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Review

Cooperative design of broadband vibration energy recovery and thermal management for structural-exhaust systems in intelligent connected vehicles: A review

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Abstract: The rapid advancement of intelligent connected vehicles (ICVs) has placed new demands on distributed electronic systems and increased the number of on-board functions that involve sensing, communication, and control. Unlike conventional vehicles, ICVs have significantly higher energy demand, and real-time sensing, communication, and control capabilities are much more feasible and are key to enabling cooperative vibration-thermal design. Structural-exhaust systems are subjected to broadband vibrations and extreme temperatures at all times and therefore seem to be a good platform for waste energy recovery and thermal control. Vibration energy harvesting and exhaust thermal management have been widely studied, but they are mostly implemented individually as subsystems. This separation ignores the thermo-mechanical coupling in exhaust structures and typically results in inefficient energy recovery and poor thermal and/or structural performance. A thorough review of the cooperative design of broadband vibration energy recovery and thermal management for the structural-exhaust system of an ICV is presented. The vibration and thermal performance of exhaust systems, and the coupling mechanisms between them, are investigated to elucidate fundamental design issues. A review of state-of-the-art broadband vibration energy harvesting technologies and exhaust thermal management technologies is conducted, highlighting their limitations operating under coupled conditions. Cooperative design concepts, structural integration strategies and multi-physics modelling and optimization methods are explained. Adaptive control, vehicle-to-everything connectivity, data-driven techniques, digital twins and system-level validation are emphasized. Lastly, problems are identified, and areas for further research are suggested.

Keywords: intelligent connected vehicles; broadband vibration energy harvesting; exhaust thermal management; cooperative design; multi-physics coupling

1. Introduction

The high-rate evolution of intelligent connected vehicles (ICVs) is essentially transforming the transportation systems of the modern era through the combination of sophisticated sensing, communications, computing, and control technologies [1]. ICVs have the potential to greatly enhance the efficiency, safety, and user experience of traffic through vehicle-to-everything (V2X) connectivity, onboard intelligence, and distributed perception architectures [2, 3]. But the same technological development causes a significant rise in onboard energy consumption for distributed sensors, wireless communication modules, and embedded monitoring systems. The provision of sustainable and reliable power to these denser and more geographically dispersed electronic elements has thus become a key problem in next-generation vehicle design. In addition to mechanical mobility, ICVs are defined by their dense cyber-physical architecture, i.e., the continuous distribution of sensing, communication, computing and controlling functions across the vehicle. It is an architectural change that increases the need for a localized, dependable, and maintenance-free energy supply in a traditional vehicle system.

It is important to note that a high-temperature exhaust environment and/or broadband vibration environment are not unique to an ICV; they can also be found in conventional internal-combustion vehicles [4,5]. What makes an ICV unique, however, is the distinct set of functional requirements and enabling conditions imposed by smart and connected designs. On the demand side, the growing density of distributed sensors, wireless nodes, and structural health monitoring devices is driving greater demand for local self-powered operation. In terms of capability, a new opportunity is emerging with the support of real-time data acquisition, onboard computation, V2X communication, and decision-making, all enabled by digital-twin facilities for adaptive energy recovery and thermal regulation. Thus, ICVs are not just a traditional exhaust space for energy harvesting, but they are also an architecture that makes cooperative vibration/thermal design more essential and feasible in a vehicle [6, 7].

Exhaust pipes, mufflers, brackets, and supporting frames are structural-exhaust system components exposed to extreme mechanical vibrations and high-temperature exhaust flows during vehicle operation. Such systems are subjected to broadband vibrations from engine combustion, rotational imbalance, road excitation, and unsteady exhaust-gas pulses. At the same time, they operate under severe thermal conditions, and the exhaust temperature regularly exceeds several hundred degrees Celsius and varies significantly over time depending on driving conditions. Historically, vibration and thermal considerations in exhaust systems have been regarded mainly as reliability issues, with the design of such systems aimed at providing vibration isolation, reducing noise, and protecting against thermal effects [8]. Nevertheless, there are some good, untapped energy sources. The structural-exhaust system is especially appealing for ICVs due to its proximity to potential monitoring locations and its constant exposure to recoverable mechanical and thermal energy, making it an ideal platform for self-powered sensing and intelligent condition monitoring [9, 10].

Vibration energy harvesting devices, devices that generate useful electrical energy by transduction, such as piezoelectric, electromagnetic, or other devices, by conversion of mechanical vibrations, have been actively studied in the last twenty years [11–13]. Vibration energy harvesters have also proven useful in automotive applications for powering wireless sensors and low-power electronics (especially for structural health monitoring and condition-based maintenance). However, most available vibration energy harvesters operate effectively within a narrow range of frequencies around a particular resonance. This narrowband property is a major drawback for their use in vehicle environments, where excitation frequencies are broadband, time-varying, and highly dependent on operating conditions. In addition, the high temperatures encountered in exhaust systems may degrade the performance and lifetime of traditional energy-harvesting materials and devices.

Simultaneously, studies on exhaust thermal management and waste heat recovery in vehicles have been conducted extensively. Thermal management, such as insulation, heat shielding, and active cooling, is necessary to protect neighboring components and ensure system reliability [14]. Another area of focus has been waste heat recovery technologies (e.g., thermoelectric generators (TEGs) as a way of enhancing the overall vehicle energy efficiency [15]. Although significant success has been achieved, thermal management and waste-heat recovery systems are often formulated without reference to structural dynamics and vibration. Thermal devices may alter the mass distribution, stiffness, and boundary conditions of exhaust structures, which in turn can change vibration characteristics and may decrease the effectiveness of vibration energy harvesting or increase fatigue.

A fundamental limitation is the separation of vibration energy recovery and thermal management in the current paradigm of design [16, 17]. The mechanical, thermal, and electrical phenomena are closely connected in a real-life structural-exhaust system. Temperature changes affect material properties, structural stiffness, and damping, which in turn influence vibration response and energy harvesting efficiency. On the other hand, vibrations may promote convective heat transfer, alter thermal contact conditions, and affect the behavior of thermal management components. This is because, in addition to the fact that ignoring these interactions will result in suboptimal energy recovery, it can also compromise system reliability and durability. This restriction is even more noticeable in ICVs, as exhaust-mounted devices are no longer passive accessories but can serve as sensing nodes, diagnostic devices, adaptive control devices or energy-self-sustaining modules in a connected vehicle network [18].

To deal with these issues, a new need is emerging to develop cooperative design schemes that can both take into account broadband vibration energy recovery and thermal management in a single scheme [19]. Cooperative design is not merely the co-location of energy-harvesting and thermal components; it focuses on integrating structures, materials, and functions in ways that enable them to meet three or more goals, such as energy-harvesting efficiency, thermal regulation, structural integrity, and long-term reliability. By leveraging multi-physics coupling effects, cooperative design can unlock performance benefits that are inaccessible under conventional sequential or independent design methodologies. Cooperative design could also be used to enhance adaptive operation in the ICV context, where information on the exhaust temperature distribution, the power demand from distributed electronic nodes, the vehicle state, and the road state is fed back to the energy harvester to alter its design parameters [20].

The applicability of cooperative design is also increased for intelligent connected vehicles. Key features of the ICVs include high-density sensing networks, adaptive control approaches, and real-time information exchange, providing new possibilities for intelligent energy and thermal management. Adaptive and self-tuning energy harvesters can respond to varying vibration spectra, and data-driven control strategies can optimize energy recovery and thermal protection across a wide range of driving conditions. Additionally, digital twins and machine learning technologies can be merged to provide predictive modeling and optimization of structural-exhaust systems throughout their lifecycle, in terms of design to operation and maintenance.

ICVs can offer continuous feedback from their embedded sensors and vehicle networks, unlike conventional vehicles, in which exhaust energy recovery devices are typically fixed, passive components. This feedback allows cooperative systems to detect the dominant vibration bands, calculate thermal risk, foresee degradation and modify energy management strategies in real time. From this point of view, V2X connectivity, digital twins and data-driven control do not only sound like an option, but rather it is the intelligence layer that allows for cooperative structural-exhaust systems to function adaptively and reliably in a nonstationary environment [21,22].

Although systematic reviews of vibration energy harvesting and exhaust thermal management have become increasingly popular, cooperative designs on their application in structural-exhaust systems have yet to be provided. Current review articles are inclined to discuss either vibration energy harvesting or thermal management independently, and it is not mentioned much on how they interact, how they can be integrated, and the implications of this interaction to intelligent connected vehicles [23,24]. This disconnect prevents the emergence of holistic design processes and the subsequent pace of research discoveries into actual automotive products. More importantly, few studies have explicitly separated the physical energy environment of conventional vehicles from the intelligent, data-rich, and sensor-rich architecture uniquely suited to ICVs for cooperative energy recovery and thermal management.

This review is distinctive because of multiple aspects: firstly, it brings together a multi-physics point of view, covering thermo-mechanical, electrical and structural aspects of the system; secondly, it includes integration at the structural level; thirdly, it includes intelligent control and system level validation in the same framework, and fourthly, it is not a review of vibration energy harvesting or exhaust waste heat recovery or vehicle thermal management or intelligent vehicle energy systems, but rather it is a review specifically focused on the cooperative design of a broadband vibration energy recovery and thermal management system for a structural-exhaust energy system in ICVs. This review offers an alternative view of the potential for structural-exhaust systems to become adaptive, self-powered, thermally resilient vehicle subsystems, given the increased demand for distributed energy and the real-time control capabilities of ICVs [25,26].

To this end, the present review will critically and in-depth examine cooperative design principles for broadband vibration energy recovery and thermal control in structural-exhaust systems of intelligent connected vehicles. The first aspect considered in the review is the vibration and thermal properties of structural-exhaust systems, as well as the thermo-mechanical coupling mechanisms. It then recapitulates state-of-the-art broadband vibration energy harvesting technologies and exhaust thermal management strategies, as well as the weaknesses of their integration. Based on this, the review focuses on cooperative design, structural integration techniques, and multi-physics modeling and optimization techniques. Lastly, intelligent control measures and system-level validation activities are addressed, and a perspective on the remaining problems and future research is presented.

This review aims to provide a single outlook on the cooperative design of structural-exhaust systems by synthesizing knowledge from vibration engineering, thermal sciences, energy harvesting, and intelligent vehicle technologies. The aim is to facilitate the creation of multifunctional, energy-efficient, and intelligent vehicle systems that will make next-generation transportation systems more sustainable and resilient. The main idea is that the structural exhaust systems of ICVs must be considered not just as sources of vibration and heat but as adaptive multi-physics platforms that offer the potential for self-powered sensing, intelligent thermal control, and connected-vehicle energy management [27, 28]. Structural-exhaust systems simultaneously experience broadband vibration and intense heat flux, making them natural multi-physics platforms for integrated energy recovery and thermal regulation (**Figure 1**).

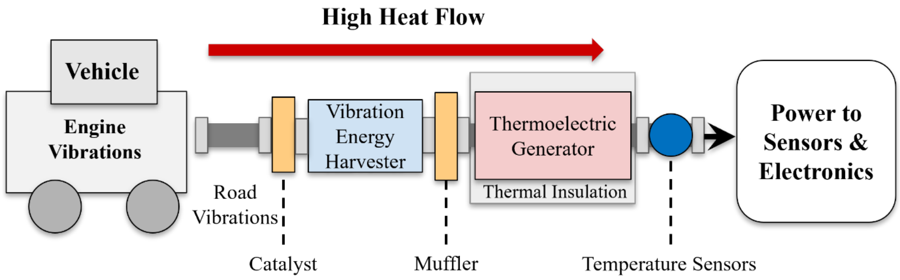

Figure 1. Structural-exhaust system in intelligent connected vehicles as a multi-physics platform for broadband vibration energy recovery and thermal management, showing major components, excitation sources, heat flow paths, and potential locations for integrated devices and powered nodes.

2. Vibration and thermal characteristics of structural-exhaust systems

The intelligent connected vehicle structural-exhaust systems have a complex environment of mechanical vibrations and thermal loads, with constant interaction with each other [29]. In contrast to independent mechanical elements, exhaust systems serve as load-bearing structures, fluid conduits, and thermal conductors. Therefore, vehicle operating conditions, system layout, and material properties have a powerful effect on their dynamic and thermal behaviors. The cooperative design of broadband vibration energy recovery and thermal management systems requires a clear understanding of vibration characteristics, the thermal environment, and the mechanisms for achieving both.

2.1. Broadband vibration sources and dynamic characteristics

Structural exhaust systems naturally exhibit non-stationary, broadband vibration environments. Primary excitation sources are caused by the engine, and periodic compressing forces and rotating imbalance create low-frequency excitation that is transferred to engine mountings and exhausts. These excitations typically dominate the vibration spectrum under idle and low-speed operating conditions. At higher vehicle velocities, further broadband vibrations are added by road roughness, chassis dynamics, and tire-road interactions, and are transmitted through the vehicle frame to the exhaust support structures [30,31].

In addition to vibrations introduced by the external environment, the exhaust systems experience internally induced excitations. The flow causes acoustic resonances in the exhaust pipe, unsteady exhaust-gas flow, pressure pulsations from engine firing cycles, and flow-induced vibrations. These excitations may have a broad frequency content and interact with the structural vibrations of the exhaust parts, resulting in complex vibration responses. This vibration spectrum consists of several peaks, which are due to structural resonances, overlaid on a broadband background due to stochastic excitations [32].

Structurally, the low natural frequencies of exhaust systems are generally explained by their thin geometry, spatially distributed mass, and loose mounting [30]. Brackets, hangers, and joints introduce additional degrees of freedom and nonlinearities, making the vibration response even more complex. Since operating conditions vary, such as in acceleration, deceleration, or gear changes, the excitation spectrum and boundary conditions continuously vary, resulting in time-varying vibration properties. Such characteristics are particularly problematic for traditional narrowband vibration energy harvesters, which are usually resonant at a single frequency.

2.2. Thermal environment and heat transfer characteristics

The structural-exhaust systems are subjected to harsh and extremely fluctuating thermal conditions [33]. When engine loads were high, exhaust gas temperatures could reach hundreds of degrees Celsius, and when the engine was not busy, temperatures dropped rapidly. There is no uniform temperature distribution along the exhaust system; temperatures are higher at the exhaust manifold and decrease steadily as heat dissipates into the surrounding environment. Strong temporal temperature gradients are also induced by transient driving conditions, such as start-stop operation and high-rate loading variations.

Convection, conduction, and radiation are some of the methods through which heat transfer takes place in the exhaust systems [34,35]. On the inside, hot exhaust gases are deposited on the pipe walls by forced convection, and on the outside, heat is removed by surrounding components and ambient air via natural or forced convection and thermal radiation. Having heat shields, insulation layers, and thermal management devices alters local heat transfer pathways and changes temperature fields. Although these thermal control provisions are necessary to reduce heat exposure to the adjacent components, they also influence the mass and stiffness distribution of the exhaust system.

Temperature changes cause contraction and expansion, resulting in additional stress on exhaust and supporting structures. Repeat thermal cycling also tends to cause material fatigue, joint loosening, and changes in contact conditions at mounts and interfaces. The enormous quantity of waste heat carried by exhaust gases represents a major potential for energy recovery. Nevertheless, proper utilization of this resource is subject to careful consideration of thermal gradients, heat-flux stability, and integration constraints [36].

2.3. Thermo-mechanical coupling effects

Vibrations of mechanical nature and thermal fields of the structural-exhaust systems do not exist in autonomy, but they are closely coupled by a variety of physical processes [37]. Temperature changes directly affect the material properties of functional materials used in energy harvesters, including elastic modulus, damping, and electrical properties. Increasing temperature reduces structural stiffness, resulting in changes in natural frequencies and mode shapes. The changes can positively or negatively affect vibration energy harvesting performance, depending on the degree of resonance alignment between the excitation frequencies and the harvester's resonance.

From a simplified structural-dynamics perspective, this coupling can be represented by temperature-dependent mass, damping, and stiffness terms, such as M, C(T), and K(T). For a dominant vibration mode, the natural frequency may be approximated as $f_n(T) = \frac{1}{2\pi}\sqrt{k_{eff}(T)/m_{eff}}$, indicating that temperature-induced changes in effective stiffness can cause resonance drift. In constrained exhaust components, thermal expansion may also generate thermal stress, which can be expressed in a first-order form as $\sigma_{th} \approx E(T)\alpha(T)\Delta T$, where E(T) is the temperature-dependent elastic modulus, $\alpha(T)$ is the coefficient of thermal expansion, and ΔT is the temperature rise [38, 39]. Such thermal stresses can modify local boundary conditions, accelerate fatigue damage, and alter the dynamic response of brackets, hangers, and pipe sections.

Differing expansion and thermal stresses also change exhaust mounts and connections' boundary conditions [40]. Vibration transmission paths and dynamic responses can also change depending on changes in contact pressure, friction, and constraint stiffness. In other instances, geometric nonlinearities can arise from thermal deformation, broadening the range of vibration responses useful for broadband energy harvesting. Nevertheless, high thermal effects may also elevate vibration amplitudes beyond the design limit, which hastens fatigue damage.

Another significant pathway of coupling is thermoelastic damping. Alternating tensile/compressive strain fields due to cyclic bending or vibration can establish local temperature gradients leading to irreversible heat flow within the structure. This mechanism leads to a dissipation of the energy and alters the effective damping and the quality factor of resonant components [41]. Thus, apart from affecting the resonant frequency, temperature also affects the amplitude, width, and recoverable mechanical energy of the vibration that can be harvested.

On the other hand, thermal behavior is susceptible to mechanical vibrations [42]. The movement induced by vibration enhances convective heat transfer by disrupting boundary layers and increasing the effective heat transfer coefficients. Applications to exhaust systems. This can increase the heat dissipated in exhaust systems or improve the performance of thermoelectric generators by raising temperature gradients. Simultaneously, vibrations may destroy thermal interfaces, reduce the quality of part contacts, and cause nonuniform temperature distributions.

For the piezoelectric/hybrid energy harvesters, thermo-mechanical coupling extends further into the electrical domain. The electromechanical coupling coefficient, dielectric permittivity, piezoelectric constants, capacitance and mechanical damping can also depend on temperature, and so the voltage and power generated from the vibrations depend not only on the amplitude of the vibrations, but also on the temperature of the transducer and interface [43, 44]. A reduced-order form may thus be understood as a coupled mechanical-electrical system with C(T), K(T) and the electromechanical coupling term Δ(T), all of which are temperature dependent. It is especially crucial for harvesters integrated into the exhaust system, since resonance drift, material degradation, and electrical output instability may all occur simultaneously during thermal cycling.

The reverse effect of vibration on heat transfer can also be modelled by a vibration-dependent convective coefficient h(A,ω), with A and ω the vibration amplitude and the vibration angular frequency, respectively. The mechanical vibration can break the thermal boundary layers, enhance the local mixing and change the heat transfer coefficient; however, the impacts will significantly depend on the flow conditions, vibration direction, amplitude, frequency, and thermal boundary conditions [45]. Therefore, vibration can be a useful or undesirable influence on thermal management, depending on whether it helps to remove the heat or disrupts the thermal interface.

The vibration-related and thermal interactions are especially problematic when energy harvesting and thermal management devices are combined with structural-exhaust systems [46, 47]. By introducing additional mass, stiffness, and damping, energy harvesters alter heat-flow paths and temperature fields; thermal devices change temperature fields. Unless planned together, these additions can conflict with one another and reduce the efficiency of energy recovery or thermal protection. The knowledge of thermo-mechanical coupling processes is thus a prerequisite for designing cooperative design strategies that leverage synergies rather than being affected by unwanted interactions.

Altogether, intelligent connected vehicles have structural-exhaust systems characterized by broadband, time-varying vibrations and harsh, transient thermal environments that interact through intense thermo-mechanical interactions. These attributes characterize the challenges and opportunities in cooperative design. The overall knowledge of the sources of vibration, thermal effects, and coupling processes forms the basis of creating a combination of solutions that can both facilitate the efficient recovery of broadband vibration energy and efficient thermal management [48]. To consolidate the operating environment relevant to cooperative integration, **Table 1** summarizes dominant vibration sources, thermal features, and their primary design implications.

Table 1. Dominant vibration and thermal characteristics of vehicle structural–exhaust systems and their design implications.

Domain	Main source/feature	Typical behavior	Design implication
Engine-induced vibration	Combustion and rotating components	Low-frequency, speed-dependent	Requires low-frequency harvesting capability
Road/chassis excitation	Road roughness and vehicle dynamics	Broadband, stochastic	Requires robustness under random excitation
Flow-induced vibration	Exhaust pulsation and acoustic coupling	Multi-frequency response	Supports multimodal harvesting designs
Exhaust thermal field	Hot gas flow along exhaust path	High temperature, strong gradients	Requires thermal protection and stable materials
Transient operation	Start-stop, acceleration, load change	Time-varying vibration and temperature	Requires adaptive or broadband design
Thermo-mechanical coupling	Temperature-dependent stiffness and damping	Resonance drift and stress variation	Requires coupled thermal-dynamic modeling

3. Broadband vibration energy recovery and exhaust thermal management technologies

The achievement of cooperative design for structural exhaust systems in intelligent connected vehicles depends on both vibration energy recovery technology and exhaust thermal management technology [49,50]. Over the last 20 years, a significant number of advances have been made in developing mechanisms and devices that convert ambient mechanical and thermal energy into useful electrical or thermal energy. Nevertheless, when used in the harsh, highly coupled conditions of vehicle exhaust systems, these technologies face special challenges related to broadband excitation, high temperatures, structural integration, and long-term reliability. In this section, recent developments in broadband vibration energy harvesting and exhaust thermal management are reviewed, with a focus on their performance characteristics and drawbacks in the coupled thermo-mechanical environment. To structure the discussion of candidate solutions, **Figure 2** summarizes the major technology families for broadband vibration energy harvesting and exhaust thermal management considered in this review.

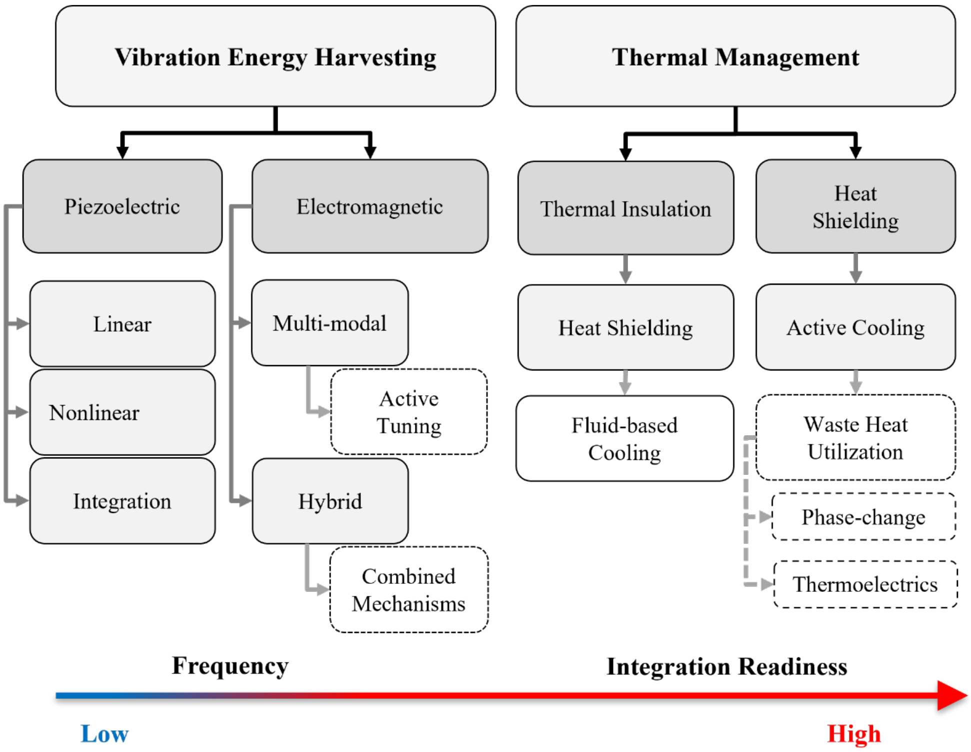

Figure 2. Technology taxonomy for broadband vibration energy harvesting and exhaust thermal management/waste-heat utilization, organized by working principle and integration readiness for structural-exhaust applications.

3.1. Broadband vibration energy recovery technologies

Vibration energy recovery seeks to translate mechanical vibrations into electrical energy via several different transduction methods, the most well-studied means of which are piezoelectric and electromagnetic, for automotive applications [11, 13]. Piezoelectric energy harvesters leverage strain-driven polarization in functional materials to generate electrical charge, enabling high energy density and easy structural integration. Electromagnetic harvesters, on the other hand, use relative motion between magnetic fields and conductive coils, which offers high endurance and consistent functionality even under enormous vibrations. Hybrid energy harvesters that combine two or more transduction mechanisms have also been considered in recent years to enhance energy conversion efficiency and operational robustness.

One of the main weaknesses of traditional vibration energy harvesters is their narrowband nature. Most designs are tuned to resonate at a specific frequency, and their power output is high only when the excitation frequency is close to the structural resonance. This limitation is especially worrisome in vehicle exhaust systems, where the vibration spectrum is wideband, non-stationary, and varies with conditions such as engine speed, vehicle load, and road roughness. To address this problem, a lot of research has been put into broadband vibration energy harvesting strategies [51].

Broadband designs can be classified as multimodal, nonlinear, and adaptive. Multi-degree-of-freedom Multi-modal energy harvesters. Multi-degree-of-freedom configurations or distributed harvesting elements are frequently used to multiply the effective frequency bandwidth of multi-modal energy harvesters. Nonlinear energy harvesters provide artificial nonlinearities, such as bistable or tristable potentials, magnetic coupling, or geometric nonlinearity, to enable large-amplitude oscillations across a broader range of frequencies. These designs have been shown to have better performance in broadband under random and low-frequency excitations as found in automotive environments. Another promising trend is adaptive and tunable energy harvesters, which enable the resonance properties to be dynamically adjusted in response to changes in the dominant excitation frequencies, by mechanical, magnetic, or electrical means [52–54]. Broadband harvesting concepts differ substantially in bandwidth-extension mechanisms, thermal tolerance, and packaging constraints; **Table 2** compares these attributes to clarify selection trade-offs for exhaust deployment.

Table 2. Comparison of broadband vibration energy harvesting technologies for structural-exhaust applications.

Harvester type	Broadband strategy	Thermal robustness	Integration potential	Main limitation
Linear piezoelectric	Resonance tuning	Low–moderate	High	Narrow bandwidth
Nonlinear piezoelectric	Bistable/multistable response	Low–moderate	Moderate	Design complexity
Electromagnetic	Inertial or multimodal motion	Moderate–high	Moderate	Larger volume
Triboelectric	Contact/separation modes	Low–moderate	Moderate	Wear and stability issues
Hybrid harvester	Multiple conversion mechanisms	Moderate	Moderate–high	Complex packaging
Adaptive/tunable harvester	Variable stiffness, damping, or load	Material-dependent	High	Control and power overhead

Although these developments have been made, the use of broadband vibration energy recovery technologies in exhaust systems remains limited by thermal effects. High temperatures may cause considerable changes in material properties, reduce electromechanical coupling efficiency, and accelerate material degradation, especially in piezoelectric materials and polymer components. Moreover, structural boundary conditions may also be altered by temperature gradients and thermal loads, causing resonance frequencies to shift and reducing harvesting efficiency. The above challenges have pointed out the need to consider thermal conditions and vibration characteristics in the assessment of energy recovery technologies in exhaust applications [55].

3.2. Exhaust thermal management and waste heat utilization technologies

The importance of thermal management in exhaust system design is that it is necessitated by the need to guarantee structural integrity, safeguard other components, and by emissions and efficiency needs [56]. Gaseous exhaust from internal combustion engines may reach many hundreds of degrees Celsius and vary significantly over time and space. Good thermal management plans are designed to regulate the heat flow within the exhaust system and the exhaust and its environment.

The traditional methods of thermal management mostly involve the use of heat insulation, shielding, and regulated dissipation [57]. Heat shields and thermal insulation materials are widely used to reduce heat transfer to adjacent parts and enhance passenger safety. Active cooling, forced convection, or coolant circulation. In rare cases, active cooling methods, like forced convection or coolant circulation, may be used in high-performance or heavy-duty vehicles, but this adds complexity and energy use [58].

Simultaneously, extensive research has been conducted on recovering exhaust waste heat to enhance overall vehicle energy efficiency. Emerging as one of the most viable technologies towards that end is the thermoelectric generator, which can directly convert temperature differences into electricity via the Seebeck effect [59]. Thermoelectric generators can be used in conjunction with exhaust systems to harness some of the exhaust heat to power auxiliary systems or recharge vehicle batteries. Alternative methods of waste heat utilization such as heat exchangers with phase-change materials or secondary power cycles, have also been studied, but have not so far been utilized in passenger vehicles because of the packaging and cost limits. Thermal management and waste-heat utilization measures can materially alter structural boundary conditions and vibration transmission paths; **Table 3** summarizes major approaches and their likely dynamic consequences.

Table 3. Exhaust thermal management and waste-heat utilization technologies and their structural implications.

Technology	Main function	Energy recovery	Structural/dynamic influence	Main limitation
Passive thermal protection	Insulation and shielding	None	Alters local mass and stiffness	Limited adaptability
Active cooling	Temperature regulation	Indirect	Adds components and controls demand	Energy consumption
Thermoelectric generator	Heat-to-electric conversion	Direct	Adds mass and thermal interfaces	Low conversion efficiency
Heat exchanger	Heat transfer enhancement	Direct/indirect	Modifies layout and flow resistance	Packaging constraints
Phase-change material	Thermal buffering	Thermal storage	Changes local dynamic response	Long-term stability
Integrated thermal module	Heat control plus recovery	Direct/indirect	Strong coupling with structure	Complex system design

Although the exhaust thermal management and waste heat recovery technologies have been proven to realize quantifiable effects, they are generally formulated with minimal references to structural dynamics [60]. Thermal devices are frequently added to the system during installation, thereby modifying the system's mass, changing the stiffness distribution, and altering the boundary conditions, which can significantly impact the vibration characteristics. In other instances, these modifications can either increase fatigue in vibration or decrease the performance of vibration energy harvesters. On top of that, thermal devices are prone to vibration loading, which may compromise mechanical resilience and durability.

3.3. Performance limitations under coupled thermo-mechanical conditions

The interactions between vibration energy recovery and thermal management technologies inevitably arise when implemented in parallel in structural exhaust systems and, in most cases, dominate. Thermal effects are known to affect the performance of vibration energy harvesters by altering material properties such as elastic modulus, damping, and electromechanical coupling coefficient. In piezoelectric harvesters, poling can cause depolarization and reduced output at higher temperatures, and repeated thermal cycling can cause fatigue and aging. EMHs tend to be more hostile to high temperatures, but in extreme conditions, there may be a loss of magnetic strength and degradation of insulation [61].

Vibration, on the other hand, has the potential to influence the thermal management performance through either increasing or interfering with the heat transfer mechanisms [62]. Structural vibrations can enhance convective heat transfer coefficients, alter contact resistance at interfaces, and induce microscale relative motion between thermal components. Although these effects can be effective in some situations, they can create thermal instability or decrease the performance of insulation and heat shielding.

It is these combined thermo-mechanical interactions that reveal the shortcomings of the conventional design methodology, which considers vibration energy recovery and thermal management as disconnected subsystems [28]. Performance trade-offs usually arise, in which one performance task is improved at the expense of another. For example, installing thermal insulation on energy harvesters could reduce vibration intensity, thereby lowering the amount of power collected. Similarly, optimizing structures for efficient vibration energy harvesting can increase thermal exposure or stress concentrations.

In terms of practical feasibility, one of the most significant conditions for exhaust-integrated cooperative systems is material survivability. For materials to be used in a high-temperature application, the piezoelectric properties, like polarization, resistivity, electromechanical coupling, and mechanical strength, should be stable at elevated temperature and thermal cycling conditions; otherwise, the resonance tuning and electrical output will be unstable. While the conventional piezoelectric materials have a high piezoelectric response, they are limited by Curie temperature and also by depolarisation-related degradation. The other families of piezoelectric materials, like high-temperature ceramics such as bismuth-layered ceramics and perovskite-layered ceramics, have better thermal stability but lower piezoelectric coefficients and more difficult processing. The practical limitations that move toward electromagnetic harvesters are the thermal stability of the magnets, the insulation of the coils, the oxidation protection, and the mechanical fixation under continuous vibration. Thus, material selection is not limited to achieving peak energy output only, but must also consider retention of the functional properties following coupled thermal-vibration exposure [9].

In addition to those conditions seen in ideal laboratory tests, real exhaust conditions become additional constraints. Exhaust-mounted devices can be subject to brief temperature swings, temperature differences in space, broadband random vibration in the exhaust, exhaust shock, exposure to soot and/or condensate, corrosion and repeated expansion and contraction of mounts and interfaces. The same issue is well known in the automotive exhaust thermoelectric generators, where the design of the heat exchanger, its pressure drop, thermal contact resistance, cold-side management, size of the packaging volume, and long-term reliability are all strong influences on the practical performance [63]. Thermal cycling is of special concern: experimental testing of thermoelectric modules has demonstrated that cyclic heating can cause significant reductions in power output and figure of merit as a result of internal damage (in particular micro-cracking) and increased electrical resistance [64]. These findings suggest that exhaust-integrated vibration-thermal systems should be evaluated under coupled thermal cycling and vibration loading rather than under steady-temperature or single-frequency excitation alone.

Therefore, not only should system-level metrics be used to assess the practical readiness of the cooperative structural-exhaust system, but the assessment should also not be based on individual peak performance. Relevant indicators include: stable average power under representative driving cycles, thermal safety margin, output degradation after accelerated thermal-vibration cycling, resonance drift, mounting reliability, pressure-drop penalty, added mass, packaging compatibility, and power-management efficiency. In ICV applications, the ability to use the harvested energy for specific low-power sensing, monitoring or communication tasks is also important. Therefore, future cooperative designs must be characterised by the incorporation of high-temperature functional materials, stable, reliable encapsulation, mechanical mounting and thermal interface stability, and efficient power-electronics management in compact, exhaust-compatible architectures [50, 65].

This is leading to more realization that the boundaries of performance of individual technologies cannot be fully realized or broken without a system-level view [61, 66]. Coupled operating conditions. The technologies used to evaluate vibration energy recovery and thermal management under coupled operating conditions are essential for identifying design trade-offs, failure mechanisms, and opportunities for synergistic integration. This knowledge is the basis of cooperative design measures, which are addressed in the next section.

4. Cooperative design of broadband vibration energy recovery and thermal management

The presence of both broadband vibration and extreme thermal conditions in structural-exhaust systems implies that traditional isolation design methods must be replaced by cooperative design strategies [67]. Cooperative design focuses on the concurrent design of mechanical, thermal, and electrical functionality on a unified basis and seeks to achieve performance improvements through synergy rather than incremental gains in different subsystems. Such a strategy is specifically applicable to intelligent connected vehicles, where structural-exhaust systems are anticipated to take on multifunctional capabilities, such as energy recovery, thermal control, sensing, and structural support.

4.1. Conceptual framework of cooperative design

Cooperative design differs fundamentally from sequential or add-on design strategies. Traditional design practices involve developing exhaust systems that meet mechanical strength, durability, and noise requirements, and then incorporating thermal management systems and energy harvesting devices as ancillary systems. Such a sequence can easily result in suboptimal integration, in which the included components impose constraints or sanctions on the original structure. Contrarily, cooperative design views vibration energy recovery and thermal control as design goals in the first place [68].

In a collaborative system, the structural geometry, choice of materials, and functional arrangement are optimized by working together to fit in various physical disciplines. The mechanical vibrations are not only reduced but also carefully controlled to enhance energy harvesting, and the thermal fields are managed to protect delicate parts while enabling stable energy conversion. This paradigm promotes the utilization of natural coupling effects, like frequency tuning by temperature or heat transfer by vibration, where the potential weaknesses are turned into strengths [69].

The cooperative design paradigm is also naturally aligned with the system-level view needed for intelligent connected vehicles. Coupled functions on one structural platform. Cooperative design eliminates system complexity, reduces wiring and maintenance needs, and enhances energy efficiency and durability. Integration such as this is especially useful for distributed sensing and monitoring applications, where self-powered operation and thermal resilience are highly important.

4.2. Structural integration strategies

A main aspect of the structural-exhaust systems cooperative design is structural integration. Instead of connecting energy harvesters and thermal devices as discrete components, cooperative strategies aim at integrating these functions into load-carrying structures or exhaust elements. Examples include adding piezoelectric layers to exhaust brackets or supports, adding electromagnetic harvesting systems to vibration-isolation mounts, or making exhaust pipes with wall structures that have multifunctional properties, providing mechanical support, heat conduction, and energy conversion.

The compatibility of the structural performance and functional requirements is critical to the success of such integration. Components of energy harvesting should be installed in high-strain or regions of relative motion to generate as much energy as possible, whereas the components of thermal management should be installed along the major heat-flow directions to provide efficient heat control. Meanwhile, the introduced mass, stiffness and damping of functional materials should be handled with care not to cause negative impacts on the exhaust system's dynamics or the fatigue life [70, 71].

Advanced manufacturing techniques, including additive manufacturing and multi-material fabrication, have opened new opportunities for structural integration. These techniques enable the creation of complex geometries and graded material distributions that are difficult or impossible to achieve with conventional manufacturing. As a result, structures can be tailored to exhibit desired vibration modes and thermal conduction paths simultaneously, supporting cooperative performance optimization [72].

4.3. Multi-physics modeling and design optimization

This connection between mechanical, thermal, and electrical phenomena inherent in cooperative design requires multi-physics modeling methods. The models to predict the behavior of the system accurately must model the interactions between the processes of vibration response, heat transfer, and energy conversion. Coupled thermo-mechanical behavior is simulated at a high level with finite element methods, and electrical domain models are combined to assess energy harvesting performance.

For structural-exhaust systems with integrated vibration energy harvesters, a representative reduced-order coupled model can be expressed as:

$$M\ddot{q} + C(T)\dot{q} + K(T)q + \Theta(T)V = F(t) \quad (1)$$

$$C_p(T)\dot{V} + \frac{V}{R} - \Theta(T)\dot{q} = 0 \quad (2)$$

where q is the generalized mechanical displacement, V is the generated voltage, M, C(T), and K(T) are the mass, temperature-dependent damping, and temperature-dependent stiffness terms, respectively, Θ(T) is the temperature-dependent electromechanical coupling coefficient, $C_p(T)$ is the effective capacitance, R is the external load resistance, and F(t) is the vibration excitation. This form is consistent with commonly used coupled electromechanical models for piezoelectric vibration energy harvesters, in which mechanical vibration and electrical output are solved simultaneously rather than independently. In exhaust-integrated systems, the explicit dependence of C, K, Θ, and C_p on temperature is important because thermal cycling can shift resonance frequency, modify damping, and change electrical output.

The thermal field can be represented by an energy-balance equation such as:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k(T)\nabla T) + Q_{ex} - h(A, \omega)(T - T_a) - \varepsilon\sigma_{SB}(T^4 - T_a^4) \quad (3)$$

where ρ, c_p, and k(T) denote density, heat capacity, and temperature-dependent thermal conductivity, respectively; Q_{ex} represents heat input from exhaust gas; h, (A, ω) is a vibration-dependent convective heat-transfer coefficient; T_a is ambient temperature; ε is surface emissivity; and σ_{SB} is the Stefan-Boltzmann constant. This represents the sum of conducting, exhaust heat input, convection and radiation. In addition to temperature, for thermoelectric generator-equipped exhaust systems, thermal-electrical modeling can include the temperature dependency of the Seebeck coefficient, electrical resistivity, and thermal conductivity, because they affect the temperature distribution, the heat flux, and power output from the exhaust system [73–75].

These relations are typically represented as coupled structural, thermal and electrical matrices for finite element implementations, and can be solved simultaneously in a single framework to obtain the displacement, temperature and voltage fields. These types of coupled-field formulations can be especially helpful for structural-exhaust systems, where electrical conversion, vibration response, and thermal deformation all occur concurrently and interact. Depending on the level of detail required, the model may be established as a full three-dimensional finite element model for local stress and temperature analysis, or as a reduced-order model for system-level optimization and control.

To maintain computational complexity and facilitate system-level analysis, reduced-order models are frequently used. These models preserve the main dynamic and thermal features of the system but allow parametric investigations and optimization to be effectively done. This is of particular interest when design trade-offs (e.g., between vibration amplitude and thermal protection) or the effects of material properties on energy-harvesting efficiency and thermal stability are to be studied.

The process of design optimization in a collaborative system is usually subject to numerous, usually conflicting goals. These can be maximizing the harvested energy, minimizing peak temperatures, ensuring structural integrity, and cyclic loading durability. Multi-objective optimization methods and constraints that are based on the considerations of manufacturing and packaging are thus necessary. Over the last few years, data-driven methods and surrogate modeling techniques have become more and more popular in order to make the optimization process faster and allow a large design space to be explored [76].

Hence, a cooperative design problem can be set up as a multi-objective optimization problem where the objective functions comprise harvested power or cycle-averaged energy, maximum structural temperature, thermal stress, bandwidth, mass penalty, and fatigue-related damage indicator. The constraints may be permissible temperature, stress, displacement, packaging volume, electrical load range and material stability limits. In the context of broadband piezoelectric energy harvesting, an application in which the optimum design trade-off between the frequency response and the harvested power is sought, similar techniques of multi-objective and topology-optimization have been used, confirming the usefulness of optimization-based design for systems under variable-frequency excitation. For structural-exhaust applications, the additional thermal constraints make this optimization problem more demanding but also more relevant to practical vehicle deployment.

In general, cooperative design is a comprehensive concept that builds upon multi-physics interactions to optimize structural-exhaust systems' performance [77, 78]. Cooperative design presents an opportunity for intelligent connected vehicles by combining broadband vibration energy recovery and thermal management at the structural level and using advanced modeling and optimization methods. **Table 4** summarizes representative cooperative strategies and explicitly links each integration pathway to the coupling mechanism exploited and the resulting system-level benefit.

Table 4. Cooperative design strategies for integrated vibration energy recovery and thermal management.

Cooperative strategy	Coupled functions	Main design lever	Expected benefit
Structural embedding	Load bearing; energy harvesting	Placement in high-strain regions	Reduced packaging and higher usable output
Thermal-dynamic co-design	Heat regulation; vibration tuning	Temperature-dependent stiffness control	More stable broadband response
Multifunctional materials	Structural; thermal; electrical roles	Material-level coupling	Weight and volume reduction
Multi-physics optimization	Mechanical; thermal; electrical domains	Coupled simulation and trade-off analysis	Balanced system performance
Intelligent control integration	Energy recovery; thermal regulation; sensing	Real-time data and adaptive control	Robust operation under variable driving conditions
Vehicle-level validation	Prototype; control; durability testing	Coupled thermal-vibration assessment	Improved readiness for ICV deployment

5. Intelligent control and system-level validation

Coupling of vibration energy recovery and thermal management of the structural-exhaust systems to broadband capabilities of cooperative design will be effective in the end, not only depending on structural integration and optimization across multi-physics, but also on the adaptability to very variable operating conditions [79]. Connected vehicles are intelligent; they operate in ever-evolving driving conditions that vary in engine speeds, road conditions, ambient temperatures, and load requirements. The differences cause drastic changes in vibration spectra and thermal fields; therefore, it is not possible to rely on static or purely passive design solutions. Evident control strategies and system-level validation are thus necessary to ensure robust, reliable performance across the full range of operating conditions.

Most importantly, intelligent control is not only an add-on feature in ICV but also a fundamental enabling layer that distinguishes the structural-exhaust cooperative systems of ICV from those of conventional vehicles. ICVs also have dense onboard sensing and real-time signal processing, V2X connectivity, and distributed control architectures, which are not possible on conventional vehicles, which provide only broadband vibration and exhaust heat output. The capacities enable dynamic coordination of vibration energy recovery and thermal management based on the vehicle state, driving situation, environmental data, and local power demand. To this end, the ICV context takes the cooperative design from a passive multi-functional structure to an adaptive cyber-physical energy and thermal management system [80].

5.1. Adaptive and intelligent control strategies

Adaptive control is important for ensuring effective vibration energy recovery and thermal management under nonstationary conditions. In the case of vibration energy harvesters, adaptive control allows dynamic features, e.g., resonant frequency, damping, and electrical load, to be varied in real time in response to changes in excitation spectra. Harvesters can vary their resonance properties with mechanical tuning techniques, such as variable stiffness mechanisms, movable masses, and electrical tuning techniques, which can vary the parameters of the circuit to maximize energy harvesting. Such adaptive techniques can be of great use, especially in exhaust systems where prevailing frequencies of vibrations vary with engine speed and driving mode [81, 82].

Real-time vehicle data streams can also provide further assistance to ICVs through adaptive tuning. The optimal operating state of the harvester can be determined based on the harvester speed, acceleration, road-condition information, exhaust temperature, structural vibration signals, and energy demand of nearby sensing nodes. This data-driven control approach is also entirely distinct from passive resonance matching, as the energy harvesting system not only responds to degradation in energy harvesting performance but can also predict or quickly adapt to changes in the excitation [2, 83].

Intelligent control is also useful in thermal management, particularly in systems that have active or semi-active thermal regulation components. Control algorithms can also optimize insulation performance, heat loss rates, or waste heat recovery by monitoring temperature fields and heat fluxes to allow temperatures to stay within specified ranges. When thermal management and energy harvesting are complementary, control strategies should be considered in terms of their effects on each other. As an example, adding thermal insulation to sensitive parts can minimize levels of vibration and therefore energy harvested, which means energy harvesting parameters should be synchronized.

This coupling is a coordinated not an independent control. An ICV structural-exhaust system requires a compromise among maximum harvested power, thermal security, structural strength, and sensor reliability, as environmental conditions are constantly changing. Under high-load and high-temperature conditions, for instance, the control system might provide thermal protection and material stability; under moderate thermal conditions with high vibration excitation, it might focus on improving energy harvesting. The intelligent vehicle architecture supports such operating-state-dependent decision-making [84].

Intelligent connected vehicles allow more elaborate control structures through the integration of sensing, control, and communication features in vehicles [85]. Structural-exhaust systems equipped with distributed sensors provide real-time information on vibration, temperature, and structural health. Such information may be processed locally or sent across vehicle networks to aid in coordinated decision-making. This capability enables collaborative systems to respond dynamically to changes, enhancing energy recovery efficiency and thermal resilience.

As such, adaptive control should be considered an essential design feature of the cooperative structural-exhaust system for ICVs. The energy harvesting unit, thermal management component, sensing node, and control algorithm shall be designed as an integrated functional module rather than as separate subsystems. From a practical integrated control perspective, converting broadband vibration and exhaust heat into stable, usable energy while maintaining thermal and structural safety is a viable approach [86].

5.2. Data-driven methods and connected vehicle perspectives

The growing supply of information in intelligent networked vehicles has enhanced the adoption of information-based controls and optimization techniques. Machine learning methods provide a strong tool for modeling complex and nonlinear relationships relating to operating conditions, vibration response, thermal fields, and energy harvesting performance. Such models will be able to forecast the behavior of a system in unobserved conditions by relying on the historical and real-time data and aid adaptive control.

Data-driven system methods are of particular importance for cooperative structural-exhaust systems, as the relationships among vibration excitation, thermal gradients, material properties, and electrical output are highly non-linear and cannot be fully captured by fixed analytical models. Dominating vibration bands can be identified, resonance drift due to temperature changes can be predicted, remaining thermal margins can be estimated, and electrical loading strategies can be optimised using data-driven models. Consequently, machine learning can be used not only as a post-processing tool but also to predict and continually refine the machine's performance.

With V2X, the operational time horizon for cooperative energy and thermal management extends to a new level. Vehicle-to-vehicle, vehicle-to-infrastructure, and vehicle-to-cloud communication enable ICVs to access information beyond the local exhaust system, such as traffic congestion, road grade, changes in speed limits, driving cycles, environmental conditions, and more. These external data sources can be used to predict future vibration and thermal loads before the load is actually applied to the vehicle. For instance, road slope, traffic density or anticipated acceleration events could be used to pre-tune harvester parameters, thermal protections and/or energy distribution before the transition to a large change in operating mode [9, 87].

A particularly promising technology for cooperative design and validation is digital twin technology. Various multi-physics models are combined with real-time sensor data to create a digital twin of a structural-exhaust system, providing a virtual representation of the real system's life cycle. With such a framework, real-time energy recovery optimization and thermal management strategies are predicted and constantly monitored, as well as performance. Digital twins may be used in the context of intelligent connected vehicles to update the models, optimize control policies, and organize energy management through vehicle fleets due to vehicle-to-cloud connectivity [88, 89].

From this perspective, digital twins can serve as the operational link among the design stage, multi-physics optimisation, and real-world adaptive control. A digital twin can continuously compare the predicted and measured responses to vibrations, temperatures, and energy output in running vehicles, allowing for the detection of deviations from the model, material degradation, or new potential failure risks. It is also able to assess, prior to implementation, alternative control actions to minimise thermal or mechanical responses that could be dangerous. This is particularly vital for structural-exhaust systems, where a direct physical test of the system under all driving and environmental conditions is not possible [90–93].

At the systems level, cooperative energy and thermal control should be consistent with vehicle-wide objectives. Vibration or exhaust heat energy can be used in various subsystems based on operational requirements, including driving some important sensors, assisting wireless communication, or minimizing auxiliary power usage in the main power system. Intelligent control structures will be able to dynamically distribute the energy that is collected, depending on the needs of the system and improve the overall performance and stability of the vehicle [94].

Therefore, V2X connectivity, data-driven modelling and digital twins are not meant to be viewed as extra technological features. They offer information, prediction and decision-making systems to achieve cooperative design under realistic ICV operating conditions. If this intelligence layer is not in place, integrated vibration energy recovery and thermal management would not be as effective, nor could they make full use of the dynamic, data-rich environment in which the intelligent connected vehicle operates.

5.3. Experimental validation and system-level demonstrations

To demonstrate the viability and usefulness of cooperative design processes under real-world operating conditions, experimental validation would be necessary.

Laboratory-scale experiments usually include test rigs that model the coupled vibration and thermal surroundings of exhaust systems, enabling the performance of energy harvesting to be studied under controlled conditions, and the thermal behavior and structural integrity to be studied. These experiments are important, as they give us information on multi-physics interactions, the behavior of materials under high temperatures, and the versatility of adaptive control measures [9, 95].

In the case of ICV-oriented cooperative systems, further experimental validation requires measuring the output power or the temperature reduction under fixed boundary conditions. Validation platforms need to be capable of creating time-varying vibration spectra, transient exhaust temperatures, control delays, sensor noise, and communication constraints [96, 97]. Road-vehicle electrical/electronic equipment is typically exposed to temperature, vibration, mechanical shock, humidity, corrosion, dust and chemical exposure and, it is believed that cooperative structural-exhaust modules should be tested under these combined stress conditions in the same manner as other reliability testing [98, 99]. This requirement is particularly important because the proposed system includes not only structural and thermal components but also sensing, power management, and control elements.

Experiments at the system level are not limited to laboratory experiments but also include vehicle-level and road experiments. These tests can capture the full complexity of actual operating conditions, including variable driving cycles, environmental conditions, and long-term durability. Demonstrations at the vehicle level can also be crucial in determining the reliability, robustness, and integration issues, including the packaging constraints and the compatibility with existing vehicle architectures [100].

A realistic driving cycle validation is particularly important for exhaust-integrated energy recovery. Transient driving cycles, thermal inertia, exhaust-flow variation and pressure-drop effects have been demonstrated to have significant impacts on practical performance of automotive exhaust thermoelectric generators which are not adequately captured by steady-state laboratory tests [101, 102]. Likewise, vibration energy harvesting in vehicles should not be considered at resonance frequencies, or measured at amplitudes of vibration that are much larger than the harvester's capability, but rather according to the low-frequency, small-amplitude, broadband, and speed-dependent nature of the excitation that occurs while driving, since the mechanical energy available to the harvester and the harvester's bandwidth depend strongly on the actual driving conditions [103]. Therefore, cooperative structural-exhaust systems should be tested using representative driving cycles, broadband random vibration profiles, exhaust temperature transients, and accelerated durability protocols.

Road validation in ICVs should also assess the cooperation between the road's structural-exhaust system and the vehicle's sensing/communication system. For instance, harvested energy stability needs to be evaluated relative to the power requirements of local sensing nodes, and adaptive thermal regulation needs to be tested under real driving cycles using vehicle-state and connectivity data. The monitoring efficacy of the digital-twin approach also needs to be validated by comparing predicted degradation trends, thermal risks, and energy-output differences with vehicle-level responses [104, 105].

System-level performance assessment needs extensive measures to consider efficiency of energy recovery, effectiveness in regulation of thermal efficiency, structural stability, and response to control. Comparative analysis of cooperative and conventional design strategies is essential for quantifying performance benefits and determining trade-offs. These validation tests not only help in the preparation of technology but also help in the direction of industrial practice and standardization.

In future system-level demonstrations, therefore, holistic evaluation criteria rather than component-specific performance indicators should be used. In addition to power density and thermal stability, relevant metrics should include adaptive bandwidth, control latency, prediction accuracy, energy autonomy of local nodes, durability under thermal-vibration cycling, and compatibility with vehicle network architectures. These would better represent the true needs for ICV applications and provide a basis for benchmarking cooperative structural-exhaust systems. As illustrated in **Figure 3**, such systems require an integrated intelligence layer that connects onboard sensing, V2X connectivity, digital-twin prediction, data-driven control, adaptive energy harvesting, thermal regulation, and laboratory- and vehicle-level validation within a closed-loop framework. The continuously varying driving states, traffic conditions, vibration spectra, and thermal gradients of ICVs make this system-level integration essential for achieving reliable and adaptive operation [84, 106].

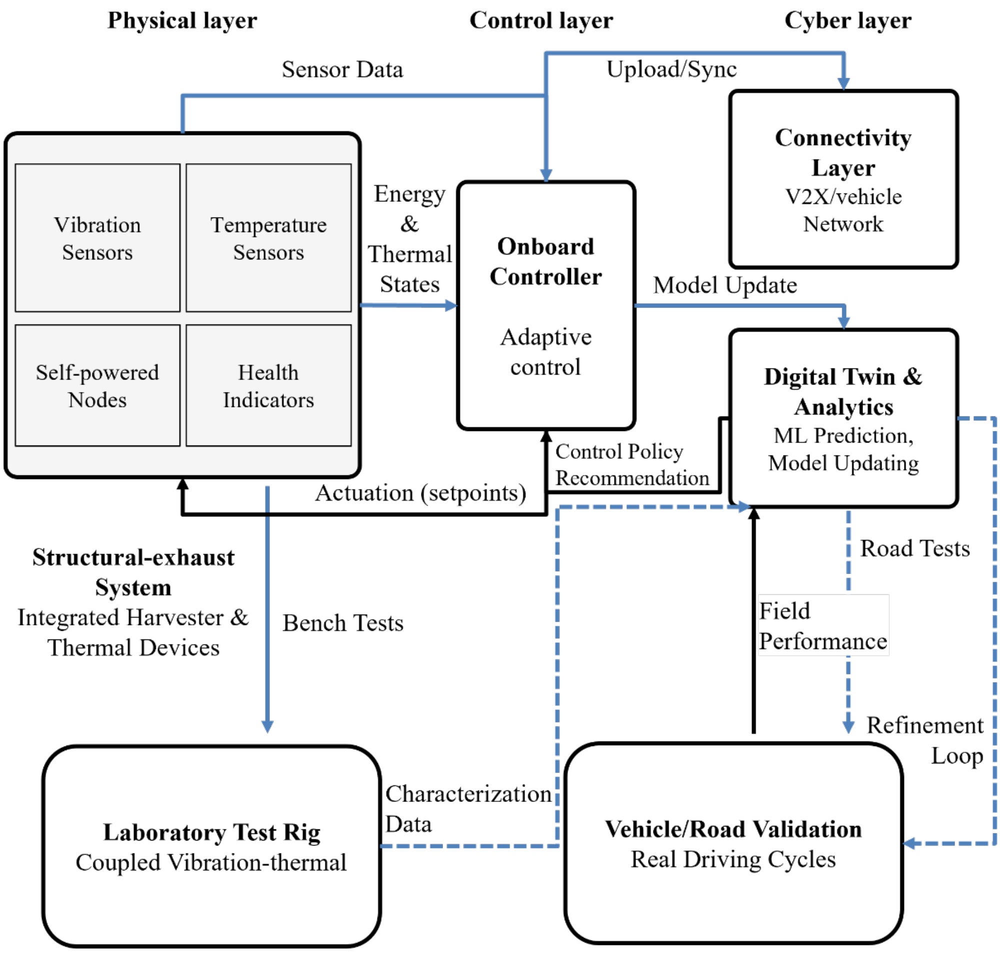

Figure 3. System-level architecture for intelligent control and validation of cooperative structural-exhaust systems in intelligent connected vehicles.

In summary, intelligent control and rigorous system-level validation are indispensable components of cooperative design for structural exhaust systems. By combining adaptive control strategies, data-driven methods, and comprehensive experimental validation, cooperative systems can achieve robust performance in the highly variable and demanding environments characteristic of intelligent connected vehicles. The key benefit in the ICV context, therefore, is not just that exhaust vibration and heat are present in such vehicles, but that the sensing, communication, and computing infrastructure is available to enable these waste energy sources to serve as intelligent, self-powered, thermo-resistant vehicle subsystems.

6. Conclusions

The cooperative design of broadband vibration energy recovery and thermal management for structural-exhaust systems in intelligent connected vehicles has been discussed in this review, and the challenges and opportunities brought by the coexistence of complex vibration environments and harsh thermal conditions have been raised. Intelligent connected vehicles are becoming more autonomous, connected, and sensing-rich, and include more onboard intelligence, while the need for reliable, distributed, and energy-efficient power solutions is also increasing in importance. The structural-exhaust system, which has been considered mainly in terms of durability, vibration suppression, and thermal protection, is demonstrated in this review as a valuable, multifunctional platform for energy recovery and thermal regulation, as well as for the intelligent integration of systems. In addition to broadband vibrations and exhaust heat, which also exist in conventional cars, ICVs will make the use of these resources particularly urgent due to the need for distributed sensors, wireless communication nodes, embedded monitoring units, and local control modules to maintain a stable, localized energy supply.

Analysis of the vibration and thermal properties shows that the thermal and mechanical environments that exhaust systems encounter are coupled, time-varying, and broadband, and are severe and nonuniform. They are key traits that have been shown to restrict the performance of traditional narrowband energy harvesters and standalone thermal management methods. The performance of these technologies, independently, is limited by advances in broadband vibration energy recovery technologies and exhaust thermal management approaches. It is very important to adopt an integrated design thinking approach, given the thermal effects on material properties, structural dynamics, and energy conversion efficiency, as well as the effects of vibration on heat transfer and thermal stability. This need is exacerbated in the ICV mode by the need for autonomous sensing, continuous structural monitoring, and the operation of distributed electronic subsystems under ever-varying driving conditions.

This review discusses the latest advancements, highlighting that the cooperative design paradigm is a viable approach to addressing these challenges. Cooperative design integrates vibration energy recovery and thermal management at the structural level, enabling the design of multifunctional components that can bear loads, convert vibration energy, regulate temperature, and ensure reliable sensing. Advanced manufacturing methods and multi-physics modelling open avenues to leverage inherent coupling effects, not just avoid them. Cooperative design can provide great improvements in system reliability, thermal strength, and energy-harvesting efficiency by optimizing the mechanical, thermal, and electrical aspects in a coordinated manner.

However, the majority of reported concepts for vibration energy harvesting and exhaust thermal management are still at the material, device, or lab-prototype level, not at the level of a vehicle-qualified integrated system. Due to the variety of exhaust vibration conditions, including broadband, stochastic, and thermally fluctuating, the net power output of existing harvesters under realistic conditions is not adequately demonstrated. Likewise, exhaust thermal management and waste heat utilization devices have been proven to have functional potential, but the trade-off of introducing them into vibration-sensitive structures has not yet been resolved regarding heat transfer, added mass, stiffness variation, fatigue durability and packaging. It is thus not only about harvesting energy or regulating heat, but also about being stable and durable enough to cope with real driving cycles.

The importance of intelligent control and system-level validation is emphasized as a means to enable practical implementation. An adaptive, data-driven control approach helps cooperative systems respond to nonstationary operating conditions, and digital twins and connected-vehicle technologies enable predictive optimization and lifecycle management. Experimental and vehicle-level validations are key to ensuring that the theoretical design is translated into a real system, offering valuable insights on durability, integration issues and performance trade-offs. These features make it clear why ICVs do not merely need to be a background application for recovering exhaust energy. Instead, the sensing, communication, computation, and connectivity infrastructure ensures the intelligence needed to coordinate vibration energy harvesting and thermal management in real time. From this perspective, ICVs are essential due to increasing distributed energy demands, but are also achievable through real-time data, V2X communication, digital-twin prediction, and adaptive control.

While the successes highlighted in this article are evident, there are still hurdles to overcome before the cooperative design method can be implemented in mass-produced vehicles. High-temperature durability of the functional harvesting material, broadband energy output under nonstationary excitation, and coupled thermal-vibration cycling long-term reliability are the most important technical barriers. Multifunctional structural-exhaust systems also need to be scalable and cost-effective, have robust control algorithms, integrate sensors reliably, and follow standard assessment protocols. Future research should go beyond reporting of peak output power, peak conversion efficiency or temperature reduction under isolated lab conditions. Newer benchmarks should also feature cycle-averaged harvested energy for typical driving scenarios, power-management efficiency, energy autonomy ratio of local sensing nodes, resonance drift under thermal loading, output degradation after accelerated thermal-vibration cycling, thermal regulation stability, control latency and vehicle-network compatibility. Such indicators would enable the field to make additional judgments about the ICV's practical deployment and laboratory feasibility.

There are various concrete research priorities. First, materials for high-temperature piezoelectric, electromagnetic, triboelectric, and hybrid harvesting should be tested under combined thermal stress, mechanical fatigue, and vibration spectra typical of exhaust environments, rather than single-field loadings. Second, cooperative modules need to be designed to deliver stable energy to specific low-power sensing or monitoring applications, rather than just a concept. Third, the distinction between isolated and cooperative designs, with respect to net energy, energy margin, thermal safety, structural durability, and adaptive response, should be assessed at the vehicle level. Lastly, there is a need to develop standardized coupled thermal-vibration test protocols to facilitate comparisons among various harvesting mechanisms, thermal management strategies, and cooperative architectures.

To sum up, the cooperative design of broadband vibration energy recovery and thermal management is a promising research path for next-generation intelligent connected vehicles. This way of thinking about structural-exhaust systems as active, multifunctional, and adaptive energy platforms helps achieve the objectives of vehicle energy efficiency, system intelligence, and sustainability. The suggestions and conclusions drawn in this review are intended to inform further research and industrial activities toward the implementation of self-powered, thermally resilient, and intelligent vehicle systems. The main point of this review is that conventional vehicles are the physical platform on which exhaust vibration and heat recovery are possible, while ICVs have a more solid application need and the intelligence infrastructure required to apply exhaust vibration and heat recovery as a collaborative resource. This idea now needs to be developed from the review-level promise to engineering practice, which requires the field to move from isolated proof-of-concept demos to quantitatively benchmarked, closed-loop, and vehicle-validated cooperative structural-exhaust systems.

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