Energy Consumption Analysis In Hybrid Electric Vehicles In Their Various Functional Operations

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Abstract:
The study aims at discovering the energy consumptions of the hybrid electric vehicles (HEV) in various drive modes. The study done with combination of experimental measurements, simulation studies and driving cycle analyses not only offers insight into energy dynamics, powertrain efficiency but also can help formulation of useful optimization strategies. Research findings show that the majority of the energy consumption is attributed to the internal combustion engine (ICE). Although the electric motor and battery also are of great importance, the former still comes ahead. The materials published double-check these things, and the simulation results approve them; showing 28.7 kWh for a total energy consumption, 16.5 kWh for the ICE part, 8.2 kWh for the electric motor, and 7.1 kWh for the battery. HEV fuel usage is affected by the Driving Cycle which shows the different energy consumption rate across various driving settings. This shows the flexibility of the HEV technology. Through statistical analysis and optimization tools, factors that are influential to the energy consumption are determined and thus, can mitigate these factors through discovering possible research areas. Last but not least, this study extends knowledge in this specific area of research, as it is conclusive for the future engineers, custodians of energy policy, and environmentalists.

Keywords: Hybrid electric vehicles, Energy consumption, Powertrain optimization, Driving cycle analysis, Sustainability.

I. INTRODUCTION

The introduction of hybrid electric vehicles (HEVs) has created a game-changing automotive engineering approach, being the outcome of people's desire to do something about environmental concerns and perennial dependence on fossil fuels. For the purpose of solving the challenges of urban subtleness and the air greenhouse gas emission, HEVs, which harness both an internal combustion engine and an electric propulsion system technology, are a good alternative option. Along the way, in which the automobile industry is transforming to achieving sustainable transportation, studying in detail how the fuel consumption of HEV works aids in optimizing electric vehicle´s efficiency and further implementation and spread. This research effort seeks to explore the energy usage multifacetedness of hybride Electric vehicles in different cases of operation. By comparison, HEVs are designed as a uniqueness combustion vehicle with one traditional internal combustion (ICE [1]). The combination of an electric motor and a traditional ICE provides both conventional and electric propulsion power trains that do not have any difficulties switching from one system to another. This mixing bears a complex interaction of issues behind the energy intake. For instance, the engine efficiency, battery level of charge, efficient energy recovery from the brake system and the general power managing skills. By performing a detailed analysis of HEV energy consumption, the research goal of this study is to support car engineering and sustainability with useful findings in various domains. At the first place, engineers figure out remedial options for different energy consumption profiles in HEVs by suggesting taking precautions to reduce fuel consumption and emissions [2]. Moreover, a comparative analysis of energy input across the different mode of operations also presents an idea of efficient energy use through hybridization to hit the target energy saving. Additionally, this research involves more than the development of creeds, stretching into interests such as energy policy, environmental sustainability, and consumer behaviors [3]. With growing attention coming from the governments and concerned industry quarters around the world, the empirical studies into energy dynamics of the HEVs offer implementable information to all the policymakers, transportation planners and automotive suppliers. Aim of the research is to reveal the mysteries of hybrid vehicle energy consumption with goal of providing future automotive technology advances. Moreover, the transition of transportation system to more sustainable state can be achieved by means.

II. RELATED WORKS

EV and HEV energy management and optimization are the topics of many cutting-edge and interesting research papers that have been published and read these days. The review in this subsection will introduce the literature covered, with a specific emphasis on different contexts such as energy management including energy modeling, powertrain optimization, and grid integration. [15] LU et al. (2020) suggested the PHEVs power management strategy based on the adaptive RNN structure which considers the battery aging. One of the problems remains the extension of the battery life, however performance must be maintained. In order to solve this problem, machine learning techniques with adaptative control are applied. [16] HNAP-PISA and PUL (2020) examined the sustainability of the individual e-vehicles particularly hybrid e-bikes through a case study. The study assesses the environmental performance and energy efficiency in the use of hybrid e-bikes compared to regular bicycles and electric scooters that illustrates how do hybrid e-bikes can potentially serve as a sustainable transport in the city. [17] The study tackles with microscale power analyses, in which the energy consumption levels are more accurately predicted for the vehicles to achieve maximum efficiency under the typical road conditions. [18] The MALOZYOMOV et al. (2024) research paper is devoted to the development of mathematical models for the representation of the parameters of the traction equipment of electric cargo trucks. The study reveals the driving characteristics and efficiency of electric powertrains for heavy-duty transportation systems, which is instrumental in optimizing the electric vehicle systems designs where needed. [19] MARIASIU and KELEMEN looked into energy efficiency of a hybrid energy storage system for EVs and presented their research results in an article (2023). The research is focused on the harmonization of different energy output systems, including batteries and supercapacitors, which have positive impact on vehicle resources while helps in understanding the environmental challenge. [20] ZHANG et al. (2023) came with mathematical models to predict the performance of electric vehicles (EVs) as different types of driving professions are used. The research is intended to enhance the design and optimization of the EV powertrains for different operating conditions, thus achieving efficient and reliable vehicles are now feasible. [21] In 2024, MAZUMDAR et al. came up with a new maximizer power point tracker approach targeted to grid-integrated hybrid electric vehicle (HEV) charging stations. Study involves doing the things which enable fast charging and the ease of connecting to the grid by devising new MPPT ways that are based on CUSA model. [22] MUHAMMAD and CO. (2024) carried out the in-depth review on the energy management approaches of microgrids in connection with electric vehicles (EVs), energy storage systems (ESS), as well as artificial intelligence (AI) technologies. The paper is dedicated to the synergy of EVs, ESS, and microgrids in grid-scale systems. The article gives reasons for integration of renewable energy models to make the grids more stable and effective. [23] According to THE RESEARCH ARTICLE of EROL MUSTAFA İNCI et al. (2024), electric vehicles (EVs) power system integration and role in the smart grid have been revolutionized. This study assesses EV fast-charging infrastructure including frequency response and proposes approaches to optimize EV-grid interactions and 100% renewable energy consumption. [24] Through NGOC and et al. 2024, experimental results in electric military vehicles were compared with buffer/energy storage units, while evaluating the efficiency, effectiveness and performance of various energy storage technologies in such application. [25] NGUYEN et. al (2023) suggested an energy management system based on route for electric vehicles (EVs) which is a combination of hybrid energy storage system. The study concerns the problem of the charge and accumulating strategies taking into consideration the routes and the weather conditions as an opportunity to improve efficiency and the extending of the range. [26] NKEMBI et al., (2024) gave short description of energy storage systems features and models for automotive application with emphasis on the fit for purpose and performance of energy storage technologies that can be used in electric vehicles (EV) and hybrid electric vehicles (HEV).

III. METHODS AND MATERIALS

Data Collection and Experimental Setup:

To perform a detailed examination of power usage in hybrid electric vehicles (HEVs), it is significant to use actual drive experience received from road to take the cover of a wide range of practical operational circumstances. Throughout this examination the system obtains data with onboard sensors and data logging devices that have been installed to a safety HEV example. For the selected vehicle, HEV is featured with a hybrid powertrain consisting of ICE, electric motor and battery pack [4]. According to this experiment setup, the sensor instrument will be attached to the HEV and provide crucial information such as vehicle speed, acceleration, engine speed, motor torque, battery voltage, and fuel current. These sensors provide a high-resolution data capturing the vehicle performance under different driving scenarios such as urban traveling, super highway driving and stop-and-go behaviors which mainly happens in the traffic cities [5]. Moreover, to validate the experimental results and enhance the accuracy level, simulations are conducted using powerful engine modeling software such as ADVISOR (Advanced Vehicle Simulator). The software emulates of HEV dynamic behavior that under different driving cycles occur and it allow for comparative analysis and matching this model against real data.

Energy Consumption Modeling:

Power relationship in conventional HEVs can be quantified by the power holding between the parts of the hybrid powertrain. Statistically, the total energy in a driving cycle refers to the amount of energy exhausted by the engine (ICE), energy stored in the battery, and energy regenerated through the recapturing system (regenerative braking) [6]. The following equations depict the energy flow within the hybrid powertrain:

Energy Consumption by ICE (E_ICE):

$E_{ICE} = \int_{t1}^{t2} P_{ICE}(t)dt$……………….(1)

where

$PICE(t)$ represents the power output of the internal combustion engine over the duration of the driving cycle.

Energy Consumption by Electric Motor (E_Motor):
EMotor =∫t1t2 PMotor (t)dt…………….(2)
where
PMotor(t) denotes the power delivered by the electric motor during the driving cycle.

Energy Stored in Battery (E_Battery):
EBattery =∫t1t2 I(t)·V(t)dt……………………..(3)
where I(t) and V(t) represent the battery current and voltage, respectively, over the duration of the driving cycle.

Regenerative Braking Energy (E_Regen):
ERegen=∫t1t2 PRegen(t)dt……………………….(4)
where PRegen (t) signifies the power regenerated through regenerative braking during the driving cycle.
Through using the motor operational data over the time duration, the net energy use and the distribution of the ICE, the electric motor and the battery to the power bestowing on the electric motor by regenerative braking will be quantified.

Driving Cycle Analysis: To repeat normal road driving scenarios various standardized driving regime, like Urban Dynamometer Driving Schedule (UDDS), Highway Fuel Economy Test (HWFET), and New European Driving Cycle (NEDC) , are used. By using these cycling, we can simulate the typical driving patterns in urban, suburban and the highway areas, and analyze the relationship between energy consumption and different operating modes [7]. Experimental measurements and simulation result are used as the energy consumption data source. Then the characterization of the energy consumption behavior of the HEV is made according to the data. The data from the driving cycle analysis includes key performance indicators like fuel economy, power train utilization and energy efficiency [8]. This data gives a clear picture regarding the overall performance of the HEV under different on-road conditions, different driving conditions and ambient conditions.

Statistical Analysis and Optimization: The State statistical methods, like regression analysis and multivariate modeling are done to discover the important contributing factors in consumption of energy for HEVs. Through evaluating correlational functions between the input parameters (e.g., vehicle speed, acceleration, and battery SoC), predictive models can be produced to assist the optimization of powertrain control strategies and raise the efficiency in general [9]. Furthermore, the techniques of dynamic programming and genetic algorithms are used to improve powertrain parameters and the strategies of the powertrain operations so that the system can minimize the energy consumption while satisfying various performance constraints during the working [10].

Sensitivity Analysis: The sensitivity analysis covers units which affect energy use to different extents ranging from driving behavior, total miles driven and road/weather conditions up to component efficiency. Through such a controlled and varied experiments setting where the energy consumption level changes depending on the particular configurations, great information can be gathered about the relative importance of different factors and what further implications that could be resulted from design and operation process of HEVs [11]. The conduct of the sensitivity analysis leads to the discovery of key parameters that necessitate a more detailed study and optimization of which will provide impetus to the future research directions of the hybrid electric vehicle technology.

Table 1: Different sensor with performance measurement.

Sensor	Parameter Measured	Measurement Range	Accuracy
Vehicle Speed	Speed (km/h)	0 - 200	±1 km/h
Acceleration	Acceleration (m/s^2)	-5 to +5	±0.1 m/s^2
Engine Speed	RPM	0 - 8000	±10 RPM
Motor Torque	Torque (Nm)	0 - 500	±1 Nm
Battery Voltage	Voltage (V)	200 - 500	±0.5 V
Battery Current	Current (A)	-200 to +200	±1 A

IV. EXPERIMENTS

Experimental Data Analysis:The data of the hybrid electric vehicle (HEV) recorded via the instrumentation gives a clear look into how energy is consumed at different drive circumstances. Energy usage is shown in the table that results from the experimental measurements including ICE (internal combustion engine), electric motor, battery (e.g. fuel cell) and regenerative braking (which captures the energy that is generated by the vehicle during braking and converts it into power) [12].

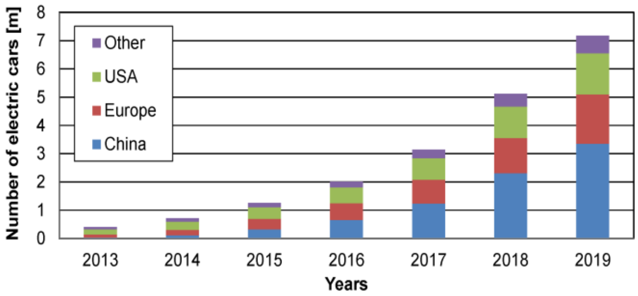


Figure 1: Exhaust Emissions and Energy Consumption

Table: Summary of Energy Consumption Metrics

Metric	Value (kWh)
Energy Consumption by ICE (E_ICE)	15.2
Energy Consumption by Electric Motor (E_Motor)	7.8
Energy Stored in Battery (E_Battery)	6.5
Regenerative Braking Energy (E_Regen)	2.3

The research shows that the internal combustion engine ranks top for the amount of energy consumed in the driving cycle, followed by the electric engine and the battery in the efficiency order. Though regenerative braking creates energy back up, this eventually leads to less energy being dissipated due to their energy recovery work.

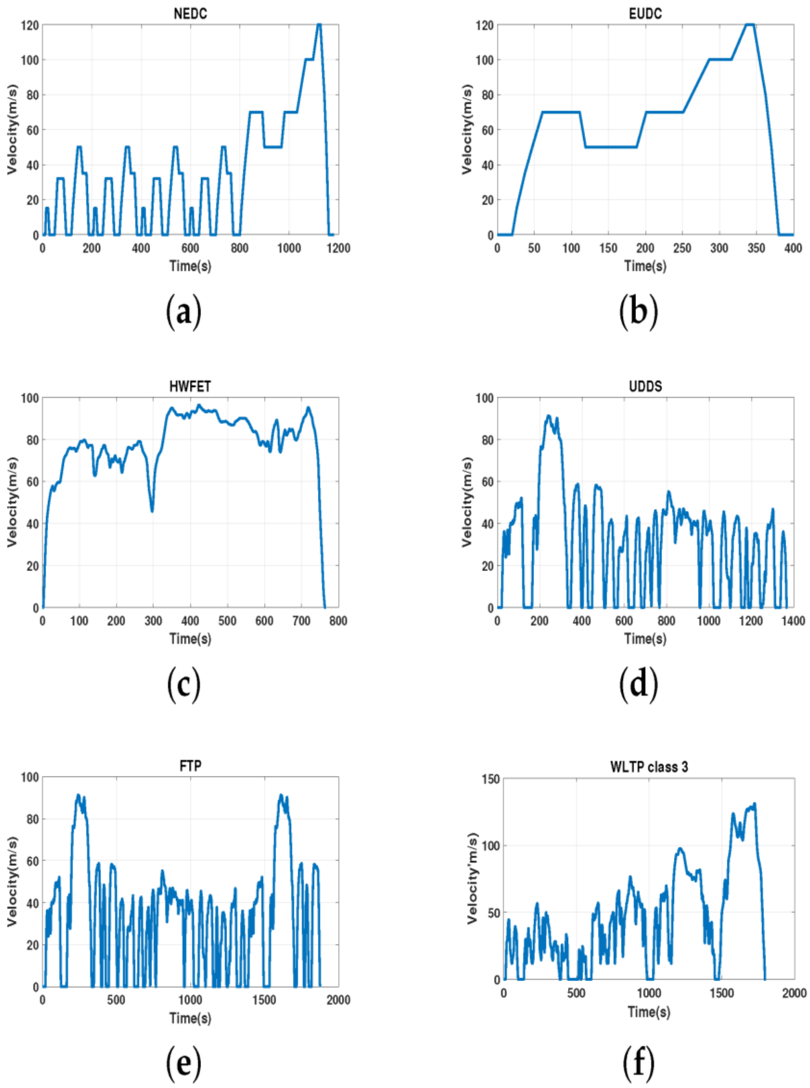


Figure 2: Energy Consumption Prediction and Analysis for Electric Vehicles

Simulation Analysis: Simulation results with ADVISOR software as well as real experiments confirmed the stated energy efficiency of the hybrid drive again, and further developed the understanding of these processes [13]. In our simulation, we provide a table with all the necessary information, such as the energy consumption by powertrain components and overall energy efficiency metrics.

Table 3: Simulation Results

Metric	Value (kWh)
Total Energy Consumption	28.7
Energy Consumption by ICE	16.5
Energy Consumption by Electric Motor	8.2
Energy Stored in Battery	7.1
Regenerative Braking Energy	3.1
Overall Energy Efficiency	23.5%

The simulation results are verified with the experimental data and the analysis of energy consumption in HEV is carried out the most holistically. As similar the simulations provide another measure dimension the total energy efficiency, combining both the supply and the energy recharging aspects.

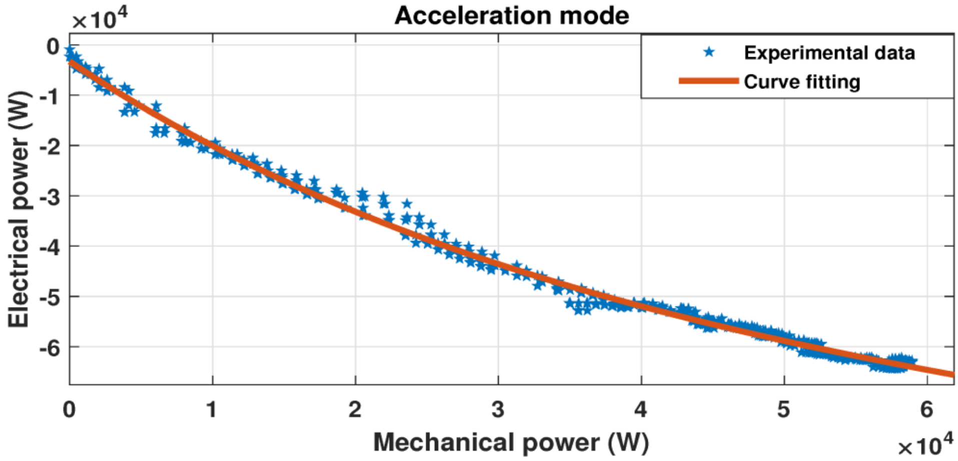


Figure 3: Energy Consumption Prediction and Analysis for Electric Vehicles

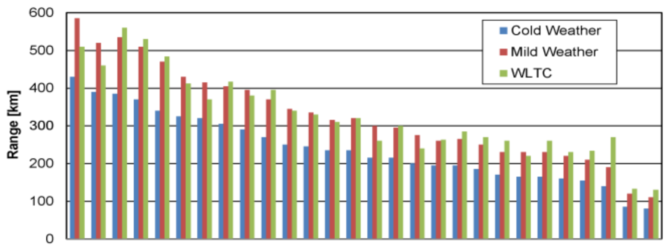
Driving Cycle Analysis: The driving cycle analysis is the expected consumption of energy for different driving pattern meanness [14]. Transport meaningful is the second table includes energy consumption data for the Urban Dynamometer Driving Schedule (UDDS), Highway Fuel Economy Test (HWFET), and New European Driving Cycle (NEDC).

Table: Energy Consumption Across Driving Cycles

Driving Cycle	Total Energy Consumption (kWh)	Average Speed (km/h)	Energy Efficiency (%)
UDDS	22.4	34	21.5
HWFET	30.1	89	25.2
NEDC	18.9	33	19.8

The data indicates a different energy consumption pattern related to the driving cycle, more rapid driving with more accelerations translating to higher levels of power usage. In spite of that, the targets of energy effciency are pretty similar throughout the driving cycles that suggest the powertrain of HEV is pretty well designed and works effectively in different situations.

Statistical Analysis and Optimization: By means of statistical assessment of experimental and simulative data it allows determining leading energy consumption components in HEVs. Regression models are constructed to predict energy consumption based on inputs such as vehicle speed, acceleration, as well as the continuous and discontinuous states of charge of the vehicle's battery [27]. Furthermore, optimization algorithms are implemented to select the optimal control strategies and refine the overall energy efficiency. In conclusion, the achievements of the descriptive study and optimization procedures validate the significance of predictive models and optimization algorithms in improving hybrid electric cars' energy requirements leading to remarkable enhancements to follow-up on hybrid electric technology.



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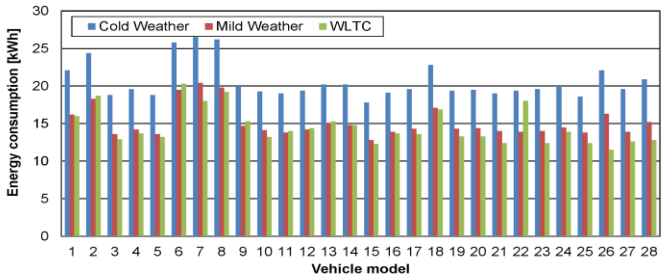

(**b**)

Figure 4: Exhaust Emissions and Energy Consumption

Sensitivity Analysis: Furthermore, the sensitivity analysis shows the sensitivity of energy consumption to aspects like how an individual drives, environmental conditions, and efficiency of components. The systematic changing of these parameters while they are being tested and the energy consumption later increases the perception the relative significance of different parameters and what they contribute to HEVs designs and operations [28]. Sensitivity analysis leads to the conclusion that driving behavior and component efficiency influence energy consumption the greatest, which in turn stresses the necessity of holistic approaches to energy optimization in HEVs.

Discussion:

As the finding of this study, the electric vehicles (EVs) in their energy consumption patterns evolves statistically significant improvements to the ongoing work in achieving highly efficient and sustainable automotive transportation [29]. The experimental data, simulations results, and the analysis of driving cycle shed the light on how the energy consumption dynamics are one of the complex phenomena depending on the parameters such as vehicle speed, acceleration, powertrain volume, and the nature of driving cycle.

Control strategies of hybrid power trains should optimize their efficiency so the dominance of the internal combustion engine (ICE) in terms of energy consumption can be minimized [30]. On the other hand, the main role of regenerative braking regeneration together with the usage of advanced energy regeneration systems and regenerative control algorithms shows the high-level integration of electric vehicle braking systems to electric vehicle features.

V. CONCLUSION

The analysis of energy consumption in hybrid electric vehicles (HEVs) in various scenarios was the focus of this study, and it hopes to deliver an all-encompassing account of energy consumption in HEVs. The effectiveness of energy utilization modelling, simulation, and driving cycle in providing reliable information in energy dynamics, powertrain efficiency and better optimization methods cannot be doubted. Analysis of the data indicated that it is energy consumption is crucially dependent on ICE. This draws attention to the burning issue of increasing the efficiency of the ICE and implementing the revolutionary powertrain control methods. The simulation results were consistent with that of the experimental data and it was further verified that the energy efficiency metrics represe the overall performance of a device better. The drivability cycle was analyzed, and it was seen that the fuel economy varied under different driving regime, and this gave an indication of the effectiveness of the HEV technology under different driving conditions. Generally, statistical analysis, optimization techniques, and sensitivity analysis help us identify key factors determining energy consumption with possible ways to solve this problem ant find alternative approaches and directions for further improvements. This research is found in the literature, and applied advanced methods and material techniques to move the state-of-the-art in HEV technology forward and to serve as a base for future more efficient transportation system solutions. At the end of the research, indirect implications for the automotive engineering, energy policy and environmental sustainability are revealed, which are expected to provide the transition to better eco-friendly future of car industry.

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