

Investigation of State of Charge for Electric Vehicle in Battery Performance

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Abstract

This paper investigates how well the two battery types which are Li-ion and NiMH perform in a sedan electric vehicle (EV) using the simulation program MATLAB Simulink. Three driving cycles categorized as urban, rural, and highway were used in the simulations to analyse battery behavior in various scenarios, with an emphasis on the State of Charge (SoC) as a crucial performance metric. The findings show that over the course of all driving cycles, Li-ion batteries consistently preserve a higher SoC than NiMH batteries. Improved general vehicle efficiency is directly correlated with this superior energy retention. Li-ion batteries offer benefits like a longer lifespan, improved charging efficiency, and lighter weight in addition to encouraging a longer driving range. These results support Li-ion batteries' suitability to be a EVs preferred energy storage selection, which enhances performance, range, and dependability in practical driving scenarios.

Keywords

Electric Vehicle, Lithium-Ion, Nickel Metal Hydride, State of Charge, Driving Cycle

1. Introduction

Electric vehicles (EVs), which run either partially or entirely on electric power, have gained attention in the new car market in major regions like Europe and China. However, the demand for EVs to replace the entire vehicle fleet is still rel-

atively low [1]. EVs offer several advantages, such as being eco-friendly by reducing the need for fossil fuels, having fewer parts that require maintenance, and having lower operating costs compared to traditional petrol or diesel vehicles [2].

The harmful nature of vehicle emissions significantly contributes to air pollution, with pollutants like nitrogen oxides (NO_x), particulate matter (PM), and hydrocarbons present in exhaust gases leading to health problems like cancer, heart disease, and respiratory issues [3]. Furthermore, these emissions have a notable impact on the environment, as they increase the levels of greenhouse gases in the atmosphere, contributing to climate change and global warming. As an alternative, using EVs can help mitigate the negative effects of vehicle emissions on air pollution, offering a solution to this issue [4] [5].

Battery electric vehicles (BEVs) exclusively utilize electricity for propulsion, while hybrid electric vehicles (HEVs) integrate both an internal combustion engine and an electric motor. Within the realm of electric vehicles (EVs), there are plug-in hybrids (PHEVs) powered by hydrogen fuel cells and fuel cell electric vehicles (FCEVs) that operate solely on electric power. Accordingly, to supply the necessary power to the vehicle, an electric vehicle (EV) utilizes a battery pack composed of numerous interconnected battery cells. This integrated unit functions as the vehicle's energy storage, delivering power to drive the motor and operate diverse systems. As a result, the EV can function completely independent of fossil fuel dependence.

Lithium-ion batteries are a satisfactory choice for electric vehicles due to their impressive energy density and ability to undergo numerous recharge cycles [6]. When employed in EVs, these batteries offer various advantages, including their high energy density, allowing for the storage of substantial energy within a compact space. This characteristic has contributed to extending the range of EVs. Research has indicated that ensuring the longevity of lithium-ion battery systems hinges on the development of exceptionally stable anode materials [7], implying that these batteries can remain functional for an extended period before requiring replacement. Moreover, lithium-ion batteries demand less maintenance and care compared to other battery types, rendering them a reasonable option for manufacturers of electric vehicles. Their great efficiency in both charging and discharging processes leads to minimal energy loss during these operations [8].

In nickel-metal hydride (Ni-MH) batteries, the positive electrode and the negative hydrogen storage electrode are both made up mostly of nickel. The metal hydride electrode of the battery absorbs hydrogen ions while charging, and it releases them during discharge. Electrical energy is both stored and released by these chemical processes [9]. It is ideal to utilise nickel hydride batteries in order to prevent 24 overcharging because they have two to three times greater capacity than nickel cadmium batteries [10]. Ni-MH batteries have a minimal environmental effect, a long cycle life, and a high energy density, making them a viable option for electric cars. However, in recent years, alternative battery types, like lithium-ion batteries, have outperformed Ni-MH batteries in terms of cost and energy density and are now the more often used choice for electric cars [11] [12].

Therefore, MATLAB Simulink was utilized in this research to design an electrical system structure for a sedan electric vehicle (EV) and to evaluate its performance under three different driving cycles: highway, rural, and urban. The State of Charge (SoC) of two battery types, Lithium-ion (Li-ion) and Nickel Metal Hydride (NiMH), was examined across these driving conditions. According to the findings, Li-ion batteries outperform NiMH batteries in EV applications due to their longer lifespan, increased charging efficiency, reduced weight, and enhanced vehicle performance. Due to their superior durability and range, Li-ion batteries are now the recommended option for powering electric vehicles. By increasing battery efficiency, encouraging the use of clean energy in transportation, and lowering emissions, this study on the State of Charge for Electric Vehicle battery performance supports SDGs 7, 11, and 13. By enhancing the reliability of electric vehicles for a future that is better for the environment, it supports climate change mitigation and sustainable urban mobility.

2. Background of Study

Conventional vehicles are powered by petrol or diesel. Fuel is burned in an internal combustion engine to power the vehicle. Fuel energy is converted into a crankshaft, which powers the wheels of the vehicle. They are also known as “gasoline” or “diesel” vehicles. Several automobile manufacturers have started introducing EVs out of concern for the environment. A pack of batteries in an EV is composed of numerous battery cells connected to provide the vehicle with the power it needs. It supplies electricity to the engine for combustion and other systems, acting as the vehicle’s energy storage system. As a result, the electric car can operate without using fossil fuels.

In EVs, battery life and degradation are crucial since range and efficiency are affected by the slow loss of capacity caused by frequent charging and discharging. Battery health and range are influenced by the SoC, which represents the energy that is accessible in the battery. Regenerative braking increases efficiency and driving range by recovering kinetic energy during deceleration and transforming it into electrical energy to recharge the battery. Driving cycles affect battery performance, SoC fluctuation, and energy consumption by simulating different road conditions, including urban, rural, and highway. Optimizing EV efficiency, guaranteeing battery longevity, and encouraging sustainable electric vehicle operation all require an understanding of these elements.

2.1. Battery Degradation and Lifetime

Battery degradation in EV refers to the gradual loss of battery capacity and performance over time due to chemical reactions during charging and discharging. This leads to reduced driving range and overall efficiency [13]. EV battery lifetime is determined by the number of charges a battery can undergo before its capacity significantly diminishes, typically measured at around 70% - 80% of original capacity. Factors like temperature, charging habits, and depth of discharge affect degradation.

Manufacturers use warranty coverage to ensure a certain level of capacity retention over a specified period, bolstering consumer confidence in EV durability [14] [15].

2.2. State of Charge

State of Charge (SoC) in an EV refers to the amount of energy stored in its battery as a percentage of its total capacity. It indicates how much power is available for driving. A higher SoC means more driving range, while a lower SoC reduces range [16] [17]. Monitoring and managing SoC is crucial for efficient EV operation and battery longevity. Charging from low to high SoC replenishes energy, while discharging from high to low SoC powers the vehicle. SoC is a key factor in optimizing EV performance, range, and overall battery health [18].

One of the methods for measuring battery charge, or SoC, is to use Equation (1) below to determine the battery cell's open circuit voltage.

$$\text{SoC}(\%) = 100 \times (V_m - V_{\min}) / (V_{\max} - V_{\min}) \quad (1)$$

where V_m is measured terminal voltage of the battery, V_{\min} is a minimum voltage (fully discharged state) and V_{\max} is a maximum voltage (fully charged state).

Although this is a straightforward procedure, voltage based SoC tests often have low accuracy since the temperature of the battery during operation might influence the outcomes.

2.3. Regenerative Braking

Regenerative braking in EVs is an energy-saving technique that converts kinetic energy into electrical energy during deceleration or braking. When the driver lifts their foot off the accelerator or applies the brake, the EV's electric motor acts as a generator, capturing the vehicle's momentum and converting it into electricity [19] [20]. This electrical energy is then fed back into the battery, recharging it and increasing overall efficiency. Regenerative braking enhances range, reduces wear on mechanical brakes, and contributes to energy conservation, making it a vital feature in modern EVs [21].

2.4. Driving Cycle

A driving cycle standard is a set of guidelines that establish a specific pattern of acceleration, deceleration, and speed for testing a vehicle's fuel efficiency and emissions. These standards are used by manufacturers, regulators, and researchers to ensure that vehicles are tested in a consistent and repeatable manner [22]. This allows for a fair comparison between different models and the ability to measure the impact of new technologies on fuel efficiency and emissions. Simply put, it is a test drive that simulates real driving conditions, is standardized, and is used to measure the performance of vehicles. The standard drive cycle used in this research is from the Artemis driving cycle [23]. The Artemis driving cycle is a standardized test procedure for evaluating vehicle fuel efficiency and emissions. It is based on real driving conditions and was developed by the European Union. It is designed to simulate a mixture of city, suburban and highway driving. The Arte-

mis driving cycle is also known as the World Harmonized LightDuty Test Procedure (WLTP) [24] [25]. Although this drive cycle is to evaluate fuel efficiency, it is also suitable for EV use.

3. Methodology

The major processes and procedures involved are represented in **Figure 1**. There are four main sections in the flowchart which are design, load data, simulation and data analysis. As referred to the flowchart, the project began by designing the electrical system structure of an electric vehicle using MATLAB/Simulink based on two different types of batteries which are Li-ion and NiMH.

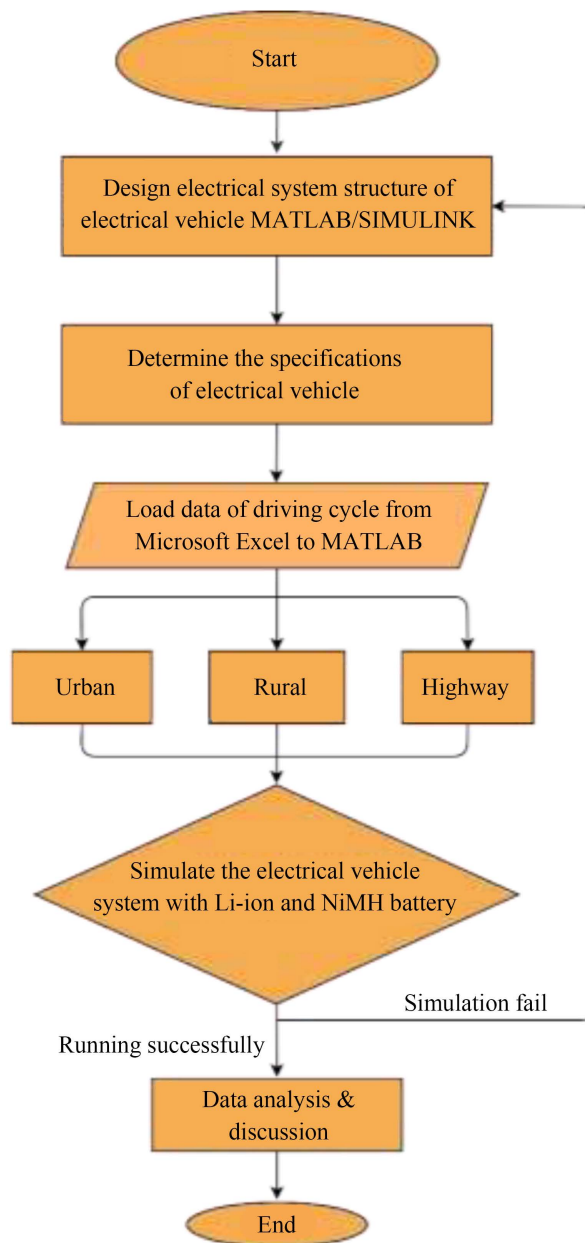


Figure 1. Major processes and procedures involved.

It is essential to understand that the simulation model was created using simplified assumptions, especially with regard to how battery type affects vehicle speed. Internal resistance and dynamic voltage behavior under load were not taken into consideration in this model, which assumed ideal energy output and treated the power delivery from both Li-ion and NiMH batteries uniformly. Consequently, for both batteries categories, the simulated vehicle speed profiles were identical during every driving cycle. While this approach allowed for a more focused analysis of State of Charge (SoC) behaviors, it restricts the ability of the model to represent variations in acceleration, power output, and efficiency that could happen in the real world due to battery-specific factors.

For this research, the type of car used is a sedan type. The sedan car parameters are related to mass, the horizontal distance of the center of gravity from the front and rear axles, and the center of gravity above the ground. These parameters affect the speed and the SoC of the vehicle. The drive cycle is imported into MATLAB in Excel format following the completion of the system design. There are three distinct types of driving cycles: highway, rural, and urban. The driving behaviours and conditions of these three driving cycle types vary. After setting the driving cycle data, the EV simulation is performed based on the three driving cycle types with the first type of battery which is Li-ion. The next simulation will be performed with NiMH battery and the data can be analyzed and discussed.

In the **Figure 2** shows the electrical system structure of electric vehicle using MATLAB/Simulink. In this structure, there are five important components that complete the structure of this electric vehicle. The components are battery, inverter, motor, vehicle dynamics parameters, and controller.

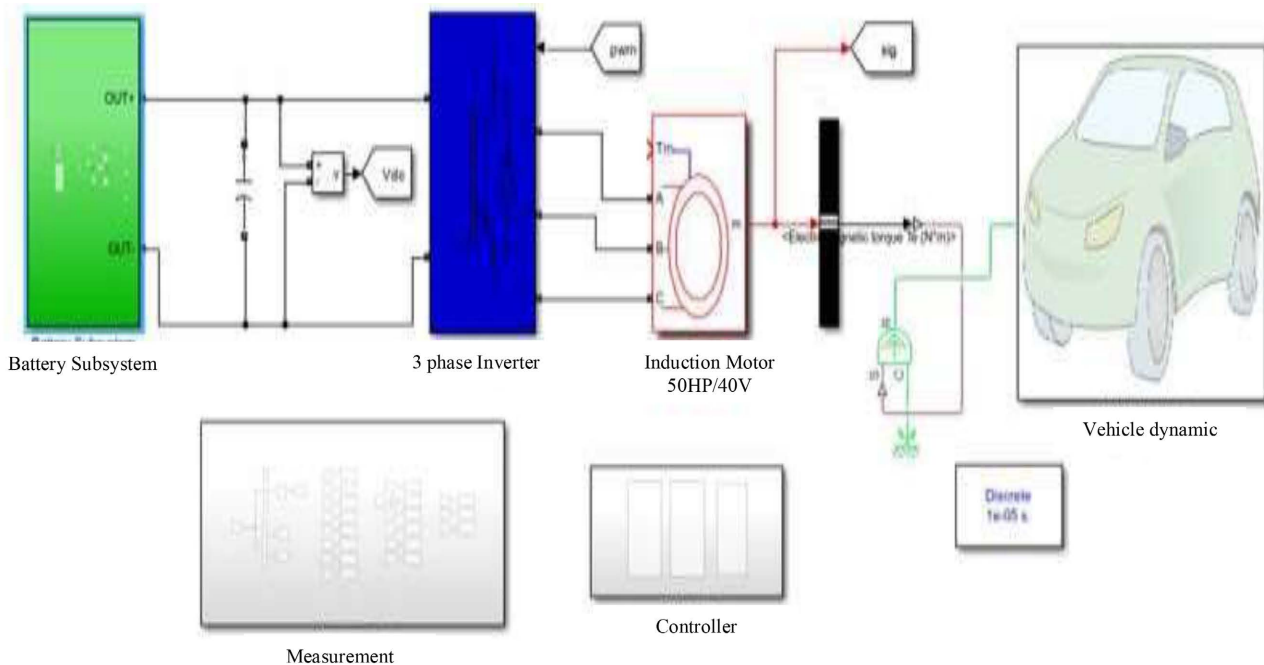


Figure 2. Electrical system structure of electric vehicle.

The EV electrical system uses a 360 V battery. A DC-DC converter in the batteries subsystem converts the power from the battery's higher voltage DC into the lower voltage DC required to charge the battery and run vehicle accessories. An electric motor in a car uses an inverter to transform DC electricity into AC current. The inverter can alter the speed of the motor by altering the AC frequency current. The power or torque of motor can also be altered by altering the signal amplitude. The motor used in this electric vehicle structure is an induction motor. The induction motor has very accurate speed control, and its speed can be varied very easily by simply changing the frequency via the controller. In the vehicle dynamics subsystem, there is a vehicle body that can be modified according to the desired specifications.

There are three controllers in this electrical structure. These include the battery controller, the DC-Link controller, and the speed controller. The function of the battery controller is to charge and discharge the battery. The function of the DC-link controller is to ensure that the voltage is always sufficient. The speed controller controls the acceleration and deceleration of the vehicle.

Table 1 shows the parameters setting for the EV during the simulation. The parameters that are varied are the mass, the horizontal distance from center of gravity to front and rear axles, and the center of gravity above the ground. The type of car is a sedan type vehicle. This vehicle is designed according to the parameters as summarized in **Table 1**.

Table 1. Electric vehicle parameters.

Vehicle Body	Setting
Mass	1200 kg
Horizontal distance from center gravity to front axle	1.4 m
Horizontal distance from center gravity to rear axle	1.6 m
Center gravity above ground	0.5 m

Battery parameters are crucial features for EVs that specify capacities and performance of battery. These consist of battery reaction time (s), starting state of charge (%), nominal voltage (V), and rated capacity (Ah). Both Li-ion and NiMH batteries have this battery parameter set to the same value. The lithium-ion (Li-ion) and nickel metal hydride (NiMH) batteries' specifications are displayed in **Figure 3**. These include a nominal voltage of 360 V, a rated capacity of 100 Ah, and an initial state of charge of 90%, respectively. Fast and effective energy transfer is also made possible by the battery's quick response time of $1e-4$ seconds. These parameters contribute to the battery's performance and capabilities, making it suitable for applications that require high voltage and fast energy delivery.

Both Li-ion and NiMH batteries have significant potential for various applications. While Li-ion batteries have higher energy density and voltage, NiMH batteries offer reliable performance and cost efficiency. The specific choice depends on the application requirements, taking into account factors such as capacity, voltage, response time and overall efficiency.

Parameters	Discharge
Type:	Lithium-Ion
Temperature	
<input type="checkbox"/> Simulate temperature effects	
Aging	
<input type="checkbox"/> Simulate aging effects	
Nominal voltage (V)	360
Rated capacity (Ah)	100
Initial state-of-charge (%)	90
Battery response time (s)	1e-4 <small>0.0001</small>

(a)

Parameters	Discharge
Type:	Nickel-Metal-Hydride
Nominal voltage (V)	
360	
Rated capacity (Ah)	
100	
Initial state-of-charge (%)	
90	
Battery response time (s)	
1e-4 <small>0.0001</small>	

(b)

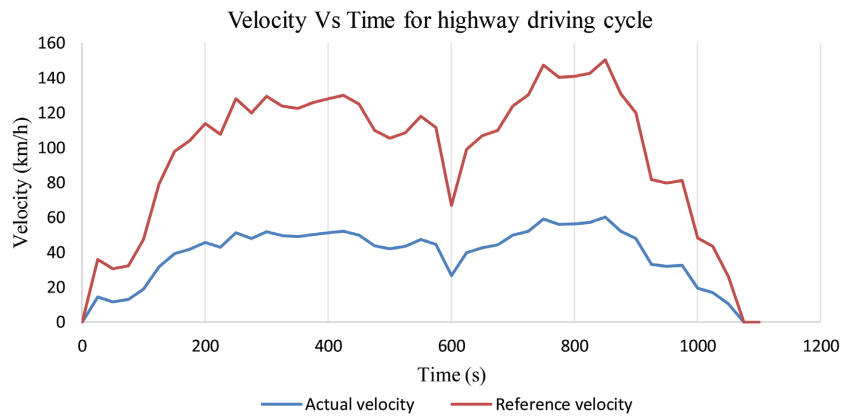
Figure 3. Battery parameters for (a) Lithium-ion (b) Nickel Metal Hydride.

4. Results and Discussion

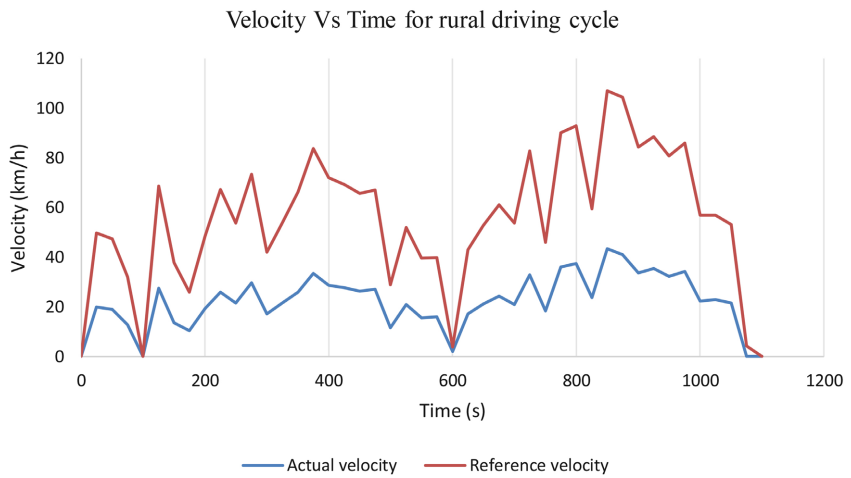
Based on driving cycles that simulate common driving patterns, electric vehicle (EV) speed fluctuates. The vehicle's velocity profile is determined by these cycles, which include the urban driving cycle, the rural driving cycle, and the highway driving cycle. During these cycles, the electric vehicle can reach different speeds, which affects energy consumption and overall performance, among other things.

4.1. Results for Velocity of Car Based on Driving Cycles

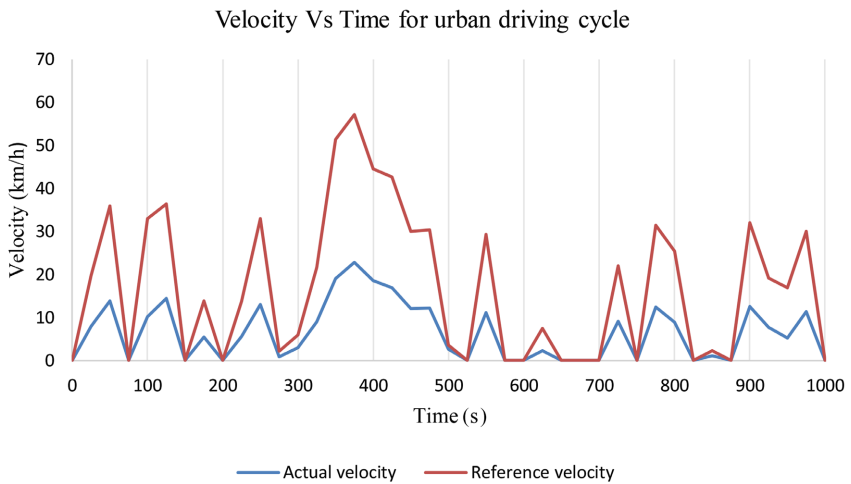
Velocity simulation in MATLAB can be successfully performed using highway, rural, and urban driving cycles as references for electric vehicles (EVs). Accurate modeling of EV systems in MATLAB enables simulation of EV behavior and performance under real-world conditions. These simulations help evaluate factors such as energy consumption and overall efficiency of an electric vehicle on the road. By including these three drive cycles as benchmarks, MATLAB simulations enable exploration and evaluation of aspects of EV design, such as power train efficiency, battery type, and regenerative braking strategies to improve vehicle performance. **Figure 4** shows the simulation results for three driving cycles. According to the legend in the figure, the blue line is the simulation velocity, while the red line is the reference velocity (driving cycles). The simulation velocity was followed by the reference velocity.



(a)



(b)



(c)

Figure 4. Velocity of (a) highway, (b) rural, (c) urban driving cycle.

The simulation velocity is quite slow compared to the reference velocity. Electric vehicle speeds are often slower compared to conventional vehicles due to several factors. Electric Vehicles typically have lower maximum power and limited

energy storage capacity in their batteries, resulting in slower acceleration and top speed.

Table 2 shows the velocity of the electric vehicle based on driving cycles with two battery types, namely Li-Ion and NiMH. These velocity data are recorded every 50 seconds. After completing the three simulations based on highway, rural, and urban driving cycles, the velocity of the vehicle with Li-ion batteries is the same as with NiMH batteries.

Table 2. Velocity of EV based on driving cycles.

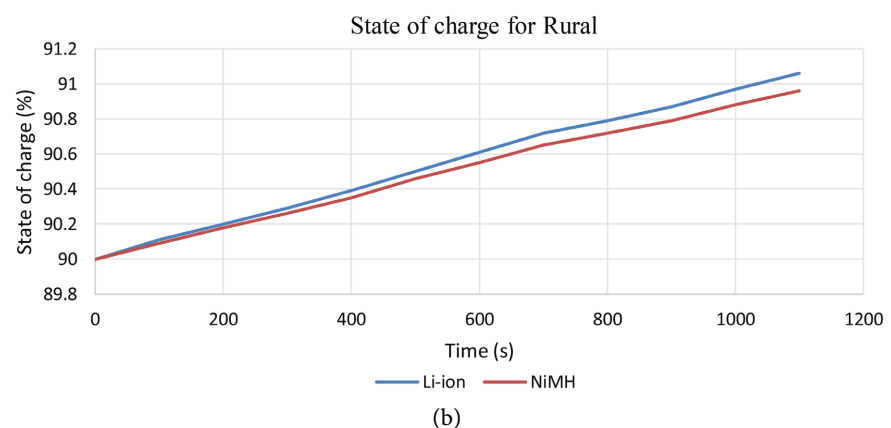
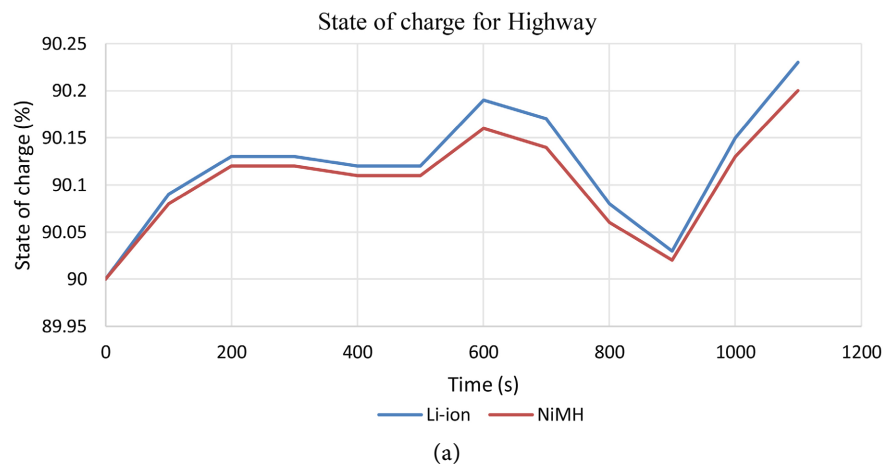
Time (s)	Highway velocity (km/h)		Rural velocity (km/h)		Urban velocity (km/h)	
	Li-ion	NiMH	Li-ion	NiMH	Li-ion	NiMH
0	0.00		0.00		0.00	
50	11.72		11.72		18.92	
100	19.00		19.00		0.00	
150	39.16		39.16		13.65	
200	45.68		45.68		19.36	
250	51.20		51.20		21.48	
300	51.84		51.84		17.09	
350	49.04		49.04		26.00	
400	51.28		51.28		28.70	
450	50.00		50.00		26.24	
500	42.16		42.16		11.52	
550	47.28		47.28		15.5	
600	26.80		26.80		2.00	
650	42.72		42.72		21.08	
700	49.80		49.80		21.00	
750	59.00		59.00		18.40	
800	56.40		56.40		37.40	
850	60.13		60.13		43.30	
900	48.04		48.04		33.70	
950	32.02		32.02		32.32	
1000	19.32		19.32		22.36	
1050	10.39		10.39		21.62	
1100	0.00		0.00		0.00	

Theoretically, the type of battery utilized should affect the results of EV speed simulation. There may be a reason for these differences, though, if the simulation indicates the same speed for all battery types. The simulation can be based on simplified assumptions that ignore the impact of battery attributes on vehicle speed. If the simulation assumes constant power output or violates the impact of internal resistance, it may produce identical results for several battery types. To improve the accuracy of vehicle performance simulations, subsequent studies should include complex electrochemical and dynamic battery models.

4.2. Results for State of Charge Based on Driving Cycle

The state of charge of an electric vehicle (EV), which reflects the amount of energy stored in the battery, varies during driving cycles. Regenerative braking or driving at lower speeds can help maintain or even increase SoC, which can affect vehicle range and performance. Higher speeds or more demanding cycles can deplete the SoC more quickly.

Figure 5 shows the state of charge (SoC) for the highway, rural, and urban driving cycles. The red line shows the SoC that uses a Li-ion battery while the red line is for NiMH. Based on these figures, the SoC of Li-ion is higher compared to the use of NiMH in each driving cycle. When observed at each graph, the Li-ion battery is superior and dominates in terms of SoC.



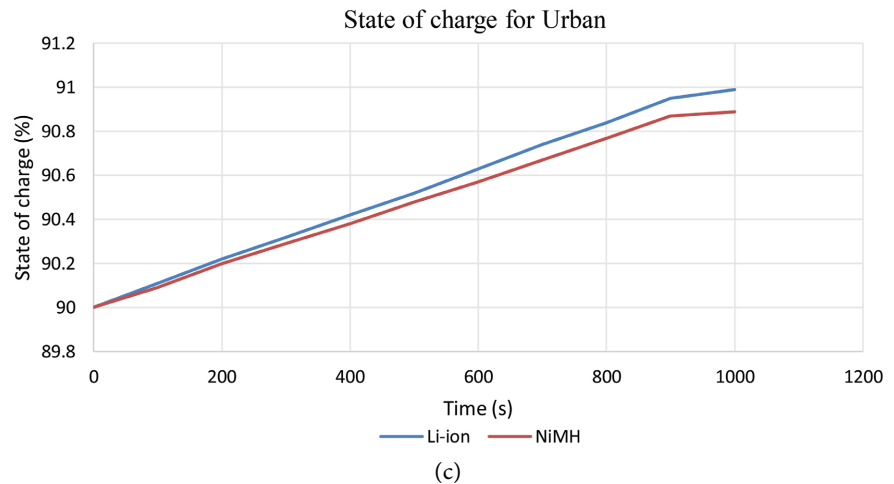


Figure 5. State of charge for (a) highway, (b) rural, (c) urban driving cycle.

Table 3 presents the State of Charge (SoC) of a highway driving cycle for two different battery types: Li-ion and NiMH. The SoC value recorded at each time interval which is every 100 seconds for 1100 seconds during the driving cycle. Based on the table, the SoC values for both types of batteries are not significantly different. The highest SoC value for Li-ion is 90.23% with an increase of 0.23% while 90.20% with an increase of 0.20% for NiMH type batteries. Li-ion batteries show a slight increase when compared to NiMH at each time interval.

Table 3. State of charge of highway driving cycle.

Time (s)	SoC% (Li-ion)	Soc% (NiMH)
0	90.00	90.00
100	90.09	90.08
200	90.13	90.12
300	90.13	90.12
400	90.12	90.11
500	90.13	90.11
600	90.19	90.16
700	90.17	90.14
800	90.08	90.06
900	90.03	90.02
1000	90.15	90.13
1100	90.23	90.20

Table 4 compares the State of Charge (SoC) for Li-ion and NiMH batteries throughout a rural driving cycle. Both battery types show an overall rise in SoC throughout the cycle. It is interesting that the SoC of the Li-ion battery remains

significantly higher than that of the NiMH battery for each period. This shows that throughout a rural driving cycle, Li-ion batteries offer increased energy retention and efficiency. The differences grow more noticeable as the cycle moves on, emphasizing Li-ion batteries' better ability to maintain larger quantities of energy. The NiMH batteries, on the other hand, have a little lower SoC, but they still hold a charge.

Table 4. State of charge of rural driving cycle.

Time (s)	SoC% (Li-ion)	Soc% (NiMH)
0	90.00	90.00
100	90.11	90.09
200	90.20	90.18
300	90.29	90.26
400	90.39	90.35
500	90.50	90.46
600	90.61	90.55
700	90.72	90.65
800	90.79	90.72
900	90.87	90.79
1000	90.97	90.88
1100	91.06	90.96

Some significant findings are provided by **Table 5**, which displays the State of Charge (SoC) for Li-ion and NiMH batteries during an urban driving cycle. Though the simulation results demonstrate that Li-ion batteries continuously maintain marginally higher State of Charge (SoC) levels than NiMH batteries during all three driving cycles, the differences generally negligible less than 0.1%. The practical impact of such small variations on overall vehicle performance and range may be limited under real-world driving circumstances, despite the fact that this trend indicates a modest efficiency advantage for Li-ion batteries in energy retention. Therefore, it is more suitable to interpret the data as a minor benefit to support the conclusion that Li-ion batteries perform better in terms of SoC. Given their benefits in other areas like energy density, weight, and cycle life, these findings still support the industry's preference for Li-ion batteries; however, the SoC difference seen presently should be understood as gradually rather than absolute.

Table 5. State of charge of urban driving cycle.

Time (s)	SoC% (Li-ion)	SoC% (NiMH)
0	90.00	90.00
100	90.11	90.09

Continued

200	90.22	90.20
300	90.32	90.29
400	90.42	90.38
500	90.52	90.48
600	90.63	90.57
700	90.74	90.67
800	90.84	90.77
900	90.95	90.87
1000	90.99	90.89

According to the results, the State of Charge (SoC) consistently demonstrates that Li-ion batteries maintain a slightly higher SoC than NiMH batteries at each time interval based on the presented tables for three driving cycles (highway, rural, and urban) utilizing Li-ion and NiMH batteries. This suggests that Li-ion batteries have greater overall energy retention and efficiency under a variety of driving circumstances. Although there aren't many distinctions between battery types, Li-ion batteries typically maintain increased charge levels. Li-ion batteries could be a better option for improving electric vehicle performance on highways, in rural areas, and in urban areas.

4.3. Relationship between the Velocity and State of Charge

Energy demand and recovery regulate the correlation between an electric vehicle's (EV) speed and its State of Charge (SoC). While lower speeds and frequent deceleration events, like stop-and-go driving, offer opportunities for regenerative braking, which can slow or even slightly increase SoC loss, higher speeds usually result in more rapidly SoC depletion due to increased energy consumption.

The results displayed in **Figure 5** clearly reflect this general relationship. The SoC of both battery types slowly increased during the urban driving cycle, which is defined by numerous acceleration and deceleration phases, low speed travel, and frequent stops. Regenerative braking, which improves energy efficiency in low-speed situations by recovering kinetic energy during deceleration and supplying it back into the battery, might be the cause of this.

In contrast, the highway driving cycle needed more frequent braking and longer periods of high speed. This contributed to the lowest SoC gain and, in certain cases, even small SoC declines, which were particularly obvious in the steadier, smooth SoC trend for NiMH batteries. These findings align with the higher energy requirements of highway speeds and the restricted energy recovery opportunities.

Moderate speeds and the combination of steady driving and occasionally stops or deceleration phases were characteristics of the rural driving cycle. As a result, the SoC climbed less than in the urban cycle but more than in the highway cycle.

Again, at almost every time point, Li-ion batteries displayed marginally higher SoC values, indicating their increased energy consumption and regenerative charging efficiency.

These trends offer authority to the concept that driving cycle dynamics, in particular braking frequency and speed, have a major impact on SoC trends and that battery type has a secondary but steady influence on overall energy retention.

5. Conclusions

This study applied MATLAB Simulink simulations to evaluate the performance of lithium-ion (Li-ion) and nickel metal hydride (NiMH) batteries in a sedan electric vehicle (EV) over highway, rural, and urban driving cycles. The findings revealed that, in every scenario, Li-ion batteries continually maintained marginally higher State of Charge (SoC) levels than NiMH batteries. Even though the variations were minimal typically less than 0.1%, they exhibit the overall efficiency advantages of Li-ion technology. By considering their benefits in terms of energy preservation, weight, lifespan, and charging efficiency, these results provide credibility to the greater use of Li-ion batteries in EVs.

Nevertheless, the simulation model had several limitations that restricted the scope to which the results could be applied. Particularly, the model neglected to account for essential real-world elements that have an important effect on long-term battery performance, such as ageing behaviour, thermal degradation, and battery temperature effects. Moreover, both types of batteries were simulated with simplified assumptions that failed to adequately account for the dynamic variations in internal resistance and power delivery. More complicated battery models and environmental factors should be included in future research to improve simulation-based EV efficiency accuracy and better represent actual scenarios.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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