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**ІНТЕГРАЦІЯ ТЕПЛОВИХ ПРОЦЕСІВ, ГІБРИДНИХ СИЛОВИХ УСТАНОВОК  
ТА ЕКСПЛУАТАЦІЙНИХ РОЗРАХУНКІВ АВТОМОБІЛЯ. ІНЖЕНЕРНІ АСПЕКТИ****В.В. Кривда<sup>1</sup>, О.П. Сакно<sup>2</sup>, К.І. Корніленко<sup>3</sup>**<sup>1</sup>доцент кафедри автомобільного транспорту, e-mail: [krivda.v.v@nmu.one](mailto:krivda.v.v@nmu.one)<sup>2</sup>доцент кафедри автомобільного транспорту, e-mail: [sakno.o.p@nmu.one](mailto:sakno.o.p@nmu.one)<sup>3</sup>старший викладач кафедри автомобільного транспорту, e-mail: [kornilenko.k.i@nmu.one](mailto:kornilenko.k.i@nmu.one)<sup>1,2,3</sup> Національний технічний університет «Дніпровська політехніка», Дніпро, Україна

**Анотація.** Оглядова стаття присвячена інтеграції теплових процесів, гібридних силових установок і експлуатаційних розрахунків автомобіля як взаємопов'язаних елементів інженерної оцінки ефективності, надійності та вартості життєвого циклу. Показано, що гібридизація змінює баланс теплогенерації між ДВЗ, електричним приводом та тяговою батареєю і вимагає багатоконтурного теплового менеджменту з урахуванням ризику теплового розгону та деградації елементів під впливом температурних полів. Узагальнено сучасні архітектури HEV, серійна, паралельна, Power-Split стратегії керування енергообміном, що мінімізують витрати палива та електроенергії за умов змішаних режимів руху. Окрему увагу приділено системам терморегулювання батареї, повітряним, рідинним, РСМ, гібридним і застосуванню теплових насосів та інтегрованого використання відпрацьованого тепла, що підвищує енергоефективність у холодному кліматі. Показано роль матеріалів і теплопровідних інтерфейсів у забезпеченні температурної однорідності модулів та безпеки. Виконано інженерну інтерпретацію експлуатаційних розрахунків: динаміки розгону, змішаного, рекуперативно-фрикційного гальмування, керованості та плавності руху з урахуванням масо-габаритного впливу батареї і розподілу крутних моментів. Техніко-економічний аналіз окреслює відмінності між типово декларованою та реальною паливною економічністю для PHEV і підкреслює важливість стандартів випробувань акумуляторних систем. Запропоновано узгоджену структуру інженерних розрахунків, яка поєднує теплотехніку, архітектуру силової установки та експлуатаційні показники як основу для подальших досліджень і практичного проектування.

*Ключові слова:* гібридні силові установки; теплові процеси; тепловий менеджмент батареї; тепловий насос; рекуперативне гальмування; енерго-менеджмент HEV; техніко-економічний аналіз.

**INTEGRATION OF THERMAL PROCESSES, HYBRID POWERTRAINS AND VEHICLE  
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**Abstract.** The review article examines the integration of thermal processes, hybrid powertrain systems and vehicle performance calculations as interrelated components of engineering assessment of efficiency, reliability and life-cycle cost. It is shown that hybridization changes the distribution of heat generation between the internal combustion engine, electric drive, and traction battery, requiring multi-circuit thermal management that accounts for the risks of thermal runaway and component degradation under varying temperature fields. Modern HEV architectures, series, parallel, and power-split, and energy-management strategies aimed at minimizing fuel and electricity consumption under mixed driving conditions are summarized. Special attention is devoted to battery thermal regulation systems, air, liquid, PCM-based, and hybrid solutions and the use of heat pumps and integrated waste-heat recovery, which enhance energy efficiency in cold climates. The role of materials and thermal interface layers in maintaining temperature uniformity and safety of battery modules is highlighted. Engineering interpretation of operational performance calculations is provided, including acceleration dynamics, blended Regenerative-Friction braking, vehicle controllability, and ride smoothness, considering the mass-dimensional impact of the battery and torque distribution. A techno-economic analysis outlines the discrepancy between type-approved and real-world fuel economy for PHEVs and emphasizes the importance of standardised testing of traction battery systems. A unified engineering framework is proposed, combining thermal science, powertrain architecture, and vehicle operating characteristics as a foundation for further research and practical design applications.

*keywords: Hybrid Powertrains; Thermal Processes; Battery Thermal Management; Heat Pump; Regenerative Braking; HEV Energy Management; Techno-Economic Analysis.*

**Introduction.** The electrification of road transport has catalyzed a profound evolution of automotive powertrains—from conventional internal-combustion engines (ICE) to hybrid configurations whose behavior is governed not only by mechanics but also by coupled thermal and electrochemical processes. In hybrid vehicles, heat is generated within the ICE, electric machines and power electronics, and the traction battery through internal resistance. This reality elevates the role of integrated thermal management as a precondition for safety, durability, and energy efficiency. Contemporary surveys on lithium-ion thermal management consistently underscore narrow admissible operating temperatures, the sensitivity of battery life to temperature non-uniformity, and the need to combine active and passive cooling approaches. Within hybrid powertrains, series, parallel, and power-split architectures redistribute energy flows between the engine and the electric drive in distinct ways, with direct implications for heat release patterns, engine efficiency corridors, and the attainable depth of regenerative braking. A particular challenge arises in cold climates: the use of heat pumps, targeted recirculation of waste heat, and integrated battery-e-drive-cabin-engine schemes can reduce HVAC energy demand and shorten battery warm-up time. At the same time, real-world fuel consumption of plug-in hybrids (PHEVs) depends strongly on user profiles and charging intensity: empirical anal-

yses based on on-board fuel consumption monitoring (OBFCEM) reveal substantial gaps between WLTP values and in-use performance, calling for explicit incorporation of usage profiles into engineering calculations. Against this backdrop, an integrated view of thermal processes, hybridization, and operational performance is timely for engineering synthesis, for the selection of materials and components of thermal machinery and devices, and for well-founded techno-economic decisions at the vehicle level.

**Aim and Objectives.** The aim of this article is to consolidate engineering approaches to the integration of thermal processes, hybrid powertrain architectures, and vehicle-level operational calculations with an emphasis on energy efficiency, safety, and operating economy. To pursue this aim, we systematize contemporary HEV layouts and associated energy-management strategies, synthesize methods of thermal management for batteries and power modules, including heat pumps and hybrid cooling schemes, analyze the impact of hybridization on acceleration performance, braking, controllability, and ride smoothness, align operational calculations with techno-economic indicators while acknowledging discrepancies between test-cycle and real-world values, elucidate the role of materials and thermal interface layers in securing temperature uniformity and functional safety; and map engineering calculations to the requirements of traction-battery testing standards.

**Review of Current Research and Sources.** Taxonomies and comparative analyses of HEV architectures indicate advantages of parallel and combined Power-Split schemes for passenger cars, while outlining potential niches for series architecture given advances in power electronics and energy storage. Recent studies highlight the contribution of wide-bandgap SiC converters and supercapacitors to overall drivetrain efficiency.

Energy-management strategies have progressed from rule-based heuristics to optimization-based methods dynamic programming, Pontryagin's minimum principle, equivalent-consumption minimization and further to data-driven and machine-learning approaches that approximate optimality in real time and can explicitly encode thermal constraints of components.

Battery thermal-management systems-air, liquid, heat-pipe, and PCM-exhibit clear trade-offs among system complexity, mass, parasitic energy, and temperature uniformity; hybrid solutions that merge passive buffers with active cooling are increasingly seen as a path to mitigating thermal runaway risk. Integrated HEV thermal systems that combine heat pumps with engine and power-electronics waste-heat recovery have demonstrated reduced heating energy demand and faster battery warm-up in cold climates in both simulation and experimental campaigns. In braking systems, blending regenerative and friction braking remains a constrained allocation problem with comfort and stability

bounds; surveys emphasize intelligent control laws and safety-critical aspects. Economic analyses and test evidence consistently show real-world PHEV fuel consumption exceeding WLTP by factors of three to five on average in many use cases, motivating regulatory adjustments utility-factor curves, OBFCM-based monitoring. Finally, ISO 12405 provides a coherent framework for validated testing of performance, reliability, and safety of HEV/PHEV battery packs and systems.

**Materials and Methods.** The review builds on high-quality open sources: peer-reviewed journals Springer, Elsevier, MDPI, IEEE, books, technical reports of the European Commission, and industry white papers by material and thermal-management OEMs. Sources were selected for relevance to three integrative strands as HEV architecture and energy-management systems (EMS), thermal processes and battery thermal-management systems (BTMS), and operational calculations and techno-economic assessment; inclusion required the presence of quantitative models or generalized test results. Terminology alignment and safety criteria reference ISO 12405-4 and companion standards reviews.

The theoretical foundation of integration is the vehicle and powertrain energy balance with explicit heat-transfer paths and sources. The instantaneous mechanical power at the wheels is formulated as with notation defined in the article body, which in turn couples to electrical and thermal sub-models for batteries, machines, and power electronics; subsequent sections provide the full expression and assumptions, along with the mapping to control and sizing tasks.

$$P_{dem}(t) = v(t) \left[ ma(t) + m \cdot g f_r + \frac{1}{2} \rho C_d A v^2(t) + m g \sin \theta(t) \right], \quad (1)$$

where  $m$  – mass;  $a$  – acceleration;  $f_r$  – rolling-resistance coefficient;  $C_{dA}$  – aerodynamic parameter (drag coefficient times frontal area);  $\rho$  – air density;  $\theta$  – road grade (slope) angle.

The demanded tractive power is provided by the combined contributions of the Internal-Combustion Engine (ICE) and the electric machine (EM), accounting for the efficiencies of the drivetrain, inverter, and battery; this establishes a direct connection between the vehicle's kinematics and HEV energy management [9–11].

Discrete ECMS statement. A discrete-time Equivalent Consumption Minimization Strategy ECMS for allocating power can be written as [12]:

$$\min_{u_k \in U} \dot{m}_f(u_k) + s \frac{P_{batt}(u_k)}{\eta_{chd/dis} LHV} \quad (2)$$

where  $\dot{m}_f$  denotes the instantaneous fuel flow rate,  $P_{batt}$  is the battery power (taken as positive during discharge),  $\eta_{chd/dis}$  is the charge/discharge efficiency, LHV is the lower heating value of the fuel, and  $s$  is the equivalence factor that converts electrical energy into an equivalent fuel penalty.

Selecting  $u_k$  the operating mode and the ICE/EM power fractions yields a quasi-optimal real-time compromise between fuel and electrical energy within the ECMS framework. For a lithium-ion battery, the instantaneous heat release can be expressed as:

$$\dot{Q}_{batt} = I^2 R_{int} + IT \frac{\partial U_{oc}}{\partial T}, \quad (3)$$

where  $I$  is the current,  $R_{int}$  is the internal resistance, and  $U_{oc}$  is the open-circuit voltage; the second term represents the entropic (reversible) component.

The corresponding heat transfer across the interface is described by Fourier's law,  $q = -k \nabla T$ , and the thermal contact resistance  $R_{th} = t/kAR$ .

This explains the engineering rationale for using high-conductivity thermal interface materials (TIMs)-increasing  $k$  lowers  $R_{th}$  and thereby reduces the temperature rise  $\Delta T$  within the module, [13].

For heat pumps, the heating coefficient of performance is

$$COP_{heat} = \frac{\dot{Q}_{out}}{W_{comp}}, \quad (4)$$

depends on the temperature levels of the source and the sink and on the defrosting regime; integrating waste heat from the ICE/EM increases COP and shortens battery warm-up time in cold conditions [14], [15].

The regenerative-friction blending is formulated by the following constraints:

$$T_{br}(t) = T_{reg}(t) + T_{fr}(t), |P_{reg}| \leq P_{ch,max}(T, SOC), V_{ar(v)} \leq \varepsilon, \quad (5)$$

where  $P_{ch,max}$  is constrained by temperature and state of charge (SOC), and the variability of deceleration,  $V_{ar(v)}$ , serves as a comfort/handling indicator;

the control problem is further complemented by tire-road adhesion limits and ABS/ESC stability requirements [16], [17].

The operational fuel economy of plug-in hybrids (PHEVs) depends strongly on real-world usage profiles, including the frequency of daily charging, trip length, the urban-highway mix, ambient temperature, and the intensity of regeneration. Consequently, for engineering assessments it is advisable to move beyond nominal (laboratory) figures to a simple and transparent rescaling that quantitatively reflects how behavioral and climatic factors magnify the type-approval fuel-consumption value. Figure 1 illustrates the sensitivity of real-world fuel use to user profiles: with infrequent charging or sustained long-distance driving, the multiplier increases and actual consumption can exceed the laboratory value by multiples—an effect that must be accounted for in techno-economic evaluations.

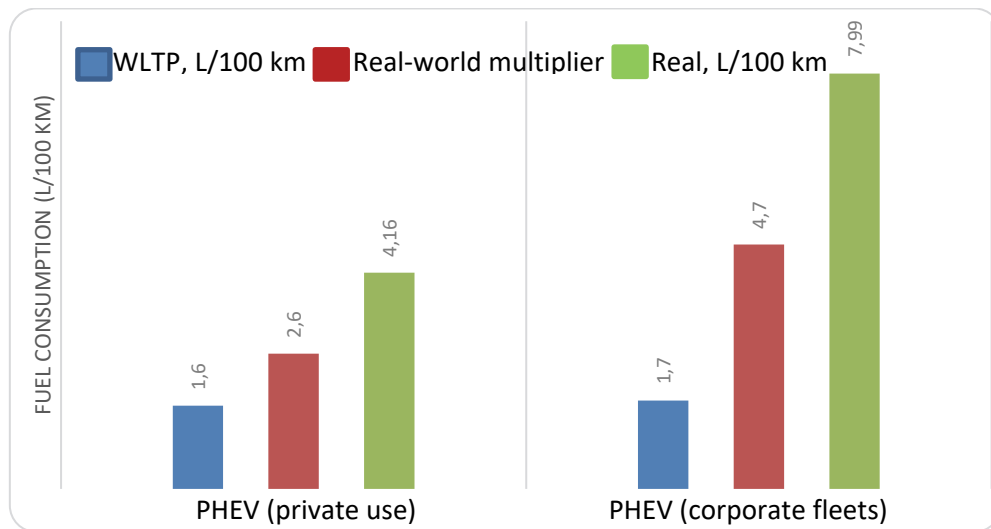


Figure 1. – Conceptual comparison of certified and real-world fuel consumption of PHEVs (WLTP vs OBFCEM).

Hybridization enables the internal-combustion engine (ICE) to operate within higher-efficiency regions while allowing peak loads to be absorbed by the electric drive, thereby reducing average thermal losses and improving overall fuel economy. The choice of powertrain architecture determines the share of electric contribution to traction and the achievable degree of regeneration, which, in turn, affects the thermal loading of braking hardware and electromechanical components. Comparative analyses of HEV layouts consistently highlight the practical advantages of parallel and combined architectures for passenger vehicles, owing to their flexibility in power distribution and lower conversion losses relative to pure series configurations.

Within battery thermal management, liquid cooling provides superior temperature controllability and uniformity compared to air systems, whereas

PCM-based and hybrid thermal solutions effectively smooth transient heat spikes and enhance passive stability, though they require integration with active loops to dissipate accumulated heat. The combined use of heat pipes can further improve performance during transient regimes.

From a techno-economic perspective, real-world PHEV fuel consumption exhibits strong sensitivity to user behavior: multi-source studies repeatedly show that actual consumption may exceed WLTP values by factors of three to five on average. This makes it necessary to incorporate correction coefficients reflecting the effective share of electric-only operation and to rely on OBFCEM data for an accurate representation of in-use conditions. Finally, ISO 12405 provides harmonized qualification procedures for HEV/PHEV battery systems, enabling consistent comparison of thermal solutions and ensuring reproducibility in engineering validation [4], [7], [14].

**Conclusions.** The integration of thermal processes, hybrid powertrain technologies, and operational vehicle calculations establishes a coherent engineering framework for decision-making. Powertrain architecture shapes thermal-release patterns and regenerative capabilities; effective thermal management of batteries and power modules reduces safety risks and extends component life; and heat-pump systems combined with waste-heat utilization offer substantial efficiency gains in cold climates. Material-level choices—particularly thermal interface layers—enhance temperature uniformity and help maintain safe operating regimes, while well-designed regenerative-friction blending strategies support vehicle stability and controllability.

Techno-economic assessments must rely on real usage profiles and on-board fuel-consumption data, as official test procedures do not fully represent operational conditions. Future research should focus on unifying EMS and thermal-management control within an integrated optimization framework, advancing hybrid cooling technologies, and refining standardized validation methods in line with ISO 12405.

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