Short thesis for the degree of doctor of philosophy (PhD)

DEVELOPMENT OF HYBRID ELECTRIC POWERTRAIN OF REDESIGNED VOLKSWAGEN CRAFTER WITH ONLINE DATA ACQUISITION SYSTEM

By: Aminu Babangida

Supervisor:
Dr. Péter Tamás Szemes

UNIVERSITY OF DEBRECEN
Doctoral Council of Natural Sciences and Engineering
Doctoral School of Informatics

Debrecen, 2025

ABSTRACT

The function of an energy management strategy (EMS) in electric vehicles (EVs) is to ensure optimal performance conditions for the vehicles in terms of fuel economy and reduced toxic gas emissions. In the Volkswagen (VW) of the Department of Vehicles Engineering hybrid powertrain, a 2.0 turbocharged direct injection common rail (TDI CR) diesel engine is integrated with a permanent magnet synchronous electrical machine (PMSM) to minimize the vehicle consumption and gas emissions. This dissertation presents the development of a hybrid VW Crafter, implemented with a novel methodology based on an online data acquisition (DAQ) approach for analyzing the vehicle controller area network (CAN) bus in electrical drives.

To facilitate the feasibility of transforming an internal combustion engine (ICE) powered vehicle into a hybrid, the vehicle CAN bus data is collected using LabVIEW software, which is based on the hardware-in-the-loop (HIL) method, decoded with the help of a database (DBC) file and analyzed by redesigning the Crafter based on the data measurements conducted and complemented by the model-in-the-loop (MIL) method on the basis of the physical background plant descriptions of the vehicle components with a computer-aided simulation (CAS) in MATLAB/Simulink/Simcape environment.

This work analyses the vehicle's traction using mathematical descriptions of the vehicle to validate its exact power source, considering trade-offs between vehicle size, battery size, engine type, vehicle mass, driving range, and fuel consumption, as well as battery capacity fade over time and its life cycles. Moreover, EMS using a proportional integral derivative-based genetic algorithm (GA-PID), proposing an integral time absolute error (ITAE) as a fitness function, is developed to allocate load demand to the power source, reducing fuel consumption and carbon dioxide (CO_2) emissions. Therefore, the vehicle's pure, conventional, and hybrid versions are developed and compared. The effectiveness of the proposed EMS is verified by the proportional integral-based particle swarm optimization (PSO-PI) and fractional order proportional integral derivative (FOPID) strategies for the hybrid powertrain. This research reduces fuel consumption, CO_2 emissions, and energy consumption by 68.620%, 70.840%, and 25.080%, respectively.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

1.1. Research Motivation

Nowadays, nations worldwide offer a wide range of manufacturing options, including hybrids, plug-in hybrids, and full EVs, and they subsequently look forward to developing future cars. However, the combined disadvantages of full EVs and internal combustion engines (ICEs) cars prompted research on hybrid electric vehicles (HEVs), which now dominate the sales market for electrified cars. Hence, research activity must focus on vehicles with low carbon emissions to avoid emerging environmental concerns resulting from gas emissions from conventional cars operating through ICEs. For the past few years, hybrid cars have received serious attention, making them a popular technology in the automotive industry to reduce fossil fuel dependency and decrease CO_2 emissions. On the other hand, their electric counterparts face challenges due to long charging times, energy storage costs, and limited operation ranges. These challenges are mitigated by the synergy of multiple power sources in a hybrid powertrain, which powers the vehicle.

HEVs combine electrical machines and engine technology, consume less fuel and lower costs than their conventional counterparts. Hence, HEVs are highly energy efficient and aim to reduce fuel consumption and achieve carbon neutrality.

1.1.1. VW Crafter Hybrid Vehicle

The VW Crafter of the engineering faculty at the University of Debrecen was transformed from a conventional ICE-powered to a hybrid by the cooperation of a PMSM Parker electrical machine with a 2011 Nissan Leaf battery pack. It is a front-wheel drive vehicle powered by a diesel ICE and an electric rear-wheel drive. It can be operated in three modes: diesel, electric, and hybrid. Therefore, the design of the hybrid vehicle became popular in the vehicle market due to low energy consumption and CO_2 emissions. It also helped overcome the limitations of pure EVs, including charging time, costs, and limited operating range. An online vehicle monitoring method utilizing the NetCAN Plus protocol was implemented for data collection.

My PhD research, built upon my master's work at the Faculty of Engineering, University of Debrecen, in 2020, focused on developing hybrid electric vehicles, specifically proposing the VW Crafter manufactured in 2020. Under the supervision of Dr. Peter Szemes at the Department of Electrical Engineering and Mechatronics, I developed a dynamic model of the pure electric version using permanent magnet synchronous electrical machines. This simulation-based model preceded the physical development of the hybrid vehicle at the faculty.

During my master's program, I made significant progress, supervising bachelor's students in electric and hybrid vehicles, leveraging control theory applications for internship projects, the Project of Mechatronics, and BSc Theses. I also presented my work at the TDK conference. However, we did not publish in TDK. Nevertheless, I graduated with the best thesis and honors. Two articles extracted from my thesis were published in 2021 at the beginning of my PhD journey. This motivated me to pursue my professional career in this area of research.

Under Dr. Szemes' supervision, I published articles in D1, Q1, Q2, and Q3 Scimago-ranked journals, as well as Scopus-indexed international conferences, during my PhD studies. The positive feedback from editors and reviewers on my initial publication during my master's degree motivated me to continue exploring this research area. My PhD research objectives, set over four years, were:

I. **Year 1:** Modeling and simulating the VW Crafter, investigating different electric vehicle types (BEV, series hybrid, parallel hybrid, and series-parallel hybrid) and studying electrical drives, vehicle design, and traction energy.
II. **Year 2:** Developing and enhancing control algorithms for energy consumption optimization.
III. **Year 3:** Using LabVIEW for vehicle monitoring via CAN bus, analyzing messages, and comparing simulated and experimental results.
IV. **Year 4:** Designing optimization algorithms to search for optimal fuel consumption and energy efficiency and designing the vehicle based on experimental data.

I made significant progress in these areas, contributing to advancing sustainable solutions in transportation electrification.

The same topic will be proposed for postdoctoral research in the following years, where we will test different electrical drives at industrial vehicle size for HIL simulations and vehicle diagnostics within the framework of the energy clutch project under the supervision of Dr. Peter Szemes. This project is already ongoing.

1.2. Research Main Objectives

This research aims to design a hybrid vehicle based on the VW Crafter, leveraging experimental data obtained from the vehicle's CAN bus system. The main objective is to transform the vehicle from conventional to hybrid-operated diesel ICE and electric modes.

1.3. Problem Statement

- The disadvantages of full EVs pose significant obstacles to their widespread adoption, necessitating further research to address these issues and improve EVs' overall performance and practicality. Therefore, developing HEVs offers a more sustainable solution by reducing gas emissions and fuel consumption while enhancing driving range.
- The proportional integral derivative (PID) controller has been widely applied due to its simplicity and practicality for mechatronic devices and industries, as well as its intuitive nature for real-world implementation. However, linear control techniques may not be a suitable control candidate for EVs due to the system's complexity and inherent nonlinear effects, which can impact its performance. To address this challenge, an optimization method is necessary to enhance the PID controller, enabling it to manage power and energy at an optimal level and thereby extend the vehicle's range.
- The CAN bus communication protocol incorporates features like message validation and arbitration, ensuring reliable data exchange. However, interpreting raw CAN bus data from vehicle Electronic Control Units (ECUs) poses a significant challenge. The raw messages contain hexadecimal CAN frames that require decoding into physical values (such as scaled engineering values like Volts, kilometres, and kilometres per hour) for meaningful analysis. To develop efficient EVs that match the performance of conventional

combustion engines, evaluating existing vehicle performance using CAN bus data is crucial.

1.4. Research Contributions

For the first time, this dissertation investigates the total traction required by VW Crafter, introduces a novel online monitoring approach, and reduces fuel consumption, CO_2 emissions, and energy consumption by 68.620%, 70.840%, and 25.080%, respectively.

1.5. Research Claims

There are six research claims listed in detail in the dissertation, but in these short theses, we presented three, one for each thesis.

1.5.1. Thesis I

Tractive force analysis serves as a basis for improving vehicle safety, design, fuel and energy consumption.

1.5.2. Thesis II

The simplified model provides a reliable and accurate investigation of optimal fuel economy, accounting for the various technical constraints of hybrid powertrain dynamics compared to the full-scale or complex model.

1.5.3. Thesis III

The NetCAN Plus 110 hardware online vehicle monitoring method is a compelling novel approach to establishing a CAN bus data analysis framework in present and future electric cars.

1.6. Methodology

The methodology of the research is summarized in four numbers based on the following:

I. **Modeling and Simulation:** In this step, the vehicle was modeled and simulated using MATLAB/Simulink/Simscape environment.
II. **Data collection:** The CAN data was collected, and the vehicle was designed and validated based on the experimental data.
III. **Control and Optimization:** The control algorithm was optimized to compute optimal consumption.
IV. **Comparative Study:** The conventional and hybrid powertrains and hybrid and pure powertrains were compared.

1.7. Dissertation Structure

This dissertation is structured into four chapters as follows:

I. Chapter Two: **Energy Storage Modeling and Traction Analysis:** Modeling of the battery pack and analysis of the traction required for the VW Crafter in MATLAB/Simulink [**Thesis I**].
II. Chapter Three: **Electric Drives Dynamics and e-Crafter Simulation:** Development of the electric powertrain of the VW Crafter according to the different modeling levels: Simple and extended or complex models [**Thesis II**].
III. Chapter Four: **Development of Hybrid Powertrain with data acquisition (DAQ) System:** Online vehicle monitoring and development of the conventional and hybrid powertrains of the Crafter [**Thesis III**].

THESIS I

Energy Storage Modeling and Traction Analysis

Publication(s) Related to Thesis I [P3, P7]

Main Results – The 2011 Nissan Leaf battery has been simulated over a realistic current profile. The thermal performance and capacity fade (degradation) of the battery over time and number of its life cycles have been investigated in its first and second life, using a realistic current profile at a 5 C-rate. The simulated battery still maintains 60.3% of its remaining capacity in its first life, with a 56% fading rate per 1000 cycles at an operating temperature of 29.30 ℃. This thesis also presents a detailed analysis of the tractive requirement to propel the VW Crafter vehicle, utilizing both analytical and simulation approaches. The excess tractive force for the VW Crafter has been presented based on the Taylor series. The excess force has been formulated in the frequency domain on the basis of Laplace Transformation. The exact energy required per 100 km of distance covered to be consumed by the proposed VW Crafter was found to be 21.354 kWh/100 km validated from the actual data of the similar model, specified at 21.54 kWh/100 km, which will help determine if there is an efficiency gain when the actual vehicle is developed based on the proposed optimization techniques in Theses II and III.

2.1. Overview of 2011 Nissan Leaf Battery

The Nissan Leaf battery pack consists of 48 modules, each with four cells; There are two pairs in series pairs in parallel, totaling 192 cells in the pack. The battery has a nominal voltage of 360 V and a capacity of 24 kWh. Each cell's nominal, maximum, and discharge voltages as well as the current capacity are 3.75 V, 4.2 V, 2.5 V, and 33.1 Ah, respectively. The maximum voltage of the entire pack is 403.2 V, the maximum capacity of 66.2 Ah, and the power of more than 90 kW. The collaboration between Nissan and NEC corporation, AESC, manufactured Nissan Leaf battery cells.

The battery pack is made of 48 modules that are connected in series. The total weight of the battery pack is 293.9 kg, and it has an energy density of 81.65 Wh/kg. Suppose the cell's rated capacity is 33.1 Ah at 0.3 C for 3 hours when discharging. In that case, this entails that the rated capacity of 33.1 Ah or 155.194 Wh/kg per cell or 66.2 Ah or 24 kWh per pack is available when the cell or the battery pack is discharged at a 0.3 C rate of 9.93 A per cell or 19.86 A per pack for 3 hours [7].

2.2. Overview of Tractive Force

A force needed to propel the vehicle is called the tractive force. This force is typically caused by the friction between the vehicle's wheels and the road surface. The frictional force in question depends on the properties of the surface, the sliding conditions between the road's surface and the vehicle's wheels, and the vehicle's weight. Therefore, the vehicle moves forward when the prime mover propels the vehicle wheels, and the friction force is large enough. Figure 1 shows the VW Crafter designed based on the resistance forces acting on it [6]. The traction force depends on the resistance forces acting on the vehicle, such as: wind resistance force, rolling resistance force grade resistance, and acceleration resistance force.

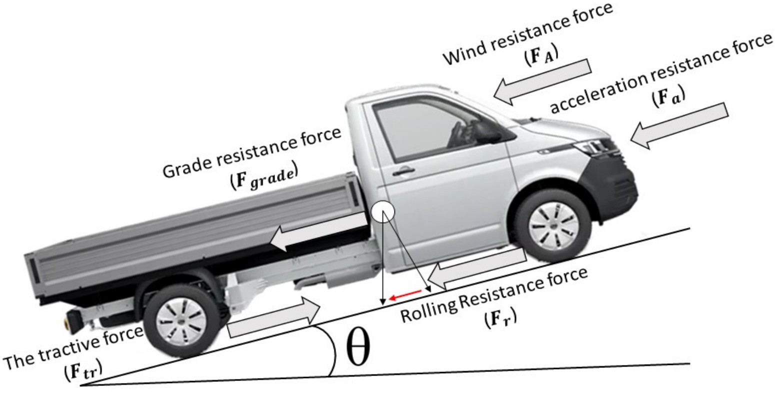


Figure 1. VW Crafter Resistance Forces [7]

The analysis of these forces gives rise to the investigation of the power and energy required to propel the vehicle on the basis of the dynamics of the vehicle, along with the factors affecting the power and energy demand, such as the vehicle size, mass, frontal area, battery and engine size, and so on. Therefore, this thesis provided an idea for the design of the VW Crafter conventional, electric, and hybrid. The tractive powers based on the resistance forces have been analyzed:

- The tractive power required to overcome the wind resistance force
- The tractive power needed to overcome the rolling resistance force
- The tractive power required to overcome the grade resistance
- The tractive power needed to overcome the acceleration resistance force

The required force can be expressed as in [7] as follows:

$$F_{tr} = F_A + F_r + F_{grade} + F_a \tag{1}$$

The parameters are defined in Figure 1 as shown. The tractive torque was calculated from the tractive force and the tire radius. However, the traction power is the product of the traction force and the vehicle's velocity.

2.3. Detailed Thesis Point

2.3.1. Simulation of the Battery Pack

The detailed battery pack was simulated to validate the simulated results, which should be close to the real-life situation of our battery pack for the VW Crafter. We took each battery cell and studied its discharge characteristics. The characteristics of the battery per cell or per pack, whose nominal current discharge characteristics at 0.3 C-rate is 9.93 A or 19.86 A as previously described. Therefore, the recommendation for each cell discharged voltage is 2.5 V, while for the pack, the recommended voltage is 250 V. In three hours, the Nissan leaf battery can provide the regulated discharge limit in the nominal area. This shows that the battery functions well at a given C-rating, delivering a current of 9.93 A per cell or current of 19.86 A for the battery pack.

Figures 2 and 3 show the simulation results for the 2011 Nissan Leaf battery pack, including SOC, capacity fade, temperature, current, voltage, and power. These results were modeled at the system level to investigate its performance before integration into our traction application. Therefore, Figure 2 shows the SOC of 0.603 from an initial of 1, which means 60.3% from an initial SOC of 100%, temperature of 54.3 ℃ from the initial ambient temperature 25 ℃ and capacity remaining of 39.92 Ah from the total capacity of 66.2 Ah and this means 26.28 Ah faded away. Figure 3 shows the battery current of 347 A, power of 92.11 kW, a maximum voltage of 357.5 V and a minimum voltage of 265 V.

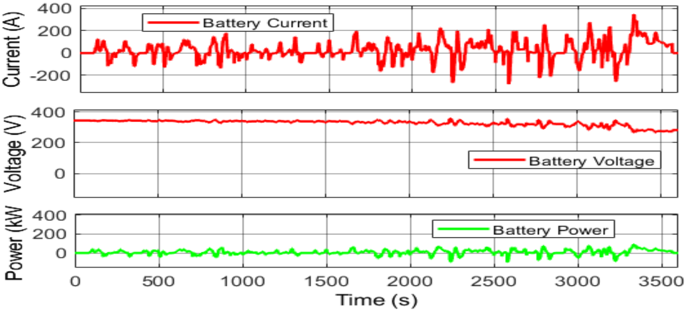


Figure 2. Simulated Current, Voltage, and Power

The complex battery pack simulation provides a detailed simulation of each cell and module. Therefore, to reduce the complexity of the entire pack due to low simulation time and to make the system faster, the detailed model has been compressed into a system-level model that replicates the detailed model behavior in real-time and provides an effective simulation environment for the battery management system. The battery has been simulated over a realistic current profile. The thermal performance and capacity fade (degradation) of the 2011 Nissan Leaf battery over time and number of life cycles have been investigated in its first and second life cycles, using a realistic current profile at a 5 C-rate. The simulated battery still maintains 60.3% of its remaining capacity in its first life with a 56% fading rate per 1000 cycles at an operating temperature of 29.30 ℃.

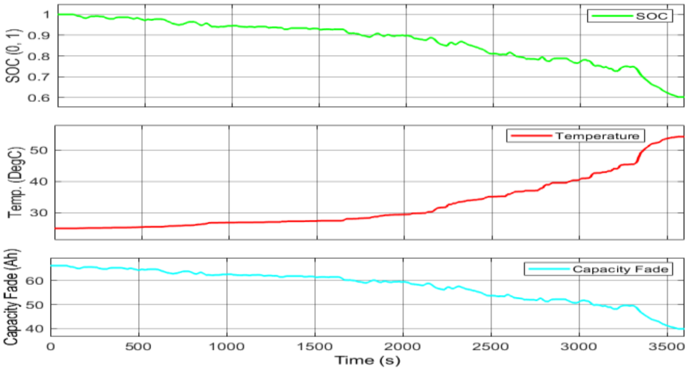


Figure 3. Battery SOC, Temperature and Capacity Fade

2.3.2. Traction Analysis for Level and Sloppy Road Conditions

Figure 4 shows the tractive force against the VW Crafter's vehicle speed at different speed ranges (0-20 km/h), assuming that the vehicle is on a level road. The 20 km/h is the maximum speed allowed for the vehicle in diesel and electric modes. However, the vehicle was tested beyond this speed limit, such as 20-120 km/h and using the worldwide harmonized light vehicles test procedure (WLTP), to estimate the exact power requirement for the vehicle to account for more realistic driving scenario. It was observed that the aerodynamic resistance force and the tractive force increase as the vehicle speed increases. At the same time, other resistance forces remain constant, which is evident based on the mathematical relations of the forces, such as the vehicle speed and the vehicle slope. Therefore, the total actual tractive torque required on the Crafter wheel is 1118.384 Nm for a tractive force of 3132.73 N.

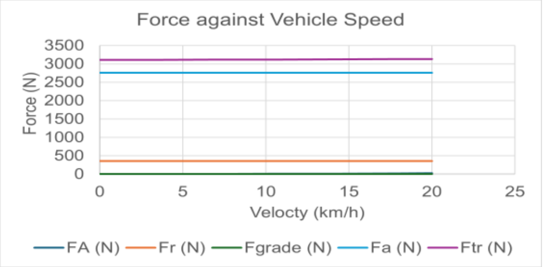


Figure 4. Tractive Force due to Level Road [7]

However, when the vehicle is inclined, normally up to the sloping angle of 30^0, the forces acting on the vehicle are shown in Figure 5. As the angle increased, some of the forces, such as the tractive and gradient forces, were increased, and so did the power and torque requirements. While the rolling resistance force was decreasing. In this case, the torque and power requirement would be significant. If the maximum tractive force is 16613.61 N, then the tractive power would be around 92.368 kW, and the tractive torque would be 5931.059 Nm. This is why the Parker PMSM electrical machine, with a peak power of 82.3 kW, the ICE with 103 kW, and the Nissan Leaf battery pack, delivering a power of 90 kW, is the right choice for this hybrid vehicle.

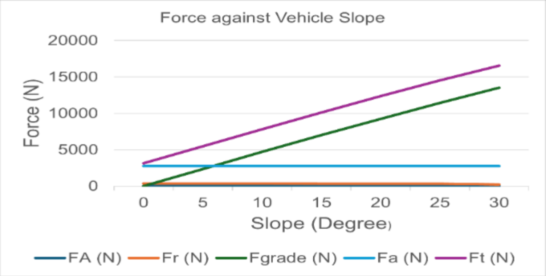


Figure 5. Forces due to Slope [7]

2.2.2. Traction Analysis for Drive Cycle Profile

The vehicle was tested beyond this speed limit using the WLTP test procedure to estimate the exact power requirement for the vehicle in a more realistic driving scenario. It was observed that the aerodynamic resistance force and the tractive force increase as the vehicle speed increases. At the same time, other resistance forces remain constant, which is evident based on the mathematical relations of the forces, such as the vehicle speed and the vehicle slope. This analysis was achieved using equation-based methods simulated in MATLAB/Simulink environment, while the electric vehicle components were modeled using physical model-based methods. To design the vehicle under real-world driving influence, we adopted WLTP as a reference speed for the vehicle. Figure 6 shows the vehicle speed based on the drive cycle and the distance covered. It has a maximum speed of 131 km/h, which is approximately 36.3889 m/s.

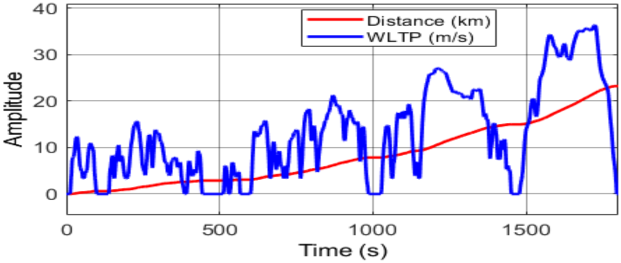


Figure 6. Vehicle Speed and Distance

Therefore, we used this drive cycle to simulate the vehicle at 1800 seconds. The vehicle covered 23.26 km. Based on the simulation results, the force due to rolling resistance was found to be 351.7 N, the force due to aerodynamics was 989.9 N, the grade force was found to be 0 N, and the acceleration resistance force was found to be 6,361.6 N. The total tractive force and torque were 5,407 N and 1,930 Nm, respectively. Based on the maximum total tractive force allowed and the tire radius, the maximum total tractive torque allowed would be 7,727.186 Nm, much greater than the simulated torque of 1,930 Nm. This also proves that there was a vehicle design. Moreover, the total tractive power, as determined by the simulation, was 79.85 kW. Figure 6 shows the tractive energy of the vehicle changing with the vehicle masses, such as 2159 kg, 2196 kg, 2758 kg, and 3500 kg, respectively. The traction energies were 18.852, 19.007, 21.354, and 24.458 kWh/100 km.

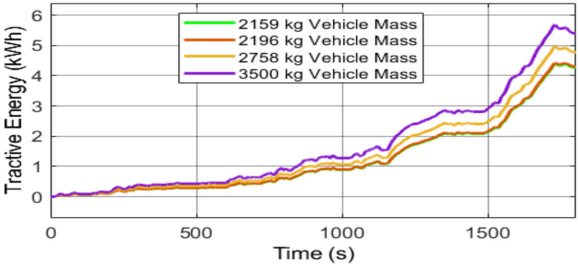


Figure 7. Traction Energy Changing with Vehicle Mass

Similarly, Figure 8 shows the traction energy changes with the vehicle's frontal area. The traction energies were 21.354, 18.929, 16.513, and 14. 106 kWh/100 km when the frontal areas were 4.05, 3.05, 2.05, and 1.05 m^2, respectively. This indicates that the vehicle's range, consumption, and emissions are influenced by its size, engine size, battery size, and mass. Therefore, this provides an opportunity to investigate the vehicle's traction as a trade-off between vehicle size, battery size, engine, vehicle mass, driving range, and fuel consumption. For the vehicle powertrain to meet the design requirements, it must be analyzed in accordance with the intended operating environment. Therefore, the vehicle must be able to overcome the resistance forces acting in the opposite direction for it to move forward. This is in line with the vehicle's power or torque requirement.

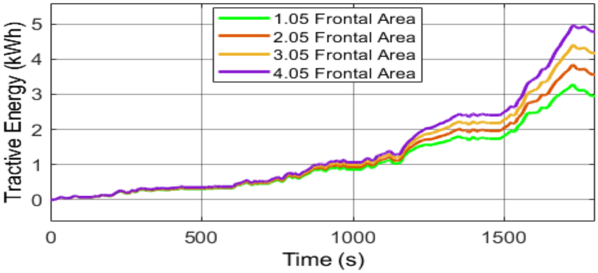
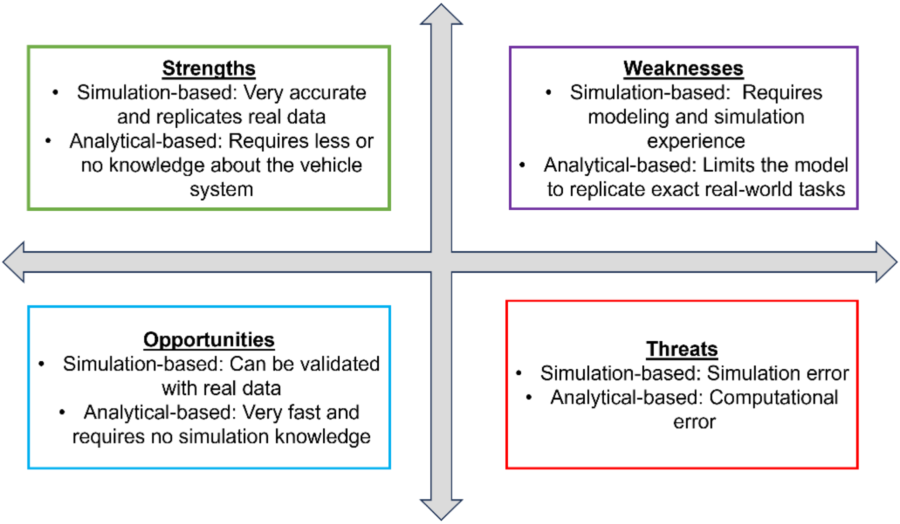


Figure 8. Traction Energy Changing with Frontal Area

Therefore, the thesis analyses the total tractive force required to propel the vehicle in electric, hybrid, or conventional modes at different speeds, sloping angles, front areas, and masses to determine the proposed vehicle's exact power source. The publications related to this thesis are [P3, P7], where most contributions were from [7], with a brief introduction of the concept from [3] under section IIID.

2.2.3. SWOT Analysis

Figure 9 illustrates the SWOT (strengths, weaknesses, opportunities, and threats) analysis of the vehicle dynamics study, employing both analytical and simulation-based approaches. The analytical approach is based on the computation of the tractive force, torque, and power requirements of the VW Crafter. The simulation is based on the use of MATLAB software (MathWorks, R2024a) to simulate the vehicle's dynamic behavior, using the drive cycle as a reference velocity.



Strengths

- Simulation-based: Very accurate and replicates real data
- Analytical-based: Requires less or no knowledge about the vehicle system

Weaknesses

- Simulation-based: Requires modeling and simulation experience
- Analytical-based: Limits the model to replicate exact real-world tasks

Opportunities

- Simulation-based: Can be validated with real data
- Analytical-based: Very fast and requires no simulation knowledge

Threats

- Simulation-based: Simulation error
- Analytical-based: Computational error

Figure 9. SWOT Analysis

THESIS II

Electric Drives Dynamics and e-Crafter Simulation

Publication(s) Related to Thesis II [P1, P3, P4, P8, P12]

Main Results - This thesis presents the dynamic modeling of electrical drives based on PMSM and BLDC electrical machines, as well as the simulation of the VW Crafter's pure electric version for the first time in literature. A dynamic model of electrical drives based on a two-level model is developed. An FOC complex control strategy is applied to control the PMSM detailed drive, while a six-step commutation logic or trapezoidal complex control is applied for the BLDC drive. Meanwhile, the simplified model is based on the torque-speed envelope. The outer-loop control strategy is enhanced using a genetic algorithm (GA-PID), which is used to control the vehicle speed and provide the load demand to the power source.

This thesis demonstrates the importance of simplifying a complex engineering system to an abstract level. With this innovative approach, EV efficiency is optimized. The energy loss is minimized, and the cost of implementation in real-world applications is reduced. Moreover, energy consumption has been investigated and compared with and without thermal effects. Thus, designing electrical machines and traction batteries for industrial vehicle size with effective thermal control is an alternative approach to efficient transportation electrification, including other traction purposes. An energy efficiency of over 90% is achieved, resulting in a 16.81% reduction in consumption. Compared to the required traction of 21.354 kWh/100 km, this thesis achieves an energy gain of 5.124 kWh/100 km using the enhanced PID controller, resulting in a 24% efficiency improvement.

3.1. Materials and Method

Figure 10 shows the development workflow of the e-Crafter modeling in MATLAB/Simulink/Simscape environment. The development of the VW Crafter hybrid vehicle in this dissertation had taken three stages: The first stage was the development of the pure electric, also called e-Crafter; the second stage was the development of the conventional Crafter; and the third stage was the integration of the two powertrains to form the hybrid version. EVs have emerged as a compelling solution to reduce the greenhouse gas (GHG) emissions and fuel consumption of ICE vehicles, steering industries toward a more sustainable and environmentally conscious trajectory.

Traction electrical machines are an integral part of electric vehicles. Therefore, careful selection is necessary to enhance drivability and achieve efficient performance. In this thesis, an e-Crafter has been developed, and its optimal energy consumption has been investigated based on two levels of electrical drive modeling approaches: simplified and complex, considering the level of complexity and technical differences.

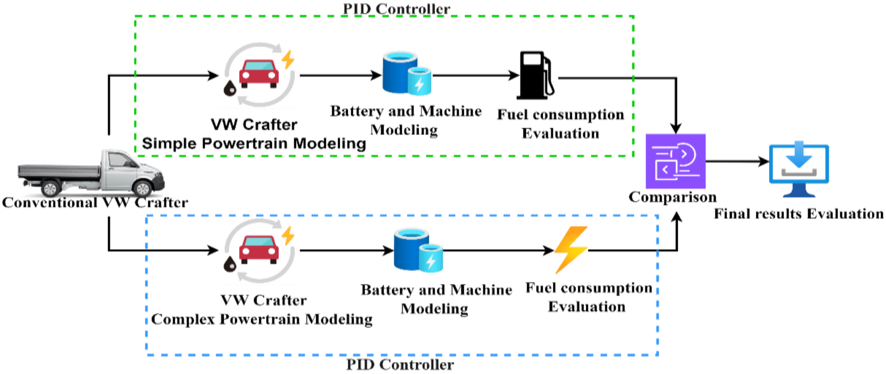


Figure 10. e-Crafter Development Workflow

Despite the disadvantages of pure electric vehicles, as discussed in the literature review section of the dissertation, it is crucial to investigate the proposed vehicle's optimal energy and power consumption and examine the technical implications of transitioning to a hybrid. The electrical components of the electric vehicle (EV) system consist of battery packs, converters, electrical machines, and a control system. The pure e-Crafter uses the Nissan Leaf battery pack as a source of traction energy to drive the vehicle. Pure electric vehicles have zero emissions and, therefore, eliminate the overdependency on fuel fuels compared to their counterparts, ICE and hybrid vehicles. The conventional VW Crafter was modeled as a pure EV based on the synchronous electrical machines' powertrains (BLDC and PMSM). Therefore, simplified and complex or extended versions of the energy consumption of the powertrain were studied in this thesis on the basis of qualitative and quantitative findings.

3.2. Modeling Levels

Figure 11 shows the general architecture of the e-Crafter control loop design with the electrical drives and the vehicle controller, which stands for the simplified model of the e-Crafter with electrical drives based on the BLD or PMSM electrical machine. The vehicle controller provides the load demand to the power source for optimal energy consumption.

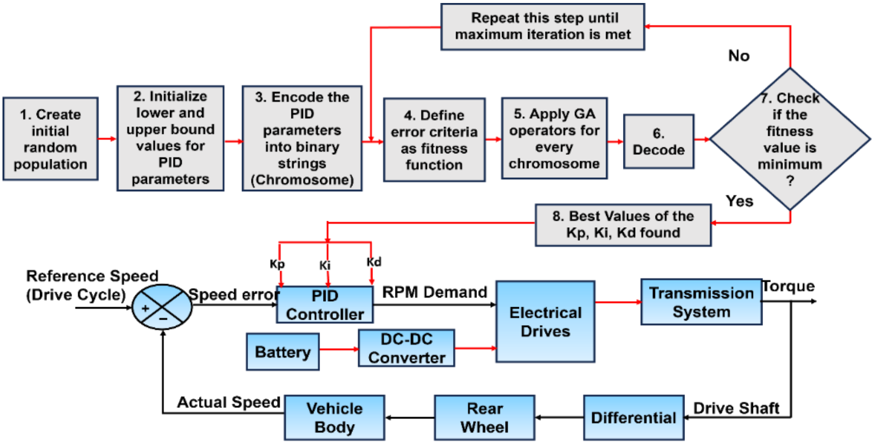


Figure 11. e-Crafter GA-PID Control Loop [7]

A dynamic model of electrical drives based on a two-level model has been developed. These models are:

- Simplified model-based PMSM and BLDC drives.
- Detailed or complex model-based PMSM and BLDC drives.

Therefore, these drives were used to model the VW Crafter at two different modeling levels:

- Simplified e-Crafter-based simplified PMSM and BLDC drives.
- Extended e-Crafter-based detailed or complex PMSM and BLDC drives.

3.3. Detailed Thesis Point

The e-Crafter-based PMSM and BLDC propulsion with 53.5 kW rated power and 82.5 kW peak power at different levels of complexity was simulated in a MATLAB/Simulink/Simscape environment. The 2011 Nissan Leaf battery of 24 kWh, 360 V rating with over 90 kW power, was cooperated with the synchronous electrical machine to provide traction energy needed to propel the vehicle. After the powertrain, the transmission system consists of a gearbox that distributes power to the vehicle's wheels, facilitating their movement, which was modeled. For the vehicle to move, it must overcome the resistance forces as described in thesis I. Therefore, the analysis ensured that the tractive force required to propel the vehicle on a flat surface and an inclined surface was calculated to be within the limit of the rated values of the proposed Parker synchronous electrical machine and the Nissan Leaf battery pack. This dissertation focuses on the transformation of the VW Crafter into an electric vehicle, aiming to reduce emissions of toxic gases and fuel consumption in the context of current global trends towards gas-powered vehicles. The first step is to develop the electric and conventional powertrains and integrate them to form a hybrid. The thesis in this chapter considers the development of the pure electric version of the proposed vehicle and studies its energy consumption under standard driving scenarios.

The successful tracking of the reference trajectory of the vehicle over the new European drive cycle (NEDC) demonstrates the robustness of the proposed GA-PID control strategy, which was performed under several iterations until either minimum errors or maximum iterations were achieved. The vehicle could achieve a top speed of 50 km/h based on the reference in 200 seconds. However, the optimal vehicle speed tracking by the controller, while allocating optimal torque and speed to the electrical machine, impacted energy consumption, necessitating the need to adjust the controller to track the reference speed until steady-state conditions with minimal oscillations. Therefore, we computed and evaluated energy consumption based on the distance travelled by the vehicle every 1 km and up to 100 km, comparing it with the adopted real measurement. This comparison serves as a benchmark to justify the real-world impact of our findings. The battery and electrical machine energy consumption, at 0.2053 kWh/1 km and 0.1618 kWh/1 km, respectively, was recorded with the optimal controller gains of [1999.8, 38.6, 41.2]. This measurement was based on the vehicle's 1 km distance, equivalent to an energy consumption of 20.53 kWh/100 km and 16.18 kWh/100 km. The values of the cost functions, such as the ISE, ITSE, IAE, and ITAE, were 3.587, 13.92, 6.371, and 49.59, respectively. The electrical power consumed was 26.93 kW, and the mechanical power consumed was 24.80 kW respectively. Therefore, the energy efficiency of the simplified powertrain was 78.81% and the power efficiency was 92%, respectively.

However, the controller tuning method and test procedure have a significant impact on vehicle performance. Moreover, it was observed that the manual tuning technique yielded fewer errors but had higher energy consumption despite different test procedures. The electrical and mechanical power consumed was 52 kW and 47.4 kW, respectively; therefore, the power efficiency was 91.15%. It can be seen that the vehicle's performance was pretty excellent in terms of power efficiency, ensuring that it operated within the battery-rated capacity limit. However, the energy consumption for the battery decreased as the vehicle was transformed into a hybrid in thesis III. Considering the energy consumption of 22.73 kWh/100 km achieved with manual tuning demonstrates the efficacy of the GA-PID-based energy management system. Therefore, the manual tuning technique is still valid due to the fewer errors achieved. Still, it does not favor energy efficiency, especially in the case of HEV, which aims to reduce CO_2 emissions and fuel consumption. Therefore, the automated tuning technique (GA) would effectively find the balance between the objective function and the overall system efficiency.

Furthermore, the electrical energy consumed (battery energy consumed) and mechanical energy consumed (motor energy consumed) were 0.1975 kWh/1 km and 0.1623 kWh/1 km, equivalent to 19.75 kWh/ 100 km and 16.23 kWh/100 km for the BLDC drive, respectively. The electrical power consumed was 26.43 kW, and the mechanical power consumed was 24.80 kW. Therefore, the energy and power efficiencies were 82.17% and 93.83%, respectively. Hence, the powertrain based on the BLDC drive demonstrates better efficiency compared to the PMSM drive on the basis of the GA optimization technique. However, our recent study reveals that the powertrain-based BDCL drive achieved an energy efficiency of approximately 90.90%, with an energy consumption of 17.34 kWh/100 km. However, the design of the electrical machine in the study in question was based on the tabulated torque envelope, with the speed at which the controller determined the peak torque set at 400 Nm. Therefore, based on this, the torque requirement would enhance the system's performance and decrease energy consumption even further than the current results with the optimizer. Thus, the GA-PID results presented remain superior due to higher efficiency. In this thesis, the design was based on the maximum torque and power in order to compare its performance with the PMSM drive. The measured energy consumption calculated using the 2011 Nissan Leaf battery capacity for the 2020 Crafter was 19.51 kWh/100 km. Although there was no exact information on which weight of the vehicle the original measured data were obtained, the reference data is still valid for our comparison since the reference vehicle is within the standard weight (3500 kg or less) of the VW Crafter group with slight decrease due to the transformation to pick up style. Therefore, this indicates an 11% reduction in energy consumption compared to the measured data.

The electrical and mechanical energy consumption was 0.1245 kWh/1 km and 0.09162 kWh/1 km, equivalent to 12.45 kWh/100 km and 9.162 kWh/100 km, respectively, for the extended or complex powertrain. Therefore, the energy efficiency was calculated to be 73.59%. However, the power efficiency was very low due to the high power of the electrical part. However, there was a potential decrease in energy consumption of 36.18% for the extended or complex powertrain based on the detailed PMSM model. However, these results may not be reliable due to the model's complexity and power losses, which could impact its performance. In certain situations, the PMSM drive outperforms the BLDC drive, depending on the driving conditions. Another advantage of PMSMs is their ability to deliver constant power over a range of speeds, which is suitable for traction applications such as HEVs.

More in-depth justification is required to justify the fuel efficiency gains obtained by integrating the advanced PID controller with the PMAC electrical drive system in the VW Crafter propulsion application. Officially, the Nissan Leaf range is 124-175 km on the NEDC test. This means that for the first three cycles (50 km/h), as proposed in this thesis, the range can be 124 km for 24 kWh on a single charge. This is roughly for the Nissan Leaf, which has a gross weight of 1965 kg, much less than the VW Crafter. Therefore, since fuel consumption increases with the vehicle's weight, a lower range than the Nissan Leaf car would be achieved. Hence, for the PMSM electrical drive based on manual tuning (22.73 kWh/100 km), a distance of 105.59 km was reached, while for the GA-PID, a distance of 117 km was achieved. However, for the BLDC drive (19.75 kWh/100 km), a distance of 121.52 km was achieved.

On the other hand, PMSM electrical machines have proven to be excellent for traction applications, such as EVs) and HEVs. Although the BLDC machine theoretically performs better in this application at the system level. We could see how the PMSM outperformed it without many issues at the detailed or extended modeling level, though it needs further design and refinement in future studies. Generally, DC electrical machines cannot be relied on in real-world traction applications like EVs because their angular velocity depends on the input voltage. Therefore, the maximum angular velocity also does if the battery voltage drops due to discharge. The angular velocity of the AC machine depends on the frequency of the AC input voltage. Thus, the inverter can keep the AC frequency constant if the battery voltage drops due to discharge. However, DC machines were still in use 30-40 years ago; due to the limitations of power electronics, MOSFETs were not powerful enough to create vehicle inverters. DC choppers were used for DC machines to control angular velocity. Therefore, old trolleys still use DC machines. Electric forklifts utilize DC machines, which are simpler, more reliable, and less expensive than AC machines and inverters. Lead acid batteries can be used as a counterweight. However, with thermal and cooling effects, the energy efficiency increased to 99.07%, and the power efficiency increased to 98.81% due to the temperature decrease. Based on this, the reduction in energy consumption increased to 16.81%.

THESIS III

Development of VW Crafter Hybrid Vehicle

Publication(s) Related to Thesis III [P6, P7, P8, P10, P11]

Main Results - This thesis presents the development of a hybrid powertrain for VW Crafter for the first time. The research proposes a novel data collection approach facilitated by NetCAN Plus hardware to decode the CAN bus message, which is based on the HIL method, to investigate the vehicle performance by leveraging the acquired experimental results to design the vehicle on the basis of MIL method, creating the control loop in MATLAB/Simulink/Simscape simulation environment using an enhanced PID control algorithm (GA-PID) as an energy management strategy. Despite the complexity and nonlinear effects of EV and HEV dynamics, the proposed energy management system demonstrated robust performance. In addition to this control strategy, PSO-PI and FOPID are applied to compare the performance. The results obtained prove the superiority of the proposed control algorithm as a valuable and alternative control scheme in transportation electrification. This research reduces fuel consumption, CO_2 emissions, and energy consumption by 68.620%, 70.840%, and 25.080%, respectively.

4.1. Materials and Method

This thesis presents the final stage of the development of the hybrid powertrain using the model-based approach (MIL method) transition and physical assembly process of the VW Crafter from the conventional diesel-powered drivetrain to hybrid, introducing a novel methodology of experimental vehicle CAN Bus analysis acquired through a NetCAN Plus hardware devices (HIL method). This new approach formed the basis for vehicle transformation for optimal consumption and reduction of the CO_2 emissions.

The physical assembly process of the VW Crafter started from construction to assembly, as investigated and led by a research group of the faculty of engineering. The engineering faculty unveiled the real transformation of this vehicle within the framework of the TKP project funding scheme. The vehicle is allowed at a maximum speed of 20 km/h. Therefore, the hybrid vehicle was tested in the range of 0-20 km/h (precisely 13 km/h).

However, we tested the simulated vehicle at different inputs based on standard road profiles, such as the NEDC for pure electric vehicles (at 50 km/h) and the WLTP for hybrid vehicle (at 45 km/h), to investigate its performance under standard real-world conditions. The WLPT was proposed in the hybrid case because it is more closely aligned with real-world driving scenarios, allowing for exploration of fuel economy and gas emissions. Figure 12 illustrates the development of the hybrid vehicle workflow.

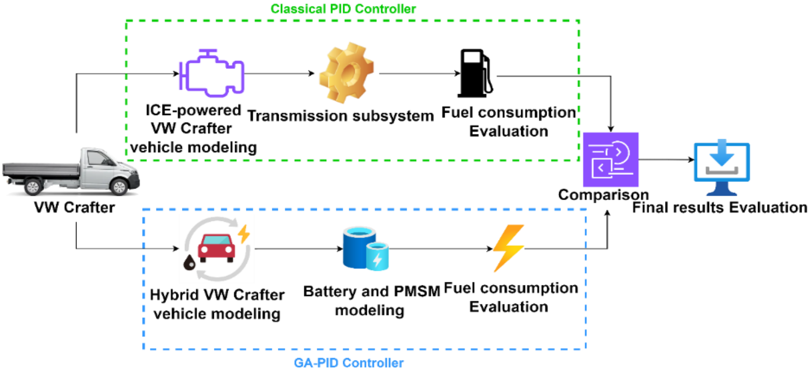


Figure 12. HEV Powertrain Development Workflow [7].

The arrow in Figure 12 represents the design process or step, not the system's energy or power flow. The methodology or workflow consists of two main processes or methods. Method 1: In this stage, the MIL method was employed to design the conventional Crafter, powered by a 2.0 TDI CR diesel engine, incorporating a six-speed manual transmission. A control loop was created based on the classical PID control technique to investigate the vehicle system's fuel consumption and carbon emissions. The results achieved served as a benchmark for the design, control, and optimization of the hybrid powertrain. Method 2: The hybrid vehicle was developed and analyzed. In this method, the design approach was based on the experimental verification of the developed model. In other words, the design method was based on the experimental data obtained from the measured data. Therefore, an improved PID controller was implemented for the hybrid vehicle to reduce fuel consumption and CO_2 emissions. Figure 13 shows the architecture of the VW Crafter with the implemented DAQ approach. The DAQ system consists of four NetCAN Plus devices, the FL Switch, WLAN, Industrial PC, and Power supply. The host PC, running the LabVIEW application, is connected via an Ethernet cable to read the raw CAN data.

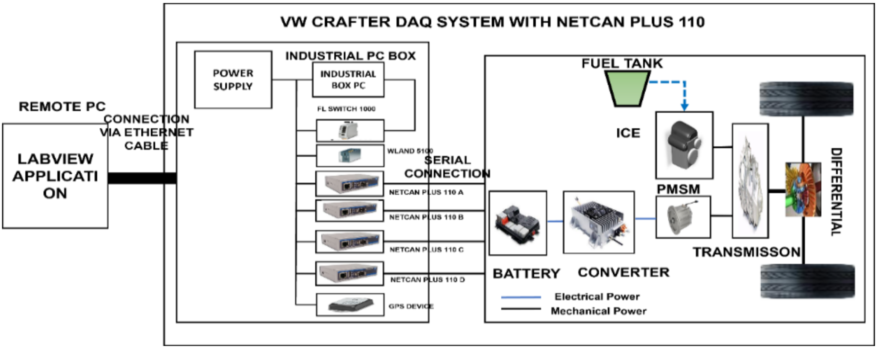


Figure 13. VW Crater Hybrid Vehicle with the Proposed DAQ Approach [7].

4.2. Detailed Thesis Point

The VW Crafter was successfully transformed from conventional to hybrid, significantly reducing fuel consumption, energy consumption, and CO_2 emissions. An energy management strategy using GA-PID, which achieves optimal gains of [70.6657, 0.3339, and 72.4406], was proposed to compute the fuel economy and optimize the overall hybrid powertrain performance. Hybrid and conventional powertrains consumed 3.069 L/100 km or fuel economy of 32.59 km/L and 9.739 L/100 km or 10.27 km/L fuel economy, translating into a 68.488% reduction in fuel consumption. On the other hand, the PSO-PI controller reduced fuel consumption by 77.38%, with a consumption of 2.203 L/100 km. Furthermore, based on the GA-PID control strategy, the electrical and mechanical energy consumption was 12.95 kWh/100 km and 12.12 kWh/100 km, respectively, while the electrical and mechanical power consumption was 50.80 kW and 46.85 kW, respectively. Therefore, the energy and power efficiencies would be 93.59% and 92.22%, respectively. The battery pack would be extended from the initial range of 128.75 km to a final range of 185.3281 km. For CO_2 emissions, there was a significant reduction in converting the traditional diesel ICE-powered vehicle to a hybrid vehicle. Although, according to the datasheet of the vehicle manufacturer, the emissions range from 223 gCO_2/km to 232 gCO_2/km on the basis of the WLTP test, the simulated VW Crafter emitted 255.4122 gCO_2/km into the atmosphere, which was reduced to 74.79 gCO_2/km when hybridized according to the proposed energy management strategy.

Table 1. Fuel and Energy Consumption for Different Control Strategy [7]

Controllers	L/100 km	MPG	km/L	kWh/100 km	gCO_2/km
GA-PID	3.069	32.59	76.65	12.95	74.79
PSO-PI	2.203	45.39	106.8	14.03	53.58
FOPID	2.229	44.86	105.5	14	54.1743

Table 2. Fuel Consumption and CO2 Emissions Comparison [7]

Powertrains	L/100 km	MPG	km/L	TFU[L]	gCO_2/km
Conventional	9.739	10.27	24.15	0.09566	255.4122
Hybrid	3.069	32.59	76.65	0.02801	74.79

Furthermore, with a PSO-PI-based energy management strategy achieving optimized gains of [1243.1, 1.3453], the energy consumption for the battery and the electrical machine was 14.03 kWh/100 km and 12.81 kWh/100 km, respectively, while the power consumption was 55.06 kW and 50.68 kW, respectively. Hence, the efficiencies would be 91.30% and 92.04%. For FOPID, the power consumption of the battery and electrical machine was 54.99 kW and 50.62 kW, respectively, and the energy consumed by the battery and electrical machine was 14 kWh/100 km and 12.80 kWh/100 km, respectively. Hence, the efficiencies would be 91.43% and 92.05%. Therefore, it was observed that all implemented energy management strategies achieved acceptable levels of consumption and system efficiency. Thus, the proposed control strategy or energy management performed better, giving a wider battery range. In addition, there was less energy loss in the case of GA-PID, which translated to better efficiency compared to FOPID and PSO-PI controllers. Table 1 presents the comparison of the energy and fuel consumption as well as the fuel economy for the hybrid powertrain for different energy management strategies, while Table 2 presents the comparison of the fuel consumption and economy for the hybrid and conventional powertrains, respectively.

In terms of energy efficiency, the e-Crafter has achieved an energy consumption of 20.53 kWh/100 km, while the hybrid has achieved 12.95 kWh/100 km, which means a 7.58 kWh/100 km reduction in the energy consumption of the battery as well as reduction of 4.06 kWh/100 km in energy consumption for the PMSM electrical machine. This means there was a 36.922% reduction in electrical energy consumed and a 25.093% reduction in mechanical energy consumed when adding the ICE to the pure drivetrain to form the hybrid. However, when comparing the manual and automated tuning processes, a significant improvement was observed in the latter, particularly with the application of the GA optimizer. In the case of manual tuning, the hybrid vehicle achieved energy consumption of approximately 22.07 kWh/100 km.

To compare the measured and simulated fuel consumption, the acquired dataset via the OBD-II was obtained from the same engine type of the VW group, which has almost similar configurations, including fuel system and fuel type. Hence, the exact fuel consumption may not be the same, but we used it to justify whether we achieved fuel economy. This is because the onboard computer data is unrealistic and may not provide exact data. The computational approach is used for accurate results based on experimental data. Therefore, if the MAF is the air mass flow [g/s], AFR is the actual air-fuel ratio [14.5 in our case], FD is the fuel density [g/L], then knowing the MAF, engine rpm and vehicle speed, the fuel consumption can be calculated. Therefore, if MFF [g/s] or MAF [g/s] is available, we can determine the fuel consumed.

Based on the measured data, the MAF was found to be 56.5905 g/s when the MFF was 3.9 g/s. Hence, the volume flow rate was calculated to be 17.1342 L/h, equivalent to 15.5766 L/100 km. Therefore, the estimated fuel consumption for the Crafter would be 6.4181 L/100 km. This result was as expected, considering the operating conditions and the vehicle speed. The average fuel consumption for the VW Crafter of the same engine type was measured to be 10.582 L/100 km, while the same version manufactured in 2020 had a fuel consumption of 8.8 to 10 L/100 km on the basis of the WLTP drive cycle. The mass flow of the simulated VW Crafter was 3.781 g/s, equivalent to 9.739 L/100 km cumulatively. Therefore, this shows that we have achieved a good design with a classical PID controller. While in the hybrid, we have achieved 3.069 L/100 km for the GA-PID at [70.6657, 0.3339, 72.4406] control gains.

The MAF and engine speed were measured in an idle situation. Under idle conditions, the vehicle was stationary, i.e. at 0 km/h. The speed of the engine was measured to be 819 rpm when the peak speed was 1470 rpm to keep the flow of the fuel. Therefore, the MAF and MFF were 15.7644 g/s and 1.0872 g/s at this speed. The simulated fuel flow (MFF) was 1.062 g/s when the simulated engine's idle speed was 800 rpm. Then, the simulated MAF would be 15.399 g/s. This indicates that the vehicle was performing in nearly the same condition under idle conditions. Moreover, the engine's speed and pressure, specifically the specified pressure and actual boost pressure, are factors that affect the engine's performance. The specified pressure and actual boost pressure were measured to be 1.0275 bar and 1.1645 bar when the engine's speed was 2310 rpm at 180 seconds. The turbocharger spun faster as the engine speed increased to 2743 rpm, generating more boost pressure and rising to 2.466 bar. Therefore, under this condition, the specified boost pressure is less than the actual boost pressure, which would decrease the engine efficiency and cause other damage to the engine. Hence, it is essential to monitor the boost pressure and adjust its regulator as required to keep the specified boost pressure. Further, engine management should be implemented to control the engine's speed for the conventional Crafter to avoid potential damage due to the high rpm. Diesel ICEs should not run at high speed.

The experimental measurements served as the basis for designing and developing the simulated vehicle. However, not all the measured data was used for that purpose because not all were available. Therefore, since we are familiar with the hybrid vehicle components and their specifications provided by the manufacturer, we adopted the fixed parameters to build the starting model. This may not always provide accurate results. Therefore, we implemented an advanced control strategy for energy management to realize the vehicle's optimal performance based on the standard real-world driving scenario. Thus, after determining the measured results, we tested the simulated vehicle's performance under the same conditions as the experiment. This provides the basis for comparing the simulated and experimental results.

The online DAQ approach for the hybrid VW Crafter was based on HIL approach, implemented on the vehicle's electrical drive, and utilized for the analysis of the vehicle's Controller Area Network (CAN) bus. The DAQ system, which was implemented using the standard CAN frame protocol known as J1939, employs a novel approach to interconnecting four NetCAN Plus 110 hardware sets. Thus, all the NetCAN Pluses and GPS modules ran its HTTP server. Therefore, the host PC's static IP address was set and connected to the devices' network with an Ethernet cable. Since the network used a mixed configuration, we specified the MAC addresses of the devices and assigned static IP addresses provided by the DHCP server. Therefore, each device on the network was assigned an IP address. The LabVIEW software runs on this Lenovo PC (host PC) to read the CAN Bus Messages from the vehicle through the four (4) NetCAN Plus 110 connected devices. The NetCAN plus 110 devices with an IP address 192.168.10.13 is used to read the charging data. NetCAN Plus, which has an IP address of 192.168.10.12, is used to read the inverter data. NetCAN Plus with an IP address of 192.168.10.10 is used for reading the temperature data, and the NetCAN Plus with an IP address of 192.168.10.11 is used for reading the auxiliary data. The application was implemented on LabVIEW software on the host PC to read the CAN bus data. The application receives IP addresses, the port number of the NetCAN Plus 110 devices, and 500 kbps as input. Then, the open button should be clicked to open the CAN channel and connect it to the NetCAN Plus to read the vehicle's data.

The vehicle was tested at 13 km/h speed for the electrical drive test, and this measured value was compared with the simulated speed. The vehicle control strategy controlled the vehicle speed using MATLAB. When the vehicle was parked and charged, the measured voltage was 388 V. This means it is 15.20 V to reach its maximum. This measured value was obtained due to the charging condition when it was increased from the initial voltage of 260 V (we assumed minimum safe discharged voltage). The peak voltage of the Nissan Leaf voltage is 403.2 V, and the nominal voltage is 360 V. The simulated voltage was measured and steady at 360 V. Based on the WLTP drive cycle, the Nissan Leaf voltage was measured to be 362. 6 V maximum and a minimum of 355.8 V. The measured battery capacity was 55 Ah at 388 V. This means it is 11.2 Ah less to reach its maximum. These measured physical results were decoded using the database (CAN DBC) file from the raw values of CAN messages and identified through the CAN ID. One of the difficulties was identifying all the messages across the CAN network due to error frames. However, it was easy to identify CAN bus messages for the measurement from the battery, which was used as the basis of our analysis in both the simulation and experiment aspects. Figure 14 shows the flowchart program for reading the CAN bus messages from the host PC.

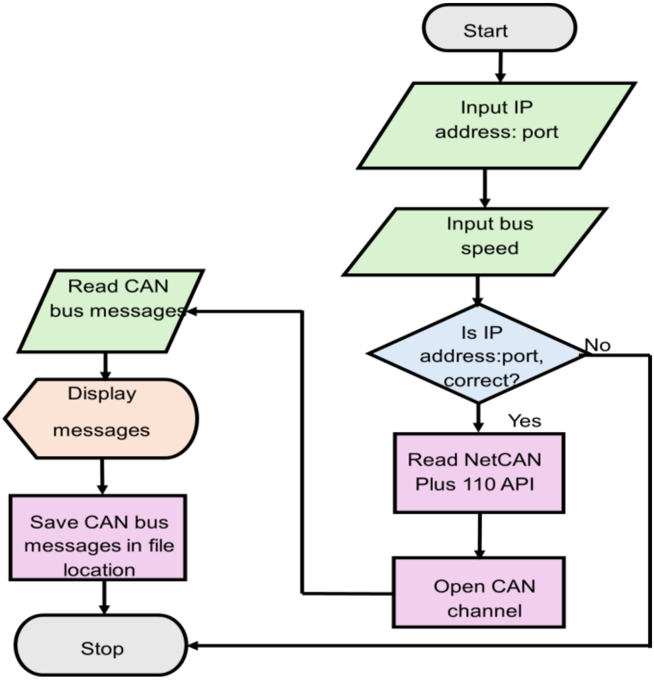


Figure 14. CAN Bus Messages Flowchart Program [11]

During the discharging mode, the measured initial state of charge (SOC) of the battery was 73%, as noted by the onboard computer for the electrical drive. Therefore, we set the initial SOC for the simulation to compare the performance. Hence, 71.5% and 72.5% at 180 s were obtained as the measured and simulated SOC. The Nissan Leaf current was measured to be 180 A based on the decoded message from the raw CAN message, and therefore, each cell can be 90 A. Additionally, the battery's current capacity was measured to be 53.5 Ah, compared to an initial capacity of 55 Ah. Therefore, the remaining battery capacity would be 23.34 kWh, given that the total capacity of the Nissan Leaf battery is 24 kWh. This means that even if we cannot identify the battery capacity over the CAN network, it was calculated based on the measured data from the current capacity. The mathematical formulations for this have been explained in Chapter Three. The initial current capacity was also set to 55 Ah to compare with the experiment, and the final capacity was 54.7 Ah. Hence, we applied the same method for the experiment, and the remaining capacity was 23.87 kWh. Therefore, the simulated and measured battery capacities were 23.34 kWh and 23.87 kWh, respectively, out of the 24-kWh rated capacity.

Finally, the control algorithm was applied to manage power and energy at an optimal level, thereby increasing the vehicle's range. Although it was seen that the proposed controller is better than other controllers, such as the PSO-PI and FOPID, in terms of the energy consumption and efficiency of the vehicle, we proposed a statistical method based on Wilcoxon signed rank test to justify how effective the proposed control algorithm is compared to others on the basis of ITAE fitness function. The Wilcoxon signed-rank test for the objective functions of GA-PID and PSO-PI controllers was proposed to justify the effectiveness of the proposed energy management strategy. Therefore, to use the Wilcoxon test method, we assumed that the data was not normally distributed (for non-parametric technique) and that the research hypothesis was one-sided. The details of this test were presented in the dissertation. Therefore, in summary:

I. In thesis III, the mechanical powertrain of the conventional VW Crafter was developed. The vehicle was powered by a 2.0 L TDI diesel engine with a maximum power of 103 kW (DAUA engine code). A 6-speed manual gearbox, a disc friction clutch, and the gearbox controller were incorporated. A classical PID controller was used to control the speed of the vehicle and compute the fuel consumption and CO_2 emissions.

II. The data measured from the engine drive unit, such as mass airflow, speed, and engine RPM, were collected using a VCDS-compatible cable as an interface between the OBD-II port and a host PC. This data collected was used to compute the optimal consumption of the vehicle's engine drive.

III. The hybrid vehicle was developed with an optimal energy management system. An enhanced PID controller was implemented for the vehicle to reduce fuel consumption and CO_2 emissions. The experimental and simulation results were compared to verify and justify the transformation of this vehicle in the field of electric and hybrid cars in general.

IV. The online DAQ system was implemented using the standard CAN frame protocol, such as J1939, via a novel approach that interconnects four sets of NetCAN Plus 110 hardware, a WLAN, a FL switch, and a GPS device for data collection. Thus, all the NetCAN Pluses, and GPS modules ran on their HTTP server. Hence, the host PC's static IP address was set and connected to the devices' network with an Ethernet cable. Since the network used a mixed configuration, we specified the MAC addresses of the devices and assigned static IP addresses provided by the DHCP server. Therefore, each device in the network was assigned an IP address. The raw CAN data were acquired using an application developed in LabVIEW software on the host PC, saved in a CSV file, and decoded using the DBC file into physical values.

V. The energy management strategy was developed on the basis of a PID-based GA optimization problem to enhance the efficiency of the system, calculate optimal fuel consumption and reduce CO_2 emissions for the VW Crafter. GA was proposed due to its global search capability, ability to solve multi-objective optimization problems, and fast convergence. Furthermore, FOPID and PSO-PI were developed to verify the effectiveness of the proposed energy management strategy, which regulates vehicle speed and provides load demand to the power source.

VI. The traction battery and the electrical machines were extended to include the heat effect with control only for the electrical machine (liquid cooling), represented by the thermal mass, which is related to the heat flow, specific heat of the material, mass, temperature, and time and subjected to an ambient temperature of 25 °C. Therefore, without the thermal model, the proposed energy management strategy reduces fuel consumption, CO_2 emissions, and energy consumption by 68.488%, 70.718%, and 36.92%, respectively. With the thermal model (employing liquid cooling to control heat), the energy management strategy reduces fuel consumption, CO_2 emissions, and energy consumption by 68.620%, 70.840%, and 25.080%, respectively.

UNIVERSITY of
DEBRECEN

UNIVERSITY AND NATIONAL LIBRARY
UNIVERSITY OF DEBRECEN
H-4002 Egyetem tér 1, Debrecen
Phone: +3652/410-443, email: publikaciok@lib.unideb.hu

Registry number:	DEENK/109/2025.PL
Subject:	PhD Publication List

Candidate: Aminu Babangida
Doctoral School: Doctoral School of Informatics
MTMT ID: 10081828

List of publications related to the dissertation

Foreign language scientific articles in Hungarian journals (4)

1. Ghareeb, A. W. J. O., **Babangida, A.**, Szemes, P. T.: Dynamic Modeling and Optimization of Permanent Magnet Synchronous Electrical Machine Propulsion Powertrain at Different Modeling Levels.
   Acta Polytech. Hung. 22 (3), 39-61, 2025. ISSN: 1785-8860.
   IF: 1.4 (2023)

2. **Babangida, A.**, Husi, G., Szemes, P. T.: Bond Graph Modeling, Simulation, and Control of Permanent Magnet Linear Synchronous Motor: PMLSM Motor Based EVs Applications.
   Recent Innov. Mechatron. 9 (1), 1-9, 2022. EISSN: 2064-9622.
   DOI: http://dx.doi.org/10.17667/riim.2022.1/3.

3. **Babangida, A.**, Szemes, P. T.: Electric Vehicle Modeling and Simulation of Volkswagen Crafter with 2.0 TDI CR Diesel Engine: VW Vehicle 2020 Based PMSM Propulsion.
   Recent Innov. Mechatron. 8 (1), 1-6, 2021. EISSN: 2064-9622.

4. **Babangida, A.**, Szemes, P. T.: Electric Vehicle Modelling and Simulation of a Light Commercial Vehicle Using PMSM Propulsion.
   Hung. J. Ind. Chem. 49 (1), 37-46, 2021. ISSN: 0133-0276.
   DOI: http://dx.doi.org/10.33927/hjic-2021-06

Foreign language scientific articles in international journals (5)

5. Kunya, A. B., Mundu, M. M., **Babangida, A.**, Szemes, P. T.: MPC based Frequency Control of an Autonomous Microgrid Integrated with Electric Vehicles.
   Results in Engineering. "Accepted by Publisher", 1-19, 2025. ISSN: 2590-1230.
   IF: 6 (2023)

6. Neamah, H. A., Dulaimi, M., Silavinia, A., **Babangida, A.**, Szemes, P. T.: Development of a Volkswagen Jetta MK5 Hybrid Vehicle for Optimized System Efficiency Based on a Genetic Algorithm.
   Energies. 17 (5), 1-25, 2024. ISSN: 1996-1073.
   DOI: http://dx.doi.org/10.3390/en17051116
   IF: 3 (2023)

7. **Babangida, A.**, Szemes, P. T.: Dynamic Modeling and Control Strategy Optimization of a Volkswagen Crafter Hybrid Electrified Powertrain.
   Energies. 17 (18), 1-38, 2024. ISSN: 1996-1073.
   DOI: http://dx.doi.org/10.3390/en17184721
   IF: 3 (2023)

8. **Babangida, A.**, Odazie, C. M. L., Szemes, P. T.: Optimal Control Design and Online Controller-Area-Network Bus Data Analysis for a Light Commercial Hybrid Electric Vehicle.
   Mathematics. 11 (15), 1-8, 2023. EISSN: 2227-7390.
   DOI: http://dx.doi.org/10.3390/math11153436
   IF: 2.3

9. Muhammad, M., **Babangida, A.**, Neamah, H. A., Szemes, P. T.: Neural Network-based Finite-time Control of Nonlinear Systems with Unknown Dead-zones: Application to Quadrotors.
   Journal of Robotics and Control. 3 (6), 735-742, 2022. ISSN: 2715-5056.

<u>Foreign language conference proceedings</u> (3)

10. **Babangida, A.**, Korondi, P., Diós, S. S., Szemes, P. T.: Development of Meta-Heuristic Optimization Based Control of Redesigned VW Crafter Hybrid Vehicle.
    In: 2024 IEEE 21st International Power Electronics and Motion Control Conference (PEMC), IEEE Explore, Pilsen, 1-6, 2024. ISBN: 9798350385229

11. **Babangida, A.**, Odazie, C. M. L., Szemes, P. T.: Fuel Economy Simulation and Development of an Online Data Acquisition System with HIL Method for a VW Crafter Hybrid Car.
    In: 2023 IEEE 32nd International Symposium on Industrial Electronics (ISIE), IEEE, Piscataway, 1-4, 2023. ISBN: 9798350399714

12. **Babangida, A.**, Szemes, P. T.: Energy Consumption Simulation and Economic Benefit Analysis for a Light Duty Urban Commercial Electric Vehicle.
    In: 2022 IEEE 20th International Power Electronics and Motion Control Conference (PEMC), IEEE, New York, 667-672, 2022. ISBN: 9781665496810

Total IF of journals (all publications): 15,7
Total IF of journals (publications related to the dissertation): 15,7

The Candidate's publication data submitted to the Tudóstér have been validated by DEENK on the basis of the Journal Citation Report (Impact Factor) database.

27 March, 2025