclosure, location of thermal insulation, clearance of the pack roof and direction of venting are structurally limited.

Studies which focus on vibration provide the third methodological family. Field-characterization efforts determine real service excitation [6], experimental cell studies determine electrical or degradation effects when vibrating [19][20], and pack-level structural analysis is based on modal tests, fatigue models or machine learning to accelerate stress and life forecasting [16]. Such techniques are of particular importance to roof-mount systems since upper-body structures may enhance local motion or relocate dominant modes with respect to underfloor packs. One of the strongest aspects of this literature is that it acknowledges the fact that exposure to vibrations is not solely a comfort issue, or a noise issue; the exposure is a durability and safety issue. One limitation that remains constant is that vibration and thermal effects are normally studied separately.

An important integrative bridge is made at bus-specific roof and rollover research. Roof-optimization studies already account for battery mass in vehicle-body design [9], and rollover-oriented battery research evaluates retention and deformation with regulatory conditions [17]. Nevertheless, it is not a very common case to find a complete thermo-mechanical design framework. This literature suggests thus a multi-layer approach where the design of roof-frames, pack-enclosure design, thermal performance, vibration-durability and severe-event safety are not developed sequentially, but jointly.

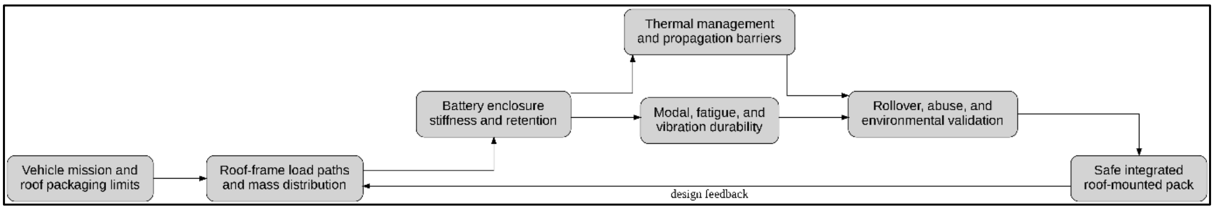

Figure 1 Conceptual framework for roof-mounted battery pack design

Figure 1 presents the literature reviewed in the form of a closed-loop design process. The figure indicates that mission profile, roof-body integration, enclosure mechanics, thermal safety, and validation must all be considered as parts of a single system. This framework aids the argument since it demonstrates why robust roof-mounted battery safety cannot be achieved by optimizing mass or temperature in isolation.

One recurring theme identified throughout the literature is the use of more powerful techniques that unite fast screening instruments with higher-fidelity checks. Reduced-order thermal models, surrogate-assisted structural optimization, and machine-learning-based fatigue prediction are best applied in association with experimental or in severe-event validation as opposed to being viewed on their own as alternatives to testing.

4. Discussion

One of the main findings across the literature is that the safety of roof-mounted batteries is governed by interactions between systems rather than by any single design feature. The research work on bus roof structures reveals that the introduction of battery mass to the roof also alters the deformation trends and undermines safety margins, unless the roof structure itself is re-engineered [9]. At the vehicle scale, bus body-frame optimization leads to similar conclusions regarding optimization of battery-electric layouts through joint lightweighting and reinforcement to maintain structural performance [10]. This directly applies to roof-mounted battery-pack enclosures: the strength of the enclosure cannot independently ensure safety when the roof frame around the battery pack is not torsionally rigid enough, able to withstand rollover loads, or capable of effectively transferring loads.

The second notable observation is in regard to modal behaviour of enclosure and resistance to fatigue. Studies on multi-objective enclosure optimization show that low mass and high natural frequency can be pursued jointly, though the design space is limited due to the deformation and manufacturability factors [7]. Subsequent work on lightweight enclosure construction using high-strength steels shows that significant weight reduction is possible without affecting primary structural performance [8]. In the case of roof-mounted packs, these results make them especially useful since an enclosure with poor modal separation could be driven to resonance by body or road-induced frequency, allowing an extremely stiff but heavy enclosure to aggravate roof load demands. The literature therefore supports a combination of design strategies: an adequate level of stiffness to maintain modal separation without the layout being too rigid, plenty of compliance in the interfaces to keep the local stress levels down to a manageable level, and a sufficiently low mass to avoid inertial amplification.

The third significant finding is that thermal safety depends strongly on structural variables that are also pack-architecture variables. The effects of spacing, thermal resistance within cells, formation of modules and the triggering conditions have repeatedly been demonstrated through thermal runaway modelling to determine the severity of propagation [4][12][13][14]. Such variables cannot be independent of structural design. Module packaging density is influenced by cell spacing; enclosure mass and structural layout may be altered by barrier plates; vent pathways can modify the enclosure geometry; and thermal pads or thermal composite may also change both the stiffness and damping. This fact is particularly critical to roof-mounted packs since strict roof-height constraints frequently promote compact packaging. The literature suggests that densification beyond a certain limit may improve packaging efficiency while reducing thermal resilience.

The fourth finding is related to passive mitigation. Experimental research on phase-change composite materials shows that it is possible to enhance the propagation resistance without very complicated active systems [11]. That is evidently valuable in applications where roof-mounted access, simplicity, serviceability, and predictable failure behaviour are important. Passive systems, however, are not a complete solution. Extra material layers may contribute to additional weight and change heat-rejection behaviour under typical use and make their inspection or replacement harder. Similar studies on chemistries and system integration indicate that the safer behaviour of packs can be achieved at the expense of reduced volumetric or gravimetric efficiency [15]. Roof-mounted design as such entails some trade-off between structural mass budget and thermal resiliency.

A fifth major finding emerges from the vibration literature. Measurements on the vibration inputs of real vehicles and review studies have revealed that the input of battery vibrations is irregular and multi-source, whereas cell-level measurements have demonstrated that capacity, resistance, and consistency measured after exposure to vibration are measurable and degraded [6][18][19]. Several studies have reported material degradation across different cathode systems [20]. These findings provide the indication that the issues of vibration safety cannot be viewed solely as preventing bracket fracture. Vibration over long periods may compromise the electrochemical performance, electrical interconnect quality and sealing integrity long before structural failure is evident. That issue is more critical in roof-mounted packs due to the potential for body sway, roll excitation, and upper-structure flexibility to increase cyclic loading on pack supports and service connections.

A sixth finding concerns design acceleration through data-driven approaches. Stress and fatigue-life prediction with the help of deep learning has demonstrated a potential to decrease the simulation computational cost of repeated iterations in the pack-structure design [16]. This is useful because roof-mounted pack design often requires repeated iteration with the bracket thickness, cross-member spacing, enclosure rib geometry and local stiffening strategy. One limitation is that the reliability of data-driven models is as good as the training conditions and validation envelope. In the absence of representative excitation data for roof-mounted systems, solar-thermal exposure cases, and realistic body-mode interaction, predictive speed fails to guarantee predictive completeness.

The seventh point of observation is based on a study on electric-bus rollovers. Recent finite-element studies of electric bus batteries operating under ECE R66 and R100 conditions have indicated retention, deformation control, and spacing remain fundamental in case of extremely severe events [17]. Although that research focused on underfloor configurations, its implications for roof-mounted packs are still clear. This increases demands on joint integrity and roof-side energy management in the case of rollover through a roof-mounted system. This implies that design of roof-mounted battery pack must address not only static roof loading, and modal analysis, but also that of credible severe-event, associated with battery retention as well as post-event isolation.

Table 2 Method comparison

Ref	Method	Strengths	Limitations
[7]	Multi-objective FE optimization with surrogate models	Efficiently balances mass, deformation, and natural frequency	Limited direct representation of service-induced degradation
[8]	Size optimization with AHSS-based enclosure modelling	Strong for lightweight structural design with manufacturable material choices	Thermal and sealing behaviour are not primary outputs
[9]	Multi-material topology optimization of bus roof structure	Captures roof-level load-path redesign under roof battery mass	Pack-internal thermal and connection details remain simplified
[10]	Collaborative optimization of electric bus body frame	Useful for vehicle-level trade-offs among mass and safety requirements	Pack enclosure physics are not deeply resolved
[11]	Experimental abuse testing with phase change composite	Directly demonstrates propagation mitigation under triggered failure	Scaling to full roof-mounted packs may require extra validation
[12]	Thermal runaway modelling of 18650 pack	Reveals sensitivity to spacing, ambient temperature, and stacking form	Cell format and enclosure geometry may limit generalization
[14]	Reduced-order pack propagation modelling	Fast scenario evaluation with acceptable accuracy	Simplified local physics can miss detailed venting and contact effects
[16]	Deep-learning-assisted vibration stress and fatigue prediction	Rapid design iteration for pack durability screening	Model fidelity depends on representative training and validation data

[17]	Bus rollover finite-element assessment	Direct relevance to battery retention and regulatory safety	Thermal abuse and long-term fatigue are outside scope
[18]	Review of dynamic loads and vibration effects	Integrates structural and electrochemical degradation perspectives	Does not provide roof-specific quantified thresholds

As indicated in Table 2, no single approach can solve the entire roof-mounted problem of design. Structural, thermal and vibration procedures will continue to be complementary and the most powerful workflow in the future is also expected to be that which is hybrid and not exclusive.

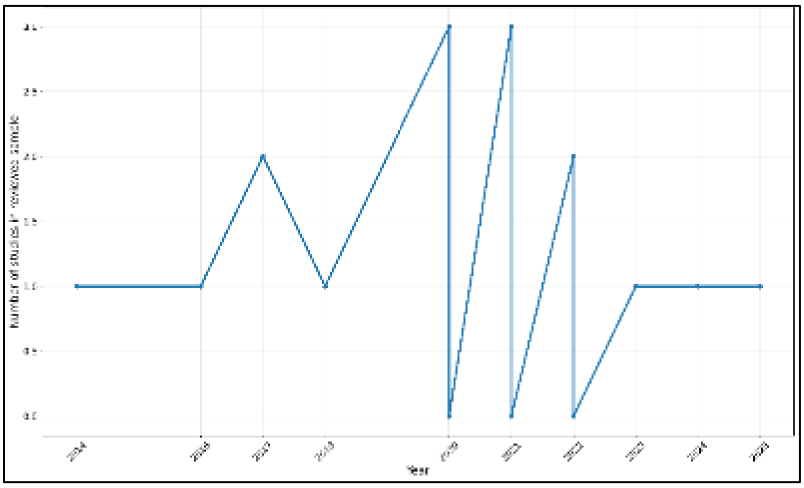

Figure 2 Publication-year trend of reviewed studies on structural, thermal, and vibration safety

Figure 2 shows how the reviewed literature is distributed over time. In the graph, one can observe that there is a shift in literature of early general pack-placement and vibration characterization analyses to more recent coupled subjects of bus roof optimization, thermal runaway propagation analyses, rollover analysis, and fatigue-life analysis. This tendency confirms the claim that the safety of battery installed on the roof has become a more active area of research.

This measure also indicates that the studies involving vibration-specific packs are still lower than the thermal ones, although the risk of vibration is intrinsic to roof-mounted systems. Such imbalance reflects the research gap, which was found in the literature under consideration.

Table 3 Results comparison

Ref	System	Metric	Outcome
[7]	EV battery enclosure	Mass; deformation; minimum natural frequency	Optimized design reduced mass while improving modal and deformation performance
[8]	Automotive battery-pack enclosure	Structural efficiency; lightweight potential	AHSS-based design achieved lighter enclosure with acceptable structural response
[9]	Electric bus roof structure	Structural deformation; lightweight ratio	Roof redesign reduced weight while controlling deformation under roof battery loading
[10]	Electric bus body frame	Strength; rollover safety; mass	Collaborative optimization improved frame efficiency under electric-bus loading demands
[11]	Li-ion pack with phase change composite	Thermal runaway propagation resistance	Passive barrier delayed or suppressed module-level propagation

[12]	18650 lithium-ion pack	Propagation speed; peak thermal response	Packing spacing and ambient temperature strongly influenced propagation behaviour
[13]	Fast-charged NMC battery pack	Propagation order; propagation speed	Higher spacing and triggering temperature reduced propagation severity
[14]	Lithium-ion pack reduced-order model	Accuracy; computation speed	Simulation error remained low while computational speed improved substantially
[16]	Battery-pack structural model	Vibration stress; fatigue life	Data-driven prediction accelerated identification of critical fatigue-sensitive members
[17]	Electric bus battery installation under rollover	Retention; deformation; regulatory safety	Battery integrity depended on controlled structural deformation and compliant retention strategy

Table 3 supports one of the main findings of the review: the decisive design variables are interrelated. The safety of a roof-mounted battery depends on enclosure mass, roof-frame stiffness, modal separation, cell spacing, and barrier geometry, and is governed by interactions among these variables rather than by any single leading parameter.

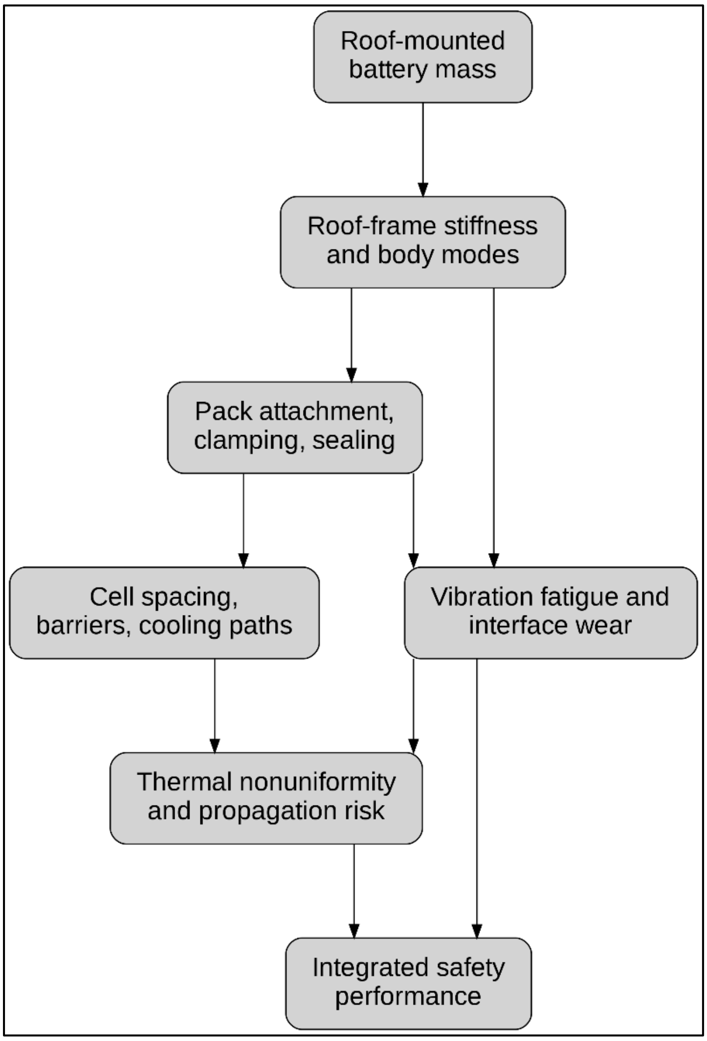

Figure 3 Relationship diagram linking roof integration, vibration response, and thermal safety

Figure 3 maps the causal associations that exist in the literature. The diagram indicates that the mass placement at the roof level impacts the body modes and inertial demand thereby increasing attachment fatigue, enclosure movement, and thermal-path stability. The figure substantiates the discussion since it brings into focus the two-way coupling between the structural vibration behaviour and thermal safety margins.

One of the basic consequences of Figure 3 seems to be that vibration mitigation and thermal mitigation must not be developed under separate design streams. The geometry of the bracket, ribbing or change in enclosure wall design can enhance the mode separation along with altering the thermal resistance as well as propagation pathways.

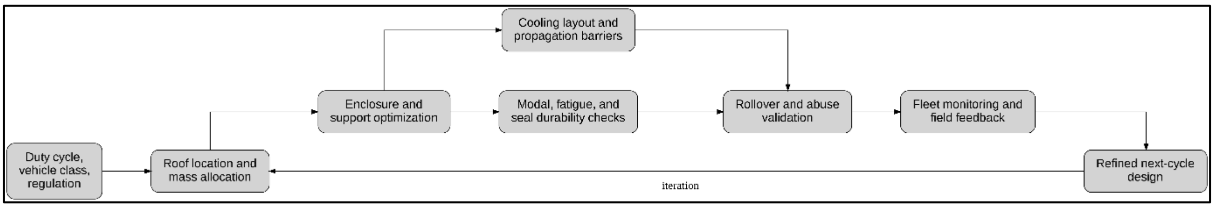

Figure 4 Integrated model for safe design of roof-mounted battery packs

The integrated design model in Figure 4 is based on the reviewed evidence. It connects the definition of the mission, structural integration, enclosure design, thermal protection, durability validation, and extreme-event testing within an iterative design process. This model helps to conclude that the safe roof-mounted battery packs must be developed through closed-loop iteration with feedback from testing and service conditions.

The integrated model shows that a significant gap is present in existing literature: service-life feedback is far less advanced in comparison with the first-cycle optimization. Since roof-mounted systems are fatigue-sensitive and temperature-sensitive, field-informed refinement will tend to be one of the characteristic patterns of future safe systems.

Future Directions

Future research should prioritize comprehensive thermo-mechanical modelling of roof-mounted battery packs. Existing research typically analyses roof construction, pack vibration and thermal abuse as different analytical entities. The next step is to incorporate body flexure, modal excitation, attachment compliance, heat generation, propagation barriers and venting behaviour in a single chain of simulation. Such a framework would also be of great use particularly in electric buses where there is strong interaction between the roof packaging, rollover requirements as well as passenger safety margins.

A second priority is characterization of roof vibration. The relevance of real-service inputs has been established in the literature on battery vibration, but most available literature is vehicle-level and not specific to roof locations. Instrumented fleet experiments on electric buses and heavy-duty vehicles would be able to compare the roof-frame acceleration spectra, local displacement amplification, bracket load histories, and temperature-vibration interaction on real routes. This would enhance fatigue prediction, enclosure optimization and development of test procedures.

The third promising area is that of multi-functional interfaces and materials. Packs mounted on the roof involve lightweight, stiffness, thermally resistant, corrosion-resistant and long-term cyclic loading structures. This opens the possibility of advanced sandwich panels, composite-metal enclosures with hybrid structural properties, fire-resistant insulation layers, and support elements with useful damping capacity. The key challenge is to ensure that gains in one property do not create hidden penalties in manufacturability and inspect ability or repair.

A fourth research requirement is an issue of validation in mixed scenarios. Overhead mounted packs can experience solar heating, ambient cycling, vibration, and water ingress, and the occurrence of rare extreme events in the combined sequences rather than in isolation. Future experimental designs must thus not rely on single-factor studies, but they need to embrace integrated loading programs that better reflect service conditions. Such transition will entail interdisciplinary effort involving vehicle structures, battery research, thermal research, longevity and safety control.

5. Conclusion

The literature review demonstrates that structural design of roof-mounted battery packs is an integrated safety concern where thermal performance, vibration performance, roof-body mechanics, and structural integrity are not to be managed independently. This same general conclusion appears across studies of pack location, enclosure optimization, bus-roof strengthening, vibration characterization, and thermal modelling, all of which highlight the coupled roles of mass, stiffness, damping, thermal resistance, spacing, and mechanical integrity.

Roof-mounted applications are particularly challenging because the added battery mass changes the global structural behaviour of the vehicle, while the enclosure must also provide modal robustness, environmental protection, and thermal compartmentalization. Structural investigations show that safety margins can be recovered by redesigning the roof and enclosure, but the vibration literature depicts that durability cannot be inferred from static strength alone. Thermal analyses also indicate that compact, high-energy-density packaging can reduce safety margins unless propagation barriers, spacing, and cooling channels are carefully designed. Important gaps remain in the literature, particularly in coupled modelling, data on roof excitation, and systematized validation under combined dynamic and thermal load. Recent studies increasingly address severe events, but evidence on long-duration rooftop-pack durability remains limited. Existing knowledge is sufficient to establish the fundamental design principles, but not to eliminate all real-world uncertainties.

More broadly, the academic importance of this area lies in treating battery-pack design as a component-to-vehicle integration problem. Roof-mounted battery packs are feasible and can be safe, but only when structural and thermal decisions are made through a rigorous design process and refined through real operating experience.

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