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Optimized Eco-Driving with Real-Time Telemetry in a Lightweight Electric Vehicle

Zoltán Pusztai, István Kecskeméti, Ferenc Friedler*

Széchenyi István University, Vehicle Industry Research Center, Egyetem tér 1, 9026, Győr, Hungary.
f.friedler@ga.sze.hu

In this paper, the application of an advanced telemetry system is introduced, which is used to monitor an electric, energy-efficient experimental urban vehicle. The system enables real-time observation of both the pilot's actions and vehicle parameters. The vehicle's pilot drives according to a predetermined driving strategy, optimized for minimizing energy consumption during vehicle operation. The telemetry system aims to provide real-time information about the pilot's driving and deviations from the predetermined strategy, offering additional opportunities for correction during operation. Additionally, it facilitates real-time observation of all vehicle and sensor data on the vehicle's CAN network. The paper discusses the determination of the driving strategy and presents its graphical representation for the pilot. A detailed description of the telemetry system's operation through wireless connection is provided in the paper. In terms of implementation, the driving strategy was formulated using MATLAB through optimization, while graphical display, data collection, and telemetry system development were implemented in the LabVIEW environment. The functionality of the created energy-efficient driving support framework was examined under real driving conditions. The application of the telemetry system and proposed hybrid optimization approach helped to further reduce the energy consumption by 8.54%.

1. Introduction

Efforts to mitigate pollution include regulations and the development of new technologies, with electric and hybrid vehicles offering a promising solution due to their lower fuel consumption (Hawkins et al., 2012). There have been significant developments in electric vehicles in recent years, which have contributed to the spread of electromobility. The main areas include battery technology, charging infrastructure, electrical machines, semiconductors and drive circuits (Rahman et al., 2017). Lightweight electric vehicles are particularly suitable for urban transportation. A parametric study has shown that these vehicles can achieve significant economic savings through reduced energy consumption, especially when production is scaled up (Nicoletti et al., 2021). The global demand for battery electric vehicles is increasing, with a growing emphasis on lightweight designs to enhance driving range (Burd et al., 2021). The application of telemetry systems in road vehicles could contribute to data-driven developments in many fields, such as improving traffic management, optimizing fuel efficiency, and enhancing vehicle safety. Dashcam telemetry data can be used to replicate the speed profile to evaluate CO2 emission and energy consumption, for this purpose a novel simulation methodology was introduced using optical character recognition (Hind et al., 2024). Characteristics of transit routes were studied based on digital record reports to analyze the key factors related to vehicle driving losses (Burski et al., 2016). The implementation of a telemetry system by a cargo logistics service provider in Brazil resulted in reduced operational costs and a reduction in driver-related accidents (de Oliveira Neto et al., 2017).
Telemetry system is also vital part of motorsports to maximize the performance. Motorsport also serves as an excellent platform for exploring new technologies, where racing teams can test innovative solutions to achieve optimal results. While speed is often the primary focus, some racing categories also prioritize range and energy efficiency. The SZEnergy Team from Széchenyi István University has been participating in the Shell Eco-marathon (SEM) for many years. The primary goal of the SEM is to complete a race distance of approximately 16 km within a 40 min time limit on a designated track, with the distance divided into laps. In the Urban Concept category, vehicles must stop and accelerate again in each lap, unlike the Prototype category where continuous

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motion is allowed. The competition evaluates participants using the km/kWh efficiency index, with the highest efficiency determining the winner. In 2024, the SZEnergy Team achieved a record 308,9 km/kWh in the Battery Electric Urban Concept category at the Shell Eco-marathon Europe in Nogaro, France.

Despite extensive research in this field, comprehensive studies on the application of telemetry systems in lightweight vehicles for reducing energy consumption are still uncommon. Key knowledge gaps include the need for a simple, low-consumption telemetry system, which can be easily implemented in such applications. The currently presented research addresses these gaps by introducing a low-consumption telemetry system and demonstrating how the gathered data can be used to optimize driving strategies, directly contributing to energy savings. The paper is structured as follows: first, an overview of the hardware components of the unique telemetry system is presented, detailing the vehicle's hardware setup and onboard display that aids the driver. The process of determining the driving strategy is then briefly outlined to highlight the relevance of the telemetry system. The collected data is utilized to optimize the driving strategy, focusing on achieving energy-efficient vehicle operation, which is crucial for sustainable road transportation.

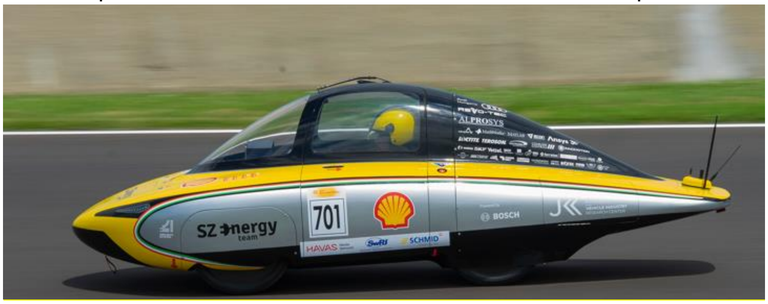


Figure 1: The energy efficient vehicle of the SZEnergy Team

2. Vehicle Hardware Environment

The electronic system of the SZEmission is developed focusing on energy efficiency and weight reduction. Each device is individually designed to meet the specified functions, while minimizing energy consumption. Communication within the vehicle is via a CAN bus, designed in accordance with automotive standards (Corrigan, 2008). The nominal voltage of the electronics is 48 V, which is converted to 5 V or 3.3 V potential level by each device using high efficiency DC/DC converters. The idle power consumption of the system, i.e. when the vehicle is ready to drive, is less than 0.5 W, which is extremely low compared to its functionality.

2.1 Vehicle Control Unit

The Vehicle Control Unit (VCU) is the central hub of the vehicle's electrical system, functioning as a microcontroller-based embedded system that oversees the propulsion system. The VCU allows the driver to select various drive modes to control the powertrain. In manual mode, the driver directly sets the torque reference using the throttle. In automatic acceleration mode, the VCU optimizes the reference torque based on the current vehicle speed. Additionally, there is a mode where the vehicle automatically accelerates at predefined profiles stored in the VCU's memory. This mode requires the VCU to accurately calculate the distance travelled, as the vehicle is not equipped with a positioning system and relies on speed and elapsed time for distance measurement. Beyond propulsion control, the VCU also manages the vehicle's lighting system and alerts the driver in case of a battery malfunction.

2.2 Telemetry Hardware

The telemetry system utilizes the CAN protocol to ensure all units receive messages sent from the vehicle. The system is ideal for collecting vehicle data and transmitting it wirelessly, despite potential obstructions from track buildings. The telemetry hardware includes a transmitter and a receiver. The transmitter is powered by the vehicle's 48 V supply, which is converted to 5 V using a high efficiency LT7101 DC/DC converter. The board includes a microcontroller (MCU) and a low power radio module operating on the 868 MHz frequency band, which allows license-free operation in the European Union. Due to the low transmission frequency, module's power saving features were utilized, resulting in an average 8mW power consumption, which is significantly less than the used hardware in (Albayrak 2017) without impacting output power. At these small loads the DC/DC converter operates above 90 % efficiency. The system updates data every 200 ms, organizing it into 64-byte blocks, which are then transmitted using frequency-shift keying (FSK). The receiver decodes the data and sends it to a computer for real-time monitoring.

A mobile weather station measures wind direction and speed, crucial for optimizing vehicle performance on the racetrack. The station, powered by batteries, is strategically placed along long straights during competitions. The transmitter processes sensor data and communicates it wirelessly to the receiver, which then sends the data to a computer via a serial port. The LabVIEW based telemetry software allows engineers to monitor vehicle status and driver performance through a custom user interface. The software handles data from both the vehicle and weather station, processing vehicle data at up to 5 Hz and wind data at 1 Hz. The interface includes tabs for main race data, track map, charts for real-time analysis, and diagnostics to predict potential malfunctions. Communication is one-way, adhering to regulations to prevent external influence on the vehicle.

2.3 Onboard Display

The vehicle has an on-board computer running data acquisition software developed in the LabVIEW programming language based on similar principles as Khan and Sonti (2009). Its primary function is the dashboard, where the pilot can read the most important data from the CAN bus and diagnose a malfunction. A graph on the main screen displays the race strategy showing the optimized speed profile for a lap alongside the throttle application points and the current profile. The software calculates distance travelled, and current energy consumption based on information read from the CAN network (Figure 2.). The data received and calculated are continuously saved in a log file, with a total of 95 different parameters. The data acquisition and saving runs at 20 Hz, cumulating to around 35 MB data per race distance.

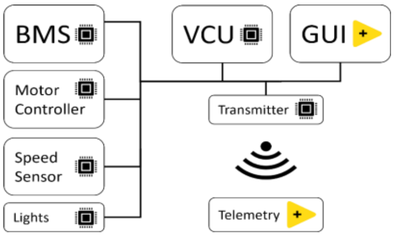


Figure 2: Overview of CAN network. The devices shown with the processor sign, are purpose designed embedded systems, while the yellow logos indicate a LabVIEW software running

3. Driving Strategy Optimization

Advanced electronic and telemetry system is adequate tool of vehicle development, vehicle operation monitoring and to provide possibility to adjust race tactics. In our case, the developed telemetry system supported the driving strategy optimization in many aspects. In this paragraph the main steps of the applied driving strategy optimization approach are presented. The direct application of collected telemetry data in driving strategy optimization with this hybrid approach represents the novelty of the study, contributing to further energy savings.

3.1 Modelling

For vehicle development goals functional and accurate simulation vehicle model is needed. Accurate component identification for replicating the exact behaviour of the vehicle is essential. There are several methods for approaching vehicle modelling. Since the car is meant to compete in an energy efficiency competition, even little simplifications could lead to a higher degree of model error. Grey-box modelling was used to reduce model inaccuracies and take into consideration elements that are usually neglected in analytical models. The vehicle's unique features and remarkably light weight (165 kg) highlight the need for this modelling strategy even more. Based on this grey-box modelling approach, a subsystem methodology has been used to construct a mathematical model for the investigated electric vehicle. Both the powertrain and vehicle resistance models incorporate the unique features of the vehicle. The track model is used to determine the arising slope force. The model considers the forces of traction, resistance, and slope, which are all used to calculate and subsequently minimize energy usage. The optimization routine calculates the drive state (locations on acceleration), optimal torque limit, and switching speed. The reference torque value for the vehicle is then obtained by using these established parameters inside a state machine, the detailed principles of torque switching control is discussed by Kőrös et al. (2024). The vehicle motion described in Eq(1) depends on the arising forces. Each force is calculated in separate block in the mathematical model. These blocks can be viewed as subsystems, which needs to be properly modelled.

$$ma(t) = F_{traction}(t) + F_{resistance}(t) + F_{slope}(t) \quad (1)$$

The used extended resistance model describes the cumulative resistance force (F_{res}). The resistance force includes the effect of cornering and straight-line motion. Both driving states need to be evaluated to form eco-driving control problem properly (Padilla et al., 2020). The presented model calculates based on the actual cornering radius and speed value. The model was set up by field test measurements, where the telemetry system provided the sufficient data for evaluation. In the presented case the track of Nogaro was measured with a high-precision GNSS with RTK correction to obtain height value with high accuracy. Several measurements were processed to obtain and store the x, y and z coordinates of the track. The cornering radius can be calculated from x- y data.

3.2 Optimization

Genetic Algorithm (GA) optimization approach was selected and implemented for finding the driving strategy. GA is successfully applied for solving driving strategy problems as discussed by Stabile et al., (2023) and Sawulski and Ławryńczuk, (2019). This approach is providing robust tool for solving hard, non-linear problems such as the described vehicle model-based optimization problem. The optimization process can utilize both conventional and hybrid setups. In the conventional method, a genetic algorithm generates an initial population for optimization, typically used before the race without prior samples. Conversely, the hybrid approach is ideal during competitions, leveraging track-recorded driving patterns for faster convergence and strategy adjustments, especially useful when the track is unknown beforehand (Pusztai et al., 2023). In this case, a hybrid approach was used supported by the collected telemetry data. The initial population was partially derived from measured driving data via the telemetry system. This human driving data is processed offline, converting it into optimization-ready driving patterns. This processing occurs during initialization, removing the need for real-time processing. The transformation resolution can be adjusted to control the variable number in the optimization, using linear interpolation to create equidistant points in the optimization vector based on the chosen resolution. The fitness function is defined Eq(2), where the traction force (F_{trac}) is modified according to the control variables to minimize the calculated energy consumption throughout the track. Distance (s) and lap time (T) constraints are defined in Eq(3).

$$Minimize\ E = \int_0^T F_{trac}(t)\ v(t)\ \eta_{drive}(t)\ dt \tag{2}$$

$$s_{max} - 2 \ \leq \int_0^T v(t)\ dt \ \leq \ s_{max}\ T \ \leq \ T_{max} \tag{3}$$

The optimization variable number is defined in Eq(4) based on the track length (s_{max}) denoted in [m]. The optimized parameter vector is constructed with corresponding d_i - z_i vectors Eq(5), from which the torque application points are specified. The amount of applied torque (M_i) depicted in Eq(6) is based on the value of z_i.

$$n = \frac{s_{max}}{10} + 1 \tag{4}$$

$$d = (d_0, d_1 \ldots ds_{n-1}) \quad d_i = i \cdot 10 \quad (i = 0, 1 \ldots n-1) \tag{5}$$

$$z = (z_0, z_1, \ldots z_{n-1}) \quad z_i = \begin{cases} 0, & if\, M_i = 0 \\ 1, & if\, M_i = M_{act} \end{cases} \tag{6}$$

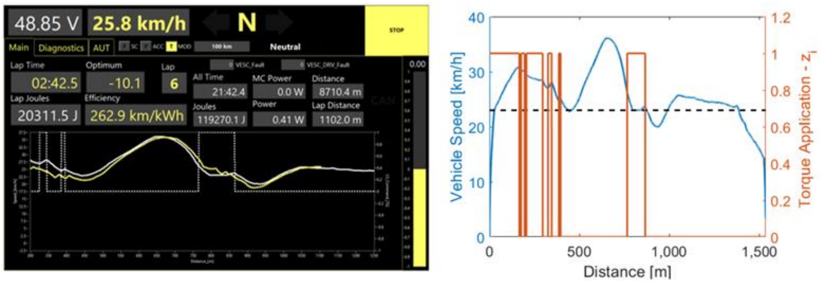
Due to the control approach the vehicle is operated by two torque values depending on the vehicle speed. The first torque value, the maximum of available drive torque (M_{max}), is applied before the switching speed, while after the torque limit is applied Eq(7). The values of switching speed and torque limit (M_{limit}), are also searched during the optimization.

$$M_{act} = \begin{cases} M_{max}, & if\, v(t) < v_{switching} \\ M_{limit}, & if\, v(t) > v_{switching} \end{cases} \tag{7}$$

The optimization was carried out with the hybrid approach using the described equations. Altogether 77 human driving patterns were gathered during the test run in the 2023 SEM in Nogaro. Generation limit was applied to control the running time of the optimization, because of this and the nature of GA, the proposed solution could not be considered global minimum.

4. Results

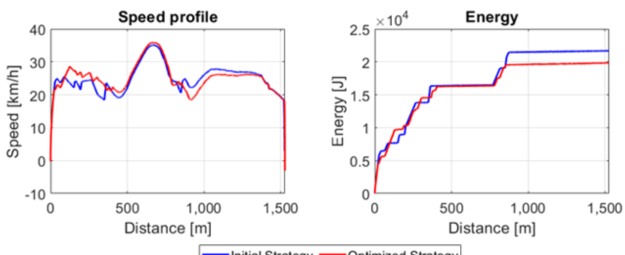
The vehicle model creation and driving strategy optimization were both supported by the telemetry system. The vehicle data was used to set up the resistance model, while the driver data was used to initialize the hybrid population for the optimization. The resulting speed profile and control parameters (M_{limit} , $v_{switching}$) are shown on the onboard display and programmed in the VCU. The switching is done automatically by the VCU, the driver just needs to press the accelerator button at the displayed positions, which simplifies the following of the speed profile. It could be further simplified by automatizing the button pressing, but it is not allowed as the driver needs to have full control over the vehicle. The onboard display with the optimized strategy is shown in 3. Figure during vehicle operation.



(a) (b)

Figure 3: Simulation results of optimized speed profile is shown on the right side (b) while the implementation with white line on the onboard display on the left side (a). The actual speed profile of the vehicle is marked by the yellow line. The driver tries to follow the simulation results and consider the external effect of the wind

The combined application of telemetry system and onsite hybrid optimization further improved the efficiency index. Before the competition initial optimization was done, the acquired strategy was followed in the first practice by the driver. It resulted in 21.683 J energy consumption with the best lap. After the practices the track model was corrected, and human driving was collected due to the telemetry system. The gather information was used for the onsite hybrid optimization, which resulted in 19.832 J energy consumption with the best valid lap. It is important to note that the driver was the same and no modification was done with the vehicle, The compared laps were chosen as the best valid laps from their run (full race run consisted of 10 laps). The achieved 8.54 % improvement in energy consumption is mainly due to the correction of track model, but without the hybrid approach the optimization would have not converged in time. The logged data from the initial and optimized strategy is displayed in 4. Figure. The difference of the simulated and logged energy consumption is related to the external effect of wind. In that case tailwind helped the vehicle both cases, making less acceleration phases enough to follow the speed profile. The fault detection role of telemetry system during race is an indisputable advantage, but the utilization can have additional benefits as proposed. Based on the findings the current system provides great support during the vehicle development and driving applications as well.



(a) (b)

Figure 4: Logged speed profile (a) and energy consumption (b) are compared both before and after onsite optimization. The initial strategy, based on estimated parameters, is shown in blue, while the final strategy, refined by the telemetry-supported hybrid approach, is shown in red

5. Conclusion

The telemetry system and optimization approach successfully combine the real-time data transfer, offline optimization and manual speed profile following. The main goal was to showcase the applicability of the low-consumption telemetry system in supporting the driving strategy optimization through collected data. The application of the resulted driving strategy resulted in 8.54 % energy consumption reduction, which shows the viability of the proposed approach. In the presented case the effect of tailwind helped the vehicle, and the driver could easily adapt as shorter acceleration phase was needed. Although the telemetry provides real-time data, currently it is not used for real-time modification of the driving strategy. This is partly because external control is not allowed in the competition, and vehicle model-based optimization requires more time. External factors, such as wind, can significantly affect the predetermined speed profile, and the driver is responsible for making corrections. This process could be improved by developing a control-oriented vehicle model, enabling the use of model predictive control methods. Future research will focus on achieving faster evaluation of telemetry data, as this study has demonstrated its importance. Additionally, the development of more advanced drive control and online optimization are key research goals, aiming to further enhance energy savings and broaden the applicability to urban driving scenarios.

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