UNIVERSITY OF MISKOLC

FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

Research and Development of Energy Harvesting Systems

PhD thesis book

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I. DESCRIPTION OF THE RESEARCH PROJECT AND THE PURPOSE OF THE THESIS

My research topic is the research and development of Energy Harvesting systems. At the beginning of my research, I set myself the goal of investigating the possibilities of recycling the energy losses used, comparing the methods based on different parameters and developing possible applications in vehicles.

At the beginning of my PhD research, I analysed energy harvesting systems in detail. I will discuss the sensors and actuators in harvesting systems. I have considered the devices for harvesting energy from mechanical energy, thermal energy, radiant energy and biochemical energy. I compared the possibilities in terms of energy density.

After that, harvesting systems, also known as energy harvesting systems, used in automobiles will be presented. I will complete the literature review with research on automotive diagnostics and driver assistance systems.

After the literature review, I will turn to the analysis of the energy that can be recovered from thermoelectric phenomena. The main area of research within Energy Harvesting Systems is the application of thermoelectric energy recovery systems in automotive applications.

I started my analysis of thermoelectric harvesting systems by studying and analysing thermoelectric generators (TEGs). I performed a finite element simulation of the generator operation, which allowed me to study the electrical parameters of the generator output under different temperature conditions. I extended the simulation by testing another generator with different material composition. The simulation results have been published in several scientific papers.

After running the simulation, I felt it necessary to validate my simulation results with real measurements. To perform the measurements, I designed a thermoelectric generator measurement and control device. The equipment is able to receive TEG modules of different sizes, to control the temperature on the hot and cold sides, and to measure temperatures and electrical parameters at the same time as the control. The detailed design of the device, its control and measurement software, and the measurement results obtained with the device have been published in several scientific journals. After the evaluation of the measurement results, the parametric equation of the internal resistance dependence and the terminal voltage of the TEG module under test was determined based on the characteristics given in the manufacturer's data sheet using BMA algorithm. The results obtained from the parametric equations identified from the manufacturer's data sheet follow the characteristics obtained from the real measurements in a correct way. After the simulation and real measurements of thermoelectric generators, the focus of my research is on the selection of in-vehicle parameters for a heat recovery system based on the TEG module. After conducting various finite element simulations, I concluded that the thermal energy recovery system is capable of generating electricity by extracting thermal energy from the electric motor casing surface.

I developed a vehicle diagnostics software that can measure and analyse driving dynamics data during vehicle operation. I also added a GPS module to the measurement system, which adds topography and speed data to the measured data set in addition to the driving dynamics data. I have added to the complexity of the measurement system a driving recording camera, which adds visible and audible information to the measurement system. To test the measurement system, I mounted the previously developed heat recovery system in the engine compartment of the test vehicle and simultaneously measured the heat loss recycling parameters due to the vehicle operation, the vehicle's driving dynamics, GPS coordinates and distance travelled camera images. After simultaneous processing and evaluation of the data, I was able to determine heat recovery information. I conclude my research work by developing a camera-based driving support system that can detect pedestrian crossing, pedestrian and traffic control signs using artificial intelligence with real-time image processing.

In summary, my PhD research work involved the analysis and development of a complex energy harvesting system.

II. Energy Harvesting state of the art

I also examined in detail the latest research on the topic, in the course of which I reviewed several articles and studies on the subject. First of all, I reviewed the study by Lan et al. who describe a method for fitting an optimised thermoelectric generator (TEG) to an electric vehicle based on two criteria. Based on this approach, they optimized the electrical load resistance and configuration of the TEG, resulting in a net power density increase of 11.6 percent over the previously designed TEG [1]. Lan et al. compare the performance of a TEG prototype from simulation and real-world test results on a conventional combustion engine vehicle and an electric vehicle [2]. Nader examines the fuel-saving potential of an extended-range hybrid electric vehicle [3]. Mohamed et al. have set up a simulation based on a test system to recover heat from low-quality waste heat [4]. Luo et al. present a new fluid-thermal-electric multiphysics numerical model for predicting the performance of a thermoelectric generator system for automotive waste heat recovery [5]. Talawo et al. conducted an experimental study on a vehicle to evaluate the electrical potential of a solar thermoelectric generator consisting of 20 thermoelectric modules, each with 127 torques, and a vortex tube to power a hybrid vehicle in motion [6]. Abbasi et al. present a flexible measurement system that transmits the measured values to a computer. The system measures the temperature of the vehicle at different points while driving [7]. Sousa et al. present the optimization and evaluation of a temperature-controlled thermoelectric generator concept for a heavy-duty commercial vehicle [8]. Coulibaly et al. are using a new approach to harness the heat generated when braking electric cars. They present simulated results where they test several scenarios [9]. Aljaghtham et al. used the heat loss from the oil tank of an internal combustion vehicle, introducing an extensive multiphysics simulation framework to accurately simulate the conversion of heat into electricity [10]. Atmajaya et al. have started developing a thermoelectric generator specifically to recycle heat losses from diesel engines [11]. Dipon et al. propose a system that is a self-powered, multi-sensor system fed by the vehicle's energy recovery system from vibrations generated by other vehicles and the temperature gradient between the road asphalt and the ground below [12]. Olabi et al. present a study on the integration of thermoelectric systems with other technologies for environmentally friendly energy production [13]. Khoshnevisan et al. have dynamically designed and modelled a hybrid electric vehicle with a thermoelectric generator [14]. Kumar et al. investigated the usability of exhaust heat loss from internal combustion vehicles [15]. Omar et al. studied the energy recovery effect of thermoelectric generators on a Honda motorcycle [16]. Yanez et al. focus on the thermal management of heat sources in the design of thermoelectric generators and present methods for evaluating specific energy sources and prototypes [17]. Zhu et al. developed a two-stage energy harvesting strategy for efficient exhaust gas energy recovery under dynamic driving cycles [18].

III. Research methodology

After defining the objective of the research, a thorough analysis of the related literature followed, in order to determine how real an engineering problem I will be dealing with. The literature search soon revealed that the use of energy harvesting systems in engineering is on the rise. I created a model of a thermoelectric generator, the basics of which I understood through my literature research. I performed various finite element simulations on the model, which proved the correctness of the model. I identified a multivariable equation from the manufacturer's data sheet characteristics, which was determined by machine learning using BMA algorithm. The parametric equations approximate the data sheet curves to greater than 99 percent accuracy. I developed a measurement concept and validated the simulated results with the measured results. In the rest of my research, I formulated hypotheses and proved the claims by measurement and evaluation methods.

In developing the driving analysis system, I used different behaviours and evaluated the measured data based on these behaviours.

IV. New scientific results

Following the literature search, it soon became clear that my PhD research would be directed towards thermal energy recovery systems, and I set myself the goal of analysing the operation of thermoelectric generators. The literature discusses the operation of Peltier modules in great detail, but makes little mention of the dependence of the internal resistance of thermoelectric generators on temperature. And for generators, operating point analyses are almost impossible to find, since each module has a different material composition and therefore different operating point characteristics.

For the analysis of the modules at the operating point, I first created a finite element model from which I was able to generate a series of output characteristics. After simulation, I designed and developed a calibration device capable of measuring output electrical parameters under controlled temperature parameters and processing them in real time. The self-developed device allowed me to perform work point analysis measurements on various TEG modules, from which I was able to deduce the basis of my thesis 1. Figures 1 and 2 illustrate the measurement results of two completely different TEG modules.

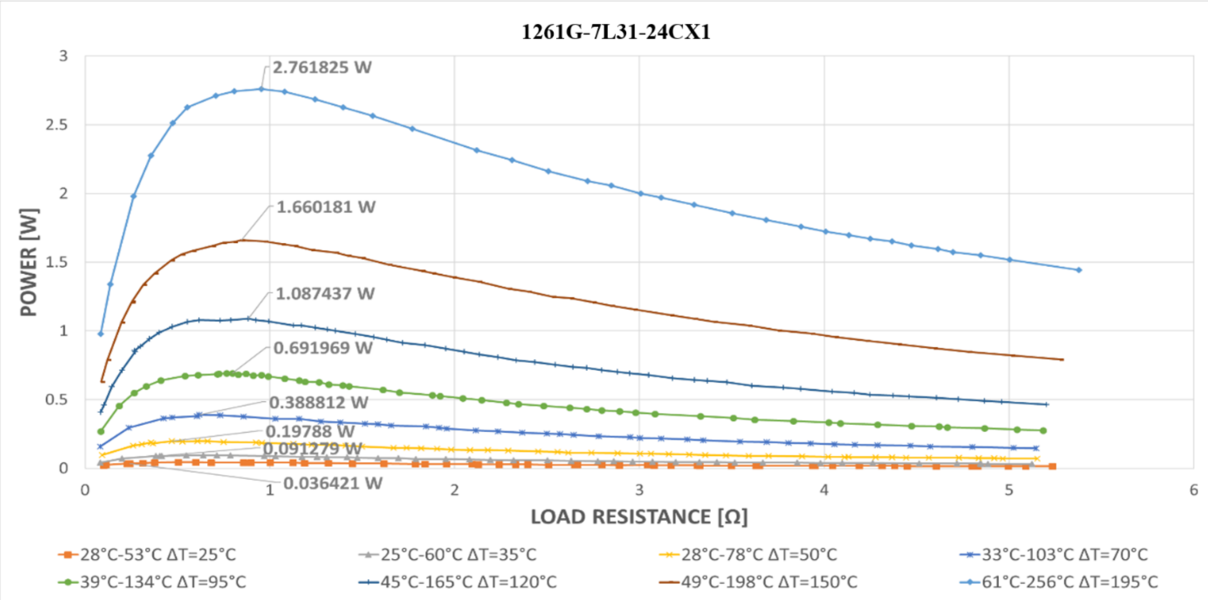

Figure 1. Results of TEG's operating point measurements

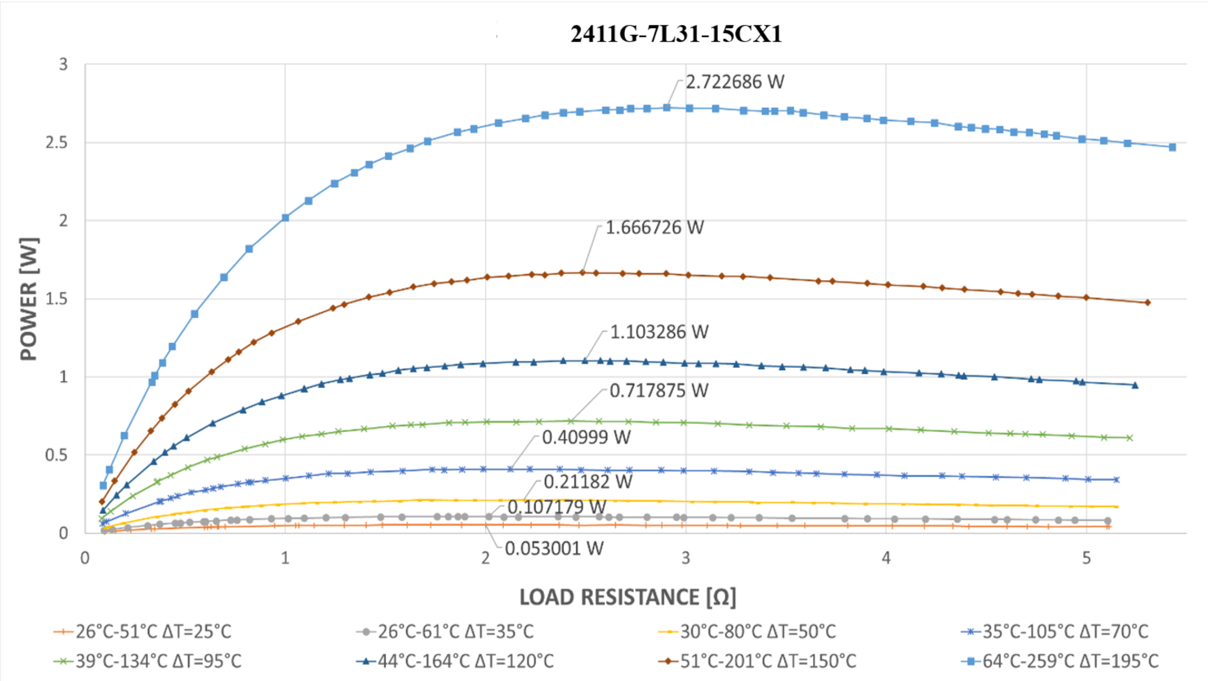

Figure 2. Results of TEG2 operating point measurements

I examined the deeper connection between the data, so that I could write down in a closed formula the internal voltage and internal resistance values as a function of the hot and cold side temperatures. Based on the factory datasheet, each curve can be approximated by an exponential function alone, in order to get an approximation that is true at all temperatures, I looked for a multi-parameter description method. Due to the relatively large number of parameters, it is expedient to use a machine learning algorithm to implement the parameters. The machine learning algorithm chosen was the Bacterial Memetic Algorithm (BMA). I applied this parameter description to several characteristics from the manufacturer's datasheet and to the measurement dataset I prepared. Using the results, I can state my thesis 1:

Thesis 1: Based on the measurement results, the idle terminal voltage can be approximated by the following equation from the cold and hot side temperatures:

$$\boldsymbol{U_{k_{sz\acute{a}m\acute{i}tott}} = U_{B0} + UbT_m \cdot \left(1 - e^{\left(Ub_{Texp} \cdot T_{meleg}\right)}\right) - UbT_h \cdot T_{hideg} -}$$

$$\boldsymbol{-I \cdot \left(R_{B0} + mRT_m \cdot \left(1 - e^{\left(R_{Texp} \cdot T_{meleg}\right)}\right) - mRT_h \cdot T_{hideg}\right)}$$

The equation has 8 parameters and their values can be obtained by machine learning. The equations identified from the characteristics in the TEG manufacturer's datasheet using the Bacterial Menetic Algorithm (BMA) approximate the measured values with greater than 99 percent accuracy.

Related publications: [P5][P6][P7][P8][P9]

As a continuation of my PhD research, I started to investigate the applications of thermoelectric generators. My goal was to find an application environment where TEG can operate optimally without degrading the efficiency of the drive motor. In my research I used a 4kw DC motor. To understand the thermal profile of the traction motor, I started with a finite element simulation to investigate the optimal location of the heat recovery system. The finite element simulation included analysis of the static, dynamic and contact physics parameters of the motor. As a result of the simulation, I obtained a heat profile that allowed me to draw conclusions on where to design the heat recovery system.

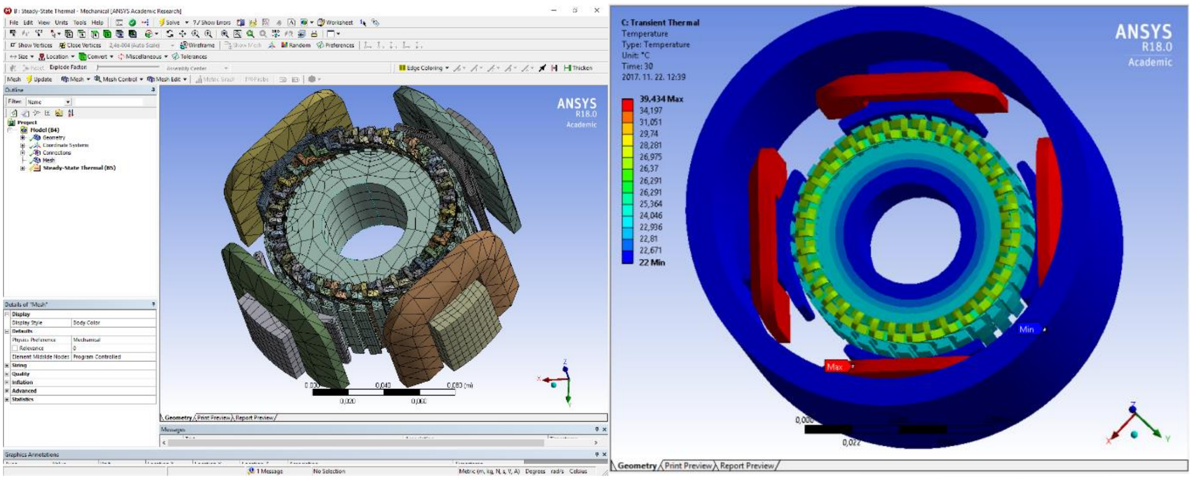

Figure 3. Finite element simulation of DC motor

From the results of the finite element simulation, I concluded that the optimal location for the thermal energy recovery system is on the engine casing surface. In order to prove my theory, I first had to design and construct the mechanical containment system of the thermal energy recovery system. I placed the hot side of the thermoelectric generator on the engine shroud surface and provided the cold side with a controlled water cooling system. I tested the engine using a test bench, taking measurements at various shaft loads while measuring the power drawn by the engine, the hot and cold side temperatures on the thermal energy recovery system and the electrical parameters of the module.

The measurement results shown in Figure 4. demonstrate that the thermal energy recovery system can be used to extract electrical power from the surface of an engine casing. The electrical power absorbed by the traction motor did not vary depending on whether the thermal energy recovery system was connected to the motor or not.

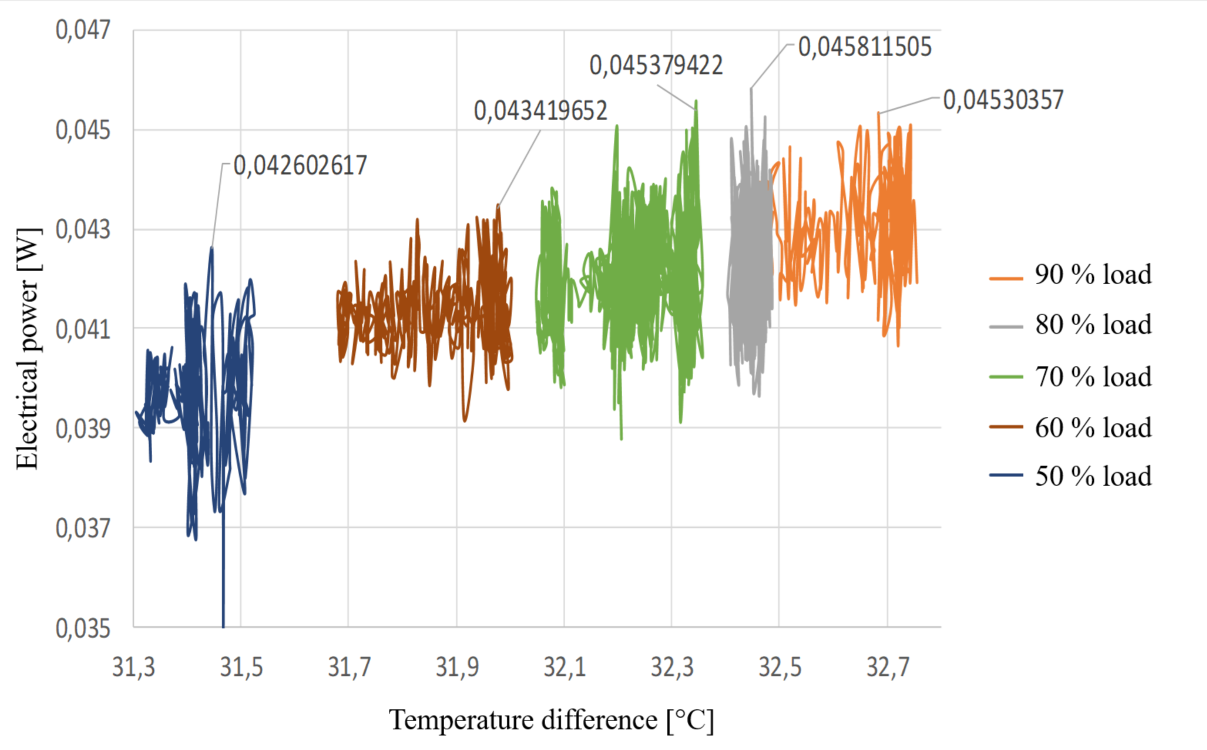

Figure 4. Power produced by TEG as a function of temperature difference

Thesis 2: I have developed a new method for cooling and recovering energy losses in electric motors and verified its functionality by measurements and simulation. A thermoelectric generator can be used to recover waste energy from the casing surface of an electric motor. The new method achieves energy densities of up to 1.5mW/cm^2.

Related publications: [P2][P3][P4][P10][P13] [P14]

After the development of the thermal energy recovery system, my research has been directed towards the field of automotive diagnostic analysis. In the literature, I could not find any relevant solution where the electrical power recoverable from the vehicle is analysed as a function of the driving dynamics of the driver. Therefore, I set myself the goal to develop a new measurement method that is able to find a relationship between driving dynamics and recoverable energy.

I developed a measurement system that can communicate with vehicles and analyse vehicle dynamics data in real time on a high-speed CAN bus. The measurement system is connected to the vehicle via the vehicle's OBD diagnostic connector. In addition to the driving dynamics data, a self developed GPS based positioning system provides the route coordinates. The measuring system is also equipped with a video recording camera, which records the trip made by the vehicle. From all this data I developed a processing program that can consider data with the same time stamps as a linked pair of data and process all the data for a given time point when analysed.

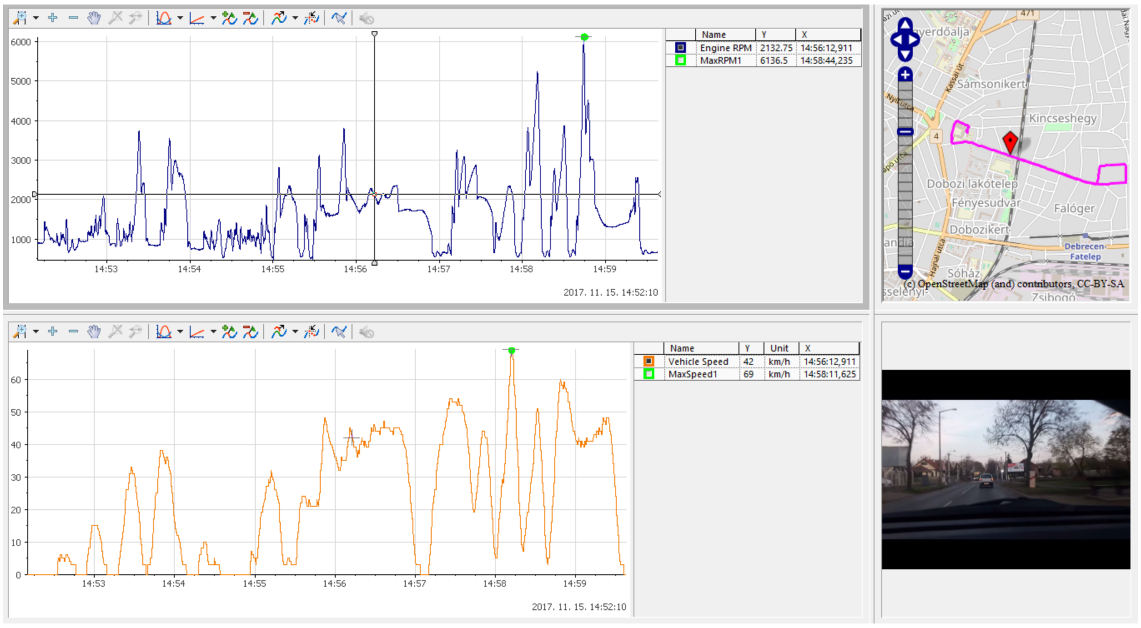

Figure 5. Driving analytics management interface

While testing the driving analysis system, I collected data on different driving dynamics. Figure 5. shows a test where I simulated a relaxed slow driving during the first half of the test and a more dynamic, forced driving during the second half of the test. From the vehicle diagnostic data it is clear that the temperature readings are much higher for the more dynamic driving style. It is clear that more electrical power can be obtained from the thermal energy recovery system with a more dynamic driving style. The optimised system also needs to consider the driving modes of the vehicle, which are usually eco, normal, sport. In state-of-the-art vehicles, it would be necessary to monitor simultaneously many parameter variations, most of which are considered industrial secrets and are therefore not covered in this research topic.

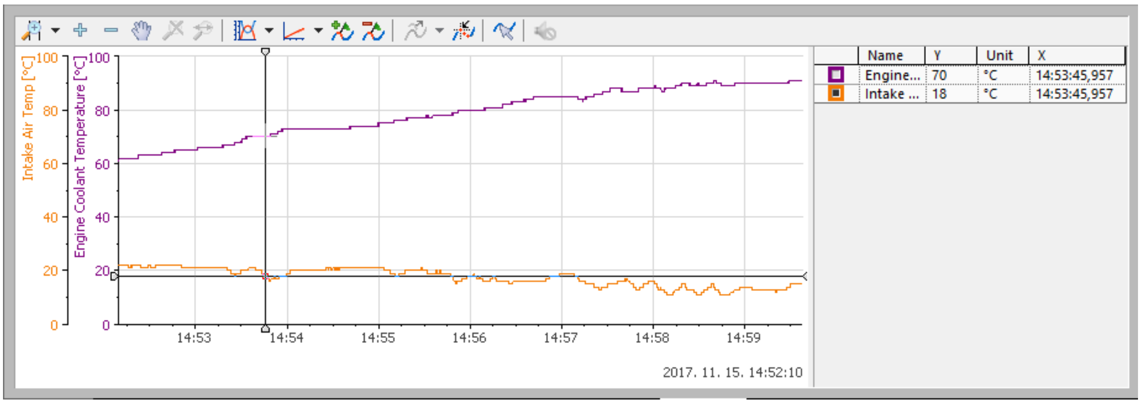

Figure 6. Temperature change of the air flowing into the engine and cooling it

Thesis 3: The driving dynamics of a vehicle, which depend on human behaviour, influence the electrical power produced by a thermal energy recovery system. I developed a new measurement method to analyse the driving dynamics of a vehicle, which automatically analyses the driving dynamics based on real-time OBD diagnostic, GPS, video recording data and human behaviour, and deduces the extent of heat loss recovery. The measurement system demonstrates that the driving style, which depends on the driver's behaviour, is clearly related to the electrical power that can be recovered from the vehicle's heat loss.

Related publications: [P11][P12]

The final chapter of my research presents the development of a camera-based driving assistant system using computer vision and deep learning. The system runs on a NVIDIA Jetson Nano development kit and is able to detect pedestrian crossings, pedestrians and traffic signs and, upon detection, sends a warning signal to the driver, informing him of his obligation to yield the right of way. The system can be installed in a car and used in real time.

Computer vision is achieved by using a deep neural network trained by its own images. The system can run in real time at 45 FPS with a recognition rate of more than 98 percent in varying visibility conditions, day and night.

Figure 7. Driving assistance system

Thesis 4: A driver assistance system can detect moving pedestrians, pedestrian crossings and traffic signs using real-time image processing and a deep learning algorithm with SSD MobileNet architecture, which outperforms human reaction time. Real measurement results demonstrate that the developed driver assistance system is capable of performing the detection function regardless of time of day and weather conditions, and its detection time and accuracy exceeds human reaction time and detection accuracy.

Related publications: [P1]

V. Use of new scientific results

My research is focusing on the range improvement and driving safety issues of hybrid and electric vehicles. One of the biggest questions today is whether electric transport will be a sustainable option for people or the planet. I am optimistic that my research and achievements have contributed to the development of energy harvesting systems for vehicles, and I consider the driver assistance system, which can save human lives in vehicles, a great success. I have published all my achievements in Hungarian and English, making them available to the international research community. My articles related to the research topic are also cited.

VI. AZ OWN PUBLICATIONS RELATED TO THE SUBJECT OF THE THESIS

Q-rated international journal articles:

[P1] **Kornel Sarvajcz**; Laszlo Ari; Jozsef Menyhart, AI on the Road: NVIDIA Jetson Nano-Powered Computer Vision-Based System for Real-Time Pedestrian and Priority sign detection, APPLIED SCIENCES-BASEL (2076-3417): 14 4 Paper 1. 24 p. (2024)

- Folyóirat szakterülete: Scopus - Engineering SJR indikátor: Q2

[P2] Sziki Gusztáv Áron; **Sarvajcz Kornél**; Kiss János ; Gál Tibor ; Szántó Attila; Gábora András; Husi Géza; Experimental investigation of a series wound dc motor for modeling purpose in electric vehicles and mechatronics systems; MEASUREMENT (0263-2241): 109 pp 111-118 (2017)

- Folyóirat szakterülete: Scopus - Education SJR indikátor: Q1

[P3] Sziki Gusztáv Áron; **Sarvajcz Kornél**; Szántó Attila; Mankovits Tamás; Series Wound DC Motor Simulation Applying MATLAB SIMULINK and LabVIEW Control Design and Simulation Module; PERIODICA POLYTECHNICA TRANSPORTATION ENGINEERING (0303-7800 1587-3811): 48 1 pp 65-69 (2020)

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[P5] Sarvajcz Kornél; Váradiné Dr. Szarka Angéla; Végh János; Energy harvesting jelentősége és lehetőségei; Környezettudatos energiatermelés és -felhasználás III. Környezet és Energia Konferencia; Konferencia helye, ideje:: Debrecen, Magyarország 2014.05.08. - 2014.05.09.; Debrecen: MTA DAB Megújuló Energetikai Munkabizottság, pp 147-152 (2014)

[P6] Sarvajcz Kornél; Váradiné Dr. Szarka Angéla; Simulation and calibbration test of thermoelectric generators; XXI IMEKO World Congress "Measurement in Research and Industry": Full papers; Konferencia helye, ideje:: Prága, Csehország 2015.08.30. - 2015.09.04.; Prague: Czech Technical University in Prague, pp 1003-1008 (2015)

[P7] Sarvajcz Kornél; Váradiné Dr. Szarka Angéla; Termoelektromos Generátor Szimulációs És Kalibrációs Mérései; MŰSZAKI TUDOMÁNY AZ ÉSZAK-KELET

MAGYARORSZÁGI RÉGIÓBAN 2015; Konferencia helye, ideje: Debrecen, Magyarország 2015.06.11.; Debrecen: Debreceni Akadémiai Bizottság Műszaki Szakbizottság, pp 505-510 (2015)

[P8] Sarvajcz Kornél; Váradiné Dr. Szarka Angéla; Termoelektromos generátor szimulációs és kalibrációs mérései : Simulation and Calibration Test of Thermoelectric.; Konferencia helye, ideje:: Arad, Románia 2015.10.08. - 2015.10.11.; Kolozsvár: Erdélyi Magyar Műszaki Tudományos Társaság (EMT), pp 124-129 (2015) (Nemzetközi Energetika–Elektrotechnika konferencia 1842-4546)

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[P13] István Kovács; Kornél Sarvajcz; Modelling and Simulation of a Series Wound Direct Current Motor Using Ansys; Konferencia helye, ideje: Oradea, Románia 2018.05.31. - 2018.06.01.; Oradea: University of Oradea Publishing House, pp 241-244 (2018)

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VII. THE LITERATURE AND REFERENCES USED IN THE THESIS

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