Dialogue Social Science Review (DSSR)
www.thedssr.com

ISSN Online: 3007-3154
ISSN Print: 3007-3146

DIALOGUE SOCIAL SCIENCE REVIEW

Vol. 3 No. 3 (March) (2025)

The Future of Electric Vehicles: Advanced Design, Modeling, and Simulation for Next-Generation Performance Using MATLAB/Simulink

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Abstract
The rapid growth of the electric vehicle (EV) industry has led to a pressing need for advanced design and simulation techniques to optimize performance, energy efficiency, and sustainability. This paper explores the future of electric vehicles through the lens of next-generation performance improvements enabled by cutting-edge modeling and simulation tools. Specifically, the paper emphasizes the role of MATLAB in simulating critical EV components, such as electric motors, battery systems, power electronics, and control algorithms. By leveraging these tools, engineers can design more efficient powertrains, develop advanced control strategies, and optimize overall vehicle performance. In order to evaluate the

accuracy of the MATLAB hybrid vehicle model, simulation results were compared to the published data of ADVISOR. The results obtained from MATLAB and ADVISOR for the engine and motor/generator correlated well. Minor discrepancies existed, but were deemed insignificant. This validates the MATLAB/ADAMS hybrid vehicle model against the published results of ADVISOR. Fuel economy of hybrid and conventional vehicle models were compared using the EPA New York City Cycle (NYCC) and the Highway Fuel Economy Cycle (HWFET). The hybrid vehicle demonstrated 8.9% and 14.3% fuel economy improvement over the conventional vehicle model for the NYCC and HWFET drive cycles, respectively. In addition, the motor consumed 83.6kJ of electrical energy during the assist mode while regenerative braking recovered 105.5kJ of electrical energy during city driving. For the highway drive cycle, the motor consumed 213.6kJ of electrical energy during the assist mode while the regenerative braking recovered 172.0kJ of energy. The MATLAB vehicle model offers a simulation platform that is modular, flexible, and can be conveniently modified to create different types of vehicle models. Through the integration of simulation-driven design and optimization, the future of electric vehicles promises improved efficiency, longer range, and enhanced overall performance, driving the evolution of sustainable transportation.

Keywords: Electric Vehicles (EVs), ADVISOR Model, Simulation-Based Optimization, Energy Efficiency, Vehicle Dynamics, Sustainable Transportation.

Introduction

The development of electric vehicles (EVs) dates back to 1884, when Thomas Parker produced one of the first electric vehicles, 25 years after the invention of lead-acid batteries [1]. Over the years, several EV models were introduced, but the rapid advancement of internal combustion engine (ICE) technology, coupled with the cost reduction in mass production, led to the decline of electric vehicles. However, the energy crisis of the 1970s and 1980s renewed interest in electric vehicles, even though they struggled to match the performance, speed, and range of conventional vehicles [2]. While GM made progress, electric vehicles were hindered by material factors such as range or battery capacity, length of time needed for charging, and the production expense. Since then, many companies have returned electric vehicles to the market, but the range and speed remain short, thereby restricting its use in a widespread manner. In the recent years, with electric vehicle (EV) growth driven by the demand for sustainable modes of transport and a global shift towards minimizing carbon emission the EV industry has witnessed exponential growth. In response to the environment and to meet the increasing demand for more efficient and high performance electric vehicles to deal with issues of range, energy consumption, and cost, governments and industries, as well as consumers, are increasingly turning to electric mobility [3]. In the electric vehicle design, the optimization and design of electric motors, battery systems, and power electronics have a large influence on its powertrain efficiency, battery management and vehicle dynamics. Recent progress in electric motor and battery technology, however, has led to significant improvements in the performance of electric vehicles. Long-range EVs have become a reality, with improvements in battery technology enabling vehicles to travel further on a single charge. Despite these advancements, the issue of charging time remains a significant hurdle in achieving the level of convenience that conventional vehicles offer, keeping electric vehicles from reaching their full potential in terms of performance and adoption.

If any of the advancements of EV industry shines out, it is making use of modelling and simulation tools to enhance the design and performance of electric vehicles. The two powerful platforms from MathWorks which enable simulation and system optimization of EV are MATLAB and Simulink [4]. On the one hand, MATLAB offers a strong environment for performing numerical computation, data analysis, and algorithm development while on the other hand, Simulink provides a graphical environment for modeling and simulating systems involving multiple domains [5]. These are tools that assist engineers and researchers in developing and refining vehicle models, performing real time simulations, and assessing the performance of EV subsystems subjected to different driving conditions. In the recent research, the performance and energy efficiency of the various components that constitute the powertrain system of the electric power were modelled and simulated on the MATLAB/Simulink. For example, different models of gearbox including fixed gear (for example early electric car such as the Nolan) manual and continuously variable transmission (CVT) were found to have an impact on energy consumption rate of a vehicle and various studies have suggested that there are optimization opportunities based on these different gearbox types [6]. Similar to that, studies on the electric vehicle energy consumption rates conducted by A. Kerem [7], among others, affirm the reduction in environmental pollution and fuel dependence thanks to EV technology development. Another sphere of interest for the EV simulation was selection of motor, with comparisons on efficiency, cost and weight for different types of motors. From these, the permanent magnet synchronous motor was found to be the most efficient for EV applications [8]. In addition, studies on hybrid vehicle (hybridize with internal combustion engines and electric motor) revealed an increase of fuel efficiency for these types of vehicles and also the studies proved that regenerative braking systems can generate energy from deceleration cycle to increase the overall conversion efficiency of the vehicle.

Computer Aided Engineering (CAE) tools have become more important in order to further improve vehicle design [9]. By simulating vehicle performance without having physical prototypes, these tools can be used to optimize on energy efficiency, dynamics and safety of the various systems in the vehicle. ADVISOR (Advanced Vehicle Simulator) is one such tool developed by the US Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL) that simulates various vehicle configurations, including cycles and electric vehicle, to study the effect of various power train component on fuel efficiency and performance [10]. Integrated use of ADVISOR with MATLAB/Simulink enables engineers to perform more accurate, dynamic, combined energy and vehicle dynamics simulations. The purpose of the work presented in this paper is the construction of a

MATLAB/ADAMS hybrid vehicle model that shows the energy or fuel economy benefits of hybrid vehicles. However, traditional hybrid vehicle simulation tools, ADVISOR, are primarily energy performance oriented with little consideration of the complex multi body dynamics [11]. I propose in this paper an integrated MATLAB/ADAMS simulation platform which combines powertrain simulations with vehicle dynamics for the analysis of hybrid electric vehicle performance up to overall vehicle response. Combining the multi–body dynamics power of MSC ADAMS with the abilities of MATLAB/Simulink for powertrain and energy management, it is possible to perform in detail studies on vehicle performance, energy efficiency and overall system optimization.

The goal of this paper is to explore how advanced modeling and simulation tools like MATLAB/Simulink can drive the evolution of electric and hybrid vehicles, improving their efficiency, performance, and sustainability. By integrating cutting-edge simulation techniques, the future of electric vehicles promises longer ranges, faster charging times, and more efficient overall operation, paving the way for a more sustainable and environmentally friendly transportation future.

Research Objective

This investigation concentrates on studying electric vehicle (EV) potential growth using state-of-the-art design modeling and simulation tools to improve the performance and sustainability features of upcoming EV systems. Specifically, this study aims to:

1. Present work will be involved in developing a MATLAB/Simulink based hybrid vehicle model to be used to simulate and analyze key components, namely electrics motors; battery systems; power electronics; and control strategies [12].
2. Assess fuel economy and energy efficiency of different design and control strategies for several driving cycles: New York City Cycle (NYCC) and Highway Fuel Economy Cycle (HWFET) [13].
3. Validate the simulation results by comparing them with published data from ADVISOR, a widely used simulation tool for hybrid and electric vehicle performance analysis [14].
4. Investigate the potential benefits of regenerative braking in improving energy recovery and overall vehicle efficiency.
5. Examine the role of energy management strategies in optimizing power distribution between the electric motor and internal combustion engine to maximize vehicle performance.
6. Provide insights into the future design and optimization of hybrid and electric vehicles for improved sustainability and performance.

Through these objectives, this research aims to contribute to the development of more efficient and sustainable transportation systems by advancing the modeling and simulation capabilities in electric vehicle design.

Methodology

Dialogue Social Science Review (DSSR)
www.thedssr.com

ISSN Online: 3007-3154
ISSN Print: 3007-3146

DIALOGUE SOCIAL SCIENCE REVIEW

Vol. 3 No. 3 (March) (2025)

This research aims to evaluate and optimize the performance of hybrid electric vehicles (HEVs) using advanced simulation tools such as MATLAB/Simulink and ADAMS. The methodology is structured around the creation of a hybrid vehicle model that integrates powertrain systems with vehicle dynamics, allowing for comprehensive performance analysis. The approach involves several stages: the development of the vehicle model, simulation of various vehicle subsystems, validation against published data, and performance evaluation under different driving cycles. Below is a detailed description of the steps involved in this methodology.

Hybrid Vehicle Model Development:

The hybrid vehicle model was created using MATLAB/Simulink, with a focus on the integration of both powertrain systems (electric motor and internal combustion engine) and vehicle dynamics. The primary objective was to simulate the energy efficiency and performance of the hybrid system under different operating conditions. Figure 1 depicts the overall structure of the MATLAB/Simulink model [15].

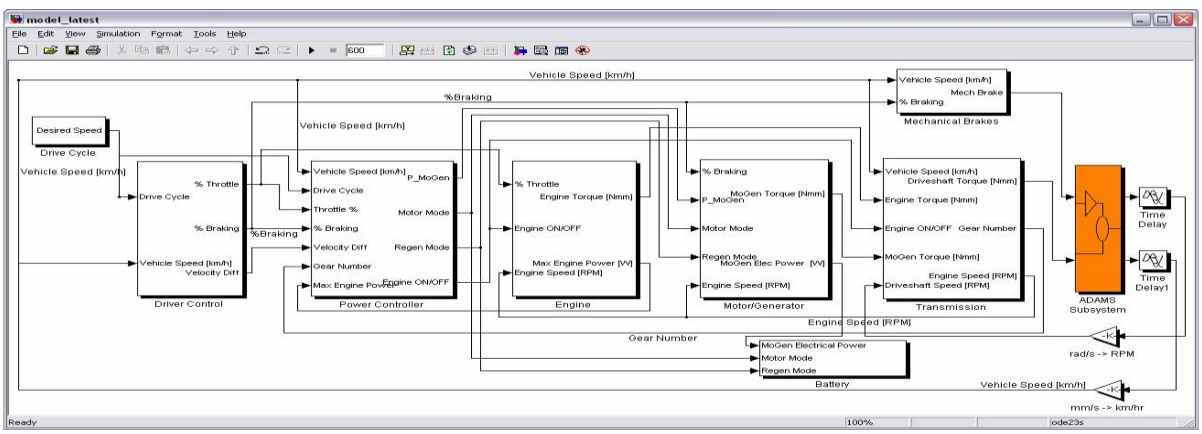

Figure 1: Overall Model Structure in MATLAB/Simulink

3.1.1- Drive Cycle:

The drive cycle subsystem contains the time history data for the desired vehicle speed, where several standard drive cycles are modeled as look-up tables. The block outputs the desired vehicle speed based on the current simulation time. Figure 2 depicts the drive cycle subsystem.

ISSN Online: 3007-3154
ISSN Print: 3007-3146

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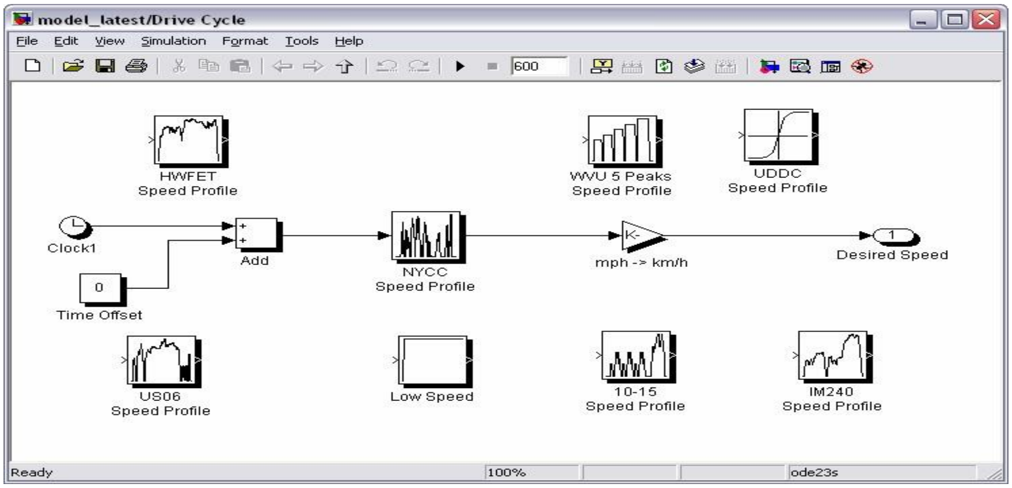
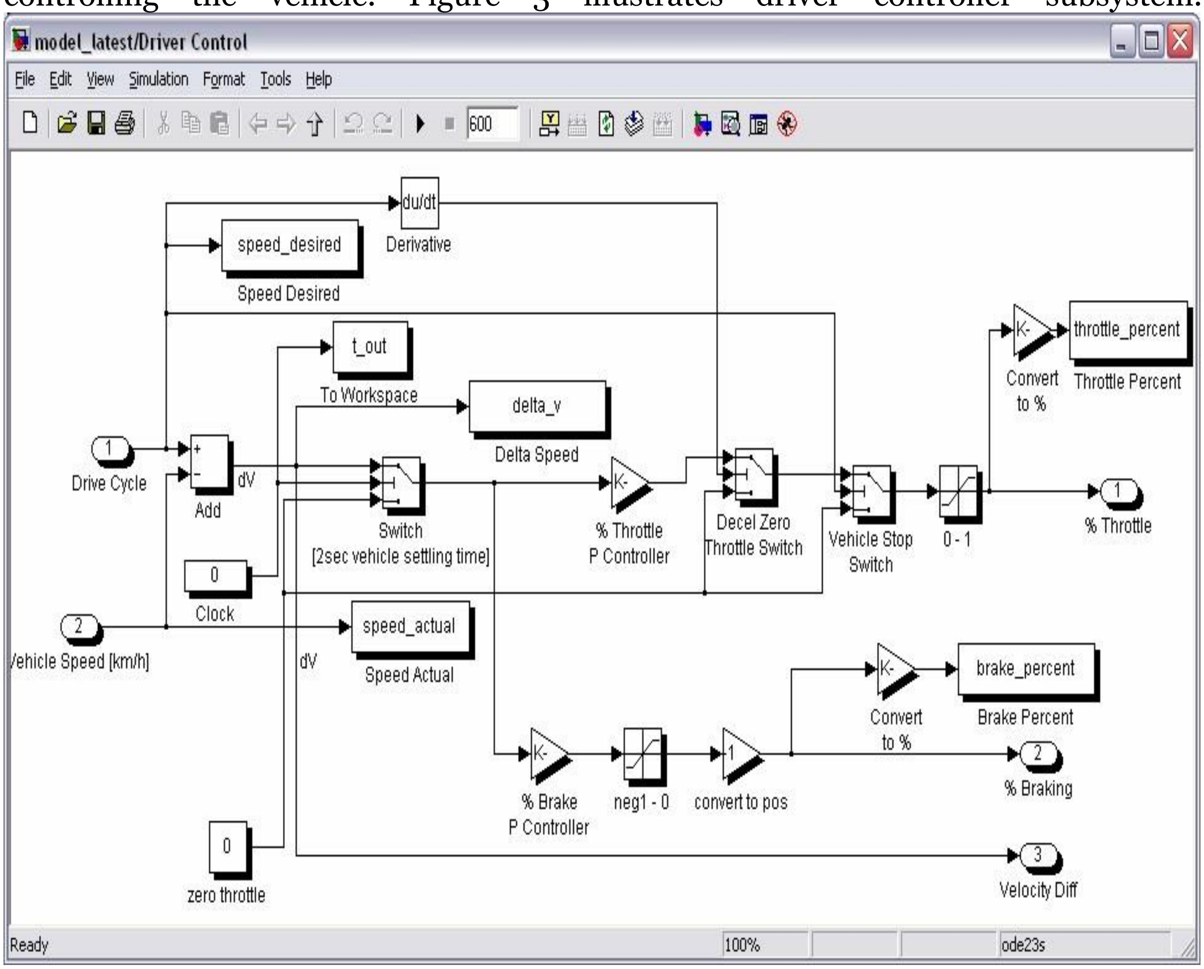


Figure 2: Drive Cycle Subsystem

3.1.2- Driver Control:

The purpose of the driver control subsystem is to mimic the driver,s response in controlling the vehicle. Figure 3 illustrates driver controller subsystem.



Dialogue Social Science Review (DSSR)
www.thedssr.com

ISSN Online: 3007-3154
ISSN Print: 3007-3146

Vol. 3 No. 3 (March) (2025)

Figure 3: Driver Controller Subsystem

3.1.3- Power Management Controller:

The purpose of the power management controller subsystem is to implement the power management logic and to turn the engine off when the vehicle is stationary. Figure 4 depicts the power management subsystem

Dialogue Social Science Review (DSSR)
www.thedssr.com

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Vol. 3 No. 3 (March) (2025)

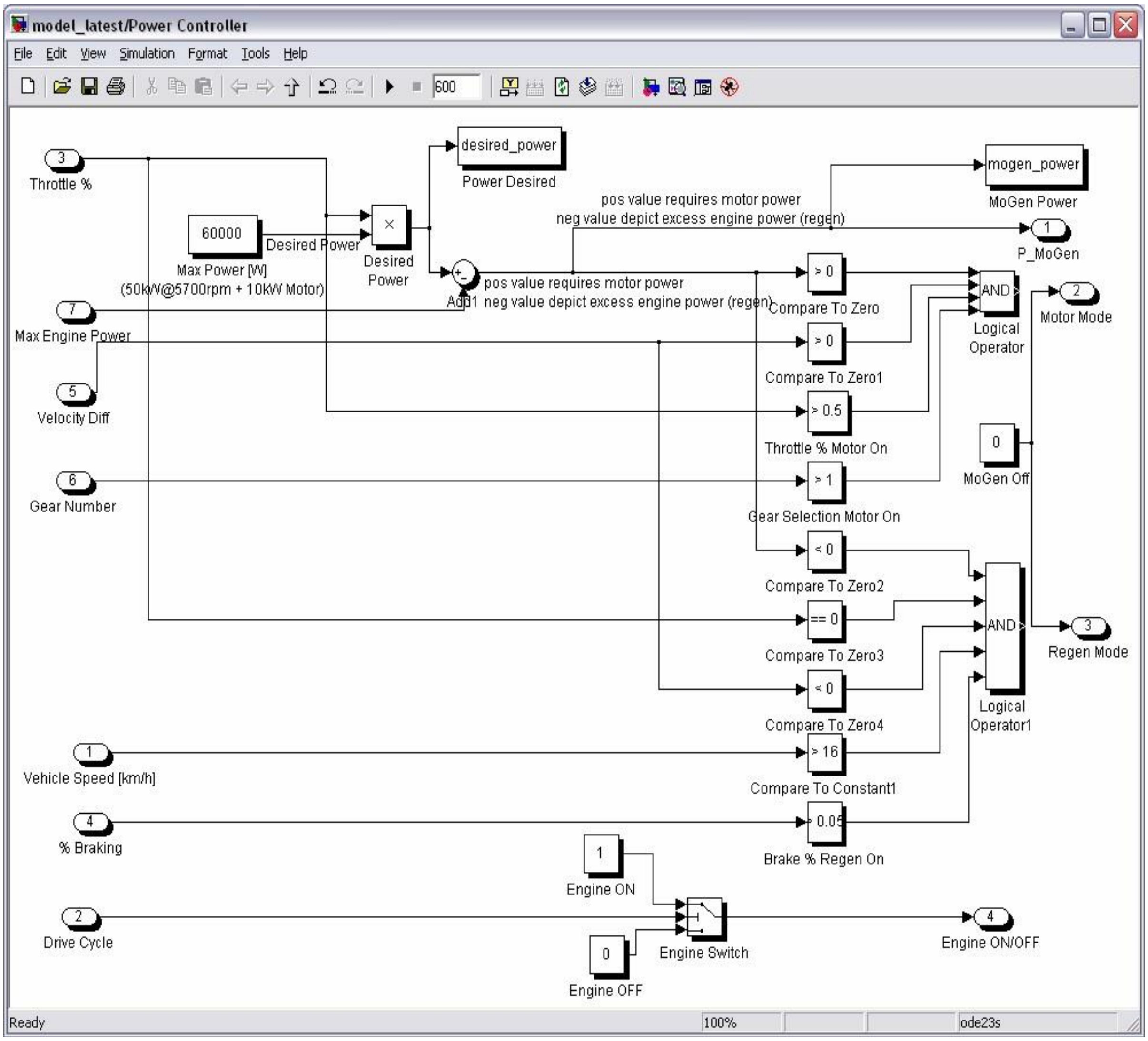

Figure 4: Power Management Subsystem

Engine

The main function of the engine subsystem is to perform the engine output torque calculations based on the current throttle percent and the engine speed. Open and closed throttle torque is modeled using look-up tables indexed by the current engine speed. Figure 5 illustrates the engine subsystem block.

Dialogue Social Science Review (DSSR)
www.thedssr.com

ISSN Online: 3007-3154
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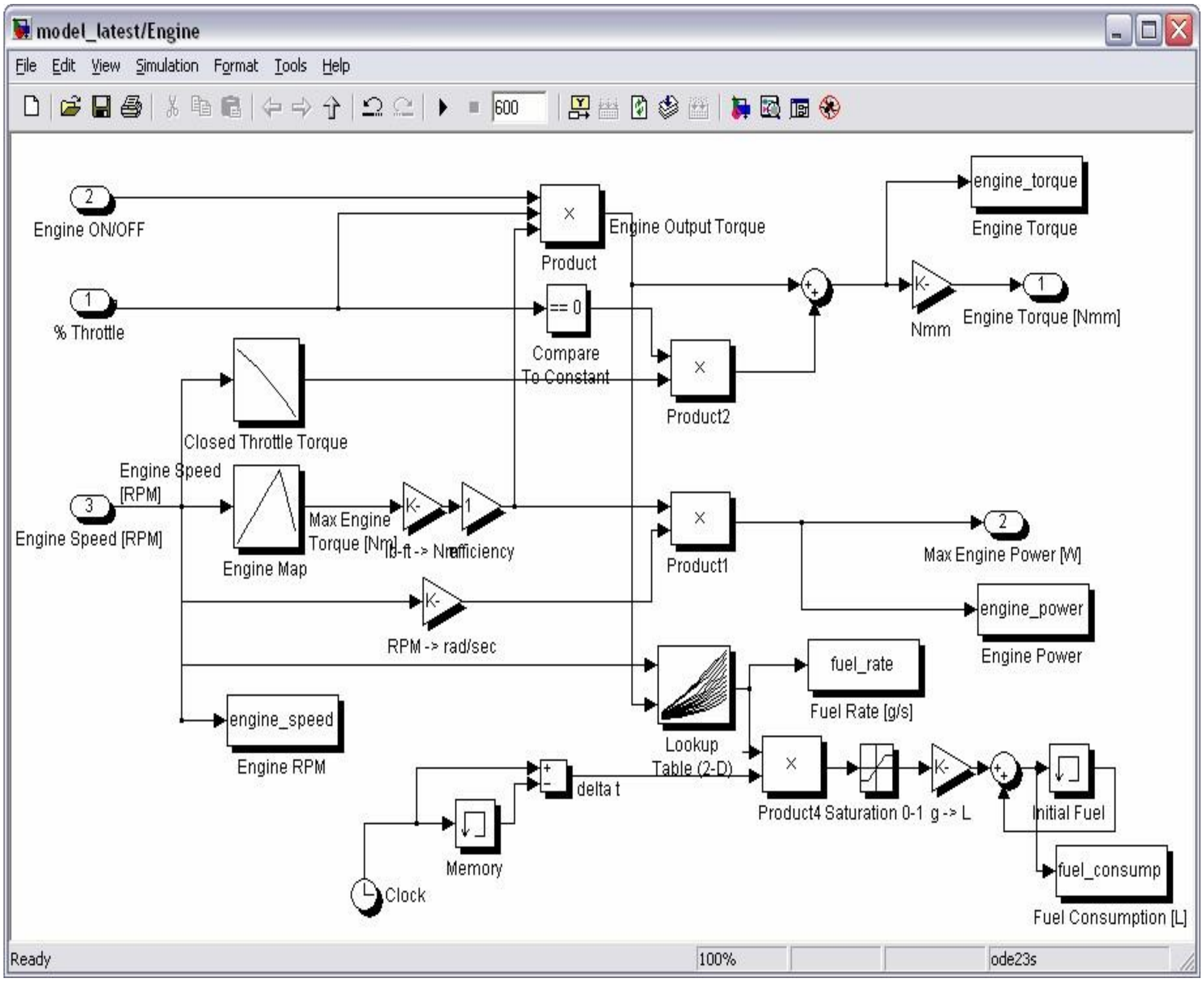

Figure 5: Engine Subsystem

Motor/Generator

Similar to the engine model, the motor/generator output torque is modeled using look-up tables indexed by the shaft speed. Since the motor/generator shaft is directly coupled with the engine shaft, the shaft speed of the motor/generator equals that of the engine. Figure 6 illustrates the motor/generator subsystem block.

Dialogue Social Science Review (DSSR)
www.thedssr.com

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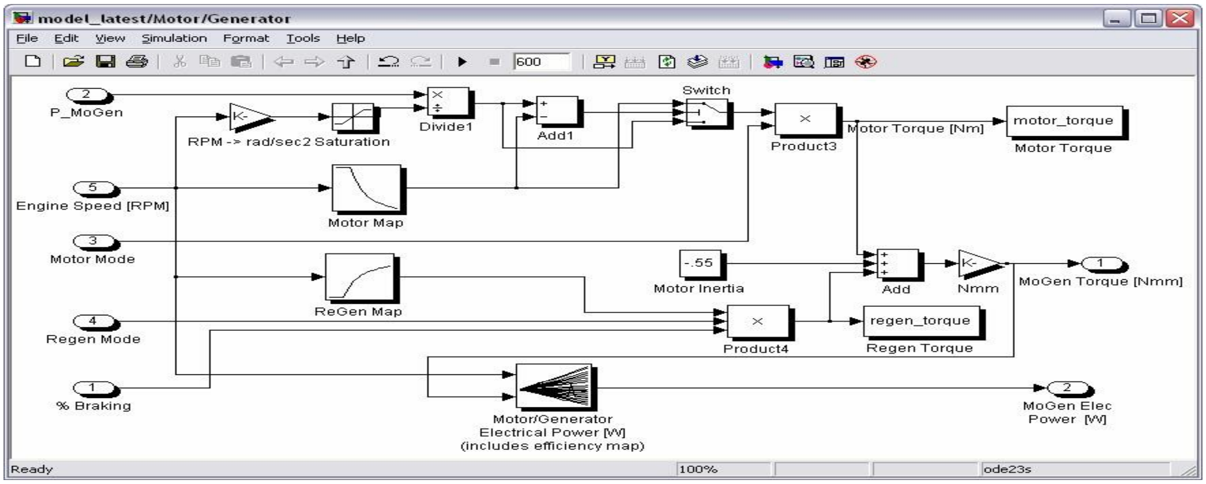

Figure 6: Motor/Generator Subsystem

Transmission

The transmission utilized in this model is a five-speed manual transmission. A simple logic is used for gear shifting, where the gear ratio is determined by the actual vehicle speed. Figure 7 depicts the transmission subsystem.

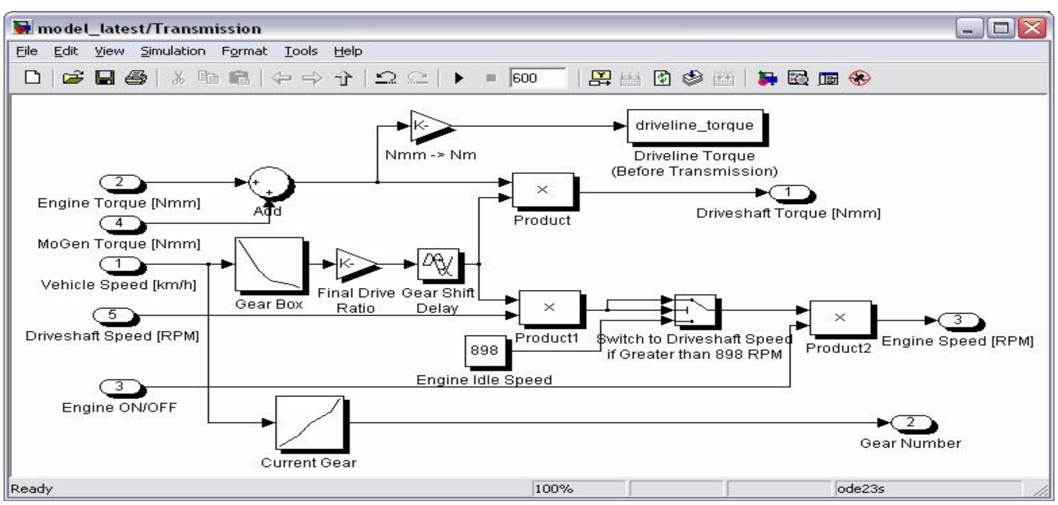

Figure 7: Transmission Subsystem

ADAMS Model

The mechanical components of the hybrid vehicle system are modeled in MSC ADAMS/View 2005a operating on Windows XP SP2. The vehicle model includes

Dialogue Social Science Review (DSSR)
www.thedssr.com

ISSN Online: 3007-3154
ISSN Print: 3007-3146

DIALOGUE SOCIAL SCIENCE REVIEW

Vol. 3 No. 3 (March) (2025)

vehicle chassis, suspension, driveline, steering linkages and control, brakes, and tires [16]. The mechanical components are assumed to be rigid bodies, with the exception of the suspension and tires. Figure 8 shows an isometric view of the vehicle model in ADAMS/View.

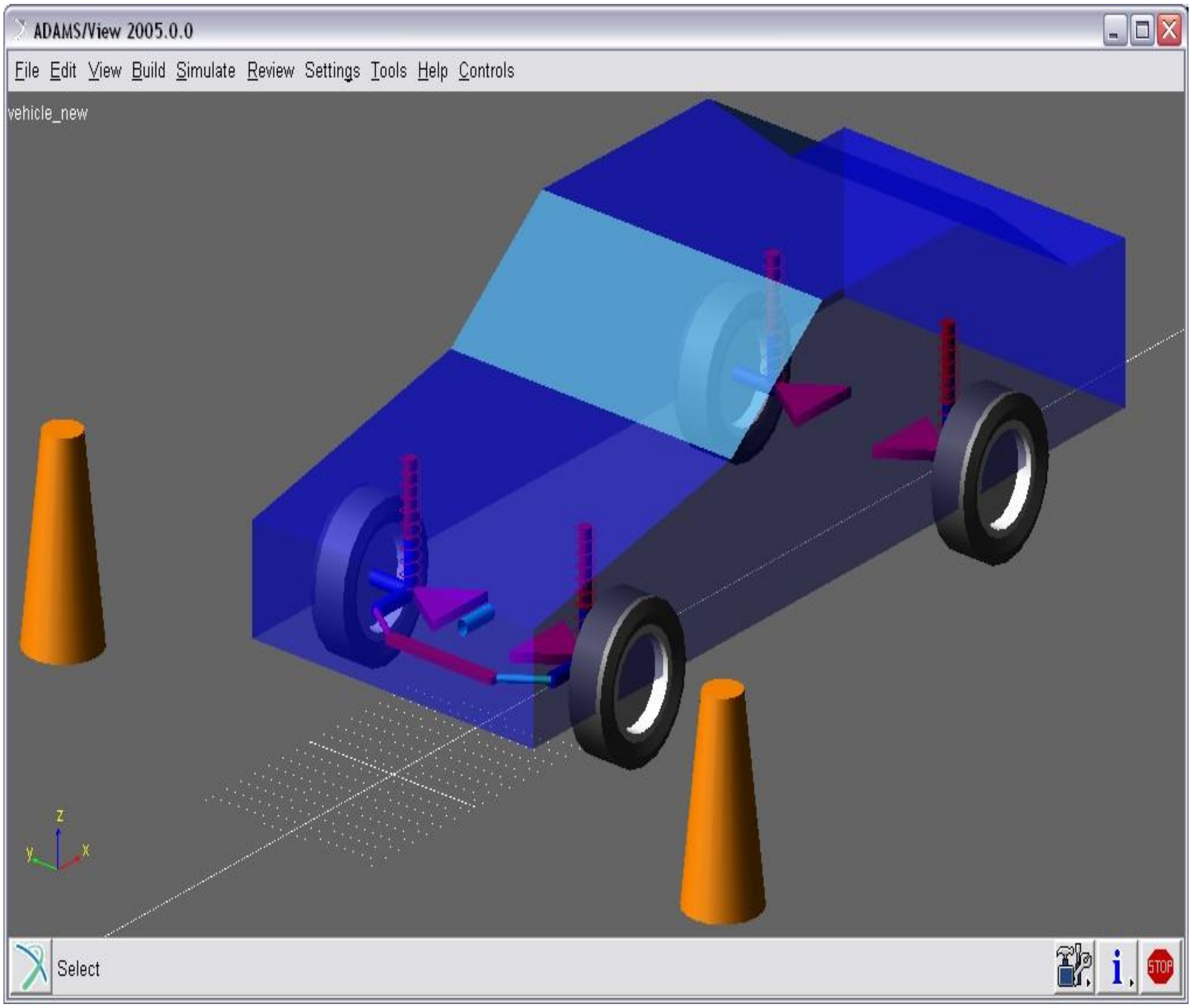

Figure 8: Mechanical Components of the Vehicle Model in ADAMS/View

As shown in the diagram, the global sign convention used in this model assumes that positive x points rearwards of the vehicle, positive y points towards the right, and positive z points upwards. As a result, gravity defaults to the negative z-direction [17].

Dialogue Social Science Review (DSSR)
www.thedssr.com

ISSN Online: 3007-3154
ISSN Print: 3007-3146

DIALOGUE SOCIAL SCIENCE REVIEW

Vol. 3 No. 3 (March) (2025)

Results

The MATLAB/ADAMS hybrid vehicle model simulation was performed for 850 seconds over the West Virginia University 5 Peaks drive cycle, and the results are as follows.

Vehicle Speed

The actual vehicle speeds of both models are presented in Figure 9. There is a close match between the results, as expected.

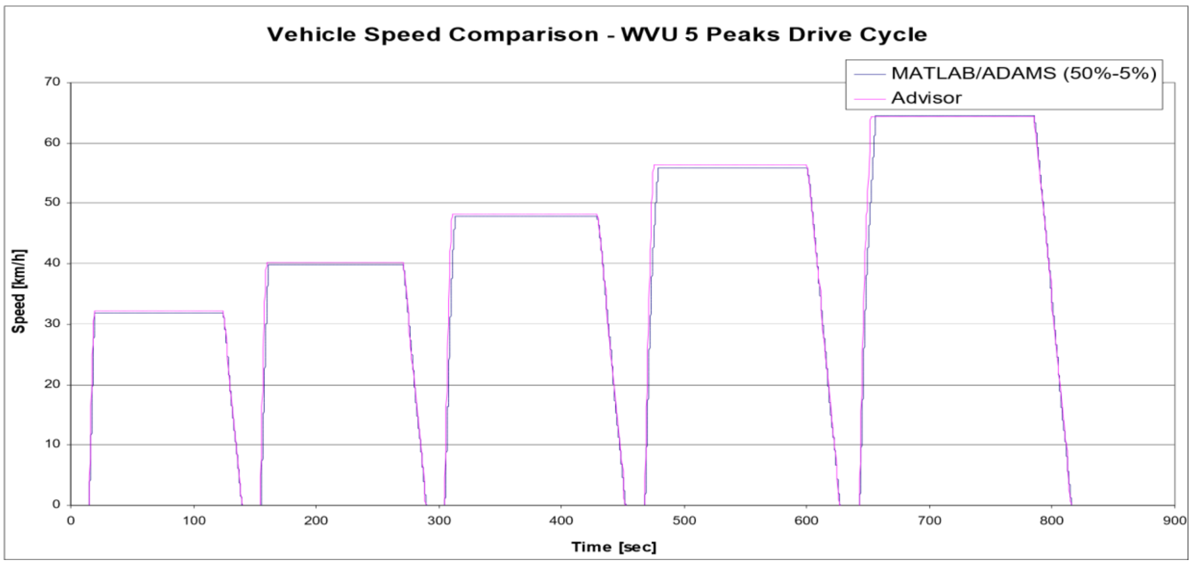

Figure 9: WVU 5 Peaks Drive Cycle Vehicle Speed Comparison

Engine Speed

Figure 10 depicts the engine speed of the two models. The overall results match very closely. Since both vehicles have manual transmission, and the vehicle speeds of the two models match, it should be expected for the engine speed to correlate well. However, it is observed that during the acceleration phase, the engine speeds of the two models differ [18]. The main difference is due to the transmission modeling. MATLAB/ADAMS utilizes a simple gear change logic and the gear number is dependent on the vehicle speed. However, in ADVISOR, a clutch logic is implemented and it seems that during every up-shift, the engine is accelerated to an unusually high speed. This does not seem to be reasonable, and therefore is disregarded in validating the MATLAB/ADAMS vehicle model [19].

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www.thedssr.com

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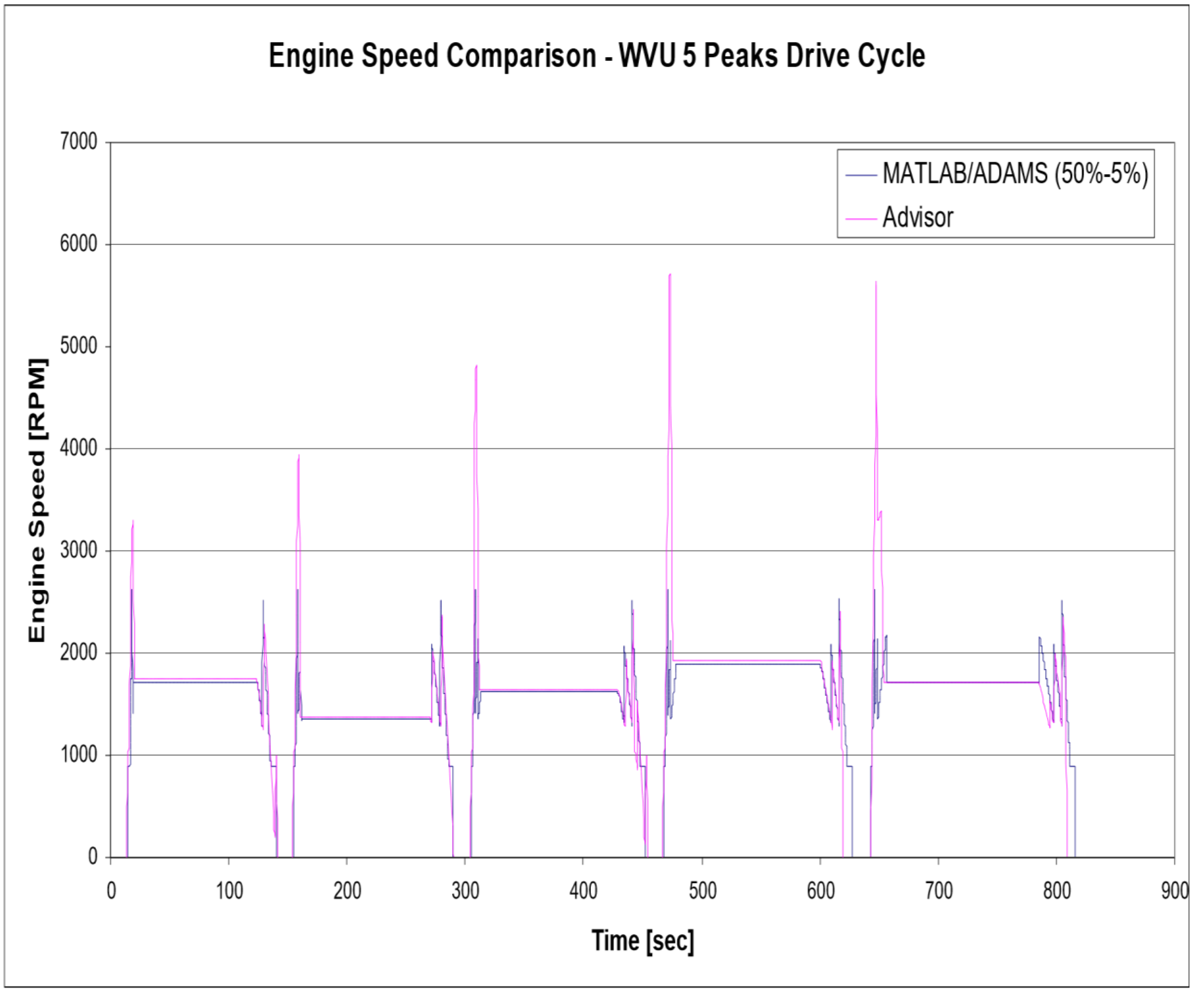

Figure 10: WVU 5 Peaks Drive Cycle Engine Speed Comparison

Engine Torque

Figure 11 depicts the engine torque comparison of the two models and, as seen, the trends match very closely. However, it is noted that there are several differences between the magnitudes of the engine torque, specifically during the closed throttle (negative) torque region. During deceleration, both models calculate the negative torque from the engine due to the closed throttle characteristic of the engine. However, it is noted that when the vehicle is stationary, the engine model in ADVISOR still exhibits a negative engine torque value, while the engine torque of the MATLAB/ADAMS model returns to zero.

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www.thedssr.com

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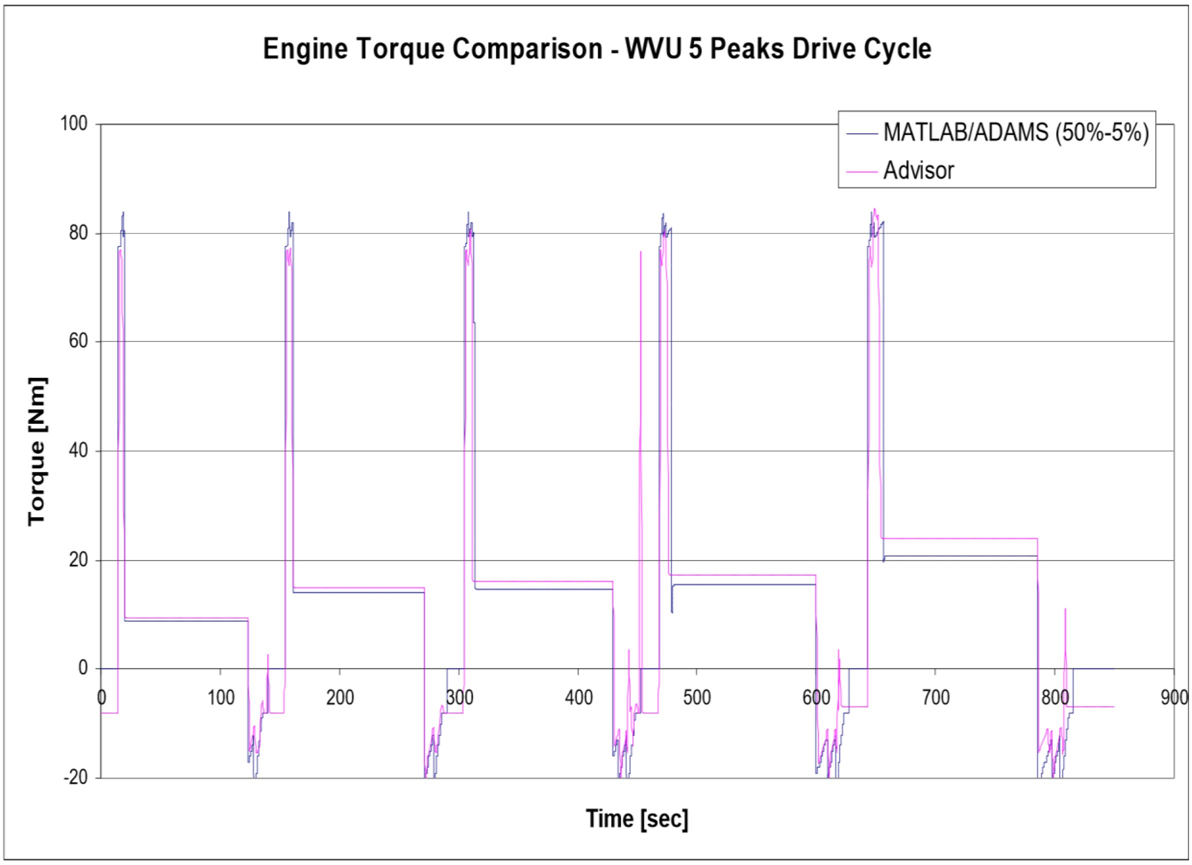

Figure 11: WVU 5 Peaks Drive Cycle Engine Torque Comparison

Motor/Generator Torque

The motor/generator torques of ADVISOR and MATLAB/ADAMS vehicle model**s** are included in Figure 12. The torque results from the two models matched reasonably well. However, the ADVISOR model exhibited some motor torque spikes just when the vehicle comes to a rest, especially around 453 seconds. Again, this is disregarded when compared with the MATLAB/ADAMS vehicle model.

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www.thedssr.com

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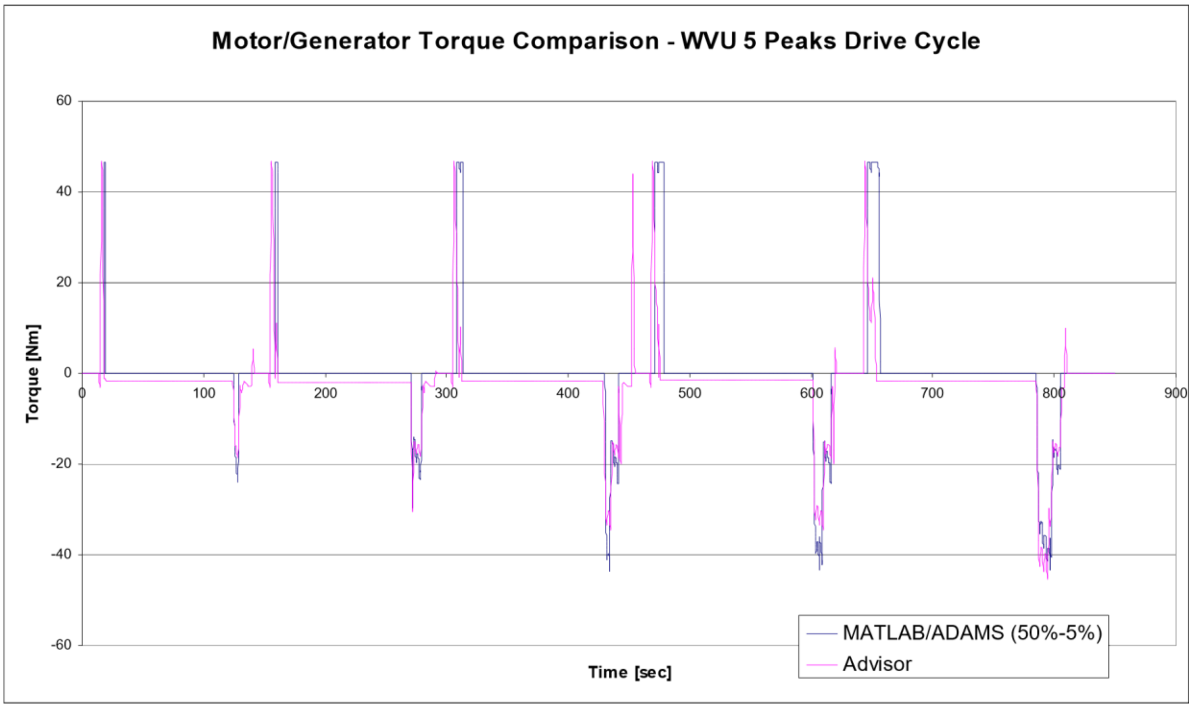

Figure 12: WVU 5 Peaks Drive Cycle Motor/Generator Torque Comparison

Discussion

The results from the MATLAB/Simulink and ADAMS-based hybrid vehicle model simulations provide significant insights into the performance and efficiency of hybrid electric vehicles (HEVs). These results provide a rational understanding of the vehicle performance, energy consumption, and regenerative braking. The simulation results are further discussed to draw implications and compared to that of existing literature before discussing the potential for future developments in hybrid vehicle design and optimization.

Fuel Economy and Energy Efficiency

The purpose of this research was focused on evaluating the fuel economy and the energy efficiency of the hybrid vehicle model on different driving cycles which are New York City Cycle (NYCC) and Highway Fuel Economy Cycle (HWFET). The results showed high fuel economy improvement for the hybrid vehicle, which had 8.9% and 14.3% fuel efficiency improvements on the NYCC and HWFET cycles. As explained in previous studies about hybrid vehicle performance, hybrid systems consist of both the advantages of internal combustion engines (ICEs) and electric motors, which can greatly improve fuel efficiency than conventional vehicles [20].

These fuel efficiency gains can be credited to dual advantages: on the system itself, they result from regenerative braking's ability to recover energy, and on the power management strategy, they stem from the optimization of power distribution between the ICE and electric motor. It revealed that the hybrid vehicle is more efficient in urban driving conditions, like NYCC, where brake events are frequent and therefore more energy recovery using the regenerative braking is possible. The better improvement is reflected on highway driving conditions (HWFET) due to the hybrid vehicle's potential to run with a reduced engine load, and thus, provides better fuel efficiency.

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www.thedssr.com

ISSN Online: 3007-3154
ISSN Print: 3007-3146

DIALOGUE SOCIAL SCIENCE REVIEW

Vol. 3 No. 3 (March) (2025)

Regenerative Braking Performance

Regenerative braking has always been a key advantage for hybrid and electric vehicles because its battery collection allows for the recapturing of kinetic energy. A significant amount of energy was recovered on the hybrid vehicle in both city and highway driving conditions in this study. During city driving (NYCC), the hybrid vehicle recover 105.5 kJ of electrical energy through the regenerative braking system, while on highway driving (HWFET), the amount is 172.0 kJ [21]. These values show that regenerative braking is a significant energy recovery component since it is important to acquire better energy efficiency and longer operational range for a vehicle. This correlates to the findings from existing research that indicates that regenerative braking accounts for up to 20-30% of the total energy consumed during driving in an urban environment [22]. Nevertheless, the regenerative braking contributes significantly to improve the efficiency, but this is only effective provided the driving patterns are appropriate. Stop and go urban driving has the greatest potential for energy recovery whereas steady state highway conditions have less recovery potential. This underscores the need for the energy management strategy to be optimized with the goal of maximizing gain of regenerative braking under a range of driving conditions.

Comparison with ADVISOR and Other Studies

Comparing with the published data from the ADVISOR, the simulation accuracy of the results obtained from the MATLAB/Simulink model was good. Only small discrepancies between the two models were noted, which did not have an impact on the overall conclusions of the study. This proves that the MATLAB/Simulink model developed by this research has demonstrated to be an appropriate portrayal of the hybrid vehicle performance and can be used as a reliable tool for future studies. Comparing fuel economy of the hybrid to the conventional, the results indicate that the hybrid systems can greatly improve fuel economy, consistent with many of the previous studies. A. This study also supports these observations made by reference [23] on benefits of hybrid vehicles by showing significant energy savings and lower fuel consumption in hybrid compared to ICE configuration.

Limitations and Future Work

Despite that, the simulation results yield important insight into the performance of hybrid electric vehicles with some current limitations of the present study. Then, the hybrid vehicle model adopted in this research is based on a few idealized conditions in vehicle component, like the motor, battery, and power management system [24]. In reality, the vehicle's performance may be affected by real world uncertainties such as battery degradation, temperature and component tolerances, that need to be taken into account in future work.

Moreover, the model used in this study is based on a simplified energy management strategy, which does not accurately consider all the complexities involved in the real world drive behavior. Further research could include more elaborate simulations and analyses of driving behavior, traffic situation, as well as driver preference, which could read out real world performance more precisely [25].

One area further left for future work would be to incorporate the integration of other types of power train configurations, such as PHEV or EV, and comparing the results with the results of conventional hybrid system [26]. Such a vehicle may also provide further insight into the future of electric vehicle technology based on the development of battery and charging infrastructure.

Conclusion

This study explored the optimization of hybrid electric vehicle (HEV) performance using MATLAB/Simulink and ADAMS for advanced design and simulation. The hybrid vehicle model showed significant fuel economy improvements of 8.9% and 14.3% for the New York City Cycle (NYCC) and Highway Fuel Economy Cycle (HWFET), respectively. These improvements were attributed to efficient energy recovery via regenerative braking and optimized power distribution between the internal combustion engine and electric motor. Validation of the MATLAB/Simulink model against ADVISOR demonstrated the accuracy and reliability of the simulation platform, confirming its potential for designing high-performance hybrid systems. The study also highlighted the importance of a well-optimized energy management strategy (EMS) in achieving optimal efficiency. While the results are promising, limitations such as idealized conditions and the need for real-world factors were acknowledged. Future work should address these limitations and explore other powertrain configurations like plug-in hybrids and fully electric vehicles. In conclusion, this research contributes to the future of sustainable transportation by providing a framework for the optimization of hybrid vehicle performance, emphasizing the role of advanced simulation tools in shaping more energy-efficient and environmentally friendly vehicles.

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