International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 05 | May - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

Analysis of Vehicle Dynamics Effects on Electric Vehicle Performance: A Mathematical and Simulation-Based Study

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Abstract - This study examines the impact of vehicle dynamics on electric vehicle (EV) performance, focusing on energy requirement and driving range. Four primary forces—rolling resistance (F_{roll}), gradient force (F_{gd}), aerodynamic drag (F_{air}), and inertia resistance ($F_{inertia}$) — are modelled using the tractive force equation $F_t = m_v g \mu_{rr} \cos\alpha + \frac{1}{2}\rho_{air} C_{drag} A v^2 + m_v g \sin\alpha + m_v a$. Detailed theoretical explanations elucidate each force's physical basis. Numerical calculations for a baseline EV on a 2° uphill slope with zero acceleration are presented, with a comparison table evaluating six values for drag coefficient, vehicle mass, rolling resistance coefficient, and road gradient at 90 km/h. A case with non-zero acceleration illustrates inertia's impact. Simulink models of vehicle dynamics and resistance forces validate analytical results, providing a robust simulation framework. Results, validated that optimizing these parameters significantly enhances EV performance, guiding sustainable transportation design.

***Key Words*:** Vehicle Dynamics, Total Tractive Force, Energy Optimization, Simulink model, EV Range.

1.INTRODUCTION

Electric vehicles (EVs) are pivotal in the global transition to sustainable transportation, addressing the pressing need to reduce greenhouse gas emissions and reliance on fossil fuels. As of May 17, 2025, EVs have gained widespread adoption, driven by advancements in lithium-ion battery technology, expanded charging networks, and supportive policies such as tax incentives, zero-emission vehicle mandates, and urban congestion pricing. Models like the Tesla Model 3 and Ford F-150 Lightning exemplify this progress, offering competitive range and performance for both consumer and commercial applications. However, a persistent challenge remains: maximizing driving range and energy efficiency to mitigate range anxiety and compete with the convenience of internal combustion engine vehicles. Vehicle dynamics, encompassing the forces resisting motion, play a critical role in determining energy consumption, range, and overall performance, making their analysis essential for advancing EV technology [1].

Vehicle dynamics involve a complex interplay of forces—rolling resistance, aerodynamic drag, gradient force, and inertia resistance—modulated by parameters such as vehicle mass, aerodynamic shape, tire properties, terrain, and acceleration. These forces collectively determine the tractive effort required to propel an EV, directly influencing battery drain and the distance achievable on a single charge. For instance, aerodynamic drag dominates at highway speeds, consuming a significant portion of battery energy, while gradient forces drastically reduce range on hilly routes, and inertia resistance increases energy demand during acceleration, such as when merging onto highways or navigating urban traffic. Understanding and optimizing these dynamics is crucial for designing EVs that deliver extended range, enhanced efficiency, and robust performance across diverse scenarios, from city commutes to long-distance highway travel or mountainous regions. Moreover, such optimization aligns with broader sustainability goals by reducing energy consumption, easing the burden on charging infrastructure, and supporting the integration of renewable energy sources into the transportation ecosystem [2].

This paper presents a comprehensive analytical and simulation-based study of how vehicle dynamics affect EV performance, focusing on four primary forces: rolling resistance (F_{roll}), gradient force (F_{gd}), aerodynamic drag (F_{air}), and inertia resistance ($F_{inertia}$). The tractive force equation, incorporating all four forces, is used to model energy consumption and range under steady-state conditions at 90 km/h, a typical highway speed where aerodynamic drag is pronounced, with a transient case to highlight inertia's role. Detailed theoretical explanations elucidate the physical basis and engineering implications of each force, providing a foundation for understanding their impact on EV performance. Numerical calculations for a baseline EV on a 2° uphill slope with zero acceleration are presented, accompanied by a comparison table evaluating six values for drag coefficient, vehicle mass, rolling resistance coefficient, and road gradient. Simulink models of vehicle dynamics and resistance forces are employed to validate the analytical results, offering a robust simulation framework to confirm findings and explore parameter effects. The study aims to inform EV design, manufacturing, and operational strategies, contributing to the advancement of sustainable transportation through enhanced performance and efficiency [3].

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2. Theoretical Background

The tractive force (F_t) required to propel an EV is the sum of four resistive forces, accounting for both steady-state and transient conditions:

$$F_t = m_v g \mu_{rr} \cos\alpha + \frac{1}{2}\rho_{air} C_{drag} A v^2 + m_v g \sin\alpha + m_v a.$$

where:

- m_v: vehicle mass (kg), encompassing the chassis, battery, passengers, and cargo.
- $g = 9.81\ m/s^2$: gravitational acceleration, a fundamental constant affecting weight-based forces.
- μ_{rr}: rolling resistance coefficient, a dimensionless factor reflecting tire and road interactions.
- α: road gradient angle (degrees), defining the slope's incline or decline.
- $\rho_{air} = 1.225\ kg/m^3$: air density at standard conditions (sea level, 15°C).
- C_{drag}: drag coefficient, a dimensionless measure of aerodynamic efficiency.
- $A = 2.5\ m^2$: frontal area, the vehicle's cross-sectional area exposed to airflow.
- $v = 25\ m/s\ (90\ km/h)$: a typical highway speed where drag is significant.
- a: acceleration (m/s^2), zero in steady-state conditions, non-zero during transient phases like acceleration or deceleration.

This equation encapsulates the four primary forces resisting EV motion, each with unique physical origins and engineering implications, crucial for optimizing performance and efficiency.

2.1 Rolling Resistance Force (F_{roll}):

$$F_{roll} = m_v g \mu_{rr} \cos\alpha$$

Rolling resistance arises from energy losses during tire deformation and frictional interactions between the tire and road surface. As an EV moves, the tire's contact patch deforms under the vehicle's weight, dissipating energy as heat through hysteresis in the rubber compound—a process where the rubber does not fully recover its shape after deformation, converting mechanical energy into thermal energy. Additional losses stem from road surface irregularities (e.g., asphalt texture, gravel), tire tread patterns designed for grip, and adhesion effects at the tire-road interface.

The rolling resistance coefficient (μ_{rr}, typically 0.008–0.012 for EV tires) quantifies these losses and is influenced by tire material (e.g., silica-enhanced compounds reduce hysteresis), inflation pressure (higher pressure lowers deformation), road conditions (wet surfaces increase resistance), and ambient temperature (higher temperatures reduce rubber viscosity, lowering resistance). The normal force ($m_v g \cos\alpha$) is modulated by the road slope, with $\cos\alpha$ =1 on flat terrain, maximizing rolling resistance, and slightly decreasing on inclines due to the reduced normal component. Unlike inertia resistance, which depends on acceleration and is zero in steady-state conditions, rolling resistance persists at constant velocity, contributing 10–20% of total resistance at 90 km/h on a 2° slope. For a 1500 kg EV with $\mu_{rr} = 0.010$, rolling resistance is approximately 147 N, a non-negligible factor. Advances in tire technology, such as Michelin's Energy Saver or Bridgestone's Ecopia tires, have reduced μ_{rr} to as low as 0.006 by optimizing rubber compounds and tread designs, enhancing EV efficiency. Engineers must balance low rolling resistance with traction and durability, as overly slick tires may compromise safety on wet or uneven roads, making tire design a critical aspect of EV optimization.

2.2 Gradient Force (F_{gd}):

$$F_{gd} = m_v g \sin\alpha$$

The gradient force represents the component of the vehicle's weight acting parallel to a sloped road, opposing motion uphill ($\alpha > 0$) or aiding it downhill ($\alpha < 0$). This force is directly proportional to the vehicle's mass and the sine of the slope angle, making it a dominant factor on steep inclines. For a 1500 kg EV on a 2° slope, the gradient force is approximately 513 N, contributing significantly to total resistance. Unlike inertia resistance, which arises during acceleration and vanishes at constant speed, the gradient force is a static force driven by terrain geometry, affecting range regardless of velocity changes.

Gradient forces are critical in real-world driving, as even modest slopes (e.g., 1–5°) can drastically reduce range, particularly for heavier EVs with large batteries. For instance, hilly suburbs or mountainous regions pose significant challenges, requiring careful route planning to minimize energy consumption. The linear dependence on mass underscores the importance of lightweight design, as a 10% mass reduction directly lowers the gradient force, preserving range on inclines. Additionally, gradient forces interact with other dynamics: on steep uphill slopes, drivers may accelerate to maintain speed, increasing inertia resistance and compounding energy demands. Engineers and navigation system designers must account for terrain variability, using topographic data to optimize routes and inform drivers of energy-efficient paths, enhancing EV practicality in diverse geographies.

2.3 Aerodynamic Drag Force (F_{air}):

$$F_{air} = \frac{1}{2}\rho_{air} C_{drag} A v^2$$

Aerodynamic drag results from air resistance opposing the vehicle's motion, comprising pressure drag (due to the vehicle's shape) and skin friction (due to surface roughness). Pressure drag arises from the pressure difference between the vehicle's front (high pressure) and rear (low pressure), creating a net force opposing motion, while skin friction results from air molecules adhering to the vehicle's surface, generating shear stress. The drag coefficient (C_{drag}, typically 0.25–0.35 for EVs) quantifies the vehicle's aerodynamic efficiency, with lower values indicating streamlined shapes, such as teardrop-like profiles. The frontal area (A) represents the vehicle's cross-sectional exposure to airflow, while air density (ρ_{air}) varies with altitude, temperature, and humidity (e.g., lower density at higher altitudes reduces drag). The quadratic dependence on velocity (v^2) makes drag the dominant force at high speeds, such as 90 km/h, where it can account for over 50% of total resistance on flat terrain.

For an EV with $C_{drag} = 0.30$ and $A = 2.5m^2$, aerodynamic drag at 90 km/h is approximately 287 N, a significant energy drain. In contrast to inertia resistance, which is zero at constant velocity but spikes during acceleration (e.g., 750 N for a 1500 kg EV at $a = 0.5\, m/s^2$), drag persists at steady-state, making aerodynamic optimization critical for highway efficiency. Modern EVs like the Tesla Model S or Lucid Air achieve C_{drag} as low as 0.24 through features such as flush door handles, tapered rear ends, and active grille shutters that reduce turbulence. However, optimizing aerodynamics must balance aesthetic appeal, manufacturing costs, and functionality (e.g., cooling requirements for batteries and motors). Environmental factors like headwinds or crosswinds further increase drag, while transient acceleration phases amplify energy demands through inertia, requiring integrated design solutions.

2.4 Inertia Resistance Force ($F_{inertia}$):

$$F_{inertia} = m_v a$$

Inertia resistance arises from the vehicle's mass resisting changes in velocity, as described by Newton's second law of motion. This force is directly proportional to the vehicle's mass (m_v) and acceleration (a), making it a critical factor during transient phases, such as accelerating from a stop, merging onto highways, or navigating stop-and-go traffic. At steady-state conditions ($a = 0$), inertia resistance is zero, contributing nothing to the tractive force, unlike rolling resistance, drag, and gradient forces, which persist. However, during acceleration, inertia resistance can be substantial: for a 1500 kg EV accelerating at $a = 0.5\, m/s^2$ (a moderate rate for merging), $F_{inertia} = 750\, N$, rivalling or exceeding other forces.

The impact of inertia resistance is most pronounced in scenarios requiring frequent speed changes, such as urban driving or highway entry ramps, where it increases energy consumption and reduces range. Unlike aerodynamic drag, which scales with velocity squared, or gradient force, which depends on terrain, inertia resistance is solely a function of mass and acceleration, making lightweight design a key strategy for mitigation. Reducing vehicle mass not only lowers steady-state forces like rolling resistance and gradient force but also decreases inertia resistance during acceleration, improving overall efficiency. However, EVs often have heavy batteries to achieve desired ranges, posing a trade-off: larger batteries increase mass and inertia, requiring more powerful motors and consuming more energy during acceleration. Engineers must balance battery size with mass to optimize both steady-state and transient performance, ensuring efficient acceleration without compromising range.

3. Energy Consumption Model

The energy consumption model quantifies the electrical energy required to propel the EV, accounting for all resistive forces and drivetrain efficiency. The power required to overcome the tractive force is:

$$p = F_t . v$$

Energy consumption per kilometre is calculated as:

$$E_{per\ km} = \frac{F_t . 1000}{3.6\eta 10^6}\ kwh/km$$

This equation provides the electrical energy consumed per kilometre, a key metric for assessing EV efficiency. The driving range for a 60-kWh battery, typical for mid-range EVs like the Nissan Leaf, is:

$$Range = \frac{60}{E_{per\ km}}\ km$$

This represents the maximum distance achievable on a full charge. In steady-state conditions ($a = 0$), inertia resistance does not contribute, and the energy consumption depends on rolling resistance, gradient force, and aerodynamic drag. However, during acceleration ($a = 0.5\, m/s^2$), inertia resistance increases F_t, raising energy consumption and reducing range, as shown in the numerical analysis. The model assumes standard conditions (15°C, sea-level air density) and excludes regenerative braking, focusing on steady-state resistive forces to isolate parameter effects. Real-world driving introduces variability—acceleration, braking, and regenerative braking (which recovers energy)—but the steady-state model provides a baseline for highway scenarios, informing design trade-offs like battery sizing, motor power, and route selection.

4. Numerical Analysis

The numerical analysis quantifies EV performance through analytical calculations, focusing on a transient case (with acceleration), and six-value parameter variations to assess sensitivity.

Table 1: Parameters reflecting a typical midsize EV:

Parameter	Value
m_v	1500 kg
C_{drag}	0.30
μ_{rr}	0.010
η	0.85
A	2.5 m^2
ρ_{air}	1.225 kg/m^3
v	25 m/s
α	2^0
Battery capacity	60 kwh
a	0.5 m/s^2

$$F_{roll} = 1500 \text{ x } 9.81 \text{ x } 0.010 \text{ x } \cos 2^0 = 147.06 \text{ N}$$

$$F_{air} = 0.5 \text{ x } 1.225 \text{ x } 0.30 \text{ x } 2.5 \text{ x } 25^2 = 287.11 \text{ N}$$

$$F_{gd} = 1500 \text{ x } 9.81 \text{ x } \sin 2^0 = 513.47 \text{ N}$$

$$F_{inertia} = 1500 \text{ x } 0.5 = 750 \text{ N}$$

Total Tractive force (F_t) is therefore: $F_t = 147.06 + 287.11 + 513.47 + 750 = 1697.64$ N

Energy required per kilometre can be calculated as:

$$E_{per\ km} = \frac{1697.64\ X\ 1000}{3.6\ X\ 0.85\ X\ 10^6} = 0.5548\ kwh/km$$

$$Range = \frac{60}{0.5548} = 108.2\ km$$

Considering the study state case (acceleration = 0), six-value parameter variations are tabulated in Table 2 to assess sensitivity of various parameters on the energy requirement per km and EV range.

Table 2: Impact of Vehicle Dynamics Parameters on EV Performance

Parameter	Value	Energy (kWh/km)	Range (km)
Drag Coefficient (C_{drag})			
	0.24	0.2909	206.2
	0.27	0.3003	199.8
	0.3	0.3097	193.7
	0.33	0.3191	188
	0.36	0.3285	182.6
	0.39	0.3379	177.5
Vehicle Mass (m_v)			
	1200	0.2664	225.2
	1350	0.2881	208.3
	1500	0.3097	193.7
	1650	0.3313	181.1
	1800	0.353	170
	1950	0.3746	160.2
Rolling Resistance (μ_{rr})			
	0.006	0.2909	206.2
	0.008	0.3001	199.9
	0.01	0.3097	193.7
	0.012	0.3193	187.9
	0.014	0.3289	182.4
	0.016	0.3385	177.3
Road Gradient ($\alpha, degrees$)			

	0	0.1419	422.8
	1	0.2258	265.7
	2	0.3097	193.7
	3	0.3935	152.5
	4	0.4773	125.7
	5	0.5611	106.9

5. Simulink Models of Vehicle Dynamics and Resistance Forces

Simulink models were developed to simulate EV dynamics and resistance forces, validating analytical results. Two models are used: a Vehicle Dynamics Model simulating motion and a Vehicle Resistance Forces Model calculating forces, integrated to compute energy and range [4-5]. In the Figure 1, the Vehicle Dynamic Model calculates the vehicle's speed, acceleration, and distance travelled based on the motor torque and resistance forces. It begins with the motor torque, adjusted for motor efficiency, which is then reduced by the total resistance torque (computed in Figure 2) to determine the net torque.

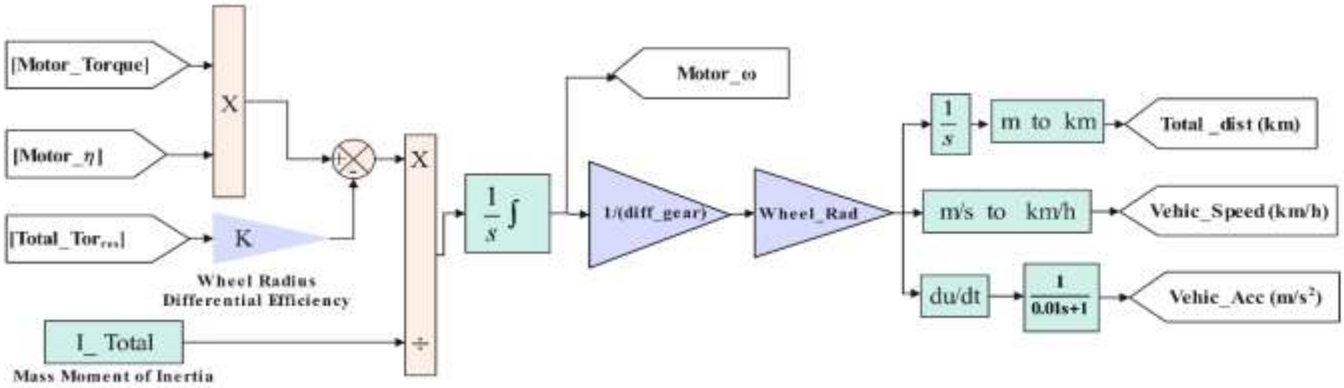

Fig -1: Vehicle Dynamics Model

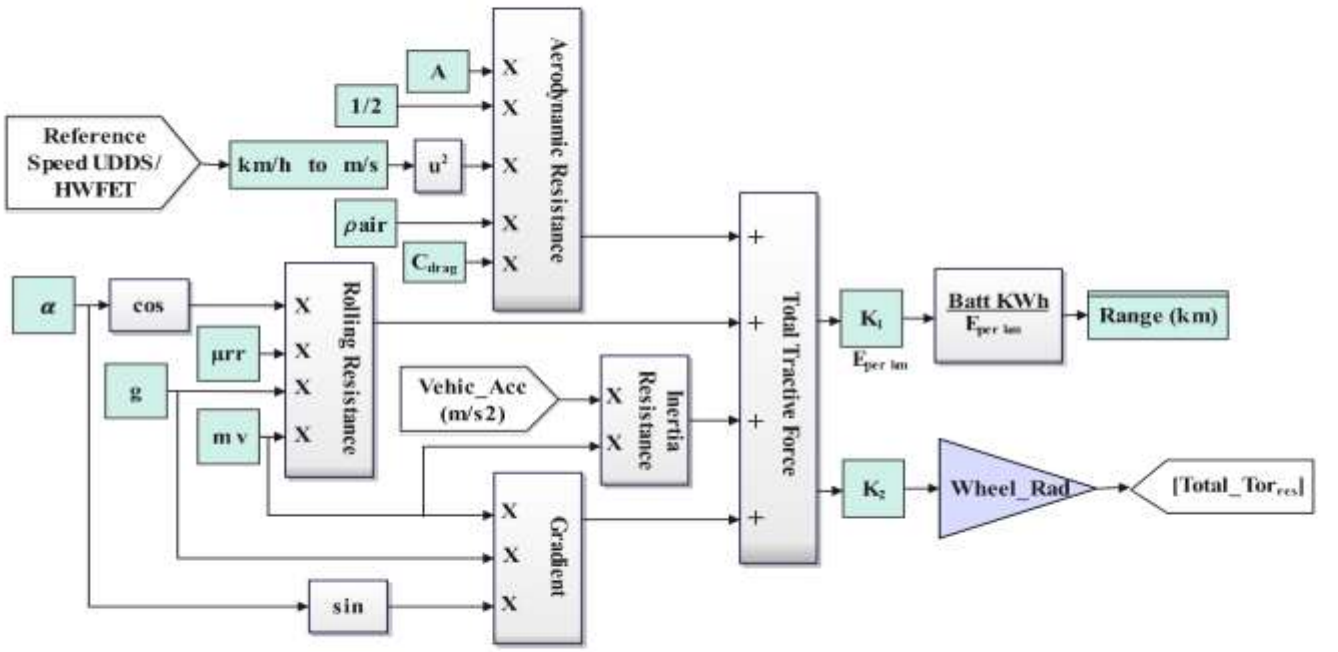

Fig -2: Vehicle Resistance Forces Model

This net torque is divided by the vehicle's mass moment of inertia to calculate the angular acceleration, which is integrated to obtain the motor's angular velocity. The angular velocity is then adjusted for the differential efficiency and gear ratio, and multiplied by the wheel radius to convert it into the vehicle's linear speed in meters per second, which is further converted to kilometres per hour. The speed is integrated to compute the total distance travelled (in kilometres) and differentiated to calculate the acceleration (in m/s²), with a low-pass filter applied to smooth the acceleration signal for a more realistic output. In Figure 2, the Resistance Forces Model, calculates the total resistance torque opposing the vehicle's motion by summing various forces: aerodynamic drag, rolling resistance, inertial force due to acceleration, and gradient resistance from road slope. These forces —aerodynamic, rolling, inertial, and gradient—are summed to obtain the total tractive force (F_t). This force is then used to calculate the energy consumption, scaled by a gain K, and divided by the battery's energy per kilometre to estimate the vehicle's range in kilometres.

The vehicle's speed and acceleration fed from Figure 1 are used to compute the resistance forces: aerodynamic drag (proportional to speed squared), rolling resistance (proportional to vehicle weight), inertial force (mass times acceleration), and gradient force (based on road slope). These forces are summed, multiplied by the wheel radius to convert them into a total resistance torque. This torque is then fed back to Figure 1, creating a closed-loop system where the two models interact. Together, these models provide a simulation of vehicle dynamics, accounting for both the driving forces from the motor and the opposing forces from the environment, ultimately determining the vehicle's performance in terms of speed, acceleration, distance, and range.

6. Results and Discussions

Numerical and Simulink analyses elucidate the impact of vehicle dynamics on electric vehicle (EV) performance, focusing on energy consumption and range. For a 1500 kg EV on a 2° uphill slope at 90 km/h, steady-state tractive force is 947.64 N (147.06 N rolling resistance, 287.11 N aerodynamic drag, 513.47 N gradient force), yielding 0.3097 kWh/km energy consumption and a 193.7 km range for a 60-kWh battery. With 0.5 m/s² acceleration, inertia resistance adds 750 N, increasing tractive force to 1697.64 N, elevating energy use and reducing range, highlighting inertia's role in transient conditions like urban driving. Parameter sensitivity analysis (Table 2) shows reducing drag coefficient from 0.39 to 0.24 lowers energy use to 0.2909 kWh/km, extending range by 28.7 km (16.2%). Decreasing mass from 1950 to 1200 kg reduces consumption to 0.2664 kWh/km, boosting range by 65 km (40.6%), emphasizing lightweight design. Rolling resistance reduction (0.016 to 0.006) increases range by 28.9 km, while gradient shifts (0° to 5°) cut range from 422.8 to 106.9 km (74.7%), underscoring terrain's impact. Simulink models validate these findings, accurately simulating force interactions and energy profiles. Aerodynamic optimization and mass reduction offer significant efficiency gains, though trade-offs include battery size and cooling needs. These insights guide EV design for enhanced range and sustainability, supporting route optimization and renewable energy integration.

7. Conclusion

This study demonstrates that vehicle dynamics significantly influence electric vehicle (EV) performance, particularly energy consumption and driving range. Numerical analyses and Simulink simulations reveal that aerodynamic drag, vehicle mass, rolling resistance, and road gradient critically affect tractive force, with steady-state energy consumption at 0.3097 kWh/km for a 1500 kg EV on a 2° slope, yielding a 193.7 km range. Transient conditions, like 0.5 m/s² acceleration, increase energy demands by 750 N due to inertia. Parameter optimization—reducing drag coefficient by 38.5%, mass by 36.8%, or rolling resistance by 62.5% —extends range by up to 40.6%, while gradients drastically reduce it by 74.7%. These findings underscore the importance of lightweight materials, streamlined designs, and route planning for EV efficiency. Future work should incorporate regenerative braking, diverse driving cycles, and environmental variables to enhance model realism, guiding sustainable EV design and supporting the global transition to eco-friendly transportation.

REFERENCES

1. Khan, K.; Samuilik, I.; Ali, A. A Mathematical Model for Dynamic Electric Vehicles: Analysis and Optimization. *Mathematics* **2024**, *12*, 224. https://doi.org/10.3390/math12020224
2. Martyushev, N.V.; Malozyomov, B.V.; Sorokova, S.N.; Efremenkov, E.A.; Qi, M. Mathematical Modeling the Performance of an Electric Vehicle Considering Various Driving Cycles. *Mathematics* **2023**, *11*, 2586. https://doi.org/10.3390/math11112586.
3. Pankaj Madheshiya *et al* 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1285** 012013**DOI** 10.1088/1755-1315/1285/1/012013.
4. Yogesh K. Kirange , Dr. Vijay S. Patil , Kiran L. Patil , Shoeb R. Patel, Harshal S. Sapkale, Jayesh B. Patil, 2023, An Overview of Matlab/Simulink Dynamic Model of an Electric Vehicle's Performance, INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH & TECHNOLOGY (IJERT) Volume 12, Issue 04 (April 2023),
5. Kıyaklı, A. O., & Solmaz, H. (2018). Modeling of an Electric Vehicle with MATLAB/Simulink. International Journal of Automotive Science And Technology, 2(4), 9-15. https://doi.org/10.30939/ijastech..475477