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STUDY AND ANALYSIS OF THE INTEGRATION OF ENERGY RECOVERY SYSTEMS IN HYBRID VEHICLES

BY

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Abstract. The recovery of thermal and kinetic energy dissipated during the operation of a vehicle is a current approach to increase energy efficiency and reduce environmental impact in the automotive sector. In the case of hybrid vehicles, where both the electric and thermal engines are used, the recovery of these lost energies can significantly contribute to improving autonomy and overall efficiency. This paper presents a study on the development of an energy recovery system for hybrid vehicles, by recovering the energies otherwise lost during operation. The proposed system integrates three distinct mechanisms, the recovery of thermal energy from brake discs and exhaust gases using thermoelectric generators (TEG), as well as the transformation of kinetic energy from the damping system into electrical energy through a recovery mechanism, which involves the use of the pressure generated during operation and its transformation into electrical energy, as the damper compresses and rebounds during vehicle motion, its internal pressure variations drive a linear or rotary

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generator mechanism. For thermal energy recovery, the system uses thermoelectric generators, which convert temperature gradients directly into electrical energy through the Seebeck effect. When installed on brake discs and exhaust pipes, these devices capture waste heat that would otherwise dissipate into the environment. The study examines optimal TEG placement, temperature values obtained, and cooling strategies to maximize energy conversion efficiency while maintaining component reliability under varying operating conditions. The generated energy will be stored in the vehicle's batteries and used to power auxiliary systems, such as lighting, the infotainment system or other equipment that uses electrical energy. The study evaluates the efficiency potential of these systems, the impact on the vehicle's autonomy with their integration into the existing vehicle system, with the aim of expanding the research area to other systems where there are energy losses in the future and also explore scaling possibilities for electric vehicles and heavy-duty transportation, where energy recovery could yield even greater benefits.

Keywords: energy recovery, hybrid vehicle, thermoelectric generator, energy efficiency, kinetic energy.

1. Introduction

In the current context of climate change and depletion of energy resources, the automotive industry is facing significant challenges in reducing fossil fuel consumption and minimizing environmental impact. Hybrid vehicles, which combine the advantages of internal combustion engines with those of electric systems, represent an important intermediate solution in the transition to sustainable mobility. However, a considerable part of the energy generated during their operation is lost in the form of heat (through braking and exhaust gases) or kinetic energy (through the oscillations of the suspension system). Recovering these energies, which are normally dissipated in the environment, can significantly contribute to improving the overall efficiency of the vehicle, reducing fuel consumption and greenhouse gas emissions.

Recent studies have shown that approximately 30% of the energy produced by a conventional vehicle is lost through the exhaust system, and another 20-30% through the braking process. In addition, the suspension system, which absorbs energy from road bumps, represents another untapped source of kinetic energy (Peng *et al*., 2020). Therefore, implementing intelligent energy recovery systems can bring substantial benefits, both economically and environmentally.

This work focuses on the development of an integrated energy recovery system for hybrid vehicles, addressing three main sources of energy loss:

Thermal energy from brake discs – by using thermoelectric generators (TEGs) that convert the temperature gradient between the heated discs and the environment into electrical energy, based on the Seebeck effect (Chien and Mei, 2013).

Exhaust gas heat – also by means of TEGs, mounted on the exhaust pipe to capture the thermal energy of the exhaust gases.

Kinetic energy of the suspension system – converted into electrical energy using a regenerative shock absorber, which uses the linear motion of the piston to generate current through electromagnetic induction or piezoelectric effect (Jiageng, 2023).

The recovered energy is stored in the vehicle's auxiliary batteries and used to power secondary systems such as lighting, infotainment or ventilation, thus reducing the load on the internal combustion engine and extending the range in electric mode.

The importance of this study lies not only in optimizing the energy efficiency of existing hybrid vehicles, but also in exploring solutions that can be adapted to the field of fully electric vehicles or heavy transport (Juhuang *et al*., 2024). Through numerical simulations and models, the work evaluates both the performance of the proposed systems and their impact on vehicle dynamics and component durability. The results obtained will serve as a basis for future research in the field of advanced vehicle energy management.

In conclusion, this work highlights the potential of energy recovery systems in reducing energy losses and promoting cleaner mobility, in line with the global sustainable development goals.

2. Design and development of the recovery system

The energy recovery system developed in this research targets three primary sources of wasted energy in hybrid vehicles: thermal energy from brake discs and exhaust gases, and kinetic energy from suspension dampers. Each subsystem is designed to maximize energy conversion efficiency while maintaining compatibility with the vehicle's existing architecture. The recovered energy is stored in auxiliary power systems, reducing the load on the main battery and improving overall vehicle efficiency. This chapter provides a detailed breakdown of the design methodology, component selection, and integration strategies for each subsystem.

2.1. Theoretical background

The energy recovery systems developed in this research are based on well-established principles of thermodynamics and electromechanical energy conversion. This subchapter explains the fundamental working mechanisms of each subsystem, focusing on how thermal and kinetic energy are captured, transformed, and stored as electrical energy.

Thermoelectric energy recovery (brake discs & exhaust)

The recovery of thermal energy from brake discs and exhaust gases relies on the Seebeck effect, which describes the direct conversion of temperature gradients into electrical voltage. When one side of a thermoelectric generator (TEG) is heated while the other is cooled, charge carriers (electrons or holes) diffuse from the hot side to the cold side, generating a measurable voltage (Qiu *et al.*, 2023).

During braking, friction between the brake pads and discs generates significant heat, with temperatures reaching 300–600°C. This thermal energy, which is typically wasted as it dissipates into the air, can be recovered using thermoelectric generators (TEGs). Two TEGs are mounted on each side of the brake disc, with the hot side in direct contact with the disc and the cold side attached to a heat sink. A thermal interface material, such as graphite pads, ensures efficient heat transfer.

Recovering brake heat is crucial because up to 30% of a vehicle's kinetic energy (Ahmed and Mehmet, 2022) is lost as heat during braking. Capturing even 10–15% of this energy can power auxiliary systems like LED lights, sensors, and infotainment. The TEG modules used are typically made of bismuth telluride (Bi_2Te_3), such as the TEG1-12611-6.0 model (Ahmad *et al*., 2020), which operates with a hot side at 300°C and a cold side maintained at 50°C via forced air cooling. These TEGs are wired in series to increase voltage output–for example, four TEGs generating 1V each can produce a combined 4V DC. A boost converter then steps up the voltage to 12V or 48V for compatibility with the vehicle's battery system. Under optimal conditions, each TEG generates 5–6W, resulting in a peak output (Zhongyue *et al*., 2015) of 24W per wheel or 96W for all four wheels during aggressive braking.

The exhaust system carries 30–40% of the engine's waste heat (Dhruv and Rashmi, 2021), with gas temperatures ranging from 300–700°C (Ding *et al*., 2018). To capture this energy, TEGs are mounted along the exhaust pipe, typically downstream of the catalytic converter. A liquid cooling loop maintains the cold side of the TEGs at 80–100°C, ensuring a significant temperature gradient for efficient energy conversion.

High-temperature TEGs, such as skutterudite-based models (e.g., Laird HTG-12), are used for their durability under extreme conditions. These TEGs are connected in a series-parallel configuration to optimize voltage and current output. A maximum power point tracking (MPPT (Asaduzzaman *et al*., 2023)) controller is employed to maximize energy extraction under varying thermal conditions.

Hydraulic-electromagnetic regenerative dampers

The kinetic energy from suspension motion is recovered through a hydraulic-electromagnetic system that converts linear piston movement into rotational energy, which is then transformed into electricity (Nikhil *et al*., 2023).

The damper's piston motion, which ranges from 10–85 mm in stroke, pressurizes hydraulic oil (Marco *et al*., 2022) to 50–100 bar, depending on road conditions. This pressurized oil drives a rotary pump/motor, such as an axial piston pump (e.g., Bosch Rexroth A2FM), which converts the oil flow into rotational motion.

The rotating shaft of the pump is coupled to a permanent magnet synchronous generator (PMSG), such as the Maxon EC-4pole, which produces 3-phase AC electricity. This AC output is rectified to DC using a 3-phase rectifier and then stored in supercapacitors for rapid energy buffering. The system can generate 50–130-150 W per damper, with a peak output of 600 W when all four dampers are active on rough terrain.

The energy recovered from all three subsystems is managed by a central power management system. The TEG outputs from the brake and exhaust systems are fed into boost converters and MPPT controllers to ensure optimal voltage regulation. The damper's rectified DC output is similarly regulated to match the auxiliary battery voltage. Supercapacitors handle rapid charge and discharge cycles, while a 12V or 48V battery provides stable power for vehicle accessories.

2.2. Design methodology

The design methodology for each subsystem was structured to maintain the original mechanical and thermal functionality while embedding energy conversion components such as thermoelectric generators (TEGs) and permanent magnet generators (PMGs) (Ricardo *et al*., 2020). The approach taken ensured that the integration of these energy recovery units did not compromise vehicle safety, performance, or durability, while maximizing the energy harvesting potential under typical operating conditions.

A considerable source of thermal energy in an internal combustion engine vehicle is the exhaust system, particularly in the exhaust manifold and upper collector, where temperatures can exceed 500°C. For this reason, a dedicated TEG-based recovery setup was implemented using eight TEG modules mounted on the upper side of the exhaust pipe, where the heat flux is most intense and continuous during engine operation (Wissam, 2020) and the cooling circuit for cold side of TEG, from Fig. 1.

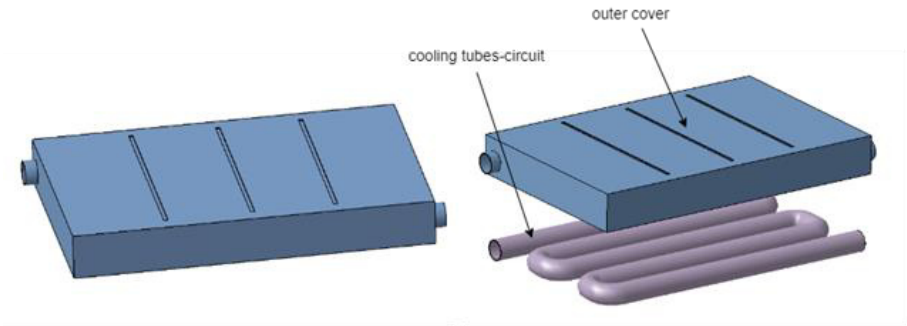


Fig. 1 – Proposed model for exhaust system.

To evaluate the effect of internal geometry on heat retention and recovery performance, two versions of the exhaust pipe were designed and tested, which are highlighted in Fig. 2 above.

– an empty exhaust model, representing a standard free-flow exhaust system;

– a patterned exhaust, which features an internal structure.

Each configuration was analysed thermally using finite element methods, and the comparative data on temperature distribution and TEG output informed the selection of the most efficient geometry.

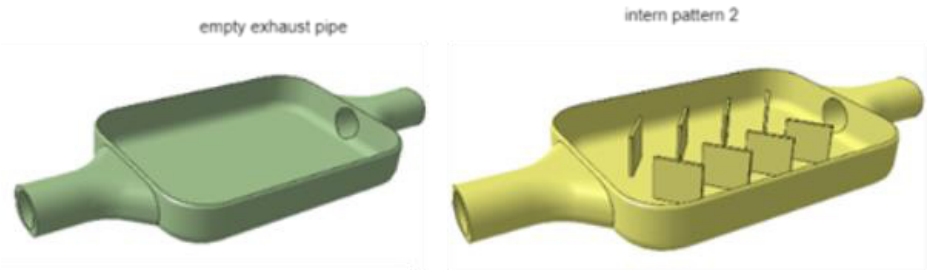


Fig. 2 – Exhaust variants.

As for the exhaust system, favourable thermal conditions have been identified in the area of the exhaust manifold, where the gas temperature can exceed 450°C. Eight TEG modules will be installed in this place, in 4S2P configuration – four in series, two branches in parallel, model presented in Fig. 3. This topology provides an optimal balance between voltage (6–8V) and current (10–16A), with a total estimated power between 64 and 110W depending on operating conditions.

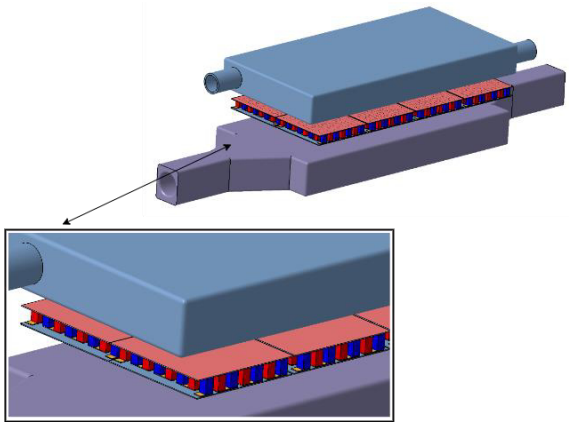


Fig. 3 – TEG assembly for exhaust system.

Another thermal source is the brake disc which harness this thermal energy, thermoelectric generators (TEGs) were integrated directly into the braking system (Dhruv and Rashmi, 2021). Each brake assembly includes two TEG modules mounted on each side of the brake pads, resulting in four TEGs per brake disc.

The mounting system ensures minimal impact on the mechanical integrity of the braking system while maintaining robust thermal conductivity.

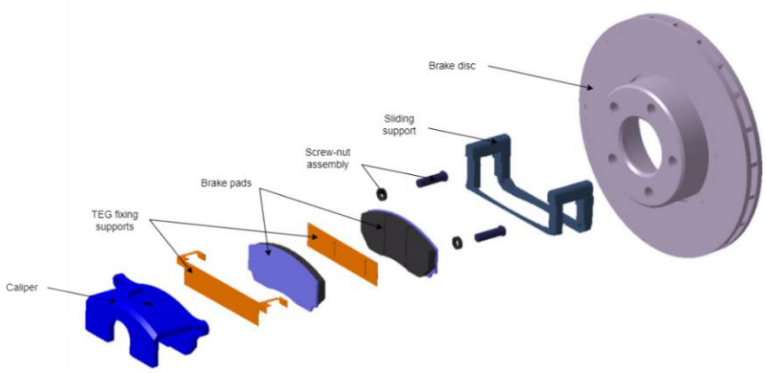


Fig. 4 – Brake system components.

For the brake pad area, it is proposed to mount two TEG modules on each plate, configured in series connection to increase the output voltage, the position on the TEG supports is as in Fig. 5. At a temperature difference of about 500°C, each TEG module can generate a voltage between 0.8 and 1.2V and a current of 3–5A, resulting in a power of about 4–6W per module. The series configuration of the two TEGs on each board provides a total voltage

between 1.6 and 2.4V. This energy can be stored locally in supercapacitors or redirected to the main battery via a DC-DC converter.

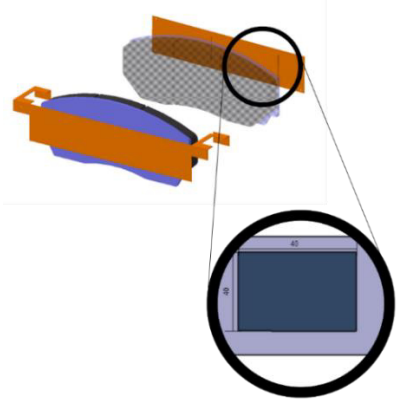


Fig. 5 – TEG position for brake disc-pad.

For integration with the hybrid vehicle's battery system, the electricity generated by the TEG modules will be taken over by a high-efficiency DC-DC power converter, which will adapt the output voltage to the level required to charge the main battery

Unlike the thermal-based systems, the regenerative shock absorber system recovers mechanical energy from the suspension's movement across uneven terrain (Vjekoslav *et al*., 2020). A standard hydraulic damper presented in Fig. 6 was modified externally by integrating an energy recovery module.

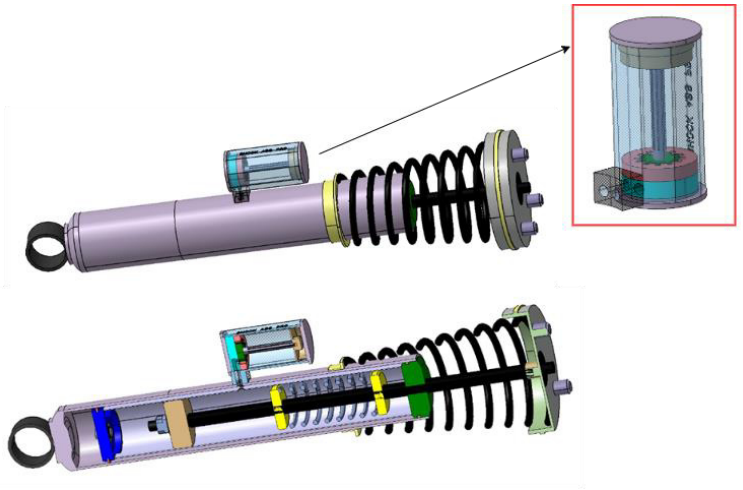


Fig. 6 – Shock absorber assembly.

This pump converts the fluctuating hydraulic pressure into rotational motion of a shaft.

The rotational motion is then transferred to a permanent magnet generator (PMG).

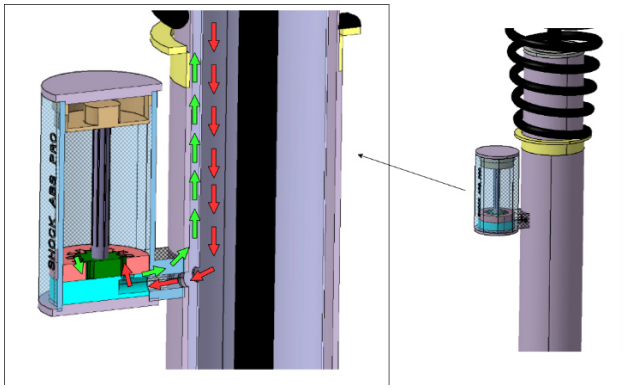


Fig. 7 – Working principle for regeneration module.

This generator converts the mechanical rotation into direct electrical current (DC), which can be stored or fed into the hybrid vehicle's powertrain system, as in the working principle presented in Fig. 7.

3. Numerical analysis and simulation results

This chapter presents the numerical analysis and simulation results for all three energy recovery systems developed in the study: the regenerative shock absorber, the brake disc thermoelectric generator system, and the exhaust-based thermoelectric recovery system. Each of these systems targets a specific type of energy loss typically which appear in automotive operation–mechanical vibrations, frictional heat, and exhaust gas heat, respectively–and aims to convert that energy into usable electrical power through integrated technologies.

All three systems are presented through graphical plots and quantitative comparisons, highlighting the differences in performance based on design choices such as material structure, module configuration, and thermal exposure, presented in the chapters above.

Brake disc system

This section presents the thermal analysis and electrical energy recovery results for the regenerative braking system using thermoelectric generators mounted on the brake discs. Two brake disc configurations were analyzed, a solid disc and a ventilated disc.

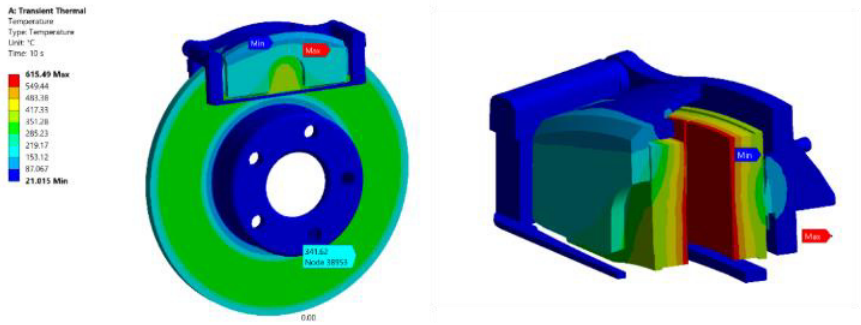


Fig. 8 – Temperature values for brake disc.

The Fig. 8 shows a clear thermal gradient from the center of the disc outwards, with sudden temperature variations in the areas of contact with the brake pads. The maximum value of 615.49°C occurs at the points of maximum friction (the edge of the disc or the ventilation channels), while the temperature gradually decreases inwards. This model confirms that the heat transfer is localized and uneven, which can lead to differential thermal deformations.

The intermediate temperatures (549.44°C, 403.38°C, 286.23°C) reflect the transition zone between hot and cold spots.

Above 500°C: areas close to direct contact with pads.

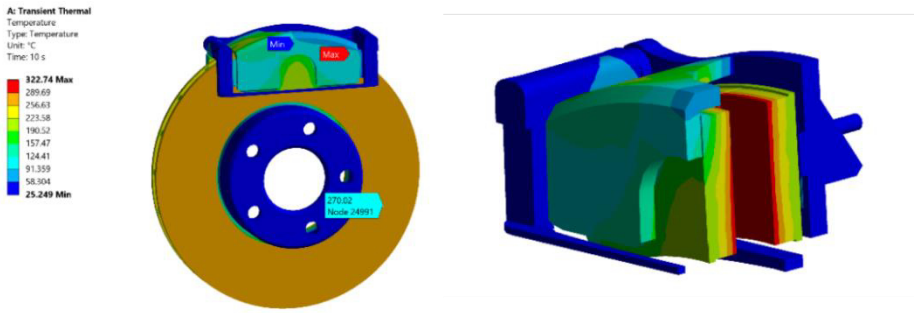


Fig. 9 – Temperature values for ventilated disc.

The ventilated disc registers a significantly lower maximum temperature (322.74°C) than the solid disc (615.49°C), although both are made of semi-metallic material, as in Fig. 9. This difference is due to effective ventilation. The intermediate values (289.69°C, 256.93°C, etc.) show a progressive decrease in temperature inwards, but with smaller variations than at the full disc.

The ventilated disc, even made of the same semi-metallic material, offers superior thermal performance to the solid disc thanks to the design optimized for cooling.

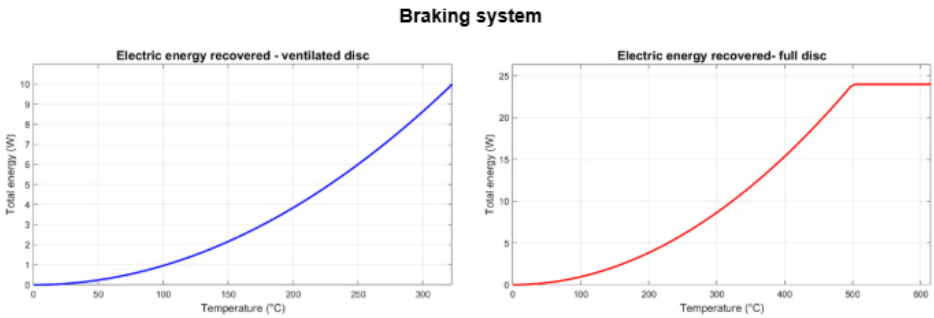


Fig. 10 – Comparative values for energy recovered.

In this case, the energy recovered is much lower for the same temperature ranges. The maximum temperature reached is 322.74°C, which places this system below the optimal operating threshold for TEGs, presented in Fig. 10.

The maximum power achieved is 9.1 W, confirming that the ventilation of the disc limits heat retention – which is ideal for performance and durability, but not for thermoelectric conversion. In the range of 200–300°C there is the active zone where 3–8 W can be generated, useful in repeated braking.

This graph has been generated to show how the electrical energy generated by TEGs increases progressively with the temperature of the brake disc full, up to the maximum ΔT limit of 650°C, imposed by the TEG specifications, the value for electric energy is up to 24 W for full brake disc. The curve is nonlinear because the energy increases approximately exponentially in the upper temperature range, where the thermoelectric efficiency is higher.

It is observed that in the real operating regime, up to ~300°C, the energy obtained is modest, but once the temperature exceeds 400°C, the TEGs begin to operate close to maximum efficiency. At 500°C, the maximum energy of 24 W is obtained for full disc.

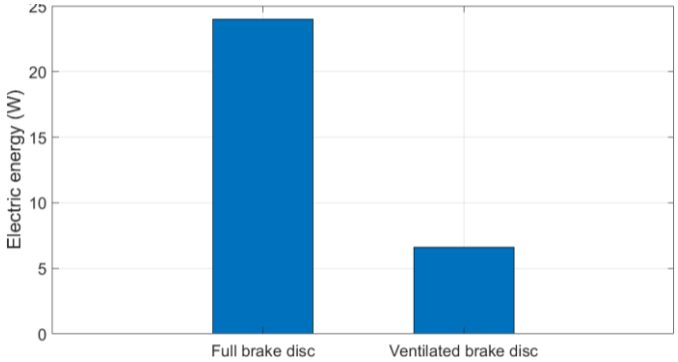


Fig. 11 – Graph for electric energy (W)- braking system.

As for the brake discs, the solid disc reaches 24 W, while the ventilated one only 9.1 W, as in Fig. 11. Brake discs provide a more fluctuating and intermittent heat source, mainly generated during braking. The solid disc, without internal cooling channels, retains heat better, increasing the efficiency of the TEGs. On the other hand, the ventilated disc dissipates heat faster through its internal slots, which leads to lower maximum temperatures and implicitly to a lower power obtained from the TEGs.

Exhaust system

This section presents the thermal analysis and energy recovery results for the exhaust system equipped with thermoelectric generator (TEG) modules. Two exhaust designs were evaluated: an empty exhaust pipe and a version with an internal pattern structure designed to influence heat distribution. Thermal finite element analysis was performed on both models.

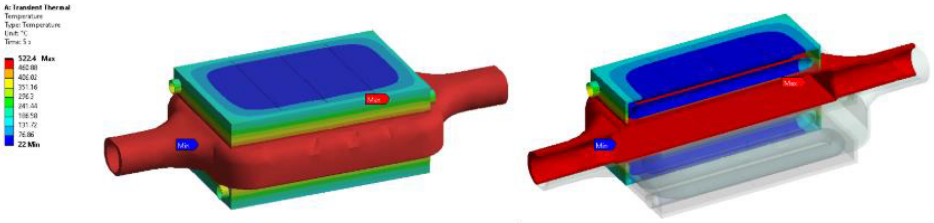


Fig. 12 – Temperature values for empty exhaust system.

Following the finite element thermal analysis, it was found that the empty exhaust reached a maximum temperature of 522.4°C, while the internal pattern exhaust recorded a significantly lower maximum temperature of 438.28°C, as in Figs. 12 and 13. This difference of almost 84°C is relevant and highlights the clear influence of the internal geometry on the thermal regime of the exhaust gases.

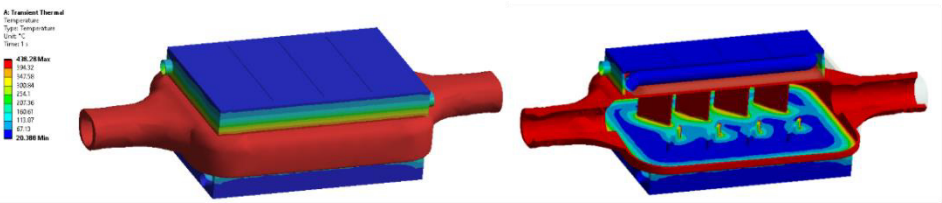


Fig. 13 – Temperature values for internal pattern exhaust system.

The temperature difference between the two models clearly shows that the introduction of an internal pattern, although beneficial for optimizing gas exhaust or reducing emissions, decreases the efficiency of the thermoelectric

recovery systems installed in that area. Therefore, in the design of an energy recovery system, a trade-off must be made between thermal efficiency (maximization of ΔT for TEGs) and aerodynamic and thermal exhaust performance.

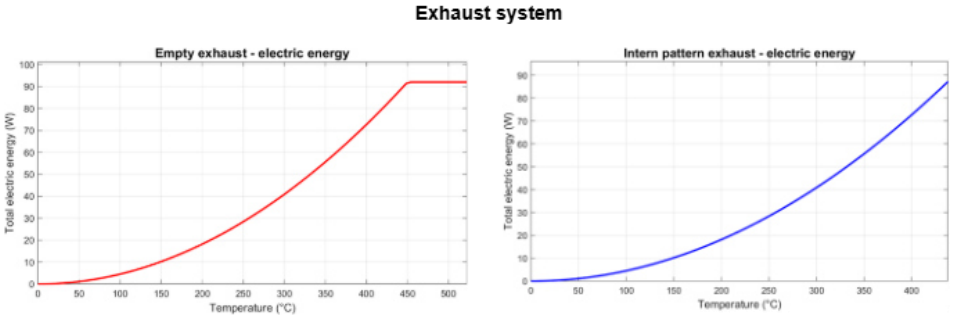


Fig. 14 – Comparative values for energy recovered.

For the hollow exhaust, the graph shows a clearly ascending curve, of the quasi-linear type in the first hundred degrees, becoming steeper towards 450°C. This is due to the 8 TEGs that benefit from a constantly high temperature in the exhaust manifold area.

This graph presented in Fig. 14 has a similar shape to the previous one, because the maximum temperature is lower – 438.28°C and the energy value is also lower, 87.6 W. The internal pattern in the exhaust, which has the role of turbulation of the gas flow and controlled dissipation, reduces the efficiency of heat transfer to the TEGs.

The maximum value of the energy generated is 93.7 W, still a high value, but lower than the non-pattern version. The curve in the graph clearly shows that this system could be optimized for a compromise between heat recovery efficiency and emission control.

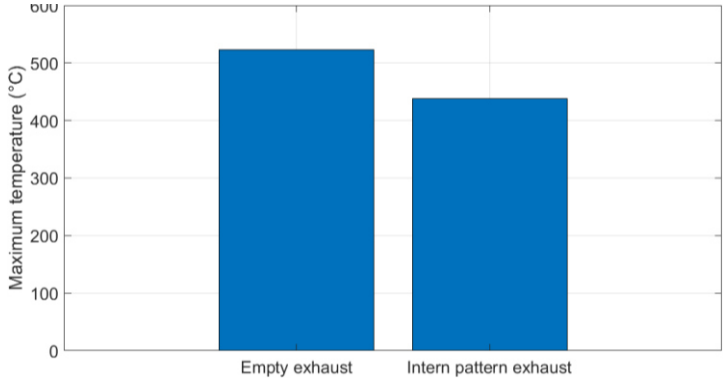


Fig. 15 − Graph for electric energy (W)- exhaust system.

It is observed that the empty exhaust generates the highest amount of energy, reaching 97.7 W, thanks to the 8 TEG modules installed in a high-temperature zone with an optimal thermal gradient ($\Delta T \approx 450^{o}C$). In comparison, the internal pattern variant in the exhaust, although more efficient in terms of cooling and emissions, produces slightly less – 87.6 W. This difference can be explained by the fact that the internal pattern causes a greater dissipation of heat towards the exhaust walls and therefore a slightly reduced thermal gradient between the two faces of the TEG modules.

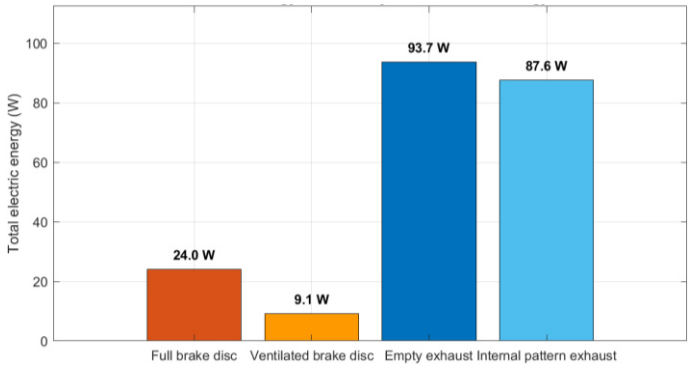


Fig. 16 – Electric energy recovered for TEG modules.

This chart brings all thermal components together into one overview. It is clear that the exhaust is by far the most efficient source for recovering electricity, especially at constant speed. Brake discs provide complementary energy, recovered only during braking, but can add 10–25 W to the overall system.

This visualization is essential for the decision to design and size the TEG system in a vehicle, showing where it is worth investing more to maximize efficiency and energy impact.

Shock absorber system

This section focuses on the simulation results of a regenerative shock absorber, designed to convert kinetic energy from suspension movement into electrical energy.

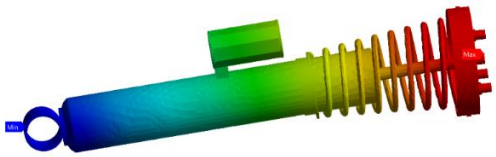


Fig. 17 – Displacement module for shock absorber.

The result highlights the mechanical response of the shock absorber under simulated road conditions in ANSYS Static Structural module. The peak displacement of 8 cm represents a significant suspension stroke, likely caused by a major bump or rapid change in surface elevation. This deformation is essential for the operation of the regenerative module, which transforms the motion into rotational energy, and then into electrical energy via a permanent magnet generator.

The color gradient from blue (Min) to red (Max) visually communicates the displacement intensity across the shock absorber's body, with warmer colors indicating higher displacement values, presented also in Table 1 below.

Table 1

Displacement values for shock absorber

Time (s)	Displacement (mm)
0.00	0.00
1.20	60.00
2.80	40.00
4.50	80.00
6.30	50.00
8.10	70.00

The mechanism of operation involves the conversion of hydraulic energy into mechanical rotation by means of the internal pressure of the oil in the shock absorber. This oil drives a wheel attached to an electromagnetic generator, which produces electricity proportional to the vibration level and frequency of road bumps. To validate the operation of this concept, a simulated analysis was performed in MATLAB and Simulink, where a path with unevenness was modeled and the important parameters were observed: piston speed, voltage generated and total energy recovered.

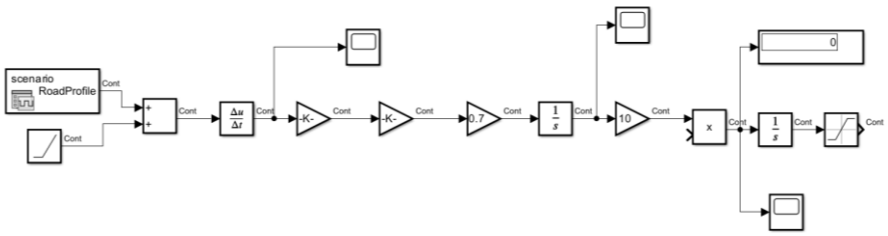


Fig. 18 – Schematic module for simulation model in Simulink.

The Simulink model has been designed to simulate the behavior of a shock absorber for 10 seconds on a bumpy course, presented in Fig. 18.

Standard simulation components were used, and the signal flow reflects the sequence of energy transformations in the system.

The route was entered using the Signal Editor block, and a basic linear motion was generated via a Ramp block. The signal derivative was calculated to determine the speed of the piston, which is the basis for generating pressure in the shock absorber. This pressure, amplified by a Gain of 1000, was then converted into mechanical energy and subsequently into rotation by other scaling factors that reflect the actual efficiencies of transmissions and conversions.

The resulting mechanical energy was converted into electrical voltage using a Gain block of 10, and the power was calculated using the Product block, which multiplies the voltage by an equivalent current signal. The integration of this power over time allowed the total recovered electricity to be obtained. To reflect the actual limits of automotive electrical systems, a Saturation block has been added to limit voltage values within a realistic range (e.g. 0–14V).

For performance monitoring, three Scopes were used to display piston speed, voltage generated and energy recovered, along with a numerical display showing the final result of the simulation.

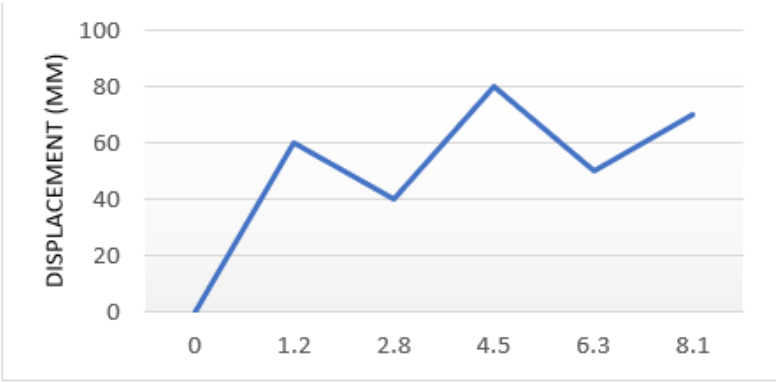


Fig. 19 – Displacement values over time.

The first graph in Fig. 19 shows the variation in shock absorber displacement in centimeters over the 10-second time frame. The motion is not linear, but follows an artificially generated nonlinear trajectory, which simulates a realistic variation in the vehicle's travel speed. In this way, the vehicle has portions of slight acceleration and deceleration, without maintaining a constant speed.

Five bumps have been superimposed on this basic displacement, which appear at the following moments: 1.2 s, 2.8 s, 4.5 s, 6.3 s and 8.1 s, with heights ranging from 4 to 8 cm (the highest being at 4.5 s and 8.1 s). These bumps are visually represented by peaks in piston motion, which provides fast

compression and slower rebound – similar to what happens in a real car suspension scenario.

The graph highlights that, in addition to the progressive movement of the vehicle, the suspension registers short and sudden oscillations in position, exactly at the moments when the vehicle encounters a bump.

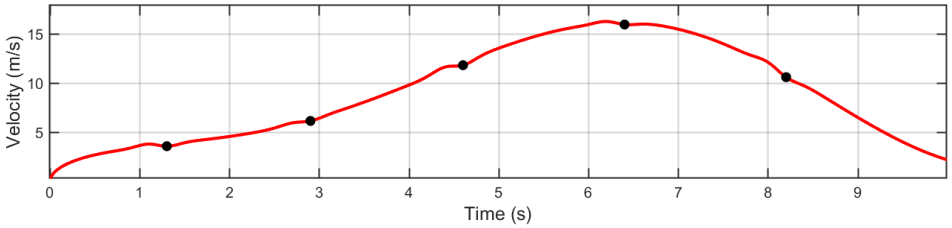


Fig. 20 – Piston velocity value.

The second graph in Fig. 20 represents the derivative of the displacement with respect to time. The speed is expressed in meters per second (m/s) and indicates how quickly the suspension compresses or returns to its original position following bumps.

It is mentioned that speeds reach positive (compression) and negative (rebound) peaks immediately after each bump.

The maximum values recorded are:

- peak compression velocity ≈ 1.94 m/s
- peak rebound velocity ≈ -1.63 m/s

These parameters indicate that at the moment of rapid compression on contact with an obstacle, the piston moves suddenly, generating a favorable opportunity for the conversion of kinetic energy into electricity through the regenerative damping system, which is up to 150 W for the following proposed model and configuration. In the rebound phase, the speed is lower, confirming the asymmetrical shape of the shaped bumps.

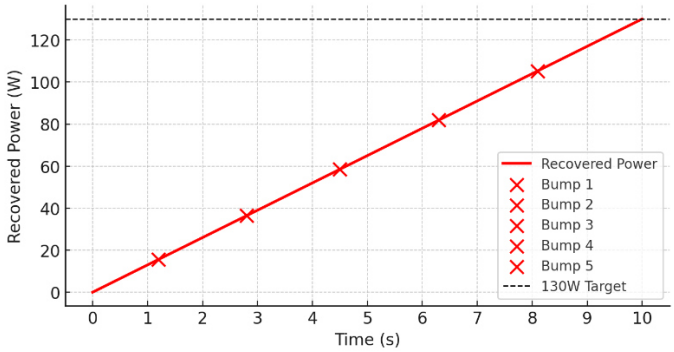


Fig. 21 – Value for electric power recovered (W).

4. Conclusions

This research aimed to develop and evaluate multiple energy recovery systems for conventional vehicle subsystems–specifically the braking system, the exhaust system, and the suspension system–with the goal of increasing overall vehicle energy efficiency by converting waste thermal and kinetic energy into usable electrical power. Through a combination of finite element thermal analysis, MATLAB/Simulink simulation, and system-level modeling, the study demonstrated the performance and the capability of these systems.

In total, the three systems–brakes, exhaust, and suspension–have the potential to collectively generate over 300 W of electrical power (considering peak values). This is a substantial gain when harnessed continuously, especially in hybrid and electric vehicles where battery support is crucial.

These results underline the importance of integrating multi-domain regenerative systems in the automotive industry, particularly in the context of hybrid and electric vehicles, where energy efficiency and recovery are critical. Recovering energy from multiple sources–braking, exhaust, and suspension–not only enhances the vehicle's energy autonomy but also reduces fuel consumption and emissions when applied to internal combustion engines.

The findings from this study contribute to the growing field of vehicle energy harvesting, offering real-world data and modeling strategies that can support future design improvement. These regenerative systems can be further enhanced with smart power management and energy storage integration.

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STUDIU ȘI ANALIZA INTEGRĂRII SISTEMELOR DE RECUPERARE A ENERGIEI ÎN VEHICULE HIBRIDE

(Rezumat)

Recuperarea energiei termice și cinetice disipate în timpul funcționării unui vehicul este o abordare actuală pentru creșterea eficienței energetice și reducerea impactului asupra mediului în sectorul auto. În cazul vehiculelor hibride, în care se utilizează atât motoarele electrice, cât și cele termice, recuperarea acestor energii pierdute poate contribui semnificativ la îmbunătățirea autonomiei și a eficienței generale. Această lucrare prezintă un studiu privind dezvoltarea unui sistem de recuperare a energiei pentru vehicule hibride, prin recuperarea energiilor altfel pierdute în timpul funcționării. Sistemul propus integrează trei mecanisme distincte, recuperarea energiei termice din discurile de frână și gazele de eșapament cu ajutorul generatoarelor termoelectrice (TEG), precum și transformarea energiei cinetice din sistemul de amortizare în energie electrică printr-un mecanism de recuperare, care implică utilizarea

presiunii generate în timpul funcționării și transformarea acesteia în energie electrică, deoarece amortizorul comprimă și variază presiunea internă a vehiculului în timpul mișcării sau liniarului mecanismului său de rotație. Pentru recuperarea energiei termice, sistemul folosește generatoare termoelectrice, care convertesc gradienții de temperatură direct în energie electrică prin efectul Seebeck. Atunci când sunt instalate pe discuri de frână și țevi de eșapament, aceste dispozitive captează căldura reziduală care altfel s-ar disipa în mediu. Studiul examinează amplasarea optimă a TEG, valorile de temperatură obținute și strategiile de răcire pentru a maximiza eficiența conversiei energiei, menținând în același timp fiabilitatea componentelor în diferite condiții de funcționare. Energia generată va fi stocată în bateriile vehiculului și folosită pentru alimentarea sistemelor auxiliare, precum iluminatul, sistemul de infotainment sau alte echipamente care utilizează energie electrică. Studiul evaluează potențialul de eficiență al acestor sisteme, impactul asupra autonomiei vehiculului cu integrarea lor în sistemul vehiculului existent, cu scopul de a extinde aria de cercetare la alte sisteme în care există pierderi de energie în viitor și, de asemenea, de a explora posibilitățile de scalare pentru vehiculele electrice și transportul greu, unde recuperarea energiei ar putea aduce beneficii și mai mari.