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Simulation-Based Optimization of Voltage Architecture for Belt Starter Generator Mild Hybrid Electric Vehicles Using Fuel Economy and Cost–Benefit Analysis

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Abstract

The increasing demand for improved fuel economy and reduced greenhouse gas emissions has accelerated the development of mild hybrid electric vehicles (MHEVs) as an economical alternative to full hybrid and battery electric vehicles. Among the available architectures, the Belt Starter Generator (BSG)-based mild hybrid system has emerged as an attractive solution owing to its relatively simple integration with conventional internal combustion engine vehicles while providing significant improvements in fuel efficiency. However, the selection of an appropriate electrical system voltage remains a critical engineering challenge because higher voltage levels improve electrical performance but simultaneously increase system complexity, manufacturing cost, and safety requirements. This study presents a comprehensive simulation-based optimization of voltage architecture for BSG mild hybrid electric vehicles by simultaneously evaluating fuel economy improvement and system cost. A validated vehicle model was developed using the Autonomie simulation platform and calibrated against experimental data obtained from a 48 Vdemonstration vehicle. Six vehicle configurations comprising a conventional internal combustion engine vehicle, a 12 V stop-start system, and BSG mild hybrid systems operating at 24 V, 36 V, 48 V, 84 V, and 120 V were evaluated under the Worldwide Harmonized Light Vehicle Test Cycle (WLTC). The analysis included battery performance, motor operating characteristics, state-of-charge behaviour, regenerative braking capability, and overall fuel economy. A detailed component-level cost analysis was also performed to determine the economic viability of each voltage architecture. The simulation results demonstrated that fuel economy increased progressively from 30.6 mpg for the baseline vehicle to 34.22 mpg for the 120 V system. However, the incremental improvement beyond the 48 V architecture was minimal, whereas component costs increased substantially because of larger electrical machines, higher-capacity batteries, power electronics, and mandatory high-voltage safety equipment. Cost-benefit analysis revealed that the 48 V BSG architecture achieved the optimum balance between fuel economy improvement, electrical efficiency, packaging requirements, and manufacturing cost. The findings indicate that the 48 V mild hybrid architecture represents the most practical and economically sustainable solution for large-scale deployment of next-generation mild hybrid passenger vehicles

Keywords: Mild Hybrid Electric Vehicle; Belt Starter Generator; 48 V Architecture; Vehicle Simulation; Fuel Economy; Cost–Benefit Analysis; Autonomie; Voltage Optimization

1. Introduction:

The global automotive industry is undergoing a rapid transformation driven by stringent emission regulations, increasing fuel prices, and the growing demand for sustainable transportation technologies. While battery electric vehicles (BEVs) and full hybrid electric vehicles (HEVs) offer substantial reductions in greenhouse gas emissions, their widespread adoption is constrained by high manufacturing costs, battery limitations, and charging infrastructure requirements. Consequently, mild hybrid electric vehicles (MHEVs) have emerged as an economically viable intermediate solution for improving fuel economy while minimizing modifications to conventional internal combustion engine (ICE) vehicles (Ehsani et al., 2018; Miller, 2014).

Among the various mild hybrid configurations, the Belt Starter Generator (BSG) architecture has gained significant attention because of its simple integration with existing powertrains and its ability to provide start-stop operation, regenerative braking, and torque assist without major drivetrain modifications (Emadi, 2015). These functions improve engine efficiency, reduce fuel consumption, and decrease exhaust emissions, making BSG-based systems attractive for mass-market passenger vehicles (Onori et al., 2016).

The electrical system voltage is one of the most critical design parameters influencing the performance and economic feasibility of mild hybrid vehicles. Lower voltage systems (12–24 V) offer lower implementation costs but provide limited electrical power, whereas higher voltage systems (84–120 V) improve power capability at the expense of increased component costs, packaging complexity, insulation requirements, and additional safety measures. The 48 V architecture has recently emerged as a promising compromise by delivering significant improvements in fuel economy while remaining below the high-voltage safety threshold adopted in many automotive applications (Miller, 2014; Guzzella & Sciarretta, 2013).

Although several studies have investigated individual mild hybrid configurations, comprehensive comparisons of multiple voltage architectures using both technical performance and economic evaluation remain limited. Therefore, the present study aims to optimize the voltage architecture of Belt Starter Generator mild hybrid electric vehicles using simulation-based analysis. Various voltage configurations (12 V, 24 V, 36 V, 48 V, 84 V, and 120 V) were evaluated under the Worldwide Harmonized Light Vehicle Test Cycle (WLTC) using the Autonomie simulation platform. Fuel economy, battery performance, motor characteristics, and system cost were analyzed to identify the most cost-effective voltage architecture for future mild hybrid vehicle applications.

2. Materials and method

2.1 Vehicle Simulation Platform

A simulation-based methodology was adopted to evaluate the performance of Belt Starter Generator (BSG)-based mild hybrid electric vehicles operating at different electrical voltage levels. The vehicle models were developed using the **Autonomie** vehicle simulation platform, which is based on the MATLAB/Simulink environment and is widely used for the development and assessment of advanced vehicle powertrains. The software enables detailed modelling of vehicle propulsion systems, energy storage devices, electric machines, controllers, and driving cycles under realistic operating conditions (Guzzella & Sciarretta, 2013; Onori et al., 2016).

2.2 Vehicle Configuration

A mid-size passenger vehicle equipped with a 1.8 L four-cylinder spark-ignition internal combustion engine and a six-speed automatic transmission was selected as the baseline model. The conventional internal combustion engine (ICE) vehicle was modified to incorporate Belt Starter Generator (BSG)-based mild hybrid systems operating at different voltage levels. Seven vehicle configurations were investigated:

- Baseline conventional ICE vehicle
- 12 V Stop-Start system
- 24 V BSG Mild Hybrid
- 36 V BSG Mild Hybrid
- 48 V BSG Mild Hybrid
- 84 V BSG Mild Hybrid
- 120 V BSG Mild Hybrid

All vehicle configurations were evaluated under identical operating conditions to ensure a reliable comparison of fuel economy and system performance.

2.3 Mild Hybrid Architecture

A **P0 Belt Starter Generator (BSG)** architecture was employed in this study because of its simple integration with existing internal combustion engine vehicles. The BSG unit was connected to the engine crankshaft through the front-end accessory drive (FEAD) belt system, enabling engine cranking, regenerative braking, torque assistance, and automatic stop-start operation without modifying the existing transmission system (Miller, 2014).

The hybrid control strategy coordinated the operation of the internal combustion engine, battery pack, inverter, and electric machine to optimize energy utilization throughout the driving cycle.

2.4 Energy Storage System

Lithium-ion battery models were employed to represent different voltage architectures. Separate battery configurations corresponding to 24 V, 36 V, 48 V, 84 V, and 120 V systems were developed by varying the number of battery cells connected in series. The initial battery state of charge (SOC) was fixed at 70%, while the allowable operating range was maintained between 20% and 80% SOC to ensure charge-sustaining operation and to prevent battery overcharging or deep discharge (Ehsani et al., 2018).

2.5 Electric Machine and Power Electronics

The BSG system consisted of a permanent magnet electric machine coupled with a bidirectional inverter and a DC/DC converter. The inverter converted direct current supplied by the battery into alternating current required by the electric motor and enabled regenerative braking during vehicle deceleration. The DC/DC converter maintained the conventional 12 V electrical system while supplying power from the high-voltage battery pack. Component ratings were selected according to the corresponding voltage architecture investigated in the simulation.

2.6 Driving Cycle

Vehicle performance was evaluated using the **Worldwide Harmonized Light Vehicle Test Cycle (WLTC)**, which provides realistic vehicle speed profiles representing urban, suburban, rural, and highway driving conditions. Compared with the New European Driving Cycle (NEDC), the WLTC offers a more representative assessment of real-world vehicle performance and fuel consumption (UNECE, 2014).

2.7 Simulation Procedure

Each vehicle configuration was simulated under identical WLTC operating conditions. During simulation, the hybrid controller managed engine start-stop events, regenerative braking, battery charging, torque assist, and power distribution between the engine and electric machine. Performance parameters recorded during each simulation included:

- Fuel economy (miles per gallon)
- Battery state of charge (SOC)
- Battery charging and discharging power
- Electric motor operating characteristics
- Regenerative braking performance
- Vehicle electrical power demand

The simulation outputs were compared to determine the influence of voltage architecture on vehicle performance.

2.8 Model Validation

The developed simulation model was validated using experimental performance data obtained from a commercially developed **48 V mild hybrid demonstration vehicle**. Fuel economy values predicted by the simulation were compared with dynamometer measurements under both WLTC and NEDC driving cycles. The deviation between simulated and experimental fuel economy remained below 2%, confirming the reliability and accuracy of the simulation model for subsequent analyses.

2.9 Cost Analysis

A component-level cost analysis was performed to evaluate the economic feasibility of each voltage architecture. The total system cost was estimated by considering both direct manufacturing costs and indirect engineering costs associated with the following components:

- Battery pack with battery management system
- Belt Starter Generator (electric machine)
- Inverter
- DC/DC converter
- High-voltage wiring harness
- Battery disconnect unit

The overall system cost for each voltage level was calculated by summing individual component costs. Cost-effectiveness was assessed by calculating the **cost per percentage improvement in fuel economy**, allowing direct comparison of the economic performance of different voltage architectures.

2.10 Data Analysis

Simulation results obtained for all seven vehicle configurations were comparatively analyzed. Fuel economy improvement, electrical performance, battery behaviour, and system cost were evaluated to identify the optimum voltage architecture providing the best balance between technical performance and economic feasibility. The results were interpreted to determine the most suitable mild hybrid configuration for future passenger vehicle applications.

3. Results and Discussion

3.1 Validation of Simulation Model

The developed Autonomie simulation model was validated using the experimental results obtained from the 48 V demonstration vehicle. The comparison between the dynamometer results and simulation outputs showed excellent agreement under both WLTC and NEDC driving cycles, with deviations below 2%. This confirms the accuracy and reliability of the simulation model for evaluating different mild hybrid voltage architectures.

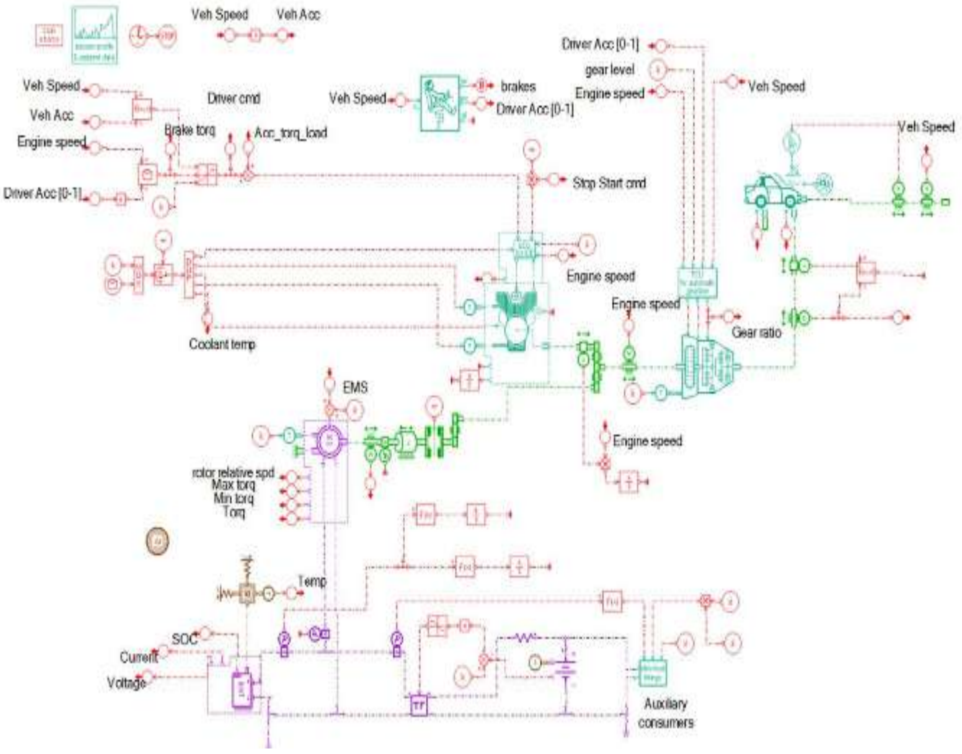


Figure 3.1: *48V Mild Hybrid Vehicle Model*

The validated model served as the basis for evaluating the performance of various mild hybrid configurations operating at different voltage levels.

3.2 Battery Performance Analysis

The battery voltage outputs confirmed the successful implementation of different voltage architectures within the simulation model. Each battery pack maintained the specified operating voltage throughout the simulation, demonstrating stable electrical performance.

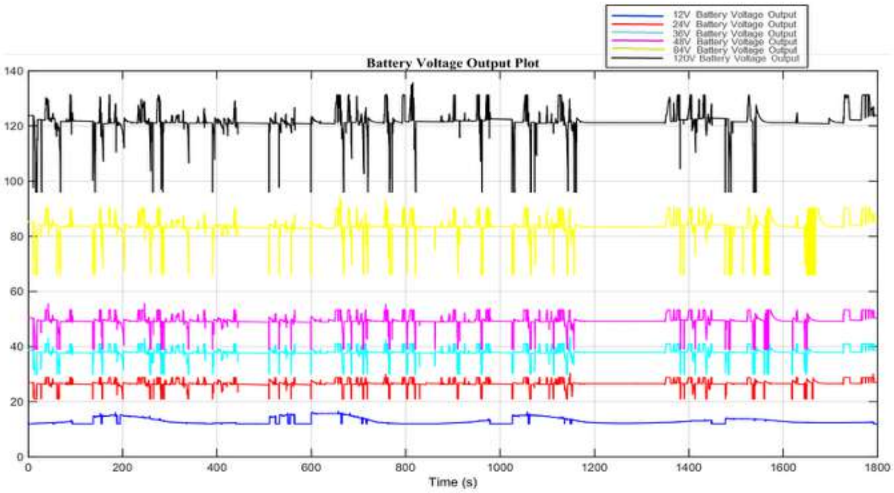


Figure 3.2: *Simulation Battery Voltage Output (Simulated)*

The battery state-of-charge (SOC) remained within the predefined operating limits (20–80%) during the WLTC drive cycle. The final SOC differed by less than 1% from the initial value, indicating charge-sustaining operation and ensuring that fuel economy comparisons among different configurations were unbiased.

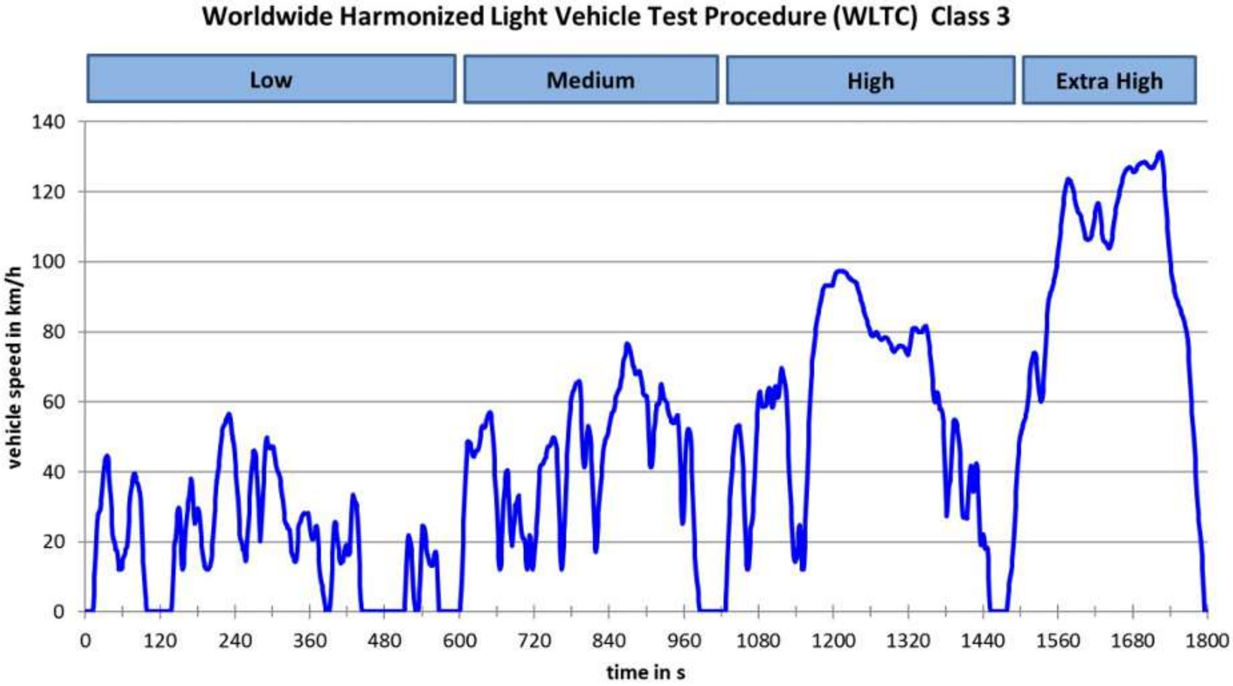


Figure 3.3: *Worldwide Harmonized Light Vehicle Test Procedure (UNECE Global Technical Regulation No. 15, 2014)*

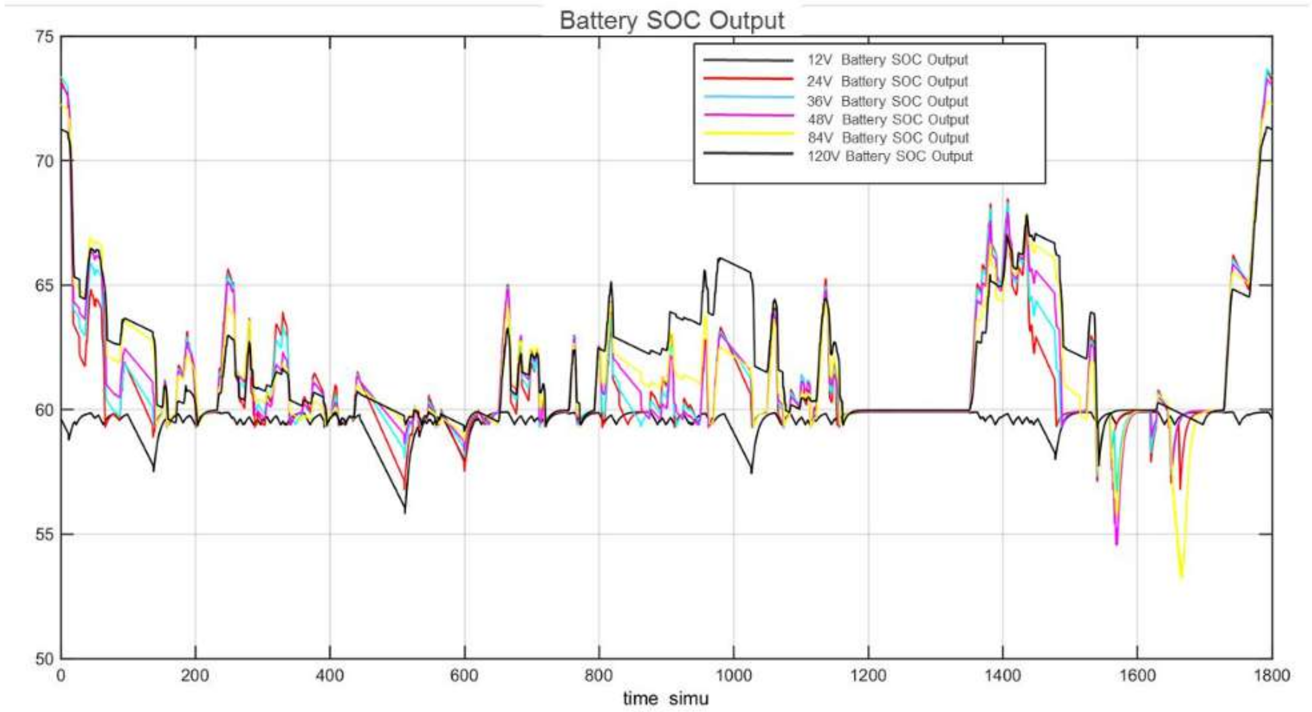


Figure 3.4: *Battery SOC over Drive Cycle (Simulated)*

3.3 Conventional ICE and Stop-Start Vehicle Performance

The conventional ICE vehicle relied solely on the 12 V electrical system for auxiliary loads and demonstrated a fuel economy of **30.6 mpg**. The addition of the 12 V stop-start system improved fuel economy to **31.8 mpg**, representing a **3.9% improvement** due to reduced idle fuel consumption.

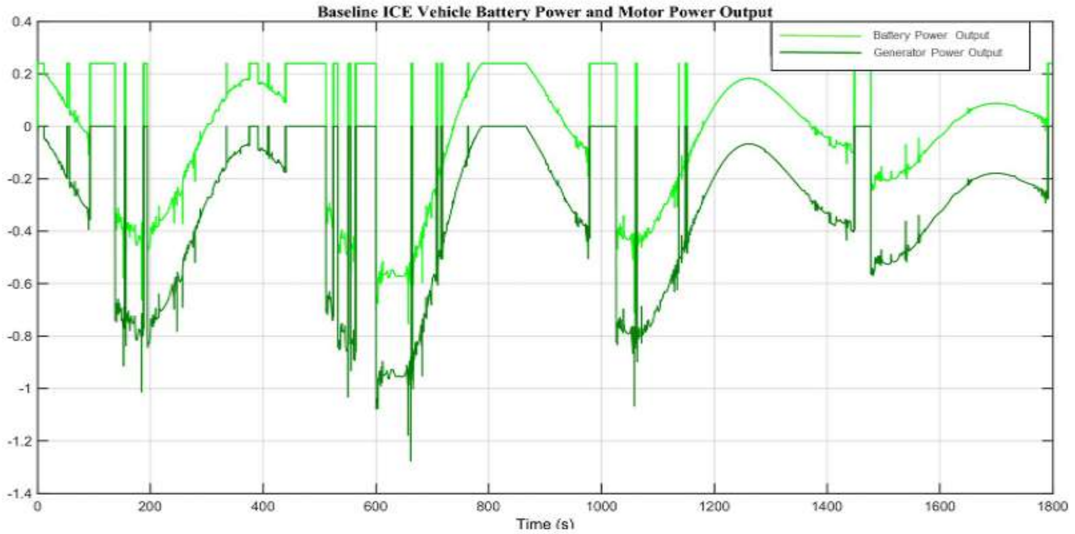


Figure 3.5: *Baseline Conventional ICE Vehicle Battery Power Output (Simulated)*

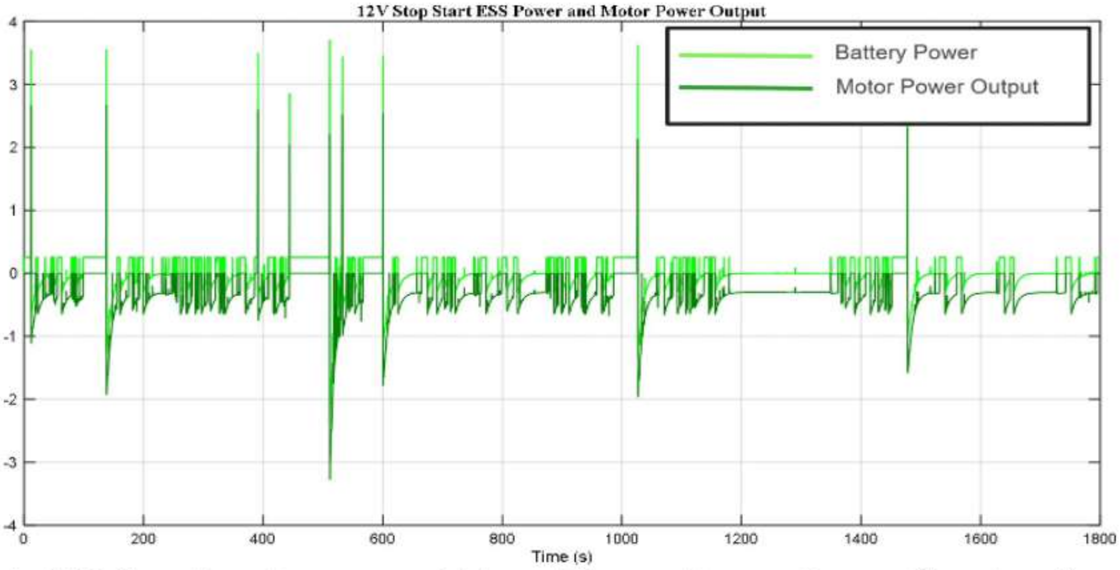


Figure 3.6: *12V Stop Start Battery and Motor Electric Power Output (Simulated)*

3.4 Performance of 24 V Mild Hybrid System

The 24 V BSG system enabled regenerative braking and torque assistance, resulting in a fuel economy of **32.75 mpg**, corresponding to a **7.0% improvement** over the conventional vehicle. However, battery charging and discharging capabilities remained limited because of the lower voltage architecture.

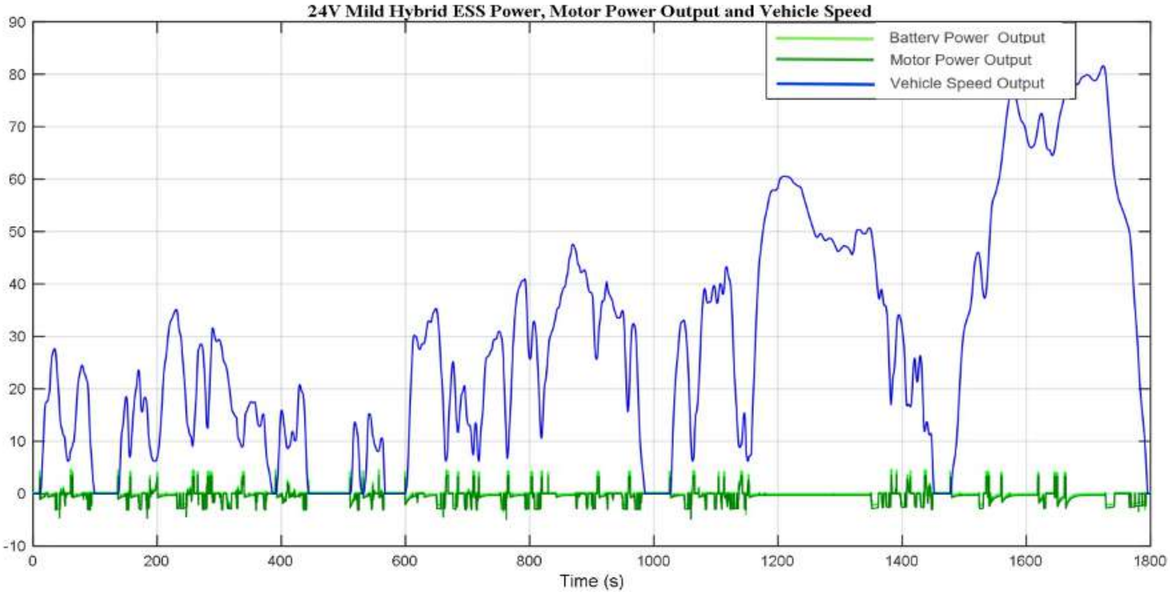


Figure 3.7: *24V Battery and Motor Electric Power Output vs. Vehicle Speed (Simulated)*

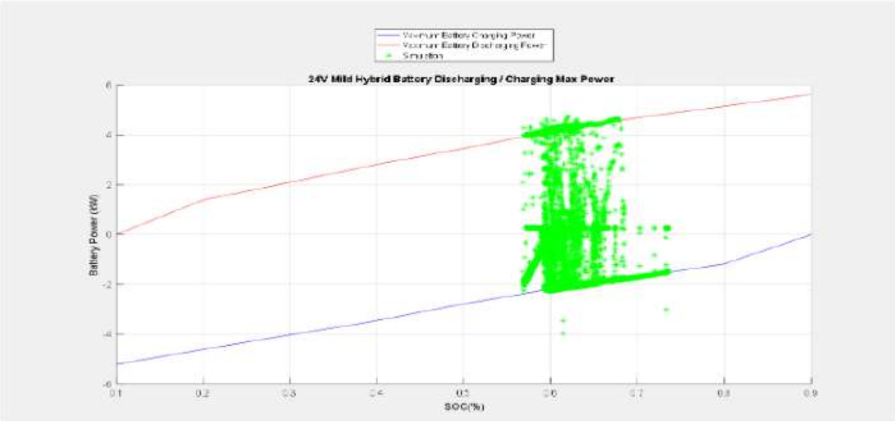


Figure 3.8: *24V Battery Discharging/Charging Max Power (Simulated)*

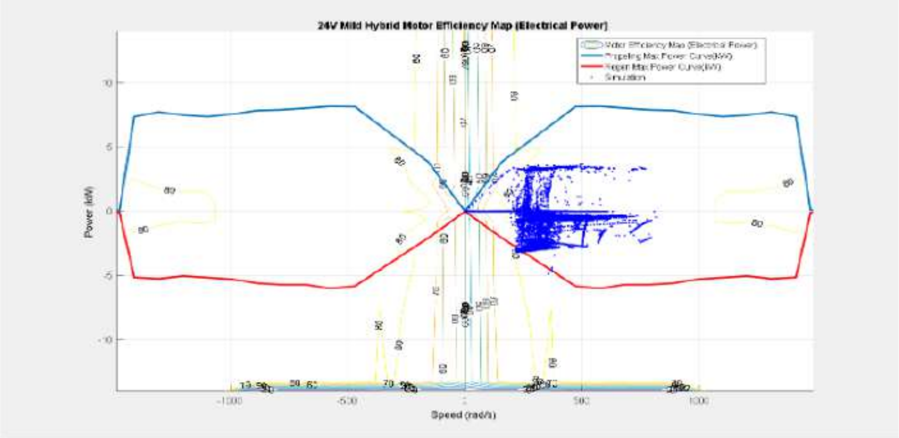


Figure 3.9: *24V Mild Hybrid Motor Efficiency Map (Simulated)*

3.5 Performance of 36 V Mild Hybrid System

The 36 V mild hybrid configuration demonstrated improved regenerative braking efficiency and enhanced torque assist compared with the 24 V system. Fuel economy increased to **33.42 mpg**, representing a **9.2% improvement** over the baseline vehicle.

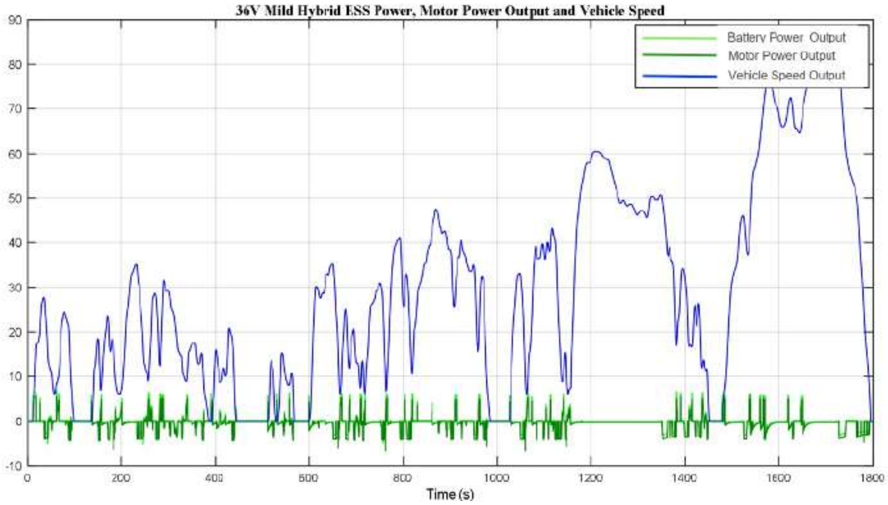


Figure 3.10: *36V Mild Hybrid Battery and Motor Electric Power Output vs. Vehicle Speed (Simulated)*

3.6 Performance of 48 V Mild Hybrid System

Among all evaluated configurations, the 48 V architecture demonstrated an excellent balance between electrical performance and fuel economy. The system effectively supported regenerative braking, torque assist, and stop-start functionality while maintaining stable battery operation. Fuel economy reached **34.02 mpg**, corresponding to an **11.2% improvement** compared with the conventional vehicle.

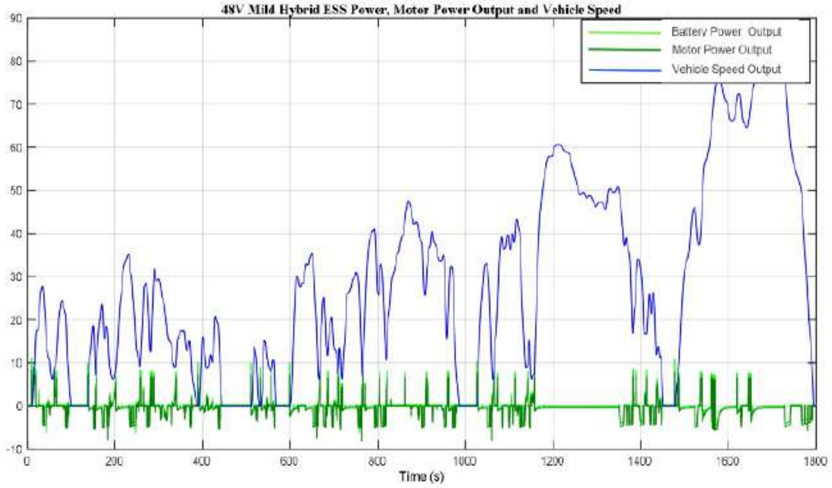


Figure 3.11: *48V Mild Hybrid Battery and Motor Electric Power Output vs. Vehicle Speed (Simulated)*

3.7 Performance of 84 V Mild Hybrid System

The 84 V system further increased battery power capability and regenerative energy recovery. However, the improvement in fuel economy was relatively small (**34.19 mpg; 11.7% improvement**) compared with the additional system complexity and higher component costs.

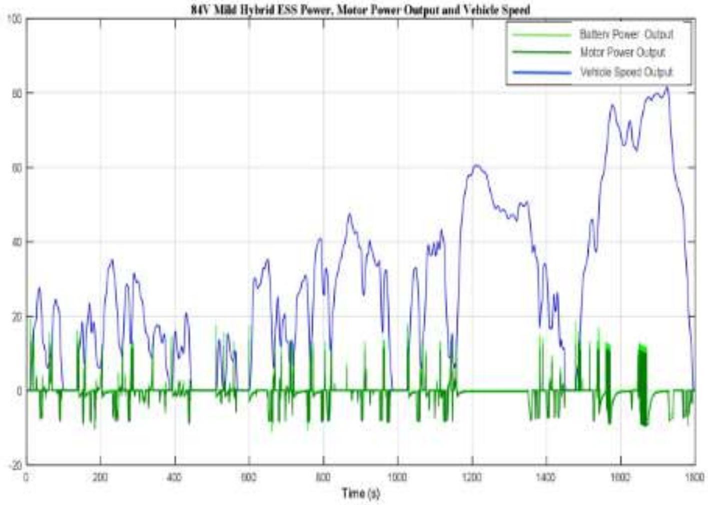


Figure 3.12: *84V Mild Hybrid Battery and Motor Electric Power Output vs. Vehicle Speed (Simulated)*

3.8 Performance of 120 V Mild Hybrid System

The 120 V mild hybrid configuration achieved the highest simulated fuel economy (**34.22 mpg**), corresponding to an **11.8% improvement** over the baseline vehicle. Nevertheless, the increase compared with the 48 V system was only **0.6%**, indicating diminishing returns despite substantially higher component ratings and safety requirements.

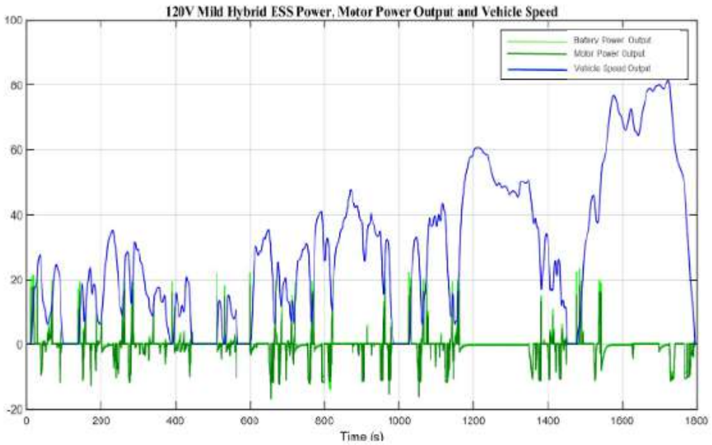
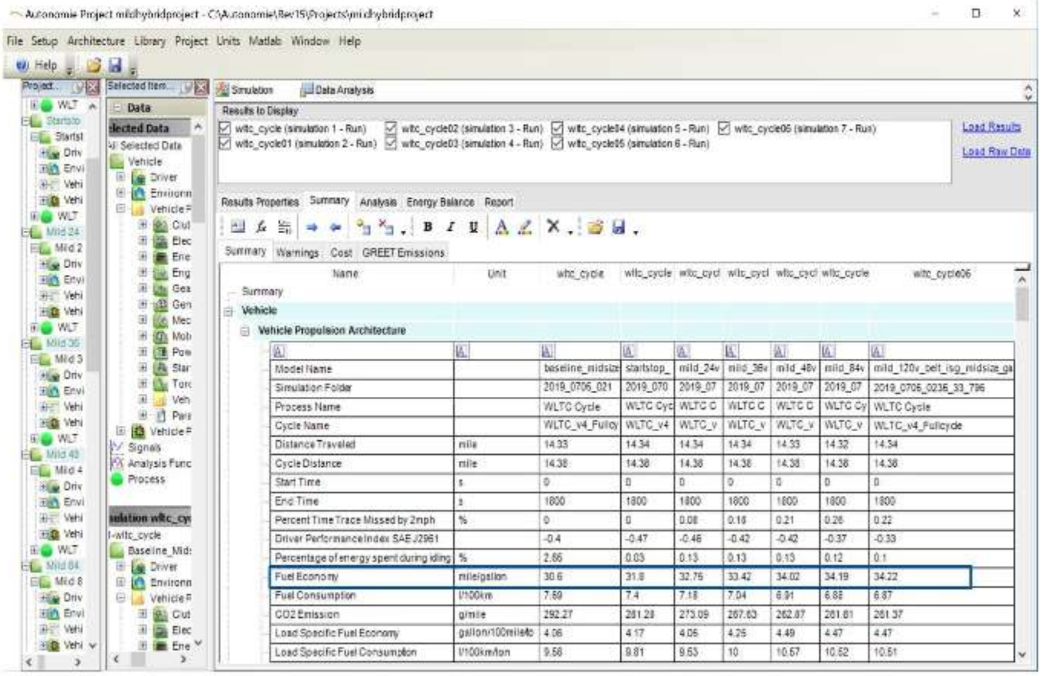


Figure 3.13: *120V Mild Hybrid Battery and Motor Electric Power Output vs. Vehicle Speed (Simulated)*

3.9 Fuel Economy Comparison

Fuel economy increased progressively with increasing system voltage. The simulation results demonstrated improvements from **30.6 mpg** for the conventional vehicle to **34.22 mpg** for the 120 V mild hybrid. However, the incremental gains beyond the 48 V architecture were marginal, indicating that higher voltages provided limited additional benefits.



☑ wltc_cycle (simulation 1 - Run) ☑ wltc_cycle02 (simulation 3 - Run) ☑ wltc_cycle04 (simulation 5 - Run) ☑ wltc_cycle06 (simulation 7 - Run)
☑ wltc_cycle01 (simulation 2 - Run) ☑ wltc_cycle03 (simulation 4 - Run) ☑ wltc_cycle05 (simulation 6 - Run)

Summary
Vehicle
Vehicle Propulsion Architecture

Name	Unit	wltc_cycle	wltc_cycle	wltc_cycl	wltc_cycl	wltc_cycl	wltc_cycle	wltc_cycle06
Model Name		baseline_midsize	startstop_	mild_24v	mild_36v	mild_48v	mild_84v	mild_120v_belt_isg_midsize_ga
Simulation Folder		2019_0706_021	2019_070	2019_07	2019_07	2019_07	2019_07	2019_0706_0236_33_796
Process Name		WLTC Cycle	WLTC Cyc	WLTC C	WLTC C	WLTC C	WLTC Cy	WLTC Cycle
Cycle Name		WLTC_v4_Fullcy	WLTC_v4	WLTC_v	WLTC_v	WLTC_v	WLTC_v	WLTC_v4_Fullcycle
Distance Traveled	mile	14.33	14.34	14.34	14.34	14.33	14.32	14.34
Cycle Distance	mile	14.38	14.38	14.38	14.38	14.38	14.38	14.38
Start Time	s	0	0	0	0	0	0	0
End Time	s	1800	1800	1800	1800	1800	1800	1800
Percent Time Trace Missed by 2mph	%	0	0	0.08	0.18	0.21	0.26	0.22
Driver Performance Index SAE J2951		-0.4	-0.47	-0.46	-0.42	-0.42	-0.37	-0.33
Percentage of energy spent during idling	%	2.66	0.03	0.13	0.13	0.13	0.12	0.1
Fuel Economy	mile/gallon	30.6	31.8	32.75	33.42	34.02	34.19	34.22
Fuel Consumption	l/100km	7.69	7.4	7.18	7.04	6.91	6.88	6.87
CO2 Emission	g/mile	292.27	281.28	273.09	267.63	262.87	261.61	261.37
Load Specific Fuel Economy	gallon/100mile/to	4.06	4.17	4.05	4.25	4.49	4.47	4.47
Load Specific Fuel Consumption	l/100km/ton	9.58	9.81	9.63	10	10.57	10.52	10.51

Figure 3.14: *Autonomie Simulation Results of All Voltage Levels (Simulated)*

3.10 Cost–Benefit Analysis

Component cost analysis revealed that system cost increased significantly with increasing voltage level because of larger batteries, higher-rated electric machines, inverters, DC/DC converters, and additional high-voltage safety components. The 48 V architecture exhibited the lowest cost per percentage improvement in fuel economy among all mild hybrid systems, providing the best compromise between technical performance and economic feasibility.

Figure 3.15: *System Cost per % MPG Improvement*

Overall, the results indicate that although higher voltage architectures (84 V and 120 V) produced slightly greater fuel economy, the performance gains were not proportional to the substantial increase in manufacturing cost and system complexity. Therefore, the **48 V Belt Starter Generator mild hybrid architecture** represents the most practical and cost-effective solution for future passenger vehicle applications.

Conclusion

This study presented a simulation-based evaluation of Belt Starter Generator (BSG) mild hybrid electric vehicles operating at different voltage architectures ranging from 12 V to 120 V. The simulation results demonstrated that fuel economy improved progressively with increasing system voltage due to enhanced regenerative braking, torque assist, and start-stop functionality. Among the investigated configurations, the 48 V mild hybrid system provided the optimum balance between fuel economy improvement, electrical performance, and manufacturing cost. Although the 84 V and 120 V architectures achieved slightly higher fuel economy, the additional gains were marginal when compared with the significant increase in component cost and system complexity. The model validation confirmed the reliability of the simulation approach for predicting vehicle performance under the WLTC driving cycle. Overall, the findings indicate that the 48 V BSG mild hybrid architecture is the most practical and economically viable solution for next-generation passenger vehicles, offering substantial fuel savings without the high cost and safety requirements associated with higher-voltage systems.

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