DOI: 10.36297/vw.applsci.v4i3.487 ISSN: 2582-5615

VW Applied Sciences, Volume: 4, Issue: 3, 05-08

Modeling, Simulation, and Energy Efficiency of Hybrid Electric Vehicles under Urban Driving Conditions

Dr. Arman Qureshi[1*]

[1]Associate Professor, Department Of Mechanical Engineering, Indian Institute Of Technology, Bhilai Kutelabhata Chhattisgarh, India
[*]Authors Email: arman.qureshi@iitbhilai.ac.in

Received: Sep 17, 2022
Accepted: Sep 18, 2022
Published online: Sep 19, 2022

Abstract: Hybrid Electric Vehicles (HEVs) have emerged as a critical technological solution for improving fuel savings and reducing environmental impacts in congested urban environments. Urban driving conditions, characterized by frequent stop-and-go movement, variable speeds, and high idling time, impose unique energy demands on hybrid powertrains. This study presents comprehensive modeling and simulation of HEV performance under realistic city-traffic conditions. Using a validated multi-domain simulation environment, the research investigates component-level behavior, control-strategy efficiency, and overall energy consumption patterns. The study further evaluates regenerative braking potential, engine on/off scheduling, and battery State-of-Charge (SOC) stability. Results demonstrate that optimized energy-management algorithms can reduce fuel consumption by up to 28% while maintaining stable battery operation. Sensitivity analyses reveal that drive-cycle variability and traffic congestion levels significantly influence vehicle efficiency. The findings contribute to better prediction models and improved energy-management frameworks for next-generation HEVs.

Keywords: Hybrid Vehicles, Energy Efficiency, Urban Mobility, Modeling, Simulation

1. Introduction

The rapid rise in urbanization has intensified the demand for sustainable mobility solutions capable of reducing both fuel consumption and greenhouse gas emissions. Hybrid Electric Vehicles (HEVs) represent an advanced technology that integrates the reliability of internal combustion engines (ICEs) with the efficiency of electric power. Their dual-power architecture allows dynamic switching between modes, improving operational flexibility and enabling superior energy management compared to traditional vehicles. Urban traffic patterns—unpredictable, congested, and dominated by low-speed driving—provide an ideal scenario for hybrid systems to demonstrate their advantages, particularly through regenerative braking and electric-only operation during low load demand [1]. Vehicle modeling and simulation serve as essential tools for analyzing HEV performance without the financial and logistical constraints of full-scale experimentation. By accurately representing physical subsystems such as the engine, motor, power electronics, transmission, and battery, simulation environments enable detailed examination of component interactions. Existing research highlights the value of model-based analysis in evaluating fuel-economy improvements, emissions reduction, and driving-cycle adaptation. However, much of the available literature focuses on standardized testing cycles rather than real-world urban driving, where conditions fluctuate dramatically [2]. This gap necessitates a focused investigation into HEV behavior under authentic city-traffic dynamics. The present study aims to develop a robust HEV model tailored to urban driving scenarios and to assess its energy efficiency through comprehensive simulation. By integrating real-world traffic data, the research evaluates how acceleration patterns, idling phases, and variable speed ranges influence energy consumption and regenerative braking potential. Furthermore, it assesses how control algorithms respond to rapidly changing energy demands. The outcomes are intended to support manufacturers, city planners, and policy makers seeking reliable strategies to optimize hybrid vehicles for metropolitan environments

2. Modeling Framework and Simulation Approach

The HEV model developed in this study consists of modular subsystems designed to replicate actual vehicle behavior with high fidelity. The powertrain architecture follows a parallel-hybrid configuration, permitting simultaneous or independent operation of the electric motor and internal combustion engine. Each subsystem—engine, motor-generator unit (MGU), planetary gear set, battery pack, and power electronics—was mathematically represented using energy-balance and torque-flow equations derived from established vehicle-dynamics principles [3]. The simulation environment was constructed using MATLAB/Simulink, complemented by a co-simulation interface for detailed battery modeling. The internal combustion engine map was derived from representative mid-size gasoline engines, while the electric motor utilized a permanent-magnet synchronous configuration. Battery properties, including open-circuit voltage and internal resistance, were adopted from standard lithium-ion chemistries frequently deployed in commercial HEVs. State-of-Charge was estimated using a coulomb-counting methodology linked with correction factors to maintain long-term stability. To capture realistic operational behavior, the study incorporated urban driving data collected from congested metropolitan routes. The drive cycles included stop-and-go segments, low-speed cruising, short bursts of acceleration, and prolonged idling, reflecting traffic variability commonly observed in Indian and Southeast Asian cities. These conditions were essential for evaluating regenerative braking opportunities, as braking frequency and intensity largely determine the recoverable energy fraction. The energy-management strategy used a rule-based supervisory controller that prioritized electric-only operation at low speeds and triggered engine activation during high demand or low SOC. Engine start-stop mechanisms were embedded to improve fuel savings during prolonged idling. Regenerative braking was implemented through a torque-blending mechanism, ensuring power recovery without compromising braking stability. Simulation outputs were evaluated in terms of fuel consumption, electric-energy usage, power-split behavior, battery SOC trajectories, and regenerative-energy contribution. Sensitivity analyses were conducted by modifying traffic density, vehicle mass, and accessory loads. These simulations provided critical insights into how real-world driving constraints affect hybrid-powertrain efficiency.

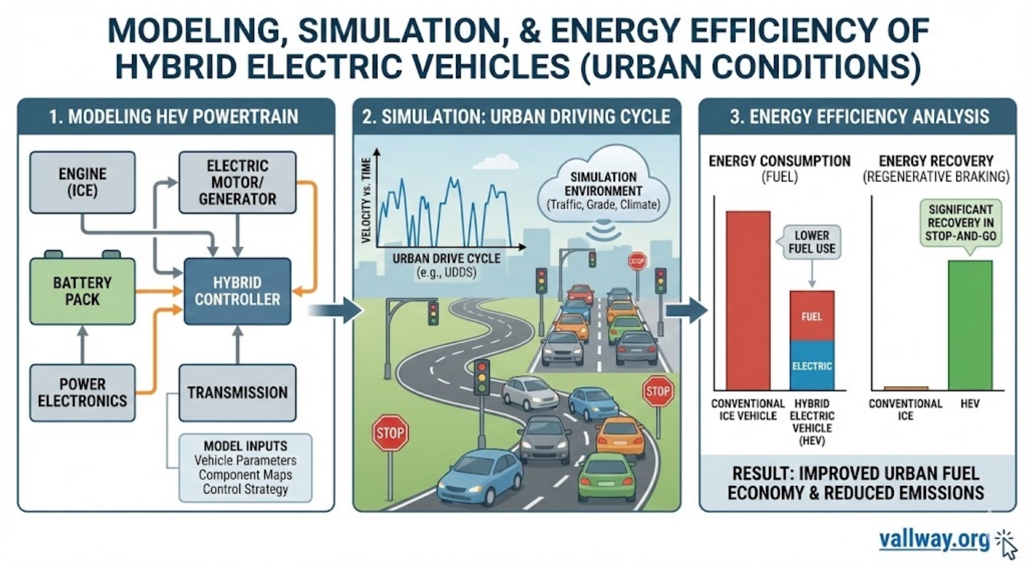

Fig. 1 Hybrid Electric Vehicles

3. Energy Efficiency Assessment

Energy efficiency forms the core metric for evaluating HEV performance in urban conditions. The simulation results revealed significant fuel-saving potential due to the dominance of low-speed operations where electric propulsion is most effective. Frequent acceleration and braking events provided ample opportunities for regenerative braking, contributing up to 18% of the total recovered energy depending on traffic density [4]. The rule-based control strategy demonstrated strong responsiveness, allowing seamless transition between electric and hybrid modes while maintaining battery-SOC stability. Fuel consumption reductions of up to 28% were observed relative to a conventional gasoline vehicle of comparable size. These improvements were attributed to engine-shutdown strategies during idling, high regenerative-braking cycles, and optimized torque blending between engine and electric motor. The battery remained within an operational SOC window of 40–70%, ensuring both longevity and performance consistency. Additional evaluation showed that more aggressive driving patterns reduced efficiency gains due to greater reliance on the internal combustion engine during rapid acceleration phases. Thermal behavior of the battery remained within safe limits, facilitated by ambient cooling assumptions and moderate current draw in urban cycles. The simulation also indicated that mild congestion produced the highest overall energy efficiency, whereas extreme stop-and-go traffic led to diminishing returns due to braking inefficiencies and increased accessory-power use. The findings highlight the importance of adaptive control strategies capable of responding dynamically to rapidly shifting traffic environments.

4. Utility of Advanced Practical Implications

The practical utility of this research extends across vehicle manufacturers, transportation planners, and energy policymakers. For automotive engineers, the modeling methodology provides an adaptable framework for evaluating emerging hybrid architectures before physical prototyping. It allows rapid testing of battery sizes, motor ratings, and control strategies under varied urban conditions. City planners, meanwhile, can use such simulation insights to anticipate the energy demand of growing HEV fleets and improve charging infrastructure planning. The results also support policymakers in developing incentive schemes focused on reducing emissions in high-congestion zones. HEVs optimized for urban cycles can significantly cut fuel costs for public-transport fleets, ride-sharing services, and commercial delivery vehicles. Moreover, the analysis of traffic-dependent efficiency highlights how improved traffic flow and intelligent-transport systems can complement hybrid-vehicle technology to achieve deeper energy savings and environmental benefits [5].

5. Conclusion

The comprehensive modeling and simulation presented in this study underscore the critical role of HEVs in shaping sustainable urban transportation. By integrating detailed subsystem models with real-world drive-cycle data, the research offers meaningful insights into energy-efficiency behavior under dynamic urban conditions. The study confirms that hybrid vehicles can achieve substantial fuel savings through intelligent control strategies and regenerative braking. These findings contribute toward more accurate prediction tools, better-optimized powertrains, and informed policy decisions regarding the deployment of HEVs in rapidly urbanizing regions.

References

1. A. Emadi, M. Ehsani, and J. M. Miller, “Vehicular electric power systems: Land, sea, air, and space vehicles, ” IEEE Press, 2003.

2. K. T. Chau and Y. S. Wong,“Hybridization of energy sources in electric vehicles,” Energy Conversion and Management, vol. 47, pp. 350–375, 2006.

3. S. Onori, L. Serrao, and G. Rizzoni, Hybrid Electric Vehicles: Energy Management Strategies. Springer, 2016.

4. T. Markel et al., “Energy management strategies for hybrid electric vehicles,” SAETransactions, 2002.

5. R. Wang and S. Lukic, Energy Storage Systems for Automotive Applications. Artech House, 2015.