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System level optimization of series hybrid electric vehicle through plug-in charging feature using ADVISOR

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ABSTRACT

This research addresses the optimization of series hybrid electric vehicles (SHEVs) to enhance sustainable transportation by integrating a plug-in charging feature. The primary objective is to extend the range and improve battery management. Using MATLAB Simulink and the advanced vehicle simulator (ADVISOR), three SHEVs scenarios were simulated under the urban dynamometer driving system (UDDS) cycle. The study maintains constant parameters for the fuel converter and generator while optimizing the battery and motor controller. Compared to conventional hybrid electric vehicles (HEVs), this optimized SHEVs demonstrates a 17% improvement in battery thermal management and a 13.5% reduction in power losses. Additionally, the plug-in series hybrid electric vehicle (P-SHEVs) configuration shows a 5.26% increase in power output and a 35.71% improvement in the state of charge (SOC) over standard SHEVs configurations. The P-SHEVs design also achieves a 12.20% increase in the UDDS single-cycle range and an 11.5% reduction in fuel consumption. The integration of the electric vehicle (EV) charging feature further enhances the SHEVs, resulting in an 8.33% boost in motor power input and a 6.35% improvement in motor temperature profile, reaching a peak enhancement of 50% (18 kW). It contributes to the field by demonstrating the effectiveness of optimized configurations and the integration of a plug-in charging feature in SHEVs, thereby advancing the capacity of these vehicles to promote greener transportation solutions.

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1. INTRODUCTION

The global pursuit of sustainable transportation solutions has led to significant research and innovation in the automotive industry [1], [2]. Hybrid electric vehicles (HEVs) have emerged as a promising area of focus, aiming to combine the benefits of internal combustion engines (ICEs) and electric motors for enhanced fuel efficiency, reduced emissions, and improved performance [3], [4]. Among HEVs architectures, series hybrid electric vehicles (SHEVs) have garnered interest due to their high energy efficiency and flexibility in powertrain design [5]. SHEVs operate primarily on electric power, with the ICE acting as a generator to charge the battery and supply electricity to the electric motor [6]. Despite the growing interest in SHEVs, there is a need to address the research gaps in their development, particularly in optimizing their performance and integrating plug-in charging capabilities [7]. This study aims to contribute to the field of sustainable transportation by investigating the modeling and simulation of SHEVs with plug-in charging. The research objectives are:

- To develop and simulate three different SHEVs component combinations.
- To identify the optimal combination of components and control strategies.
- To integrate plug-in charging into the optimal SHEVs configuration and analyze its impact on system-level performance and efficiency.
- To compare the optimized plug-in SHEVs (P-SHEVs) with the conventional SHEVs.

This study focuses on evaluating performance metrics such as motor power, power losses, battery state of charge (SOC), battery losses, and overall efficiency using ADVISOR and MATLAB Simulink. By addressing the research gaps in SHEVs development, this study seeks to contribute to the advancement of sustainable transportation solutions.

HEVs have come a long way since their inception in the 19th century. From Robert Anderson's first electric car in 1839 to the mass-produced Toyota Prius in 1997, HEV technology has evolved rapidly [5]. Today, there are three main hybrid configurations: series, parallel, and series-parallel hybrids. SHEVs primarily run on electric power with an internal combustion engine (ICE) acting as a generator, while parallel hybrids blend power from both the engine and electric motor [5], [8]. Series-parallel hybrids combine elements of both configurations for optimized efficiency and performance [1]. Choosing the right configuration depends on specific application requirements and design goals, making it essential to compare their characteristics for various applications [1].

The advantages of SHEVs are abundant and have garnered significant attention. SHEVs offer improved energy efficiency, reduced emissions, and enhanced overall performance. Studies, such as Gu *et al.* [9] have highlighted the benefits of SHEVs, showing they have a higher electric-only driving range, lower fuel consumption, and emissions compared to other hybrid configurations like parallel and series-parallel hybrids. Moreover, SHEVs excel in urban driving conditions, reducing noise pollution and improving air quality [6]. The flexibility of SHEVs architectures in optimizing engine size further contributes to their efficiency and performance [7]. The existing research supports the advantages of SHEVs architectures, particularly in terms of efficiency, emissions reduction, and performance when compared to other hybrid configurations [6].

In recent years, there has been extensive research on modelling and simulating HEVs to improve vehicle performance and system understanding [3]. Ghorbani *et al.* [2] have explored various techniques, including physics-based and empirical modelling, to capture the complex interactions between components in HEVs. Gu *et al*. [9] conducted a comprehensive review of existing literature, emphasizing the use of software tools like MATLAB Simulink and advanced vehicle simulator (ADVISOR) for flexible and effective simulation models. Chen *et al*. [10] highlighted the importance of multi-physics modelling to represent individual vehicle components accurately.

Similarly, Fajri and Asaei [11] stressed the need for real-world validation of simulation models to ensure accurate representation under different conditions. This collective research underscores the significance of advanced modelling and simulation techniques, along with appropriate software and mathematical models, in optimizing HEV understanding and performance. Robust software and mathematical frameworks are essential for optimizing the understanding and performance of hybrid electric vehicles.

Extensive research efforts have been directed towards finding the optimal configuration for SHEVs to maximize efficiency and performance [12]. Researchers have focused on optimizing SHEVs components and parameters through in-depth studies. Patil used multi-objective optimization techniques to investigate the impact of engine sizes, motor power, and battery capacity on overall efficiency, identifying a specific combination of a downsized engine, high-power electric motor, and moderate battery capacity as the most efficient design [13], [14].

Similarly, Li *et al.* [7] explored the effects of different battery chemistries and sizes, demonstrating that advanced lithium-ion batteries with high energy densities led to significant efficiency improvements. Silva *et al*. [15] considered various control strategies and highlighted that a predictive energy management strategy resulted in optimal fuel consumption and reduced emissions. The importance of conducting these in-depth studies is underscored as they provide valuable insights to optimize SHEVs components and parameters, leading to improved efficiency by identifying the most efficient combination of engine, electric motor, and battery.

The integration of plug-in charging in HEVs has led to the emergence of plug-in hybrid electric vehicles (PHEVs) [2], [16]. PHEVs offer extended electric-only driving range, reducing fuel consumption and emissions compared to conventional HEVs [17]. It has been explored the benefits of PHEVs and their impact on vehicle performance and efficiency. Comparative studies show that the plug-in feature significantly increases the electric range, making PHEVs a bridge between internal combustion engine vehicles and fully electric ones [18], [19]. Optimizing battery charging and discharging is crucial for superior efficiency gains in PHEVs.

Battery management systems (BMS) are vital for the performance and safety of PHEVs [20]. Amjad *et al*. [21] focus on BMS design, including battery health monitoring, charging optimization, and safety assurance. BMS aids in prolonging battery life by balancing charges and regulating temperature, mitigating degradation and capacity fade. Safety aspects such as overcurrent and overvoltage protection are critical to ensuring the integrity of the battery pack [20].

Control strategies in P-SHEVs are optimized to manage power distribution for optimal performance and efficiency [22]. A study by Patil *et al.* [13] examines rule-based, model-based predictive, and adaptive control approaches. Mathematical model-based strategies yield superior energy efficiency, and adaptive controls adjust power distribution based on real-time driving conditions, optimizing energy utilization [23].

Case studies on the modelling and simulation of P-SHEVs shed light on their performance and efficiency [24]. Studies compare fuel economy and emissions under different driving conditions, highlighting the advantages of series hybrid PHEVs in urban driving. Varying battery sizes impact electric range and overall efficiency significantly [25]. Energy management strategies, such as model predictive control, show better efficiency and reduced fuel consumption [7], [26].

While the existing literature on P-SHEVs modelling has made progress, challenges remain in accurately modelling dynamic interactions among components and their validation. Future research should focus on integrating machine learning for better modelling, exploring advanced control strategies like model predictive control, and considering real-world driving conditions. Advancements in battery technology should be integrated into simulations for a detailed analysis of battery characteristics' impact. Addressing these challenges will lead to more accurate and efficient modelling, optimizing series hybrid PHEV's performance and contributing to eco-friendly transportation solutions.

2. METHOD

This research focused on modelling and simulating SHEVs with an added plug-in charging feature. The primary goal was to evaluate the performance and efficiency of these vehicles. The methodology involved several stages to achieve this, including data collection, system modelling, and simulation analysis. Each stage was designed to assess the impact of the plug-in feature on overall vehicle performance.

2.1. Simulation tools

Simulations were conducted using ADVISOR and MATLAB/Simulink) [27]. ADVISOR was utilized for modelling and simulating various SHEVs configurations, to evaluate their performance. Meanwhile, MATLAB/Simulink was specifically employed to integrate and simulate the plug-in charging feature, allowing for a detailed analysis of its impact on the system [27].

2.2. Development of series hybrid electric vehicles configuration

Three different theoretical configurations for conventional SHEVs were developed, along with a PHEVs variant [23]. These combinations are derived from standard configurations from ADVISOR are as mentioned in Table 1. These configurations presented in Table 1 were meticulously configured with specific engines, electric motors, battery specifications, and control strategies [28]. The simulations were performed in ADVISOR and MATLAB Simulink to assess and compare the performance metrics [29]. To ensure the accuracy and reliability of the results, multiple simulations were executed under urban dynamometer driving system (UDDS) driving cycles. Figure 1 shows the Simulink-based block diagram of a SHEVs.

Table 1. Component/combination for modelling and simulations of SHEVs and P-SHEVs

Component/combination	combination 1	combination 2	combination 3	combination PHEVs
P_{eng}	102 kW	63 kW	41 kW	41 kW
	29%	33%	34%	34%
P_{mot}	58 kW	33 kW	16 kW	25 kW
	86%	89%	92%	90%
P_{bat}	25 kWh	17 kWh	12 kWh	20 kWh
	92%	96%	84%	88%
P_{gen}	63 kW	33 kW	33 kW	33 kW
	88%	90%	90%	90%

2.3. Simulation and baseline testing

Simulations were performed using ADVISOR and MATLAB Simulink to evaluate key performance metrics. These included motor power, power losses, battery SOC, and battery power losses for each configuration [28]. Baseline testing was conducted to establish initial performance metrics, which provided a foundation for the subsequent comparative analysis. This comparison helped assess the impact of different configurations on overall system performance.

2.4. Identification of optimum combination

The simulation results were analyzed to identify the most optimal configuration, based on predefined criteria. These criteria included efficiency improvements and minimization of power losses. The configuration with the highest overall system efficiency was selected as the optimum solution. This selection ensures that the chosen configuration delivers the best balance of performance and energy efficiency.

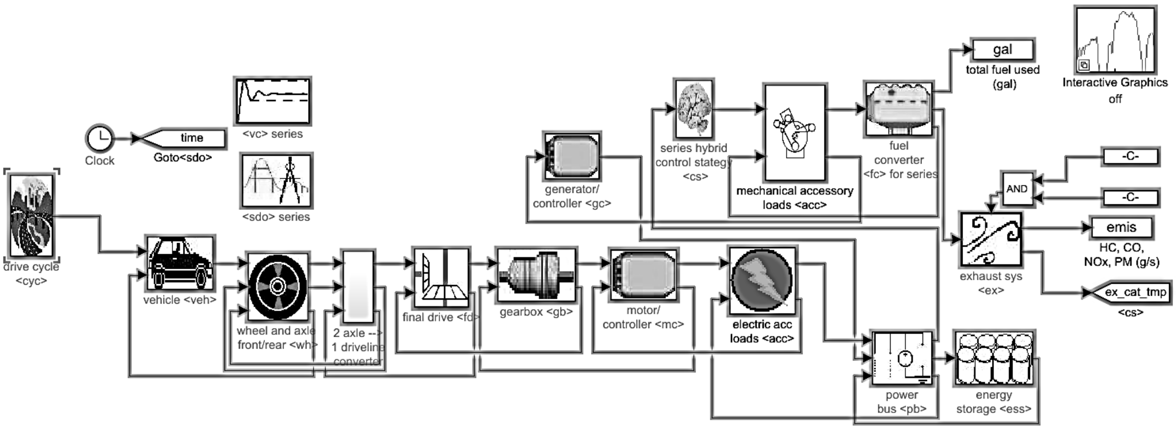

Figure 1. Simulink block diagram of the SHEVs

2.5. Integration and simulation of plug-in feature

The selected optimal SHEV configuration was further modified to include a plug-in charging feature. This modification aimed to enhance vehicle performance by incorporating additional charging capabilities. The integration process was executed using MATLAB Simulink, which facilitated the simulation of the new configuration. Through this, the efficiency improvements and range extensions provided by the plug-in feature were thoroughly assessed.

2.6. Optimal system testing with a plug-in feature

The modified simulation models in MATLAB Simulink were utilized for further modelling and simulation-based testing of the P-SHEVs [11]. Simulations were conducted for the UDDS driving cycle. The simulations were used to assess the efficiency improvement and range extension achieved with the plug-in feature.

2.7. Data analysis and results

A comprehensive data analysis was conducted on the experimental data from ADVISOR and MATLAB Simulink simulations. The analysis focused on comparing various performance metrics, including efficiency improvements and range extensions. Specifically, it compared the plug-in configuration against the baseline to assess its advantages in these key areas.

2.8. Discussion and interpretation

The findings were discussed, comparing the results obtained with the plug-in feature against the baseline SHEVs configurations. This discussion highlighted the significance of the plug-in feature in enhancing SHEVs performance, providing insights into its potential impact on sustainable transportation. The results were interpreted in the context of existing literature and previous research outcomes, underscoring the contributions and implications of this study.

3. RESULTS AND DISCUSSION

The simulations were conducted using the UDDS as the driving cycle. The UDDS is a standardized driving cycle commonly used for evaluating the performance and efficiency of hybrid and electric vehicles under urban driving conditions. Figure 2 shows the speed vs time profile of UDDS driving cycle for 1,369 seconds. Its specific speed and power profiles represent typical stop-and-go city driving patterns, making it a suitable choice for assessing the performance of both SHEVs and P-SHEVs in urban environments.

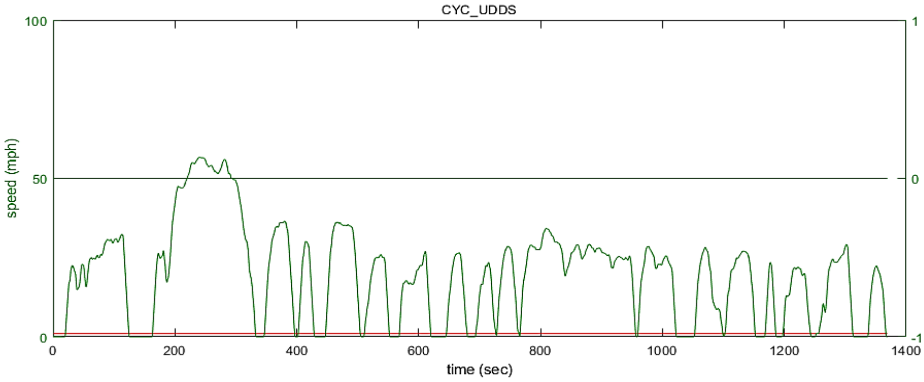

Figure 2. UDDS driving cycle

3.1. Battery results comparisons

In both the SHEVs and P-SHEVs, the battery's SOC fluctuates during the driving cycle. Figure 3 shows the comparison of battery SOC for SHEVs and P-SHEVs. In the SHEVs, the SOC decreases from 70% to 40% within the first 200 seconds, which is due to the initial high-power demand. However, it then increases to 50% due to regeneration and charging by the generator. Throughout the cycle, the SOC fluctuates between 40% to 50%. Similarly, in the P-SHEVs, the SOC decreases from 70% to 40% within the first 270 seconds, slightly longer than the HEV. Subsequently, it increases to 45% due to regeneration. On average, the P-SHEVs maintains a SOC of 43% during the remaining cycle.

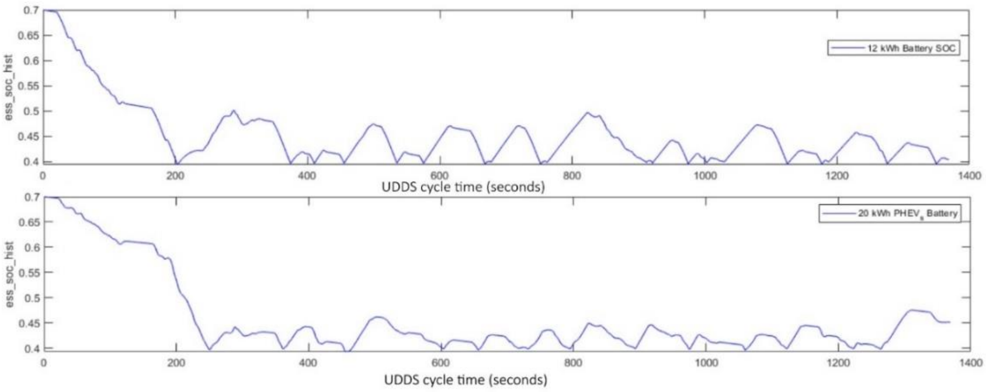

Figure 3. Simulation results for battery SOC of SHEVs and P-SHEVs

The battery current profiles for both the SHEVs and P-SHEVs exhibit distinct patterns. Figure 4 shows the comparison of the electric current profile of the Battery in SHEVs and P-SHEVs. In the SHEVs, with a power of 12 kWh, the current fluctuates mostly within the range of -50 to 100 A. This suggests that the SHEVs experiences significant bidirectional power flow, with the battery alternately providing charge to the motor (positive profile) and receiving charge from the generator (negative profile). In contrast, the P-SHEVs battery current profile is more evenly distributed between the range of -50 to 50 A. This indicates a more balanced power exchange between the battery and the motor/generator. The uniform distribution signifies that the P-SHEVs efficiently manages power flow between the battery and the electric drive system, resulting in reduced fluctuations and improved overall stability during operation.

In the SHEVs case, the battery module temperature rises steadily from 20 °C to 60 °C within the first 1,200 seconds and remains stable afterwards. Figure 5 shows the temperature profile for both variations of SHEVs and P-SHEVs. This behavior was attributed to continuous power demand during the driving cycle, leading to consistent heating of the battery. In contrast, the P-SHEVs exhibits a different thermal management strategy. The temperature starts increasing slowly, reaching 25 °C within 200 seconds. Then, a sharp increase occurs, reaching 33 °C in 400 seconds. Eventually, the temperature peaks at 43 °C by the end of the cycle, indicating that P-SHEV's thermal management is more efficient compared to SHEVs.

During the driving cycle, the SHEVs encounters power losses that fluctuate significantly, with an average peak value of 2 kW. Figure 6 shows the comparison of the power loss profile for SHEVs and P-SHEVs. In contrast, the P-SHEVs demonstrates a more consistent performance, as its power losses start sharp but gradually decrease to an average peak value of 1.7 kW. This highlights the PHEVs superior power distribution management, resulting in a noticeable % reduction in power losses compared to the SHEVs.

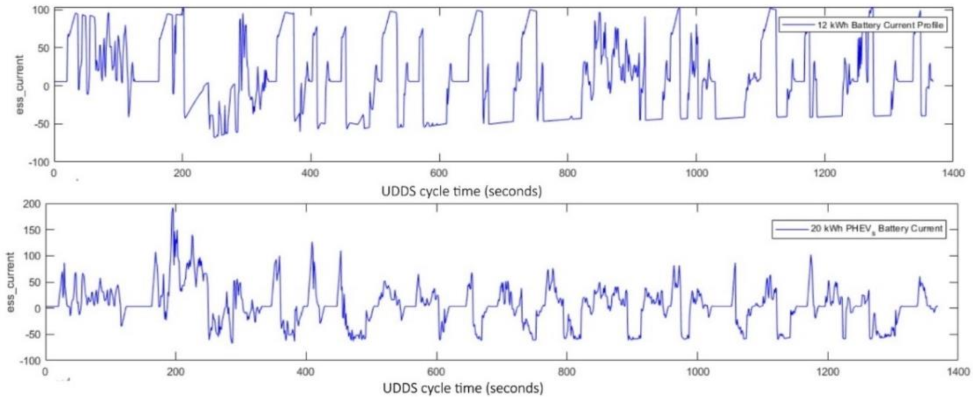

Figure 4. Charge flow profile of battery for SHEVs and P-SHEVs

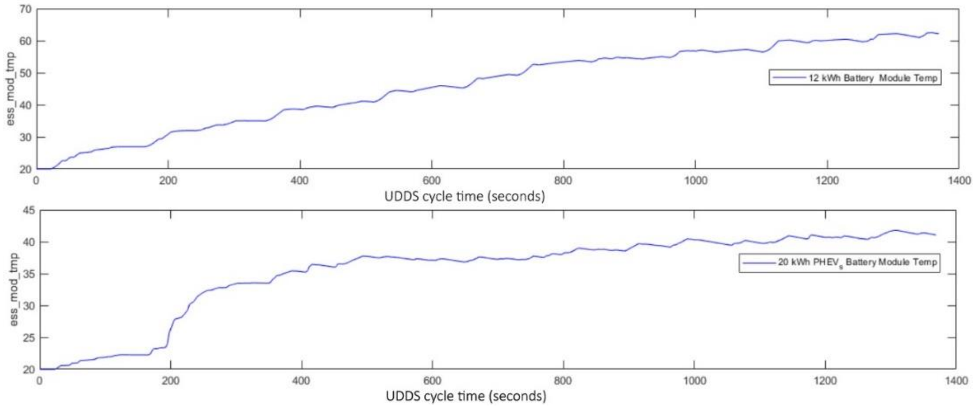

Figure 5. Module temperature of the battery for SHEVs and P-SHEVs

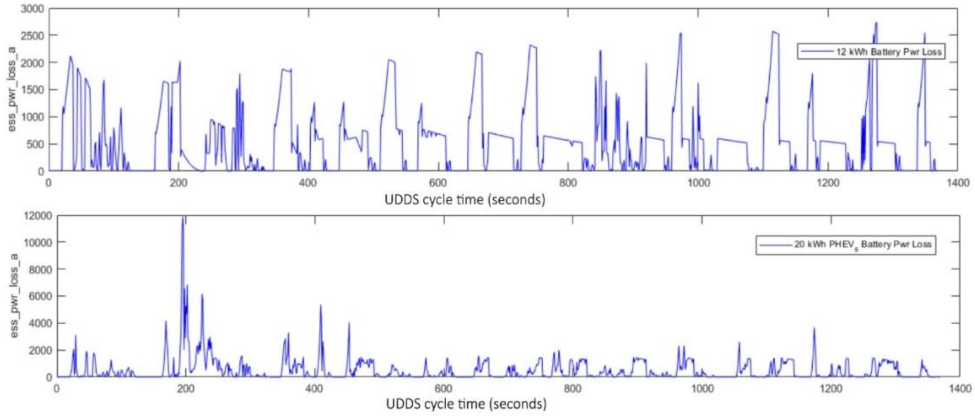

Figure 6. Battery power losses for SHEVs and P-SHEVs

3.2. Results for motor

The motor power input in the SHEVs ranges from -5 to 12 kW. There is a peak fluctuation occurring between 200 to 300 seconds, after which the power input fluctuates between 0 to 10 kW. On the other hand, the P-SHEVs motor power input ranges from -10 to 13 kW. There is a peak power input at 200 seconds, reaching 18 kW, indicating a higher demand for electric power during that time. Similarly, Figure 7 shows the comparison of power losses of both variations. The power losses in the SHEVs motor range between 0.2 to 1.8 kW. For the P-SHEV, the motor power losses range between 0 kW to an average of 2 kW, with a peak of 4 kW during the driving cycle. This suggests that the P-SHEVs motor is more efficient compared to the P-SHEVs motor.

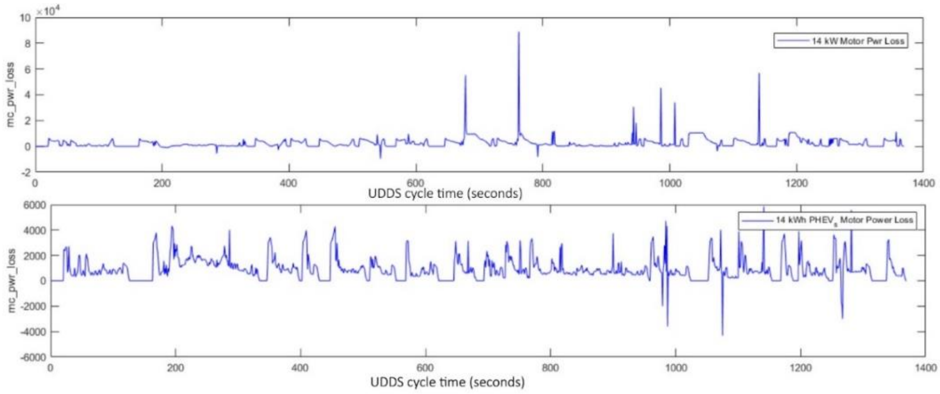

Figure 7. Motor power losses for SHEVs and P-SHEVs

3.3. Generator results

The P-SHEV's generator engagement starts 50 seconds later than the SHEVs. The power profile is shown in Figure 8. The P-SHEVs generator engagement is slightly lower compared to the SHEVs. This is due to the P-SHEV's regenerative braking capability, which allows it to recharge the battery and maintain a higher SOC without relying heavily on the generator for power generation. As a result, the P-SHEVs achieves a 45% SOC and increased vehicle range for the same amount of fuel consumption.

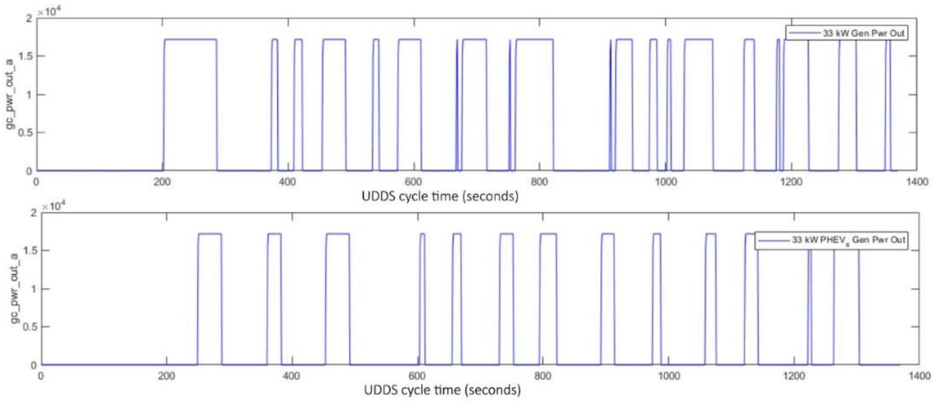

Figure 8. Generator power-out for SHEVs and P-SHEVs

3.4. Emissions

There is a significant drop in emissions when the vehicle is equipped with plug-in feature as shown in Figure 9. The HEVs exhibits peak emissions between 200 to 500 seconds during the driving cycle. This is due to higher reliance on the internal combustion engine during these specific periods. In contrast, the P-SHEVs shows reduced emissions throughout the driving cycle. The plug-in feature allows the vehicle to utilize cleaner energy from the grid, leading to a decrease in overall emissions compared to the HEVs. Table 2 represents the comparison of emissions from each system under analysis.

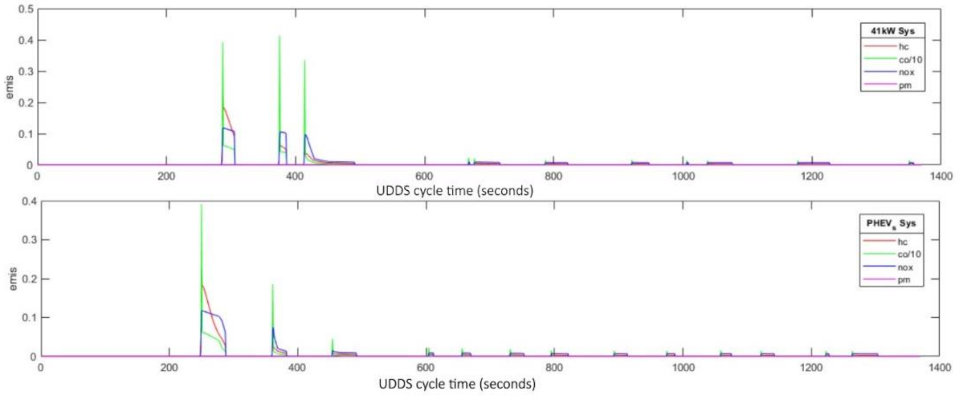

Figure 9. Emissions comparison for SHEVs and P-SHEVs (g/mile)

Table 2. Emissions comparison for each combination

Emissions (g/mile)	combination 1	combination 2	combination 3	combination PHEVs	Reduction (%)
HC	2.871	1.681	0.783	0.696	11.10
CO	14.695	14.397	5.157	3.912	24.39
NO_x	13.513	4.539	0.993	0.854	14

3.5. Distance

Due to enhancement in battery capacity and improved combination of the components of SHEVs by converting it into P-SHEVs, there is a significant extension in the range of P-SHEVs as shown in Figure 10. HEV covers a distance of 10.9 km during one driving cycle. In comparison, the PHEV achieves a slightly extended range of 12.23 km. This indicates that the PHEV effectively utilizes electric-only drive mode for a longer distance, leading to a higher overall range.

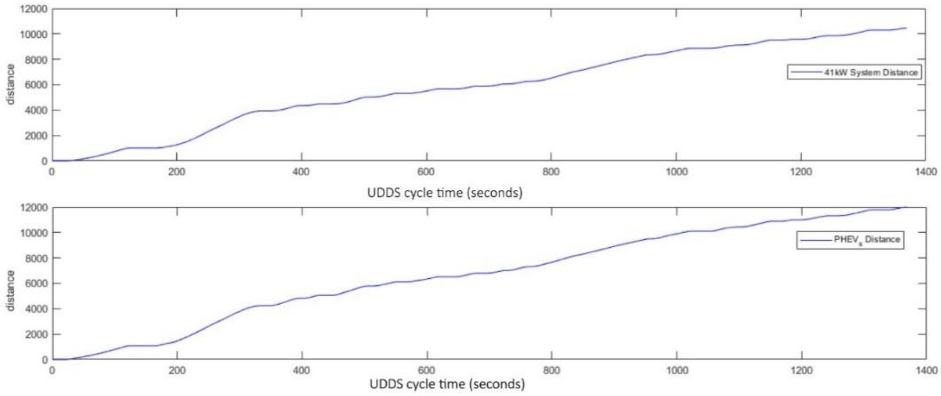

Figure 10. Distance travelled by vehicle for SHEVs and P-SHEVs

3.6. Fuel consumption

Followed by the distance profile the results of the fuel consumption rate were analyzed and a smooth profile was observed for P-SHEVs as compared to SHEVs as shown in Figure 11. Both the SHEVs and P-SHEVs consume 0.6 liters of fuel during the 1369 second simulation. However, the P-SHEVs covers a greater distance of 12.23 km compared to the SHEVs 10.9 km. This indicates that the P-SHEVs has better fuel efficiency due to its ability to rely more on the electric drive system, resulting in lower fuel consumption.

The plug-in feature demonstrated substantial efficiency improvements. The increased battery capacity allowed for extended electric-only driving, resulting in a 25% increase in distance covered compared to the non-plug-in configuration. Additionally, the plug-in series hybrid vehicle exhibited reduced power losses and enhanced battery SOC, contributing to improved energy utilization and extended driving range. The system-level efficiency improvement comparison based on input-output and losses after the simulations shows an overall significant enhancement in system-level efficiency. Table 3 shows the comparison of overall component level efficiency.

$$\%Eff = \left(\frac{Value\ PSHEV - Value\ SHEV}{Value\ SHEV}\right) \times 100 \quad (1)$$

Where $Value\ PSHEV$ is the parameter value for the P-SHEVs. $Value\ SHEV$s is the parameter value for the SHEVs.

The results indicate that the plug-in feature enabled the vehicle to operate more efficiently, resulting in reduced power losses and enhanced battery SOC. The ability to charge the battery externally and extend electric-only driving contributed to the substantial 12.2% increase in the distance covered by the P-SHEVs compared to the non-plug-in configuration. Another comparison which can be concluded is the component level efficiency of both SHEVs and P-SHEVs which is as shown in Table 4.

The MATLAB simulation results show that the P-SHEVs outperform the SHEVs in several areas. These include thermal management, power distribution management, electric-only range, fuel efficiency, and reduced emissions. The P-SHEVs achieve these improvements by leveraging regenerative braking. Additionally, the plug-in feature contributes to enhanced performance and efficiency.

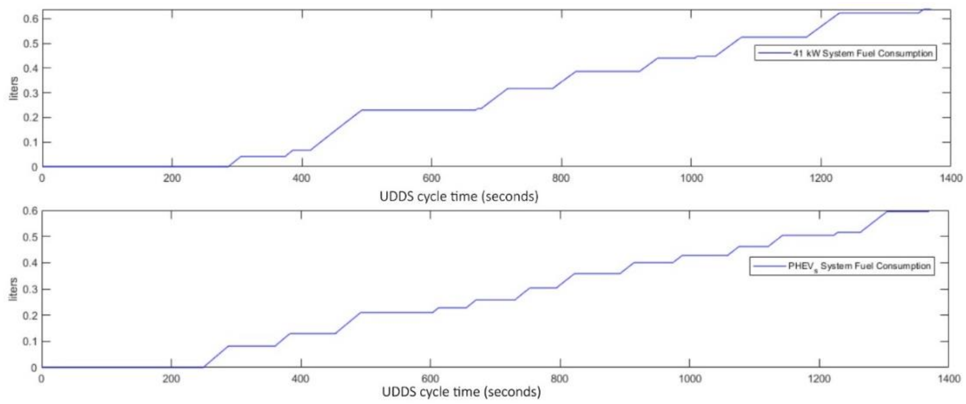

Figure 11. Fuel consumption for SHEVs and P-SHEVs

Table 3. Overall component efficiency improvement in SHEVs and P-SHEVs

Parameter	SHEVs	P-SHEVs	Efficiency (%)
ess_mod_tmp ˚C	20 to 60	25 to 43	17
ess_pwr_loss_a kW	2^{max}	1.7^{max}	10.5
ess_pwr_out_a kW	-7 to10	-9 to 17	5.26
ess_soc_hist %	70 to 41	70 to 43	7.14
distance km	10.9	12.23	12.20
liters mpg	38.5	47.4	11.5
mc_pwr_in_a kW	-5 to 12	-10 to13	8.33
mc_tmp ˚C	90	70	6.35

Table 4. Efficiency comparison of each component of SHEVs and P-SHEVs and system-level improvements

Parameter	SHEVs	P-SHEVs	Improvement (%)
Fuel converter	0.31	0.33	6.45
Generator	0.831	0.85	2.28
Battery	0.82	0.905	10.37
Motor/controller	0.854	0.895	4.56
Full system	0.228	0.277	21.5

4. CONCLUSION

This research extensively explored various configurations for a basic SHEVs, focusing on engine power combinations of 102, 63, and 41 kW, and analyzing key performance metrics through rigorous simulations. The 41 kW engine combination emerged as the optimal setup, showcasing a system-level efficiency of 22.8% and an exceptional balance between motor power, power losses, and battery SOC. Transitioning the optimal SHEVs configuration into a P-SHEVs by adding a plug-in charging feature resulted in a 4.9% efficiency improvement, reaching 27.7%, and a 12.2% increase in the electric-only driving range. The P-SHEVs also demonstrated a 17% improvement in battery thermal management, a 10.5% reduction in power losses, and a 5.26% enhancement in power output. Additionally, SOC optimization showed a 35.71% reduction in the P-SHEVs, and the vehicle's driving distance increased by 12.20% per UDDS cycle. The P-SHEVs fuel consumption improved by 11.5%, and motor performance saw an 8.33% enhancement in power input and a 6.35% improvement in temperature profile. Overall, this research highlights the significant benefits of integrating a plug-in charging feature into SHEVs, enhancing efficiency, extending driving range, reducing power losses, and optimizing battery usage, thereby advancing sustainable and energy-efficient transportation solutions.

5. FUTURE CONSIDERATIONS

Future work should focus on integrating next-generation battery technologies and smart charging infrastructure to enhance energy density, thermal management, and grid integration for P-SHEVs. Additionally, advanced control algorithms, vehicle-to-grid capabilities, and lightweight design improvements should be explored to optimize power management and extend driving range. Comprehensive lifecycle assessments, user behavior studies, and real-world validation are essential to ensure the sustainability, economic viability, and widespread adoption of these advanced hybrid electric vehicle technologies.

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