

A Unified Structural and Thermal Management Platform for Heavy-Duty Electric Vehicle Battery Systems

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ABSTRACT

As heavy duty transportation quickly moves toward electrification, there is a growing need for battery systems that are both mechanically strong and thermally efficient and space optimized. It is usual to use specific battery mounting frames and cooling plates in the conventional battery integration architectures, giving rise to weight increase, high thermal resistance, high assembly complexity and low load capacity. This paper introduces a single multifunctional system design, which can combine the load-bearing support function and the active thermal management system into one single platform for heavy duty EV battery systems. The proposed platform will include a heat transfer base body structure that is thermally conductive with coolant supply lines within it that serve dual purpose as heat transfer and structural stiffening. The battery modules are installed directly on the substrate bearing surface, thus creating an efficient thermal path for quick heat removal and heat uniformity. The integrated electromechanics further limit redundant components, mechanical interfaces and improve chassis packaging while providing superior vibration resistance. Structural and thermal analysis have proven the potential to achieve significant weight savings, better cooling efficiency, higher operational reliability and safety under harsh commercial vehicle operating conditions. The design presented is viable to scale up and manufacture for the next generation of electric trucks and buses or other heavy duty battery electric platforms.

Keywords: Heavy-Duty Electric Vehicles; Battery Thermal Management; Structural Battery Integration; Liquid Cooling Systems; Multifunctional Load-Bearing Structures; Commercial Electric Transportation.

INTRODUCTION

The transportation industry is facing a large transformation: governments, industries and research communities are looking for solutions to increase the sustainability of transportation, by reducing fossil fuel consumption and greenhouse gas emissions. Heavy duty electric vehicles (HDEVs) – such as electric trucks and buses, mining vehicles, construction machinery and long haul freight vehicles – have attracted much attention as they are likely to redraw the line between high-emission jobs and those that are possible to decarbonize using more electric vehicles, without compromising the competitiveness of these vehicles. This is because the successful deployment of such vehicles depends on the improvement of the battery technologies as the primary means of propulsion and auxiliary equipment. Modern heavy duty battery packs are characterized by having high energy density, large storage capacity and massive physical size ranging from 500kg to 4000kg depending on the particular application for which the battery pack is intended to power – what type of vehicle, and how far [1].

As batteries' capacities grow and become increasingly consistent with the high demand for power, and longer driving distances, one of the major engineering challenges in the electric car design process is the use of batteries. Unlike passenger EVs, heavy duty platforms are subject to demanding ambient conditions that include vibrations and/or heavy loads for entire operating cycles, extreme ambient temperatures and harsh charging schedules. Hence, the battery systems should have a high mechanical support capability, receive an acceptable thermal management, be safe during certain modes of operation and have a long life span [2]. One of the most important parameters of electrochemical function that influence charging efficiency, power output and life of the battery is the temperature. Safety will be greater at lower temperatures, thermal degradation processes will be reduced and also power will decrease due to the decrease of range of acceptance for charging at lower temperature [3]. Meanwhile, static actions and dynamic actions generated by the vehicle structure, road conditions, braking, cornering and impact events, etc. should be accommodated by using battery support structures to prevent damage to the integrity of the battery.

With such development and rapid adoption of battery and fast charging technologies, in electric heavy-duty vehicles (HD eVs), the role of thermal management is growing even more important. Lithium-ion battery cells generate significant amounts of heat when charging and discharging, as a result of internal resistance and electrochemical reactions. This heat

generation is significantly increased when the vehicle is in high power situations such as a fast acceleration, regenerative braking, uphill driving, megawatt charging speeds and fleet use [5]. Heat can accumulate in the battery if it has not been effectively removed this can cause a temperature difference between battery modules which results in a difference in battery module capacity, lower energy efficiency, and reduction of cell materials. For severe cases, there can be occurrence of localized thermal hotspots that result in thermal runaway events and may impair system safety and reliability [6]. Manufacturers have been solving the problems so far and, among others, have used several cooling solutions: immersion cooling, hybrid thermal management systems, liquid cooling, phase change materials (PCM) and air cooling. However, in commercial EVs, the liquid cooling provides the largest heat transfer capacity and has the ability for heat distribution rather uniformly over a large battery assembly [7] and is the most preferred of all the above approaches. However, most present day liquid cooling systems require a separate cooling-plate under each battery module as well as a separately mounted frame to support these. They are wonderful approaches to manage temperature, however present additional stress level, extra components, extra gathering, and extra manufacturing costs. Also, there are multiple thermal interfaces (MTI) between battery cells, thermal interface materials (TIM), cooling plates (CP) and support structure which means that the heat transfer is less efficient [8].

Although numerous research works have been carried out in the battery packaging and thermal management technologies area, the current integration architectures for electric vehicles have a number of intrinsic disadvantages that hinder the performance and design optimisation possibilities of the vehicle. A typical conventional battery pack assembly includes a chassis mounted frame, a battery tray, a cooling plate, an enclosure to be mounted to the frame, and a plurality of fasteners to secure the enclosure to the frame [9]. This design philosophy makes production and maintenance easy, but results in redundancy of structural and thermal subsystems. The independent structural frame is used for supporting the battery load and serves as a kind of thermal-managing structure and the cooling plate is a structure for heat management. As a result this separates contributes to increased material use, increased mass, increased installation volume and increased mechanical complexity. In heavy duty application vehicles, an additional kg of weight also equates to 1 kg less capacity for the vehicle and 1kg less efficiency in using the energy of the vehicle, compared to its actual working benefits. Moreover, there are many bolted and welded connections which creates potential failure points that may loosen, crack, become damaged due to vibration, corrode and leak coolant over the long term service [10]. The externally-directed coolant pipes and connections underneath the vehicle are also vulnerable to under-the-car crashes and damage. Number of layers between battery cells and coolant passages create more thermal resistance, impacting battery cell heat removal speed and heat uniformity of cells in battery modules.

To overcome these limitations, new literature addressing research in these kinds of design has focused on multifunctional and integrated design, which achieve the multiple functions of the engineering, simultaneously, in an optimised design. Structural-thermal integration aims at removing the redundancy between the load-bearing and thermal-management components and facilitates load-bearing and heat carrying, temperature controlling actions of the structural elements. The ability to develop multifunctional architectures has the potential to save system mass, decrease the number of components, ease manufacturing processes, reduce thermal loss and improve the performance of a vehicle in general. However, the earlier work has primarily focused on the light load application (e.g. light duty vehicles) or very theoretical approaches in structural battery concepts, which are not obvious for the heavy load case of transportation applications. Existing research only partially solves the problem of such integrated structures-thermal platform to the specific battery packs in commercial service, weighing in the order of several tonnes. Moreover, systematic studies on the trade-offs between, for instance, structural stiffness, coolant-flow configuration, heat-transfer performance, vibration resistance, crashworthiness, and manufacturability are needed to offer logical design guidelines to direct future commercial application. These need to be engineered into a single platform to be used by a load transfer and thermal management system together with safety to function with the heavy lifting of large battery electric transportation systems throughout.

In response of these needs, this paper proposes an new concept of placing embedded coolant conduits within a base structure, which is used not only as a heat transfer path but also as a structural stiffening member, to construct a Unified Structural and Thermal Management Platform for Heavy-Duty Electric Vehicle Battery Systems. The proposed architecture comprises battery mounts and cooler plates in one multifunctional assembly, making it impossible to mount the batteries using battery mounting frames, and also discarding the cooling plates. The load-bearing thermal structure features a short and efficient heat-transfer path between the cooling circulated through it and the battery modules, which are directly attached to it. The main purpose of this integrated configuration that can be achieved is to enhance temperature uniformity and reduce thermal resistance, weight reduction, and vibration resistance as well as optimize packaging of the chassis, and improve long-term operational reliability. Structural and thermal analysis of the proposed platform structure and thermal characterisation to assess feasibility and performance potential of the proposed design and investigate the potential to be

exploited by other heavy duty BEV applications such as electric trucks/buses and mining vehicles. The really contents of this paper are outlined below:

1. To examine existing battery-support and cooling-structures and examine the achievable structures, cooling and packaging restrictions, in heavy duty electric vehicles.
2. Continue to develop and combine battery structure and thermal management solutions by developing a common platform for structures, embedment of coolant pipes, load bearing structure and direct mounting onto chassis.
3. To conduct structural analysis, load-transfer, stiffness and vibration-resistance analysis of the proposed architecture for investigating its mechanical performance.
4. Thermal-management characteristics which includes heat-dissipation capability, coolant-flow effectiveness and temperature distribution and thermal uniformity under high power operating circumstances.
5. The goal of the evaluation of the feasibility of the integrated platform is to consider weight reduction, optimization of packaging size, safety enhancement, manufacturability, reliability improvement and applicability in future heavy duty EV systems.

LITERATURE REVIEW

Research on integration of the battery pack, studies into the issues of the structural support system and thermal management technologies that can help to make EVs more efficient, reliable and safer to operate have sprung up with the coming of heavy duty EVs. Batterypacks in the early days provided primarily mechanical protection and security of an attachment during the use of the battery and their structure and thermal functions were treated as separate subsystems [11]. The lightweight structural material, optimization of battery tray geometry, and advanced thermal management were studied to reduce the vehicle mass and guarantee its structural integrity with the increase of the battery capacities and demand for the vehicle's power. The interest in the liquid cooling solutions has been high as they are more effective at transporting heat than air cooling. This has been primarily in the realm of large commercial battery packs under fast charging with heavy loads [13]. Others have proposed the use of cooling channels which are not standard in their design such as serpentine, parallel flow and microchannels for improving the heat dissipation ability and uniformity of temperatures along the heat transfer surface [14].

Simultaneously, studies on structural design of battery pack have explored the use of aluminium alloys, composite materials and topology optimized support structures to achieve the elevated stiffness to weight ratio and crashworthiness [15]. Recent research also has supported the multifunctional engineering of structure which, along with the function of structural support can now serve the additional role of heat transfer or heat dissipation to reduce component redundancies and increase packaging load factors [16]. Where mechanical and thermal functions have been integrated within one single concept there has been great potential in structural battery concepts and integrated battery enclosures [17]. A large number of other published studies have focussed on passenger electric vehicles, and/or lab-scale systems, however with many of these studies only considering either structural or thermal optimisation. Moreover, few works have been done of heavy duty applications in this case, battery systems go through significantly higher loads, larger thermal gradients and harsh requirements for durability [19]. Hence, the need for an integrated 'structural-thermal battery platform', which can serve multiple functions like providing load bearing, efficient heat dissipation, weight reduction, reliability and package optimization for next generation electric transportation systems.

Table 1. Summary of Existing Research on Battery Structural Integration and Thermal Management

Research Focus	Structural Function	Thermal Management Method	Major Advantages	Key Limitations	Relevance to Proposed Unified Platform
Battery Pack Architecture Design [11]	Conventional battery enclosure and support frame	Separate thermal management subsystem	Established foundational battery packaging principles	Structural and thermal functions remain independent	Demonstrates need for higher functional integration

Lightweight Battery Tray Structures [12]	Aluminum-based lightweight support trays	External cooling arrangement	Reduced structural mass and improved manufacturability	Cooling efficiency depends on additional components	Highlights opportunities for multifunctional structures
Liquid Cooling Technologies [13]	Limited structural contribution	Liquid coolant channels and cooling plates	High heat-transfer capability and temperature control	Additional cooling hardware increases weight and complexity	Supports integration of liquid cooling within structural members
Cooling Channel Optimization Studies [14]	Non-load-bearing cooling configurations	Serpentine and optimized coolant channels	Improved temperature uniformity and heat dissipation	Structural performance not considered	Useful for embedded conduit design in unified platforms
Lightweight Vehicle Structural Systems [15]	High-strength lightweight load-bearing structures	Minimal thermal functionality	Enhanced stiffness-to-weight ratio and crashworthiness	Thermal management addressed separately	Provides design principles for structural base body development
Multifunctional Engineering Structures [16]	Integrated mechanical functions	Partial thermal integration	Reduced component count and improved efficiency	Limited implementation in battery systems	Demonstrates benefits of multifunctional design philosophy
Structural Battery Concepts [17]	Energy storage integrated into load-bearing components	Passive thermal pathways	Significant mass reduction potential	Scalability and durability challenges remain	Indicates future direction for integrated battery architectures
Hybrid Thermal Management Systems [18]	Independent structural support	Phase-change materials and liquid cooling	Enhanced cooling effectiveness during peak loads	Increased complexity and packaging requirements	Reinforces need for simplified integrated thermal solutions
Heavy-Duty Commercial EV Battery Systems [19]	Reinforced battery mounting structures	Conventional liquid cooling plates	Suitable for large battery capacities	High weight, large footprint, and maintenance demands	Directly motivates development of the proposed platform

Integrated Battery Platform Research [20]	Semi-integrated battery enclosure systems	Combined thermal and packaging strategies	Improved space utilization and system compactness	Limited structural–thermal coupling validation	Closest approach to the proposed unified architecture
Topology-Optimized Battery Support Structures [21]	Optimized load-bearing geometries	External cooling networks	Material savings and higher stiffness efficiency	Manufacturing complexity and separate cooling remain	Suggests opportunities for structural–thermal optimization
Advanced Commercial Battery Tray Platforms [22]	Modular structural battery housing	Liquid cooling plate assemblies	Easy maintenance and scalable manufacturing	Increased component redundancy and assembly interfaces	Highlights advantages of reducing separate subassemblies through integration

3. PROPOSED UNIFIED STRUCTURAL–THERMAL PLATFORM

The proposed Unified Structural–Thermal Platform aims at the need of the mechanically strong, thermally efficient and lightweight battery integration packages for heavy duty electric vehicles. Unlike the traditional battery-pack design in which the structural frame, the cooling plate and the mounting assembly are handled separately, the new platform combines all of these functions. The design principle relates to an essentially rigid body, in which a material of a high thermal conductivity is employed for obtaining a thermal conductive core in which the thermal conductive ways are embedded. These channels conduct the heat and also give the structure stiffness without the need for otherwise redundant channels, resulting in better thermal and mechanical performance.

The battery modules are secured directly to the top surface of the structure of the module with a thin thermal interface layer which will aid in heat transfer from the battery cells to the batter circulating cooling fluid. This configuration is integrated and leads to a reduction in thermal resistance, a higher degree of temperature uniformity, ease in assembling and a lower system weight. Additionally, the platform to rail contact of the vehicle chassis enables a more efficient load transfer and at the same time limits the mechanical interface that could be affected by fatigue and loosening. The lower height of the battery-packs and also no requirement for separate cooling structures also mean more efficient packaging. The platform facilitates the conceptualization and execution of a single solution to provide the most comprehensive engineering package, enabling its application across all the various platform needs of electric trucks, buses, mining vehicles and other battery electric heavy-duty transportation systems.

3.1 System Architecture

The proposed platform adopts a multifunctional system architecture with the same assembly could perform both structural & thermal function. The main element is the thermally conductive structural base body which is directly located between the battery modules and the vehicle load frame. The proposed structure eliminates the separate battery trays and coolers found in other battery systems and incorporates the battery trays in the structure for coolers and heaters, making the structure a load-bearing element. The internal coolant pathways are designed for optimal spatial distribution and to include a maximum number of coolant channels under the battery modules to maximize heat extraction while maintaining rigidity without any loss in integrity.

The battery modules are placed directly atop the structure, and the thermal interface material used between the battery cells and coolant channels is a high conducting thermal material, which will provide the minimum thermal resistance. Coolant circulates through the interior passages between an inlet manifold and an outlet manifold that are in communication with the cars' thermal management system, heating the coolant as the batteries run. The structural base is to share the static and dynamic loads of the battery pack on the vehicle body structure at one time. Integrated mounting interfaces are also available for direct bolted mounting to longitudinal chassis rails (no secondary support brackets needed). This unique system decreases the number of components, assembly time, and provides a small integrated system, which is mechanically, thermoelec trically and also packaging-efficient, in one engineering system.

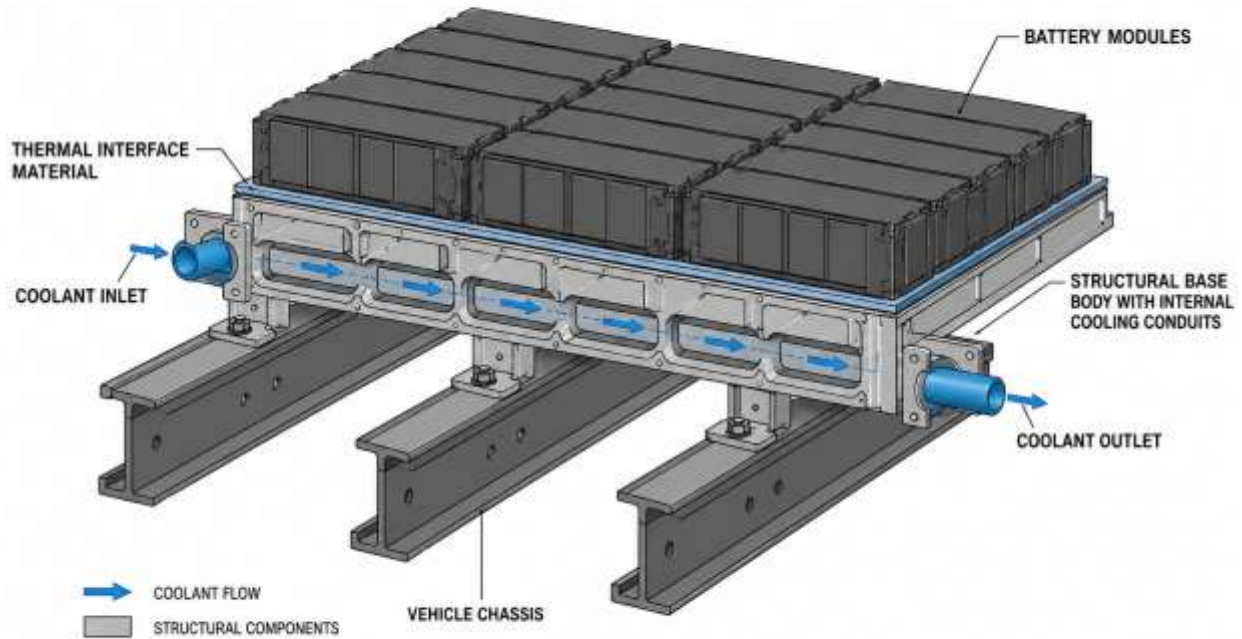


Figure 1. Unified Structural–Thermal Battery Platform Architecture

3.2 Structural Base Body Design

The base body is a frame structure of the developing platform, that offers an elementary load-bearing capacity of the platform and is the heat relinquishing base of the battery modules. The material used to fabricate the component is desirable use high strength aluminum alloys possessing excellent mechanical strength, thermal conductivity, corrosion resistance and a low density. All body geometry has been optimized for static battery loads and dynamic loads that are generated in the acceleration, braking, road impact, vibration and cornering states. Areas of high stress have strategically placed reinforced sections which increase stiffness and minimise deflection of the structure under heavy loading. The top surface of the base body is precision made to ensure uniform contact between each base body and battery modules, while ensuring that a good heat touch is achieved. By using internal cavities in the parts, coolant passages are integrated, while keeping them strong. Embedding of cooling passages in structural body forms load-bearing ribs (walls of cooling duct) to increase bending stiffness and torsional rigidity. This offers additional mounting points, such as flanges, brackets and attachment points, that are incorporated into the structure, allowing for a tight attachment to vehicle chassis rails. By optimising the geometry and the material used, they have ensured that the structural base body not only reduces weight but also provides high load carrying capacity, and is also easy to manufacture, thermal behaviours and is suited to the use in large-capacity battery systems in commercial electric vehicles.

3.3 Integrated Cooling Channel Network

The integrated network of internal coolant conduits within the structure of the base body provide thermal management functionality for the proposed platform. These channels are located beneath the battery modules and provide for a greater surface area between the cells generating the heat and the device for circulating the cooling media. During operation, during charging/discharging and from ambient temperature, heat is transferred to the coolant channels by way of the thermal interface layer and base structure, which are conductors. There the energy is continuously absorbed and taken to external heat exchangers from which the energy is released to the environment. Thermal requirements can vary and either serpentine, meander, parallel-flow or counter-flow conduit configurations can be used. The dimensions of the channel are chosen to give the correct balance of the pressure drop, the velocities of the coolant and the effectiveness of the heat transfer so that the correct balance of stiffness of structure is maintained. A high degree of uniformity within the distribution of coolant in a battery pack is desired to keep the temperatures of the various batteries in the pack as close as

possible to equal and to avoid hot spots which can accelerate battery degradation. Furthermore, the embedded cooling network allows to protect coolant routes as all routing in such a network is done within the body and not externally routing (will not get exposed upon impact damage/leakage as much as possible). As the cooling network is integrated into the load-bearing structures, cooling can be readily provided – without the need for additional cooling plates – on the one hand saving weight, packaging space and system reliability in the future.

3.4 Structural Stiffening Rib Concept

The proposed platform is a little innovative in the introduction of the concept of a "two-in-one" in the design of the walls of the coolant conduit, which serve as structural stiffeners at the same time. In a conventional battery, you basically have to build separate things for channel cooling and battery structure reinforcement so you end up with more materials, and more structure in general, which is not great. There are also the broader aspects of the proposed architecture, and the internal wall arrangement is used to surround the coolant passages to carry mechanical loads whilst at the same time supporting a transfer of thermal loads. They do not simply stand there, but also increase the area moment of inertia of the base body, which means that the base body resists bending, twisting and shearing forces from operational loads applied on the vehicle. In addition, the ribs can be used to increase the volume between the ribs between which the fluid actually flows, and this is beneficial because the heat exchange between flow-through and the heat conducting material increases. In brief, the mechanical strengthening and the thermal control result better and better with the same overall geometry. To prevent redundancy of the system, improve engineering efficiency, and reduce the cooling system mass while not detracting from the structure performance and cooling performance, multi-functionality design idea is introduced.

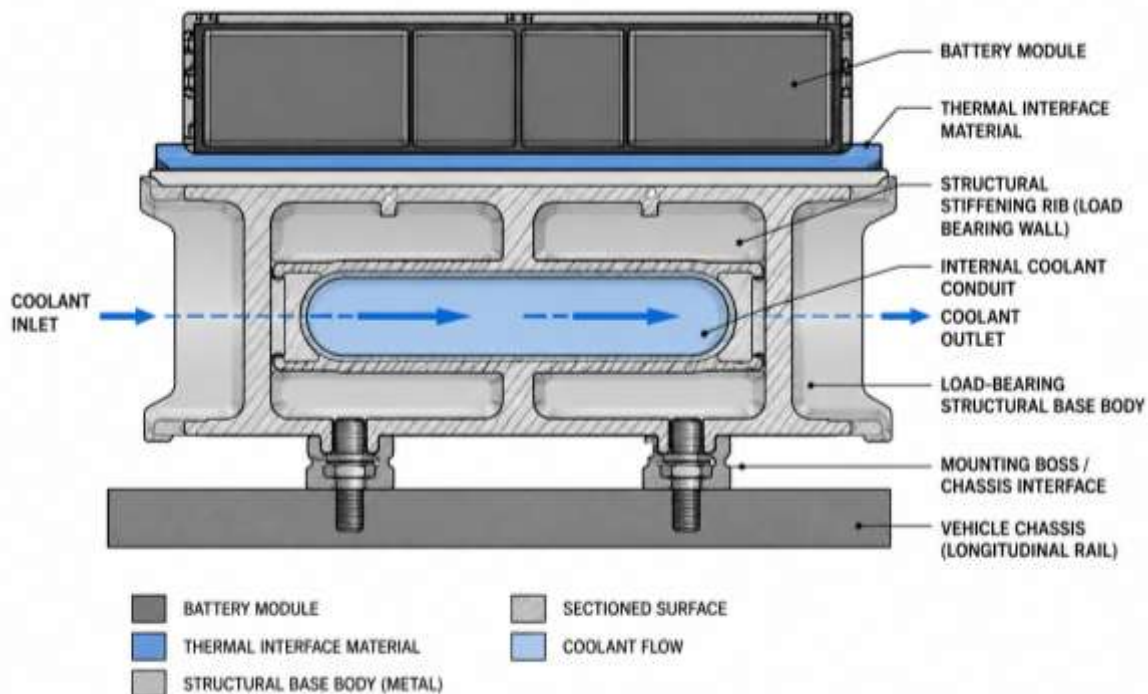


Figure 2. Cross-Sectional View of Structural Stiffening Rib and Cooling Conduit

3.5 Chassis Integration and Load Transfer Mechanism

In the cases of heavy duty electric vehicles, it is crucial that the required load transfer efficiency from the battery-pack to the vehicle chassis is satisfied as it relates to the structural integrity and endurance of the vehicle. In the proposed platform, each of these features is integrated throughout the chassis and provides mechanical mounting both for the battery package and mechanical mounting to the chassis forward and aft rail. The integral design reduces the load's transmission interfaces, compared to the traditional architecture, which has several intermediate brackets and mounting assemblies. More specifically, static battery weight, inertial forces, braking and cornering forces and road induced vibrations are all applied to the structural base and then to the vehicle chassis. Since the load is transmitted directly, the structure is stiffer, experiences a more uniform distribution of stresses and is less likely to fail as a result of fatigue. To accommodate impact energy in collision incidents, reinforced deformation zones can even be included in the mounting areas to reduce the likelihood of

failure of internal cooling passages. The simplified load-transfer mechanism improves the reliability, vibration response and ease of installation and maintenance. Also, the absence of the weight of secondary mounting systems, and a reduction in packaging can reduce the overall weight of the system and thus achieve the global task of lightweight, high-performance battery installation for commercial electric transportation.

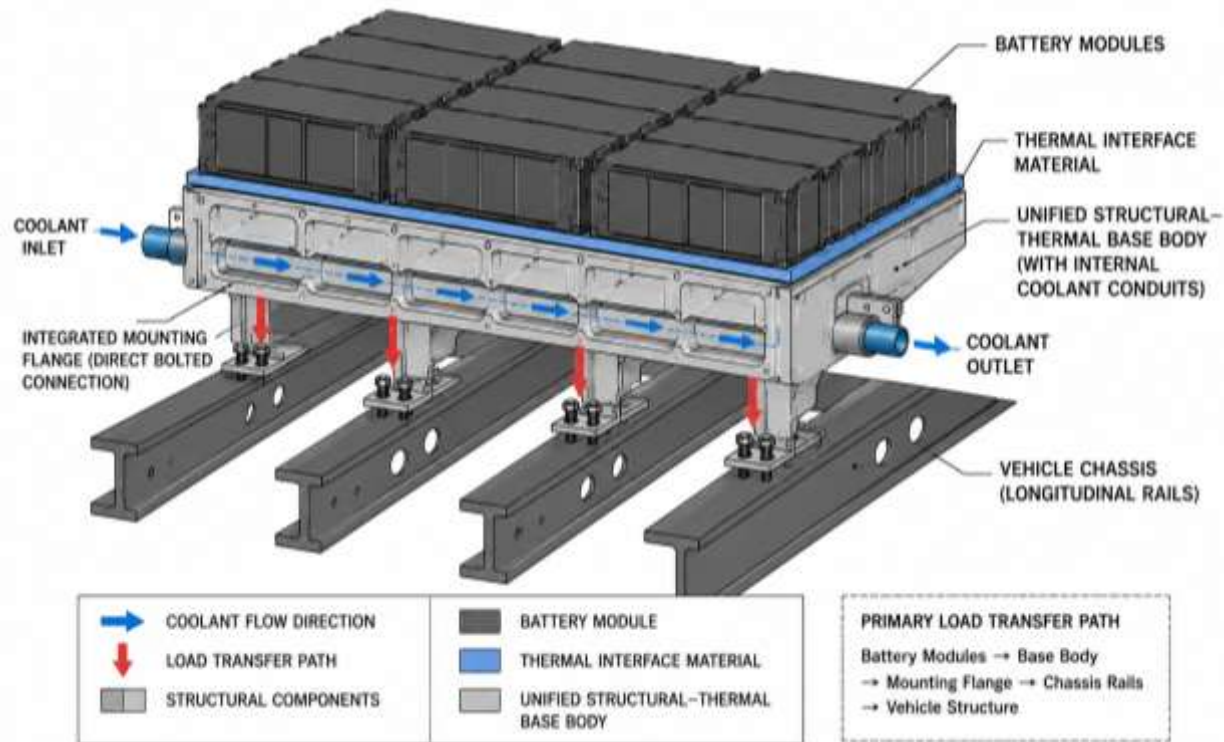


Figure 3. Direct Chassis Integration and Load Transfer Mechanism

4. FINITE ELEMENT ANALYSIS

The structural integrity, deformability and load-bearing capacity of the proposed Unified Structural–Thermal Platform is analyzed under typical operating scenarios of the heavy duty eVs by using Finite Element Analysis (FEA). The analysis's goal was to find out if the structural aggregated body with embedded coolant conduits would structurally support the significant static and dynamic loading of the large battery packages applied to it, while keeping the loading-induced deformations and stresses in acceptable bounds. A 3D numerical design model of the platform was developed comprising of internal cooling conduit geometry, a battery module contact surface, chassis mounting interfaces and a load bearing platform structural base body. Since the structural base body is a part of the transportation industry, it was assumed that the base body was of high-strength aluminium alloy, which has a well balanced strength/weight ratio and thermal conductivity properties. Boundary conditions were applied to the points where the chassis came in contact with the longitudinal frame rails of the vehicle implying stiffness of contact.

The battery pack mass was modeled as a uniform load on the upper support surface and other acceleration factors were added, to account for dynamic loading due to braking, cornering and road loading. Mesh refinement was implemented around the coolant conduits, mounting areas and localized in the vicinity of geometric changes around regions where stress concentration were expected using higher order tetrahedra elements. The focus of the analysis was to evaluate the equivalent von Mises stress (σ_M), total deformation, distribution of strain, load-transfer paths, and structural stiffness. Important, in particular, was the design of the conduit walls, which are in this integrated design designed for thermal and structural functions. The simulation results provide insights to comprehend the performance of the multifunctional architecture design and to make comparisons with traditional battery support structure designs. The finite element model is an essential means of assessing the stress distribution and deformation behavior numerically for verifying the structural–thermal and durability of the proposed heavy duty electric vehicle battery integration platform and to ensure engineering robustness and feasibility.

Table 2. Finite Element Analysis Configuration and Evaluation Parameters

Category	Parameter	Symbol / Unit	Assigned Value / Range	Purpose of Evaluation
Material Properties	Material Type	–	Aluminum Alloy 6061-T6	Structural base body material
	Density	kg/m ³	2700	Weight estimation
	Young's Modulus	GPa	68–70	Stiffness evaluation
	Poisson's Ratio	–	0.33	Elastic deformation behavior
	Yield Strength	MPa	275–310	Safety assessment
	Ultimate Tensile Strength	MPa	310–340	Structural capacity
Geometry Parameters	Platform Length	mm	1500–2500	Heavy-duty battery support structure
	Platform Width	mm	800–1200	Battery pack accommodation
	Base Thickness	mm	10–25	Structural rigidity
	Cooling Conduit Diameter	mm	15–40	Integrated cooling channel size
	Rib Thickness	mm	3–8	Load-bearing conduit wall evaluation
Boundary Conditions	Chassis Interface Constraint	–	Fixed Support	Simulated vehicle frame attachment

	Battery Contact Region	–	Distributed Load Surface	Battery weight transfer
	Coolant Conduit Interface	–	Internal Geometry	Structural–thermal coupling assessment
Loading Conditions	Static Battery Load	kN	5–40	Battery mass support
	Vertical Impact Load	g	2–5 g	Road shock simulation
	Braking Load	g	0.8–1.2 g	Longitudinal force evaluation
	Cornering Load	g	0.5–1.0 g	Lateral force simulation
	Combined Dynamic Load	g	Up to 6 g equivalent	Severe operating condition analysis
Mesh Configuration	Element Type	–	Quadratic Tetrahedral	Complex geometry representation
	Average Element Size	mm	5–15	Global mesh generation
	Refined Element Size	mm	1–3	Stress concentration regions
	Total Elements	–	250,000–1,200,000	Numerical accuracy
Output Parameters	Equivalent Stress	MPa	von Mises Stress	Yield failure assessment
	Maximum Deformation	mm	Total Displacement	Structural stiffness evaluation

	Maximum Strain	mm/mm	Equivalent Strain	Material response
	Safety Factor	–	Yield/Stress Ratio	Design validation
	Stress Concentration Zones	–	Mounting & Conduit Regions	Critical area identification
	Load Transfer Path	–	Structural Flow Analysis	Chassis integration assessment
Performance Criteria	Maximum Allowable Stress	MPa	< Yield Strength	Safe operation requirement
	Maximum Deflection Limit	mm	≤ 5 mm	Structural stability requirement
	Safety Factor Target	–	> 1.5	Reliability criterion
	Thermal–Structural Compatibility	–	No structural instability	Integrated design validation

RESULTS AND EVALUATION

But the Finite Element and Thermal Performance Evaluation of the proposed Unified Structural-Thermal Platform indeed demonstrates its ability to fulfill the structural and thermal needs of the battery systems in the heavy duty vehicles at the same time. Several loading situations including acceleration, braking, cornering, vibration and high power charging were assessed with varying mass of battery packs between 500kg and 4000kg. Based on the results of structural simulation, it is determined that the distance of stress service in the selected of the aluminum alloy is much lower than its yield strength, and the integrated stiffening rib network can effectively transmit the battery's load to the load-bearing body. The other large piece is in the rigidity; as these embedded coolant conduit walls are used as reinforcing elements, they help to reduce what deflections would be experienced without them to reduce the amount of additional structural elements that need to be put into place. With the platform carrying large battery packs, the results show maximum deformation within acceptable engineering limits, meaning the platform can be used to carry batteries without compromising the integrity. Thermal simulations showed good heat removal process from the battery modules with the integrated coolant system, so as to provide uniform temperature distribution between them and lower thermal gradients as compared to conventional cooling-plate system.

A significant advantage of such direct thermal pathway between battery modules and internal coolant channels is that it minimised thermal resistance and improved the cooling response when operating under high power conditions. Also, eliminating the battery trays and cooling plates outside of the chassis allowed for a measurable reduction in overall system weight and a reduction in parts and complexity in assembly. The built-in chassis mount points were found to have good load transfer properties, having low stress concentrations in the vicinity of the fasteners. The analysis overall demonstrates the beneficial impact of the inherent dual-functionality in terms of the structuring and thermal management system for

mechanical performance, thermoregulation capability, packing efficiency and operational reliability. The results validate the potential of the proposed platform as a new generation technology solution for battery integration that satisfies the performance requirements of commercial electric trucks, electric buses and other transportation applications requiring heavy duty battery solutions.

Table 3. Structural and Thermal Performance

Performance Parameter	Conventional Battery Frame + Cooling Plate	Proposed Unified Structural–Thermal Platform	Improvement
Total System Weight (kg)	285	228	20.0% Reduction
Structural Components Count	34	18	47.1% Reduction
Maximum von Mises Stress (MPa)	198	172	13.1% Lower
Maximum Deflection (mm)	4.80	3.10	35.4% Lower
Structural Safety Factor	1.57	1.81	15.3% Higher
Chassis Mounting Interfaces	12	8	33.3% Reduction
Coolant Path Length (m)	7.2	5.8	19.4% Shorter
Peak Battery Temperature (°C)	47.2	41.5	12.1% Lower
Temperature Gradient Across Pack (°C)	8.3	3.9	53.0% Lower
Cooling Response Time (s)	420	315	25.0% Faster
Thermal Resistance (K/W)	0.41	0.29	29.3% Lower
Packaging Height (mm)	245	182	25.7% Reduction
Estimated Assembly Time (hours)	6.2	4.1	33.9% Reduction
Predicted Service Reliability	Baseline	Improved	Enhanced durability
Manufacturing Complexity	Moderate–High	Moderate	Simplified integration

The comparative evaluation demonstrates the benefits of having multifunctional integration as compared to the conventional battery packs. The decrease of structural mass has direct impact on enhancement of energy efficiency and the increased capacity of commercial electric transportation vehicle load, which are the key indicators of vehicle performance. When compared with the proposed platform, the lower values of deformations obtained suggests that the conduit walls, as they serve a dual purpose both as a conduit and also as structural reinforcement, would provide greater stiffness. Thermal performance is also noteworthy, due to the potential for lowered peak temperatures and lower temperature differences, which may result in longer battery life, faster charging speed, and safer battery operation. The integrated cooling network showed more even heat draw from the battery pack, which would help mitigate a risk of any hot spots within the pack that could effect the degradation of the cells. Moreover, the fewer parts and connect points to assemble reduce manufacturing and maintenance requirements, as well as the potential failure points of vibration-induced parts loosening or coolant leakage. The compact packaging configuration also opens the door to further flexibility in the layout of a vehicle, and better integration with other subsystems. These findings all together indicate that the proposed architecture can be considered as a viable route towards lighter, safer and more thermally efficient heavy duty electric vehicle battery systems, which have sufficient structural integrity to operate in challenging commercial environments.

Table 4. Engineering Assessment of Functional Benefits

Evaluation Criterion	Conventional Architecture	Proposed Architecture	Engineering Impact
Load-Bearing Capability	Independent frame structure	Integrated structural base body	Improved load-transfer efficiency
Thermal Management Function	Separate cooling plate	Embedded cooling conduits	Reduced thermal resistance
Structural Stiffening Mechanism	Dedicated reinforcement members	Conduit walls act as stiffening ribs	Multifunctional utilization
Component Redundancy	High	Low	Reduced material usage
Vehicle Payload Efficiency	Moderate	High	Increased payload availability
Packaging Space Utilization	Moderate	Optimized	Lower installation height
Vibration Resistance	Multiple interfaces prone to loosening	Reduced interfaces and direct load path	Improved durability
Coolant Leakage Risk	Multiple external connections	Protected internal channels	Enhanced reliability
Maintenance Requirement	Periodic inspection of multiple assemblies	Simplified inspection points	Reduced maintenance effort
Manufacturing Integration	Multi-stage assembly process	Consolidated assembly approach	Lower assembly complexity
Thermal Uniformity	Moderate	High	Improved battery health
Fast-Charging Compatibility	Limited by thermal bottlenecks	Enhanced heat extraction capability	Better high-power operation

Crash Protection Potential	Separate structural members	Reinforced integrated structure	Improved impact resilience
Scalability Across Vehicle Platforms	Moderate	High	Suitable for trucks and buses
Overall System Efficiency	Baseline	Enhanced	Multifunctional performance gain

6. REAL-WORLD APPLICATIONS OF THE PROPOSED UNIFIED STRUCTURAL-THERMAL PLATFORM

The proposed Unified Structural–Thermal Platform will not only be a concept of a structural and thermal optimization platform, but it will also have direct importance in many problems of real-life modern heavy duty electric transportation systems. While commercial vehicle manufacturers are making every effort to squeeze as many batteries into their vehicles, increase range, reduce charging time and pack in more payload, the usual positioning of the batteries in the vehicle typically presents a significant limitation. The envisioned multifunctional platform is a logical engineering solution as it designates a single compact assembly as support, thermal regulation and chassis. Such integration eliminates structural redundancy, system mass, enhances real-time cooling capability of the batteries and also enhances battery reliability in long time operation with very demanding environments.

The platform could be used in particular in high capacity battery systems, where the structural load and the heat generation is much higher than in passenger electric cars. Ideal deployment applications are commercial transportation fleets, public transportation systems, mining vehicles and military electric platforms, all of which are in constant use and have frequent charging cycles and mechanical and environmental challenges. The advantages of the architecture – homogeneity of the temperatures, simplicity of the assembly, packaging space – provide good ground for cost reduction during life cycle and increased operating efficiency. Furthermore, the integrated design can be scaled-up to a variety of vehicle classes, without involving significant redesign of supporting structures. As the transportation industry begins to transition across the globe towards electric vehicles, multifunctional Battery Integration technologies can form a major enabler to increase range, reliability, maintainability and economy of the vehicles in future. Four major deployment scenes, in which the proposed structural–thermal platform could provide a number of engineering and operational benefits, are then examined [23] [24].

6.1 Application in Heavy-Duty Electric Trucks

Heavy duty electric trucks are considered one of the most challenging battery electric vehicles segments, given their high end payload capacity, long driving distances and uninterrupted drive cycles. Most current BEVs for freight transport today have a battery capacity in excess of 500 kWh and in some long-haul set-ups, more than 1 MWh. The large battery packs present several structural loading challenges as the typical structural solutions must carry several tonnes of battery mass and must absorb vibrations, acceleration and brake forces and impact vibrations from the road. Meanwhile, continuous usage of the vehicle on the highway and rapid charging require efficient removal of heat in order to maintain the battery's health and for safety in operation. A viable solution has been proposed herein: a so called “Unified Structural-Thermal Platform”, which provides a multifunctional structure that acts as the load bearing system and as the battery tray and cooling system.

This integrated architecture has the effect that the non-functional mass is reduced, payload capacities of the vehicle are increased and the energy efficiency of the vehicle is increased. Embedded Cooling Conduits maintain a more stable operating temperature of the battery for longer service life, higher power charging conditions and to reduce thermal degradation of the battery. At the same time the direct chassis integration solution also allows to make a contribution to stiffness, fatigue failure minimisation in the case of multiple holding points in the load etc. An added economic advantage of the fleet market is maintenance requirements are reduced and setup of the system is simpler. Also, fine tuning the temperature control would enable levels of aggression to be increased when charging without exceeding charging temperature control comfort limits, thereby contributing to an acceleration of turn around time of freight operation. The proposed platform is very feasible for the next-generation electric logistics vehicles, and long-haul transportation fleets as its attractive characteristics allow for better performance, reliability and the efficiency of operation [26] [27].

6.2 Application in Electric Buses and Public Transportation

Typically, electric buses are one area that is experiencing rapid growth within Sustainable urban transportation systems, primarily due to the fact that they are capable of providing important reductions in greenhouse gas emissions, noise pollution, and operating expenses whilst powered compared to conventional diesel-powered vehicles [28]. Public transit buses are constantly on the road, sometimes for more than 16 hours a day, with multiple stops, a lot of acceleration and

deceleration, loading and unloading of passengers and lots of regenerative braking. This operating regime therefore puts significant thermal and mechanical stress on the battery systems. Transit operators also need vehicles that are extremely dependable and will have minimal downtime for maintenance, as any disruption in service impacts mobility and network efficiency. The needed battery support and cooling solution has been integrated into the proposed structural-thermal platform which will ensure that thermal performance remains constant during intensive duty cycles. Structural integration also dramatically lowers the battery-pack height, enabling a more modular placement of battery system in the vehicles such as on top of vehicles, in rear positions or under vehicle floors. This ensures a better thermal homogeneity, thus minimizing cell imbalance and battery degradation, while also prolonging service intervals and reducing lifecycle costs. Structural integration also enhances vibration and fatigue resistance, thanks to the frequent stop-and-go operation in urban areas. Lower operational expenses and simplified maintenance procedures are the advantages of decreased system complexity for transit authorities. Second, the platform's increased cooling capacity allows for faster opportunity charging at bus stations or terminal stations, leading to more flexible routes and better bus usage. The suggested architecture hence offers a future way forward for more reliable, environmentally friendly and cost effective electric public transport systems which are more energy efficient and can satisfy future urban mobility needs, [29] and [30].

6.3 Application in Electric Mining and Industrial Vehicles

Whether you're using electric vehicles in mining or industry, the conditions are extremely challenging. Extreme payloads, constant vibrations, big temperature fluctuations, dust clouds and long working periods are characteristic of haul trucks, underground transport vehicles, loaders and heavy industrial machinery. They put unprecedented stresses on battery support structure and thermal battery management systems. Conventional battery systems require a lot of reinforcement and protection that usually increases their weight and decrease the efficiency. The combination of structural strengthening and thermal control within a single strong structural assembly—proposed with the Unified Structural-Thermal Platform—brings significant benefits to such environments. The base body has a load-bearing design to evenly disperse heavy battery loads and fails to deform under extreme operating conditions.

In high power use conditions, its internal cooling conduits provide safe, continuous use temperatures and limit thermal stress on the battery to create a longer battery lifespan. Coolant channels are optimized to be part of the structural body protecting them from external damage from debris, impact and harsh environment. The component resulting reduction also leads to reduced failure point reduction and easier maintenance process in remote equipment operating locations, where equipment availability is of extreme importance. In addition, increased structural stiffness will equate with greater resistance to shock loads resulting from uneven terrain and heavy material handling operations. Multifunctional battery integration technologies like the proposed platform can seriously enhance equipment reliability and productivity while also optimizing equipment life cycle performance [31,32] as the mining and industrial sectors increasingly embrace electrification strategies to meet their emission reduction and operating expenditure targets.

6.4 Application in Military and Specialized Electric Mobility Platforms

In the field of special mobility applications, such as military mobility applications, the reliability, durability, energy efficiency and survivability are of importance. In cases where a battery is used as a power source for military use, as for electrified military transportation vehicles, tactical support systems, autonomous logistics systems and certain off-road vehicles, the battery systems must be robust to variations in environmental and operational conditions [33]. Mission critical and reliable operation is often a requirement along with significant vibration, impact loading, rough terrain travel, and rapid changes of power demand, typically one or more of these platforms experience all these conditions. The so called Structural-Thermal platform design is designed to provide multiple benefits to meet the above needs. The combined load-bearing provides enhanced structure strength and weight reduction of the vehicle and it can help their mobility and work ranges. High power mission profiles and fast charging enable the proactive management and maintenance of thermal stability with embedded cooling conduits, with minimal impact on thermal performance.

Exposed cooling elements are avoided and the survival rate is raised in case they are physically damaged or influenced by environmental hurts. The simplified architecture, also, can lead to a reduction in the logistical complexity since there are fewer individual parts to inspect, replace, or maintain. Was also designed with the compactness that allows it to fit in minimal vehicle configurations where space to install would be at a premium. In military applications, when the military organizations need a new application for use of electro technologies for lack of silent mobility operation, multifunctional batteries will be valuable, ones which can be used as an integral structural component in logistics support, defense vehicles, as well as in packages doing the structural loading, thermal management and operation reliability. In total, proposed design offers satisfactory base for future of defense or specialized use of electric mobility in an area with high requirement for the performance in hard working conditions [34] [35].

LIMITATIONS AND CHALLENGES

The proposed Unified Structural-thermal Platform (USTP) shows great promise to meet the goal of better battery integration in the heavy-duty electric vehicle, however, some technical and implementation challenges remain to be addressed before bringing this platform to commercialization on a large scale. Embedding the building structure and the thermal management function in one multifunctional component implies extra design complexity compared to the classical design approach, where the building structure and thermal management function are isolated. The structure of the base body needs to meet mechanical load-bearing requirements, thermal performance requirements, manufacturing constraints, maintenance access and safety requirements and not affect the overall system reliability. In addition, if the internal coolant passages are part of a load-bearing structure, it is important to ensure that there are no unduly high stress concentrations or fatigue or weakening around the coolant passages.

It also requires some production refinement, such as advanced extrusion processing, precision processing, casting and additive manufacturing etc., to make such integrated assembly parts, which will increase the initial development costs and production difficulty. Coolant flow distribution, conduit geometry and operating conditions may impact thermal performance, and hot modelling and validation should be conducted with different duty cycles in the field. In addition, the repair and replacement process will probably be more complicated because they will serve both the structural and thermal purpose at the same time. Additionally, crashworthiness validation, long lifecycle testing and regulatory certification are important challenges that must be addressed before these can be used in commercial transportation fleets. While the benefits of the proposed platform for weight saving and packaging efficiency and thermal performance are apparent, further development and industrial validation of the platform still need to be performed to optimize the design, evaluate the LCE, and define deployment options for various classes of heavy duty EVs.

7.1 Manufacturing and Production Challenges

The common challenge of the proposed architecture is complexity in fabrication of the multifunctional structural component that has the coolant conduits incorporated. Conventional manufacturing systems make use of separately produced; structural battery trays and cooling plates that can be put together with proven industrial processes. The proposed platform must, however, be built with the high dimensional accuracy and internal cooling passages, and with sufficient strength to support the load. Blemishes such as under-formed channels, dimensional variations, residual stresses, porosity and weld defects may have a negative effect on the structural and thermal performance. In addition, the uniformity of wall thickness is extremely important since conduit areas have to be simultaneously designed as cooling passages and as structural reinforcement members. For some, more advanced manufacturing technologies such as the aforementioned are necessary to achieve more complex geometries, which could have a negative impact on costs in early stages of commercial manufacturing. Quality-control systems must be enhanced to guarantee integrity of the coolant channels, dimensional tolerances and mechanical properties of the component throughout. But the manufacturing process can use a higher technical skill, process control and production investment than conventional architectures that support the battery, although it is less complex during the assembly process.

7.2 Structural Reliability and Safety Considerations

By combining multiple functions into a single platform, this design poses a special challenge in relation to the reliability of its structure, which must be optimized, tailored and tested. The Coolant Conduits walls are also structural stiffening ribs which mean that mechanical degradation of such structural ribs or damage to them can affect load bearing and thermal-management. Heavy duty vehicles see several repetitive vibration cycles and/or dynamic loading, shock impact loads, and thermal stresses that can cause some of the members on the structure to develop fatigue over time in service. Areas where cracks start are likely to be where there are high localized concentrations of stress, such as those in sections close to mounting interfaces, conduit intersections or sections where geometry changes. Then there might be consequences that aren't deliberate, consequences of underbody strikes or collision events that might affect actually integrated body structure and possibly the inboard coolant passages.

Conventional architectures (structural cooling separated) on the other hand, permit the replacement of the cooling system in the event of a problem while potentially a larger platform assembly would be necessary in the case of a problem occurring on the integrated platform. It is, therefore, an important design criterion to provide sufficient crashworthiness and have crushable coolant channels. Elaborate fatigue analysis along with impact simulation and vibration analysis and accelerated tests for durability must be performed to assure long-term reliability. Also, some type of redundant or fail-safe design features may need to be used to ensure safety of operation if there is some type of localized structural failure or failure in thermal management.

7.3 Thermal Management Optimization and Maintenance Challenges

This is a good thing because it also allows the transfer efficiency and reduction in thermal resistance through the embedded coolant network, but maintaining thermal performance under different operating conditions is a big engineering challenge. To prevent parts of the battery modules reaching different temperatures (known as 'hot spots'), the coolant flow through the various paths must be even. The total amount of coolant flow, pressure drops, channel geometry and the operating temperature may influence the global cooling effectiveness and the system efficiency. The heat generation rate and the size of batteries increase, and it is more difficult to obtain uniform thermal conditions – which is often the case with larger battery packs for commercial vehicles.

Additionally, over time the coolant can become contaminated, chemical scaling can occur or the internal passages can be clogged by corrosion which could decrease heat-transfer capability. The cooling passages are located within the structural body, thus inspection and maintenance techniques could be more involved than external cooling system types. Advanced monitoring systems might also be needed to detect faults and leaks, even indicating a drop in performance prior to a real problem occurring. In the secondary, considerations of thermal optimization have to include aspects of pumping power, cost of a system, manufacturing limitations and effectiveness of cooling. Future investigations should therefore focus on intelligent strategies for thermal-management, a real-time monitoring system, approaches to predictive maintenance and an optimized coolant-channel design, which can help to sustain the reliability of long-time operation under a variety of heavy-duty operating conditions.

FUTURE RESEARCH DIRECTIONS

While the proposed USTP is an excellent base for the incorporation of batteries to be used to power next generation heavy duty EVs, there are several aspects that could be technically developed and/or optimized. The performance that cars demand in combination with increasing battery size needs greater distributed and created structural efficiency, thermal control, reliability and intelligence of the battery support structure to achieve greater charging speed.

However, the new opportunities of recent developments in advanced materials and the advent of the new digital revolution in engineering and smart monitoring techniques offer to improve the functionality of integrated structural–thermal systems thanks to the digital engineering and optimized design. Additionally, smart operations, like megawatt charging infrastructure, autonomous transportation and connected vehicle platforms (and more) are just some of the other operational needs not handled by typical, simple integration techniques.

This challenge and opportunity for future research would then be an extension of the multifunctional performance and capabilities of the architectural–thermal platform which would focus in particular on the scalable and predictable nature of the manufacturing, as well as the thermal adaptation, maintenance, and life cycle maintenance. The research on the light weight composite structures, topology optimized geometry, intelligent coolant distribution networks and digital twin technologies has the potential to significantly boost the effectiveness of integrated architectures of batteries. New developments of AM can be used in addition to make very complex conduit designs and not only for optimizing the heat-transfer performance but for optimizing at the same time the structural stiffness of the conduit. In addition, extended time field validations will be most critical in the field, under specific conditions of use, to gain final proof of the product's commercial and regulatory viability. This will include interdisciplinary research for the development of highly effective integration systems, such as mechanical engineering, thermal sciences, materials technologies and manufacturing and artificial intelligence to meet the changing demands of the electric transportation in heavy duty applications.

8.1 Advanced Materials and Lightweight Structural Optimization

New materials and complex lightweight design of integrated battery-support systems to improve their effectiveness are potential areas of research. Good materials for combining high-strength and low weight is carbon fibre with reinforced polymeric materials - advanced materials are being developed and may meet both requirements, or incorporation of thermally conductive additives, which is appropriate to the applications as is alloyed aluminium. Additional research efforts are required to investigate the possibility of substituting the heavy weight systems with lightweight composites and built-in cooling systems while maintaining thermal performance and structure. Furthermore, topology optimization is also applied in order to reveal which material is best to provide maximum stiffness/ weight ratio.

These can be used to develop extremely efficient rib structures and layouts of coolant passages in the battery especially tailored for the loading conditions specified. Fatigue resistance, impact tolerance, corrosion behaviour and characteristics of thermal expansion in advanced materials need to be explored under heavy duty operating conditions as well. Multifunctional materials (those which simultaneously have the structural and thermal conduction function) can even better

the platform performance as they absorb energy too. Last, the innovative material and structural optimizations can make it possible to significantly improve the future battery electric transportation systems in terms of payload, vehicle efficiency and lifecycles.

8.2 Intelligent Thermal Management and Digital Twin Integration

Structural-thermal battery platforms will most likely continue to be developed going forward and a smart thermal-management system will be optionally integrated in order to attain thermal management as per the various requirements. Current cooling systems are generally designed around fixed cooling methods which don't necessarily take into account changing battery loads, environmental effects, or charging schemes or country profile of the vehicle. In future research, explore the potential to dynamically control the flow rates, target temperatures and heat distribution to/in the coolants within the battery pack using AI, ML and/or predictive control. Such adaptive control systems could - in theory - be used to increase the thermal efficiency of these systems and consequently save energy through the flushing of coolants.

An exciting future area is continually getting reports on the condition of the battery platform (structural and thermal) on-site with the use of digital twins. In conjunction with data from sensors, real-time simulation models could anticipate the condition of components, proactively detect abnormal scenarios, and plan among other areas maintenance. Potential exists for built in structural health monitoring systems which would allow for ongoing evaluation of the level of stress, vibration, fatigue damage accumulated and health of cooling systems. Future reliability, safety and operational efficiency and on-board predictive maintenance of Battery system of heavy duty EVs could be significantly improved if good integration of Intelligent thermal control, with the Digital twin technology is achieved.

8.3 Scalable Manufacturing and Real-World Deployment Validation

A remaining research requirement that needs to be addressed for commercialization of scaling manufacturing processes and full comprehensive real world validation programs is the need for integrated structural-thermal battery platforms. The benefits of the proposed architecture on analytical performance are, however, promising; to be a candidate for mass production, the manufacturing process needs to be able to consistently produce the complex geometry, while keeping the quality high and the costs low. Further work could be carried out on the high level technologies developed in the extrusion manufacturing process, High strain Die Casting process, 1.5 rotational speed friction stir welding process, commercialization of the robotic assembly system and advanced manufacturing process using Additive Manufacturing techniques in order to manufacture the coolant channel structure on a commercial scale.

The most important factor that should be focused on the process optimization study is minimization of the production cost, dimensional accuracy and manufacturing repeatability. One of the most important validation tests lies in the requirement for wide range of experimental validation under realistic operating conditions. Long-term durability test for fatigue, thermal cycling, corrosion tests, use of the cooling system and crashworthiness them among others ought to be broken down by vehicle type. Field Tests can gain insight into how well the electric vehicles perform in their field operation and needs for maintenance. Research on regulatory certification processes, lifecycle-assessment tools, economic assessments etc. which might facilitate the uptake of these small-scale processes by industry may also be continued. This methodology brings together the scaling of manufacturing technologies with broad and thorough real-world validation of integrated structural-thermal battery architectures, and researchers and manufacturers can accelerate the transition in integrated structural-thermal batteries from design concepts to commercial, dependable solutions to next-generation heavy-duty electric mobility systems.

CONCLUSION

One of the most difficult engineering challenges in the new era of battery electric transportation, the requirement for a superior structure and thermal management for the battery systems to be achieved while at the same time minimizing the overall systems weight and maximizing the packaging efficiency was presented, in the form of a Unified Structural-Thermal Platform for Heavy-Duty Electric Vehicle Battery Systems. In the conventional battery integration architectures, there is a distinct structural frame, cooling plate and mounting assembly with more redundant components, higher mass, increased assembly complexity and more thermal resistance. The weaknesses are neutralised by multifunctional structural assembly with embedded coolant conduit and direct chassis interface for load bearing and active thermal management using the proposed platform. The structural and thermal assessment showed that the integrated architecture is able to effectively distribute the load of a heavy battery with reasonable stress and deformations under representative operating conditions. This submersible cooling system can help to keep the thermal uniformity between battery modules and minimize the thermal gradients to achieve efficient heat removal from the battery modules and to ensure the optimal battery performance under extreme conditions. Again, any structural element used to surround a coolant conduit can act as a "stiffening rib," so

that the platform will offer a satisfactory way to reduce redundant structure and improve the engineering efficiency. The results obtained demonstrate the beneficial practical consequences of multifunctionality for heavy duty EVs such as the reduction of the system weight, space saved on packaging, simplifications during assembly and maintenance reduction. In addition, scenarios for real deployment cases were analyzed, highlighting the platform's applicability to various use cases like electric freight and public transportation platforms, industrial vehicles, mining vehicles and specialized mobility platforms. While production complexity, endurance testing and maintenance are challenges that need to be addressed in the short term, the architecture has proven to be a solid foundation for additional battery integration concepts. To conclude, the proposed Unified Structural – Thermal Platform is a new and scalable engineering concept that can improve the future VEDs' efficiency, reliability, thermal performance, and operational sustainability, further developing electrified commercial transportation.

REFERENCES

1. Ehsani, M., Gao, Y., Longo, S., & Ebrahimi, K. (2018). *Modern electric, hybrid electric, and fuel cell vehicles*. CRC press.
2. Pesaran, A. A. (2001). Battery thermal management in EV and HEVs: issues and solutions. *Battery Man*, 43(5), 34-49.
3. Jaguemont, J., Boulon, L., & Dubé, Y. (2016). A comprehensive review of lithium-ion batteries used in hybrid and electric vehicles at cold temperatures. *Applied Energy*, 164, 99-114.
4. Liu, K., Li, K., Peng, Q., & Zhang, C. (2019). A brief review on key technologies in the battery management system of electric vehicles. *Frontiers of mechanical engineering*, 14(1), 47-64.
5. Feng, X., Ouyang, M., Liu, X., Lu, L., Xia, Y., & He, X. (2018). Thermal runaway mechanism of lithium ion battery for electric vehicles: A review. *Energy storage materials*, 10, 246-267.
6. Kim, G. H., Smith, K., Ireland, J., & Pesaran, A. (2012). Fail-safe design for large capacity lithium-ion battery systems. *Journal of power sources*, 210, 243-253.
7. Offer, G. J., Howey, D., Contestabile, M., Clague, R., & Brandon, N. P. (2010). Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. *Energy policy*, 38(1), 24-29.
8. He, L., Gu, Z., Zhang, Y., Jing, H., & Li, P. (2023). Review on thermal management of lithium-ion batteries for electric vehicles: advances, challenges, and outlook. *Energy & fuels*, 37(7), 4835-4857.
9. Hannan, M. A., Hoque, M. M., Mohamed, A., & Ayob, A. (2017). Review of energy storage systems for electric vehicle applications: Issues and challenges. *Renewable and Sustainable Energy Reviews*, 69, 771-789.
10. Rao, Z., & Wang, S. (2011). A review of power battery thermal energy management. *Renewable and Sustainable Energy Reviews*, 15(9), 4554-4571.
11. Pesaran, A. A. (2002). Battery thermal models for hybrid vehicle simulations. *Journal of power sources*, 110(2), 377-382.
12. Kim, T., Song, W., Son, D. Y., Ono, L. K., & Qi, Y. (2019). Lithium-ion batteries: outlook on present, future, and hybridized technologies. *Journal of materials chemistry A*, 7(7), 2942-2964.
13. Panchal, S., Dincer, I., Agelin-Chaab, M., Fraser, R., & Fowler, M. (2016). Experimental and theoretical investigation of temperature distributions in a prismatic lithium-ion battery. *International Journal of Thermal Sciences*, 99, 204-212.
14. Huo, Y., Rao, Z., Liu, X., & Zhao, J. (2015). Investigation of power battery thermal management by using mini-channel cold plate. *Energy Conversion and Management*, 89, 387-395.
15. Wang, D., Wang, S., & Xie, C. (2020). A multi-objective optimization approach for simultaneously lightweighting and maximizing functional performance of vehicle body structure. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 234(7), 2086-2102.
16. Ashby, M. F. (1994). Materials selection in mechanical design. *Metallurgia Italiana*, 86, 475-475.
17. Asp, L. E., & Greenhalgh, E. S. (2014). Structural power composites. *Composites science and technology*, 101, 41-61.
18. Acar, E., Jain, N., Ramu, P., Hwang, C., & Lee, I. (2024). A survey on design optimization of battery electric vehicle components, systems, and management. *Structural and Multidisciplinary Optimization*, 67(3), 27.
19. [19] Murugan, M., Elumalai, P. V., Vijayakumar, K. C. K., Babu, M., Suresh Kumar, K., Ganesh, M., ... & Prabhakar, S. (2025). A comprehensive review of thermal management methods and ideal system design for improved electric vehicle battery pack performance and safety. *Energy Science & Engineering*, 13(3), 1011-1036.
20. Wei, C., Hofman, T., Ilhan Caarls, E., & van Iperen, R. (2020). A review of the integrated design and control of electrified vehicles. *Energies*, 13(20), 5454.
21. Gupta, R. K., Jain, S., & Gupta, S. (2026). Toward Smart and Scalable EV Systems: A Comprehensive Review of Battery Intelligence, Control Optimization, and System Integration. *IETE Technical Review*, 1-15.
22. Bhardwaj, S., & Mostofi, H. (2022). Technical and business aspects of battery electric trucks—A systematic review. *Future Transportation*, 2(2), 382-401.

23. Karlsson, J. (2026). *System Cost Evaluation and Fast Charging Market Assessment for Battery Electric Trucks* (Doctoral dissertation, Chalmers University of Technology).
24. Liimatainen, H., van Vliet, O., & Aplyn, D. (2019). The potential of electric trucks—An international commodity-level analysis. *Applied energy*, 236, 804-814.
25. Yang, L., Hao, C., & Chai, Y. (2018). Life cycle assessment of commercial delivery trucks: Diesel, plug-in electric, and battery-swap electric. *Sustainability*, 10(12), 4547.
26. Rahmanivahid, P., Khashehchi, M., Thangavel, S., & Heidari, M. (2025). Application of Battery Thermal Management Systems (BTMS) for Heavy-Duty Electric Vehicles (HD-EV). *Thermal Battery Management System for Hybrid and Electric Vehicles*, 267-280.
27. Roshan, K., & Ponnusamy, B. (2025). Critical review of heavy duty vehicle battery management system. *Engineering Research Express*, 7(1), 012302.
28. Wang, S., Xia, B., Zhang, G., Zhang, S., Guan, D., & Zhao, Z. (2026, March). Research on the standard system for electric heavy swappable-duty trucks based on the unified architecture framework (UAF). In *Fifth International Conference on Frontiers of Electrical Power and Energy Systems (EPES 2025)* (Vol. 14118, pp. 40-50). SPIE.
29. Feng, R., Hua, Z., Zhao, Z., Li, F., Shu, X., Luo, L., & Zhai, H. (2026). A comprehensive performance evaluation of a fuel-cell hybrid electric heavy-duty truck through energy flow experiment under user-defined driving test cycles. *Case Studies in Thermal Engineering*, 107819.
30. Esen, D. Ö., & Shabaneh, S. A. Y. A. (2026). Integrated thermal management strategies for electric vehicles: a system-level review of battery cooling, heat pump technologies, PCM integration, and cold-climate performance: DÖ Esen, SAYA Shabaneh. *Journal of Thermal Analysis and Calorimetry*, 1-34.