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# Modeling, Simulation, and Energy Efficiency Analysis of Hybrid Electric Vehicles Under Various Urban and Highway Driving Conditions

Rohit Kuldeep<sup>1\*</sup>, Ayesha Farooq<sup>2\*</sup>, Nitin Borkar<sup>3\*</sup><sup>1</sup>Department of Mechanical Engineering, Vivekananda Global University, Jaipur, India<sup>2</sup>Department of Electronics, Integral University, Lakhnow, India<sup>3</sup>Department of Automobile Engineering, Dutta Meghe Institute of Higher Education and Research University, Wardha, India

\*Email: rohit.k@vgu.ac.in, ayesha.f@igu.ac.in, nitin.b@dmihru.ac.in

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**Abstract:** The transportation sector is a major contributor to global energy consumption and greenhouse gas emissions, necessitating the development of efficient and sustainable vehicle technologies. Hybrid Electric Vehicles (HEVs) offer a practical transition pathway by combining internal combustion engines with electric propulsion systems to improve fuel efficiency and reduce emissions. This study presents a comprehensive modeling, simulation, and energy efficiency analysis of a parallel hybrid electric vehicle operating under diverse urban and highway driving conditions. A detailed vehicle dynamics model was developed to capture longitudinal motion, powertrain interactions, and energy flow between components. Simulation-based evaluation was conducted using standardized driving cycles to assess fuel consumption, energy distribution, and regenerative braking effectiveness. The study further analyzes the impact of driving patterns, traffic conditions, and control strategies on overall vehicle efficiency. Results demonstrate significant improvements in energy utilization during urban driving due to regenerative braking and optimized power split, while highway conditions highlight the importance of engine operating efficiency. The findings provide valuable insights into HEV performance optimization and support informed design and policy decisions for sustainable transportation systems.

**Keywords:** Hybrid Electric Vehicles, Energy Efficiency, Vehicle Modeling, Driving Cycles, Powertrain Simulation

## 1. Introduction

Transportation systems play a critical role in economic development but are also responsible for a substantial share of global energy use and carbon emissions. Conventional internal combustion engine vehicles exhibit low overall efficiency due to energy losses associated with combustion, idling, and braking. Rising fuel costs and stringent emission regulations have accelerated the adoption of alternative vehicle technologies aimed at improving energy efficiency and reducing environmental impact [1]. Hybrid Electric Vehicles combine an internal combustion engine with one or more electric machines and energy storage systems to exploit the strengths of both propulsion technologies. By intelligently distributing power demand between the engine and electric motor, HEVs can operate the engine closer to its optimal efficiency range while recovering otherwise wasted energy through regenerative braking [2]. This dual-energy architecture makes HEVs particularly effective in urban driving environments characterized by frequent stop-and-go traffic. Despite widespread commercialization, the performance of HEVs is highly dependent on driving conditions, control strategies, and component sizing. Urban and highway driving impose fundamentally different energy demands, influencing fuel consumption patterns and battery utilization. Understanding these dynamics through modeling and simulation is essential for optimizing vehicle design and operational strategies [3]. This study aims to develop a detailed HEV model capable of capturing the complex interactions between vehicle dynamics, powertrain components, and energy management strategies. By simulating standardized driving cycles representative of urban and highway conditions, the research evaluates energy efficiency, fuel economy, and regenerative braking performance. The

study contributes to a deeper understanding of HEV behavior under real-world operating scenarios and provides a framework for performance optimization.

## 2. Hybrid Vehicle Architecture and Powertrain Configuration

The hybrid electric vehicle considered in this study employs a parallel hybrid architecture, in which both the internal combustion engine and electric motor can independently or jointly provide propulsion torque to the drivetrain. This configuration offers flexibility in power delivery and enables efficient utilization of electric assistance during acceleration and low-speed operation. The powertrain consists of a gasoline engine, a permanent magnet synchronous motor, a lithium-ion battery pack, a power electronics module, and a conventional transmission system. The electric motor is integrated upstream of the transmission, allowing torque blending between the engine and motor. The battery serves as an energy buffer, supplying power during electric assist and storing recovered energy during regenerative braking. Energy management is achieved through a rule-based control strategy that determines power split based on vehicle speed, driver demand, and battery state of charge. The control logic prioritizes electric operation at low speeds and engine dominance during steady highway cruising. This architecture enables improved fuel efficiency without compromising vehicle performance.

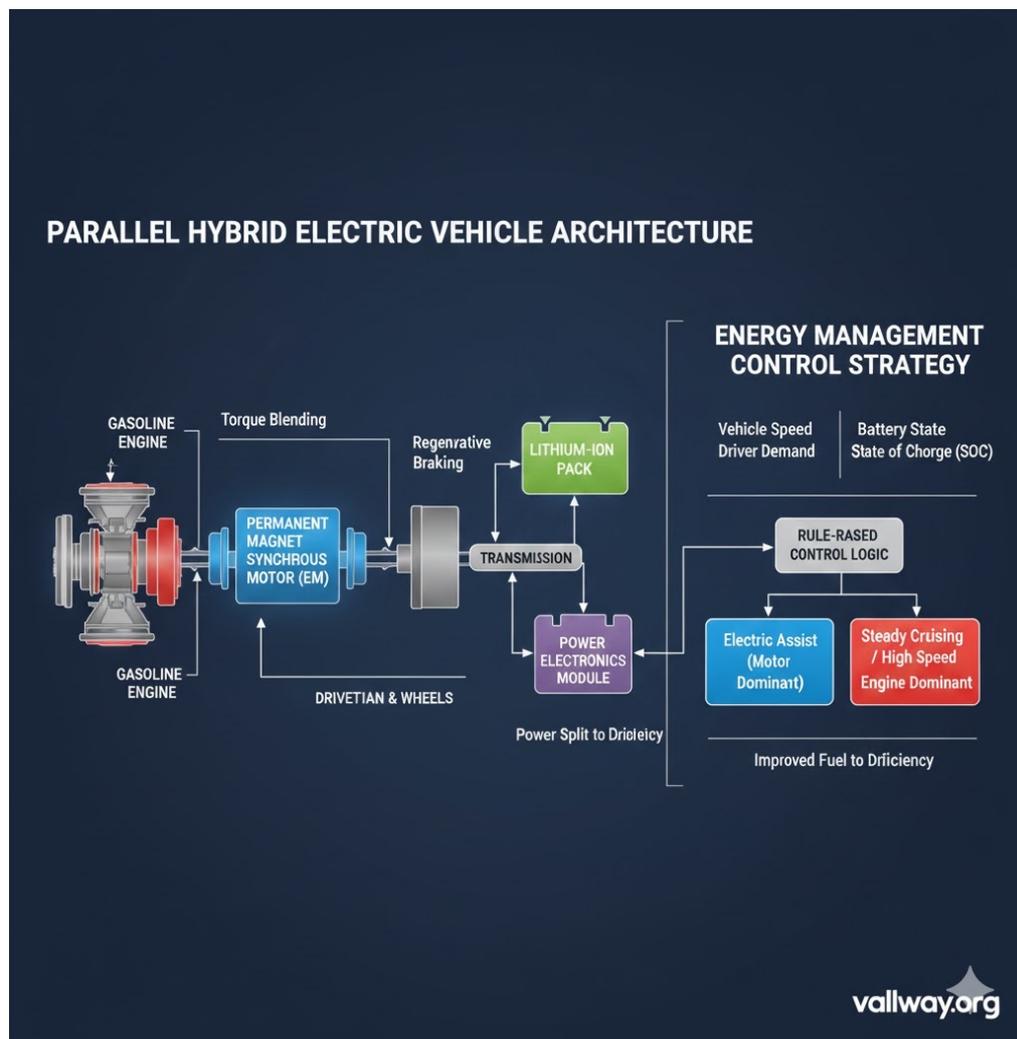


Fig. 1 Hybrid Vehicle Architecture

## 3. Vehicle Dynamics and Mathematical Modeling

A longitudinal vehicle dynamics model was developed to simulate the motion of the hybrid vehicle under varying driving conditions. The model accounts for aerodynamic drag, rolling resistance, gravitational forces, and inertial effects. Tractive effort requirements were calculated based on vehicle mass, road grade, and acceleration demands. The internal combustion engine model captures fuel consumption characteristics as a function of speed and torque, while the electric motor model includes efficiency maps reflecting real-world performance. Battery dynamics were modeled using an equivalent circuit representation to estimate state of charge and power flow. Energy losses in power electronics and drivetrain components were incorporated to

ensure realistic simulation outcomes [4]. The integrated model enables computation of instantaneous and cumulative energy consumption, fuel usage, and efficiency metrics across driving cycles. This modeling framework forms the basis for comparative analysis of urban and highway performance.

#### **4. Simulation Framework and Driving Cycle Selection**

Simulation studies were conducted using standardized driving cycles representative of urban and highway conditions. Urban cycles featured frequent acceleration, deceleration, and idle periods, while highway cycles emphasized sustained high-speed cruising. These cycles allowed evaluation of HEV performance under contrasting operational regimes. The simulation framework executed time-step-based calculations to update vehicle states, power flows, and energy consumption. Performance indicators such as fuel economy, battery utilization, and regenerative braking efficiency were recorded and analyzed. Sensitivity analyses were performed to assess the influence of traffic conditions and control parameters on overall efficiency.

#### **5. Energy Flow and Regenerative Braking Analysis**

Energy flow analysis revealed distinct patterns under urban and highway driving. In urban conditions, regenerative braking contributed significantly to energy recovery, reducing fuel consumption by capturing kinetic energy during deceleration. The recovered energy was effectively reused for subsequent acceleration events, improving overall efficiency [5]. Highway driving exhibited limited opportunities for regenerative braking due to fewer deceleration events. Under these conditions, engine efficiency and aerodynamic losses played dominant roles in determining fuel consumption. The analysis highlighted the importance of optimizing engine operating points and minimizing drag for highway efficiency.

#### **6. Results and Performance Evaluation**

The Simulation results demonstrated that HEVs achieved substantial fuel economy improvements compared to conventional vehicles, particularly in urban environments. Fuel consumption reductions were more pronounced under stop-and-go conditions due to effective use of electric propulsion and regenerative braking. Highway efficiency gains, while present, were comparatively modest and dependent on engine performance characteristics. Battery state-of-charge trajectories remained within safe operating limits across all simulations, indicating effective energy management. The results confirm that HEV efficiency benefits are strongly influenced by driving conditions and control strategies [6].

#### **7. Discussion and Design Implications**

The findings emphasize the importance of tailored energy management strategies for different driving scenarios. Urban-focused optimization should prioritize regenerative braking and electric assist, while highway optimization should focus on engine efficiency and aerodynamic improvements. The study underscores the value of simulation-based analysis in guiding HEV design and policy decisions.

#### **8. Conclusion**

This research provides a comprehensive modeling and simulation-based evaluation of hybrid electric vehicle energy efficiency under urban and highway driving conditions. The developed framework successfully captured the complex interactions between vehicle dynamics, powertrain components, and control strategies. The results highlight the strengths of HEVs in urban environments and identify key factors influencing highway performance. The study contributes valuable insights for optimizing hybrid vehicle design and energy management strategies. Future work should explore adaptive control algorithms, real-world driving data integration, and lifecycle energy assessment to further enhance HEV sustainability and performance.

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