TÜRKİYE CUMHURİYETİ
ADANA ALPARSLAN TÜRKEŞ SCIENCE AND TECHNOLOGY UNIVERSITY

GRADUATE SCHOOL
MECHANICAL ENGINEERING DEPARTMENT

DETERMINATION OF IMPACT OF BATTERY LOCATION ON ELECTRIC VEHICLE DYNAMICS

EGE ÖZSÖYLER

M.Sc.

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THESIS ADVISOR
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ADANA, 2023

ÖZET

ELEKTRİKLİ ARAÇLARDAKİ BATARYA KONUMUNUN ARAÇ DİNAMİĞİNE ETKİSİ

Ege ÖZSÖYLER
Yüksek Lisans, Makine Mühendisliği Anabilim Dalı
Danışman: Doç. Dr. Gökhan TÜCCAR
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Bu tez, batarya konumunun taşıt dinamiği üzerindeki etkisini incelemektedir. Elektrikli taşıtların artan kullanımıyla birlikte, bataryanın optimal konumu üreticiler için önemli bir tasarım düşüncesi haline gelmektedir. Bataryanın konumu aracın ağırlık merkezini, ağırlık dağılımını ve hareket özelliklerini etkileyebilmekte, nihayetinde taşıtın genel performansını ve güvenliğini etkileyebilmektedir.

Bu etkiyi incelemek için, batarya konumu ve taşıt dinamiği üzerine mevcut araştırmaların durumunu belirlemek için kapsamlı bir literatür taraması yapılmıştır. Daha sonra, taşıt dinamiği MATLAB sayısal hesaplama yazılımı kullanarak batarya konumunun taşıt manevra kabiliyeti ve istikrarı üzerindeki etkisini analiz etmek için bir dizi simülasyon yapılmıştır. Program önce taşıtın ağırlık merkezini ve her bir lastiğe düşen yükü hesaplamaktadır. Daha sonra her lastiğin hareketliliğini ve araca etki eden merkezcil kuvveti hesaplamaktadır. Eğer sonuçta oluşan kuvvet, aracın devrilmesini önleyen kuvvetten daha büyükse, taşıt söz konusu girdiler ışığında virajı dönemez olarak kabul edilmektedir. Ardından, tüm lastiklerin en düşük hareketliliği kullanılarak maksimum viraj derecesi hesaplanmaktadır. Bu veri de aracın mevcut hızla söz konusu virajı alabileceği maksimum viraj derecesini hesaplamayı sağlamaktadır.

MATLAB programı kullanılarak yazılan kod aracılığıyla girdiler işlendiğinde, farklı batarya pozisyonları, farklı taşıt ağırlıkları, farklı taşıt hızları, farklı taşıt boyutları, farklı viraj açısı, farklı sürtünme katsayıları, farklı hızlar için taşıtın ağırlık merkezini ve aracın viraj alabilme kabiliyetini hesaplamıştır. Daha sonra, farklı batarya pozisyonları, taşıtın farklı hızları ve taşıtın yükseklikleri ile ilgili maksimum viraj derecesini hesaplamak için beş farklı grafik çizilmiştir.

Sonuçlar, batarya konumunun aracın hareketliliği, istikrarı ve genel performansı üzerinde önemli bir etkisi olduğunu göstermektedir. Bataryanın daha düşük bir merkezine yerleştirilmesiyle elde edilen düşük ağırlık merkezine sahip taşıtlar, daha yüksek bir ağırlık merkezine sahip olanlardan daha iyi viraj kabiliyeti ve istikrar sergilemiştir. Ayrıca, bataryanın ağırlığının taşıt üzerindeki dağılımı, aracın dengesini ve viraj kabiliyetini etkilediği tespit edilmiştir. Bu tezin bulguları, taşıt tasarımcılarına ve üreticilerine elektrikli taşıtlarda bataryanın yerleştirilmesini optimize etmelerine yardımcı olarak, taşıtların hareketliliğini, istikrarını ve performansını iyileştirmeye yönelik değerli bir bakış açısı sağlamaktadır.

Anahtar Kelimeler: elektrikli araçlar, araç dinamiği, optimal batarya konumu, MATLAB

ABSTRACT

DETERMINATION OF IMPACT OF BATTERY LOCATION ON ELECTRIC VEHICLE DYNAMICS

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This thesis investigates the impact of battery position on vehicle dynamics. With the increasing use of electric vehicles, the optimal position of the battery has become an important design consideration for manufacturers. The position of the battery can affect the center of gravity, weight distribution, and handling characteristics of the vehicle, ultimately influencing its overall performance and safety.

To analyze this effect, a comprehensive literature review was conducted to determine the current state of research on battery position and vehicle dynamics. Subsequently, a series of simulations were performed to analyze the effect of battery position on vehicle maneuverability and stability using vehicle dynamics MATLAB numerical computation software. The software first calculates the center of gravity of the vehicle and the load on each tire. It then computes the mobility of each tire and the resultant centripetal force acting on the vehicle. If the resultant force exceeds the force preventing the vehicle from tipping over, the vehicle is considered unable to negotiate the turn based on the given inputs. After that, the maximum steering angle is calculated using the lowest mobility of all tires. This data also allows for the calculation of the maximum steering angle the vehicle can take for a given turn with its current speed.

Using the code written through the MATLAB program, when inputs are processed, the program calculates the vehicle's center of gravity and its ability to take corners for different battery positions, vehicle weights, vehicle speeds, vehicle dimensions, turn angles, friction coefficients, and speeds. Then, five different graphs were plotted to calculate the maximum steering angle related to different battery positions, vehicle speeds, and vehicle heights.

The results demonstrate that battery placement has a significant impact on the vehicle's mobility, stability, and overall performance. Vehicles with a lower center of gravity achieved by placing the battery towards the lower end exhibited better cornering capability and stability compared to those with a higher center of gravity. Additionally, it was determined that the distribution of battery weight on the vehicle affects its balance and cornering ability. The findings of this thesis provide valuable insights for vehicle designers and manufacturers to optimize the placement of batteries in electric vehicles, thereby improving the mobility, stability, and performance of vehicles.

Keywords: electric vehicles, vehicle dynamics, optimal battery position, MATLAB

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF GRAPHS

LIST OF TABLES

LIST OF ABBREVIATIONS

SoC	: State of Charge
SoH	: State of Health
EV	: Electric Vehicle
BMS	: Battery Management System
HEV	: Hybrid Electric Vehicles
ICE	: Internal Combustion Engine
PHEV	: plug-in hybrid electric vehicles
SHEV	: Serial Hybrid Electric Vehicles
AC	: Alternative Current
DC	: Direct Current
SRM	: Switched reluctance motors
NiMH	: Nickel-metal hydride
NiCad	: nickel-cadmium
Li-ion	: Lithium-ion
LCO	: Lithium cobalt oxide
NMC	: Lithium nickel manganese cobalt oxide
LFP	: Lithium iron phosphate
LiFePO4	: Lithium Iron Phosphate

LIST OF SYMBOLS

C	: Dokunun kapasitansı
H	: Isı miktarı
M_x, M_y, M_{xy}	: Moment Bileşenleri
N_x, N_y, N_{xy}	: Normal Kuvvet Bileşenleri
q	: Faz yükü
t	: Zaman
u,v	: Yer değiştirme vektörü bileşenleri
w	: Açısal hız
XC	: Kapasitif reaktans
XL	: Endüktif reaktans
a	: Asal gerilme doğrultusundan sapma açısı
r	: Yoğunluk
s_x, s_y, s_{xy}	: Kabuk iç gerilmeleri

1. INTRODUCTION

The increasing demand for eco-friendly transportation solutions has led to the rapid development of electric vehicles. Electric vehicles (EVs) are powered by an electric motor instead of an internal combustion engine, which makes them more efficient and environmentally friendly. In this thesis, the effect of battery position on the vehicle dynamics of EVs was investigated.

Electric vehicles offer several advantages over traditional gasoline-powered vehicles. One of the most significant advantages is their efficiency. EVs convert up to 62% of the energy stored in the battery to power the wheels, whereas gasoline-powered vehicles convert only about 20% of the energy stored in gasoline to power the wheels. This means that EVs are much more efficient, resulting in less energy waste and lower operating costs.

Another significant advantage of EVs is that they produce zero emissions, making them a clean and sustainable transportation option. Traditional gasoline-powered vehicles emit harmful pollutants, contributing to air pollution and climate change (Amin, Amin, & Cho, 2023). By choosing an electric vehicle, individuals can help reduce carbon emissions and their carbon footprint.

To understand the effect of battery position on vehicle dynamics, it is essential to understand the components and requirements of electric vehicles. EVs require several key components, including a battery, electric motor, controller, and charger. The battery is the most crucial component of an EV and provides the energy needed to power the electric motor. The electric motor converts the energy from the battery into mechanical energy, which drives the wheels (Bairwa, Supraja, Pratiksha, & Sumanth, 2023).

EVs also require a charging infrastructure, which can be a significant barrier to widespread adoption. Currently, charging infrastructure is not as widely available as gasoline stations, and charging times can be lengthy. However, advancements in battery technology and charging infrastructure are making EVs a more practical and convenient transportation option.

While electric vehicles offer several advantages, they are not without their challenges. One significant challenge is the cost of the vehicle and the battery. EVs are typically more expensive than gasoline-powered vehicles due to the cost of the battery and other components. However, as technology improves and production costs decrease, the price of EVs is expected to become more competitive.

To investigate the effect of battery position on vehicle dynamics, was used MATLAB software. MATLAB is a powerful software tool that allows for the modeling, simulation, and analysis of complex systems. The use of MATLAB in this thesis will enable to conduct simulations that analyze the effect of battery position on vehicle handling and stability.

In summary, electric vehicles offer several advantages over traditional gasoline-powered vehicles, including increased efficiency and zero emissions. To understand the effect of battery position on vehicle dynamics, it is crucial to understand the components and requirements of electric vehicles. While EVs present challenges, such as cost and charging infrastructure, advancements in technology and infrastructure are making them a more practical and sustainable transportation option. Finally, the use of MATLAB software in this thesis will enable to conduct simulations that provide valuable insights into the effect of battery position on vehicle dynamics.

2. THEORETICAL FOUNDATIONS AND LITERATURE REVIEW

2.1. Previous Studies

There has been a increase in research on electric vehicles due to the growing interest in the field. Electric vehicles are typically categorized into different subsystems in these studies. This categorization involves the use of various computer programs for simulations, different methods of electronic differential and motor control, and optimization of factors such as environmental and economic impacts. Different types of engines and batteries used in electric vehicles are also explored as part of this classification.

"The effect of battery pack placement on vehicle dynamics of electric vehicles" is a research study conducted by Kermani, Arjmandi-Tash, and Taghavifar, which was published in the journal "International Journal of Automotive Engineering" in 2017. The aim of this study was to investigate the effect of battery pack placement on the vehicle dynamics of electric vehicles, with a particular focus on the impact of different battery configurations on vehicle stability, handling, and performance.

The study involved the use of a three-dimensional vehicle dynamics simulation model, which was used to analyze the effect of different battery pack placements on vehicle dynamics. The simulation model was developed using MATLAB Simulink software, and it incorporated a number of key parameters, including the vehicle mass, weight distribution, and center of gravity, as well as the battery pack size, shape, and position.

In order to conduct the study, the researchers first conducted a comprehensive literature review, which involved a detailed analysis of existing research on the topic of battery pack placement and its impact on electric vehicle dynamics. This literature review provided a valuable foundation for the study, and it helped to identify key research gaps and areas of further investigation.

The researchers then developed a series of simulation scenarios, which involved varying the position and configuration of the battery pack in the electric vehicle. These simulations were designed to analyze the impact of different battery pack configurations on vehicle dynamics, including vehicle stability, handling, and performance.

The findings of the study revealed that battery pack placement has a significant impact on the vehicle dynamics of electric vehicles. Specifically, the study found that a lower battery pack placement resulted in improved vehicle stability and handling, particularly in high-speed cornering maneuvers. In addition, the study found that battery pack size and shape also played a significant role in vehicle dynamics, with larger and more complex battery configurations having a greater impact on vehicle stability and handling.

Overall, the study provides valuable insights into the impact of battery pack placement on the vehicle dynamics of electric vehicles. These findings have important implications for the design and development of future electric vehicles, and they highlight the need for careful consideration of battery pack placement and configuration in order to optimize vehicle dynamics and performance.

Another study about that topic named "Design of electric vehicle battery placement based on driving cycle optimization" by Wu, Zhou, and Liu (2018) aims to investigate the optimal battery placement for electric vehicles based on driving cycle optimization. The authors argue that battery placement is a crucial factor in determining the overall performance and range of electric vehicles. The study explores the relationship between battery placement and driving cycles, as well as the impact of battery placement on the vehicle's weight distribution, stability, and handling.

The authors conducted a comprehensive review of the existing literature on electric vehicle battery placement and driving cycle optimization. They also developed a simulation model to evaluate the impact of different battery placements on the vehicle's performance, taking into account factors such as energy consumption, driving range, and vehicle dynamics. The simulation model was based on a commercially available electric vehicle with a lithium-ion battery pack, and the authors used MATLAB software to perform the simulations.

The results of the study indicate that the optimal battery placement depends on the driving cycle. The authors found that placing the battery in the rear of the vehicle is optimal for urban driving, while placing the battery in the front is optimal for highway driving. The study also shows that the weight distribution of the vehicle is an important factor in determining the optimal battery placement. A more balanced weight distribution improves the stability and handling of the vehicle, leading to better overall performance.

The authors also conducted a sensitivity analysis to evaluate the impact of different factors on the optimal battery placement, including the battery capacity, vehicle weight, and driving speed. They found that the optimal battery placement is highly dependent on these factors, and that a one-size-fits-all approach to battery placement is not effective.

Third researched thesis is "Investigation on the impact of battery weight distribution on vehicle dynamics using a vehicle model and a driving simulator" by Tang, Chen, and Xu (2019). The aim of that thesis is to investigate the effect of battery weight distribution on vehicle dynamics using both a vehicle model and a driving simulator.

The authors conducted a series of experiments on a driving simulator and used a vehicle model to analyze the impact of battery weight distribution on vehicle dynamics, specifically in terms of handling and stability. They tested three different battery weight distributions: front-heavy, rear-heavy, and evenly distributed. The driving simulator was used to evaluate the handling performance of the vehicle under different driving conditions, while the vehicle model was used to analyze the impact of battery weight distribution on the vehicle's center of gravity, weight distribution, and handling characteristics.

The authors found that the battery weight distribution has a significant impact on vehicle dynamics, and that a front-heavy battery placement can result in poor handling and stability, especially during emergency maneuvers. Conversely, a rear-heavy battery placement can improve stability but negatively affect handling. An evenly distributed battery weight was found to be optimal for both handling and stability.

To analyze the impact of battery weight distribution on vehicle dynamics, the authors used a vehicle model to calculate the center of gravity, weight distribution, and handling characteristics of the vehicle under different battery weight distributions. They then used a driving simulator to evaluate the handling performance of the vehicle under different driving conditions.

The final thesis that is researched is "Design and simulation of electric vehicle based on dynamic analysis of battery placement," Oinam and Deb (2018) explore the impact of battery placement on the performance of electric vehicles (EVs). The authors' main objective is to determine the optimal location for the battery pack that maximizes the EV's driving range, energy efficiency, and overall performance.

The study utilizes a simulation-based approach to model the EV and battery pack dynamics. The simulation software used for this study is ANSYS Fluent, which employs a multi-physics approach to simulate the thermal, electrical, and mechanical behavior of the EV and battery pack. The simulation is run with different battery pack placements, and the results are compared to identify the optimal location.

The authors find that battery placement significantly impacts the performance of EVs, and the optimal location depends on a variety of factors such as vehicle weight, distribution, and driving conditions. The study shows that placing the battery pack at the center of the vehicle results in the highest energy efficiency and driving range. The authors also note that the battery placement affects the vehicle's weight distribution and stability, which could impact handling and safety.

To validate the simulation results, the authors conduct experiments on a real EV prototype. The experimental results confirm the simulation findings and demonstrate the importance of battery placement on the performance of EVs.

2.2. Battery Electric Vehicles

The history of electric vehicles (EVs) dates back to the early 19th century when inventors began experimenting with electric power as an alternative to steam-powered vehicles. The first electric vehicle was invented by Scottish inventor Robert Anderson in 1832, which was powered by non-rechargeable primary cells (Figure 2.1). In the following years, various inventors around the world made significant contributions to the development of electric vehicles.

Figure 2.1. Electric car that is invented by Robert Anderson (URL-1)

The first rechargeable battery-powered electric vehicle was developed by French physicist Gaston Planté in 1859. This invention laid the foundation for the modern battery technology that powers today's EVs. In 1881, French engineer Gustave Trouvé developed a three-wheeled electric vehicle that could carry two passengers, which is considered to be the first commercially successful electric vehicle.

In the early 20th century, electric vehicles were popular for their ease of use, low noise, and zero emissions. They were used for urban transportation, mail delivery, and even as taxis in cities such as London, Paris and New York. However, the introduction of the Ford Model T in 1908, which was more affordable and could travel longer distances, led to a decline in the popularity of electric vehicles (Figure2.2).

Figure 2.2. Ford Model T (URL-2)

During the 1960s and 1970s, concerns about air pollution and energy independence led to a renewed interest in electric vehicles. In 1966, General Motors developed the first modern electric vehicle, the "Electrovair", which was based on the Chevrolet Corvair. However, due to limitations in battery technology, the vehicle was not commercially viable.

In the 1990s, advances in battery technology and environmental concerns led to the development of the first mass-produced electric vehicles. In 1996, General Motors introduced the EV1, which was the first production electric vehicle designed for everyday use. However, the vehicle was only available for lease and was ultimately discontinued due to low sales.

In 2008, Tesla Motors introduced the Tesla Roadster, which was the first highway-capable electric vehicle with a range of over 200 miles (320 kilometers) per charge. The success of the Tesla Roadster helped to create a market for high-performance electric vehicles, and today Tesla is one of the leading manufacturers of electric vehicles (Figure 2.3).

Figure 2.3. Tesla Roadster (URL-3)

TOGG, which stands for Türkiye'nin Otomobili Girişim Grubu (Turkey's Automobile Initiative Group), is a recent development in the history of EVs in Turkey (Figure 2.4). TOGG was established in 2018 with the aim of producing Turkey's first domestically produced electric vehicle. The project is backed by a consortium of five Turkish companies: Anadolu Group, BMC, Kök Group, Turkcell, and Zorlu Holding. The TOGG project is seen as a major step towards transforming Turkey's automotive industry and reducing the country's dependence on imported vehicles and fossil fuels. The company's first prototype, the TOGG C-SUV, was unveiled in December 2019, and the first production models roll off the assembly line in late 2022. The success of TOGG will not only promote the use of EVs in Turkey but also contribute to the global efforts towards sustainability and reducing carbon emissions.

Figure 2.4. TOGG T10X (URL-4)

To optimize the performance, safety, and longevity of these batteries, TOGG will rely on sophisticated monitoring and control systems that can accurately measure the state of health (SoH) and state of charge (SoC) of the battery pack.

The SoH of a battery refers to its current capacity and ability to deliver power relative to its original state when it was new. Over time, batteries degrade due to various factors such as usage, temperature, and aging, which can reduce their SoH and limit their lifespan. TOGG's battery management system (BMS) will constantly monitor the SoH of the battery pack using various sensors and algorithms and adjust the charging and discharging cycles accordingly to prevent overcharging, undercharging, or overheating. The BMS will also alert the driver or maintenance personnel if the SoH drops below a certain threshold, indicating the need for replacement or repair.

The SoC of a battery refers to its current level of stored energy relative to its total capacity. Knowing the SoC is critical for determining the range, performance, and safety of an EV. TOGG's BMS will measure the SoC of the battery pack using a combination of voltage, current, and temperature sensors, and calculate the available range and remaining time based on the driving conditions and behavior. The BMS will also regulate the charging and discharging of the battery pack to maintain the SoC within safe and optimal limits and prevent over-discharging or overcharging that can damage the battery or reduce its lifespan. The BMS will also provide real-time feedback to the driver about the SoC status and estimated range through the instrument cluster or infotainment system.

In recent years, the popularity of electric vehicles has increased rapidly due to concerns about climate change and the increasing affordability of EVs. Governments around the world are promoting the adoption of electric vehicles through incentives such as tax credits, subsidies, and the construction of charging infrastructure.

2.2.1 All-Electric Vehicles

Electric vehicles (EVs) have gained a lot of attention in recent years due to their potential to reduce emissions and dependence on fossil fuels. They offer several advantages over conventional vehicles, including high efficiency, lower operating costs, and reduced greenhouse gas emissions. One of the main advantages of EVs is their high efficiency. Unlike internal combustion engine vehicles, which lose a significant amount of energy through heat and friction, EVs use electric motors that convert up to 80% of the energy stored in the battery to power the wheels. This results in higher energy efficiency, lower fuel costs, and less pollution.

Another advantage of EVs is their lower operating costs. EVs are more energy-efficient than conventional vehicles, which means they require less energy to operate. In addition, EVs have fewer moving parts, which results in less wear and tear and lower maintenance costs. Furthermore, as the cost of batteries continues to decrease, the cost of EVs is becoming more competitive with conventional vehicles.

EVs also offer reduced greenhouse gas emissions. As they run on electricity, which can be generated from renewable sources such as wind or solar power, they emit little to no greenhouse gases. In addition, the overall carbon footprint of an EV is lower than that of a conventional vehicle, even when considering the emissions generated during the production of the battery.

However, EVs still have some disadvantages that limit their widespread adoption. One of the main disadvantages is the high cost of purchasing an EV. The battery system is the most expensive component of an EV, and although the cost of batteries is decreasing, it is still a significant expense. This can make EVs less accessible to many consumers, especially those with lower incomes.

Another disadvantage of EVs is their limited driving range. Although the range of EVs is increasing, they still have a shorter driving range compared to conventional vehicles. This can make them less practical for long-distance travel, and also creates a need for a charging infrastructure that is not yet fully developed in many parts of the world.

EVs also face some challenges related to the production and disposal of batteries. The production of batteries requires significant amounts of energy and raw materials, which can have environmental impacts. Additionally, the disposal of batteries can also be problematic, as they contain hazardous materials that require proper handling and recycling.

2.2.2 Hybrid Electric Vehicles

Hybrid electric vehicles (HEVs) are a type of vehicle that combines an internal combustion engine (ICE) with one or more electric motors to provide propulsion. There are two main types of HEVs: series hybrids and parallel hybrids. In a series hybrid, the ICE is used to generate electricity, which is then used to power the electric motor. In a parallel hybrid, both the ICE and electric motor are used to power the wheels (Figure 2.5)

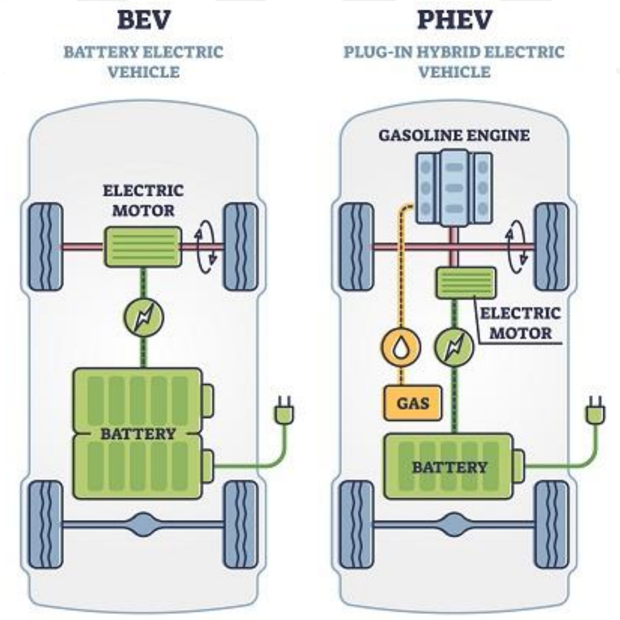


Figure 2.5. Difference between EVs (URL-5)

One of the main advantages of HEVs is their improved fuel efficiency and reduced emissions compared to traditional ICE vehicles. The electric motor assists the ICE during acceleration and at low speeds, allowing for more efficient operation of the engine. HEVs also have regenerative braking systems, which convert kinetic energy into electrical energy during braking, further improving efficiency.

Another advantage of HEVs is their flexibility in terms of power sources. HEVs can use gasoline, diesel, or alternative fuels such as ethanol or biodiesel as their primary fuel source, while still benefiting from the added efficiency of the electric motor. This flexibility can also make HEVs a good transition vehicle as the world moves towards fully electric vehicles.

However, there are also some disadvantages to HEVs. They tend to be more expensive than traditional ICE vehicles, due to the added complexity of the hybrid system. In addition, HEVs require regular maintenance on both the ICE and electric components, which can be more expensive than maintenance on a traditional ICE vehicle. HEVs also tend to be heavier than traditional ICE vehicles due to the added weight of the electric components, which can impact handling and performance.

There are many examples of HEVs on the market today, including the Toyota Prius, Honda Insight, and Ford Fusion Hybrid. The Toyota Prius is perhaps the most well-known HEV, with over 4 million units sold worldwide since its introduction in 1997. The Honda Insight was the first HEV to be sold in the United States, and the Ford Fusion Hybrid has won numerous awards for its efficiency and performance.

In recent years, plug-in hybrid electric vehicles (PHEVs) have also become popular. PHEVs have larger battery packs than traditional HEVs, allowing them to operate solely on electric power for a limited range before the ICE kicks in. This can offer even greater fuel efficiency and emissions reductions, but at a higher cost than traditional HEVs. Examples of PHEVs include the Chevrolet Volt and Toyota Prius Prime (Zhang et al., 2022).

2.2.2.1 Serial Hybrid Electric Vehicles

Serial Hybrid Electric Vehicles (SHEVs), also known as range-extended electric vehicles, have been gaining popularity as an alternative to conventional internal combustion engine (ICE) vehicles due to their superior fuel efficiency and reduced emissions. In a SHEV, the primary power source is an electric motor that is powered by a battery pack. However, the battery pack is not directly charged by an external power source like in a plug-in hybrid electric vehicle (PHEV), instead, it is charged by a small ICE generator that runs on gasoline or diesel fuel. The generator supplies power to the electric motor, which in turn powers the wheels of the vehicle (Bhatia et al., 2005) (Figure2.6).

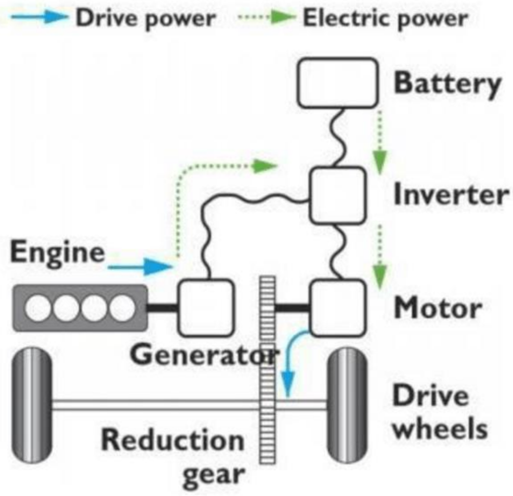


Figure 2.6. Structure of a series hybrid vehicle (Zia, 2017)

The main advantage of SHEVs is their ability to travel long distances without the need for frequent recharging, making them suitable for long commutes or road trips. The ICE generator provides additional power to the electric motor when the battery pack runs low, effectively extending the vehicle's range. Additionally, SHEVs have lower emissions than conventional ICE vehicles, as the ICE generator runs at a constant speed and is optimized for efficiency, reducing fuel consumption and emissions. SHEVs also allow for regenerative braking, where energy is captured during braking and stored in the battery pack, further improving efficiency.

However, SHEVs also have some disadvantages. The ICE generator adds complexity and weight to the vehicle, reducing overall efficiency and increasing maintenance costs. Additionally, the ICE generator still produces emissions, although at a lower rate than a conventional ICE vehicle. SHEVs are also typically more expensive than conventional ICE vehicles due to the added technology and components.

Some examples of SHEVs include the BMW i3 with Range Extender, the Chevrolet Volt, and the Fisker Karma. The BMW i3 with Range Extender has an electric range of 110 miles and a total range of 180 miles when the ICE generator is used. The Chevrolet Volt has an electric range of 53 miles and a total range of 420 miles when the ICE generator is used. The Fisker

Karma has an electric range of 50 miles and a total range of 230 miles when the ICE generator is used (Cox & Leamy, 2016).

2.2.2.2 Parallel Hybrid Electric Vehicles

Parallel Hybrid Electric Vehicles (PHEVs) are another type of hybrid vehicle. In these vehicles, both the engine and electric motor are connected to the transmission and can individually or simultaneously drive the wheels. Unlike series hybrids, PHEVs can operate in all-electric mode, gasoline mode, or a combination of both, depending on the driving conditions and battery charge (Zakrzewicz et al. 2020).

PHEVs have several advantages over conventional vehicles, including improved fuel economy, reduced emissions, and better performance. Since the electric motor provides additional power, the engine can be smaller, which leads to better fuel economy. The electric motor can also be used to provide extra power during acceleration, resulting in better performance. PHEVs can also reduce emissions since they can operate in all-electric mode, which produces no tailpipe emissions.

However, PHEVs also have some disadvantages. The battery system and electric motor increase the cost of the vehicle, which can make them more expensive than conventional vehicles. Additionally, PHEVs require charging infrastructure, which is not as widely available as gasoline stations. The added weight of the battery system and electric motor can also reduce the overall efficiency of the vehicle.

Some examples of PHEVs include the Toyota Prius Plug-in Hybrid, Chevrolet Volt, and Ford Fusion Energi. These vehicles can operate in all-electric mode for short distances, but switch to gasoline mode once the battery charge is depleted. PHEVs are a popular choice for consumers who want the benefits of electric vehicles but have concerns about range anxiety and the availability of charging infrastructure (Figure 2.7).

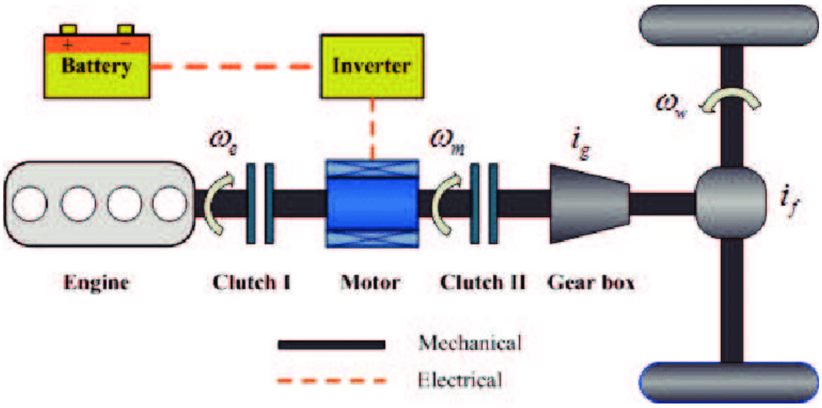


Figure 2.7. Structure of a parallel hybrid vehicle (Fan, Zhang, & Shen, 2015).

2.2.2.3 Serial-Parallel Hybrid Electric Vehicles

Serial-Parallel Hybrid Electric Vehicles, also known as Power-Split Hybrid Electric Vehicles, combine both series and parallel hybrid architectures. In this configuration, the vehicle can operate as a series or parallel hybrid or switch between the two, depending on driving conditions and energy requirements. This type of hybrid electric vehicle has become increasingly popular in recent years due to its flexibility and efficiency.

In a Serial-Parallel Hybrid Electric Vehicle, the powertrain consists of a gasoline engine, electric motor/generator, battery pack, and power-split device, such as a planetary gear set. The engine can either drive the wheels directly or charge the battery pack, while the electric motor/generator can provide additional power to the wheels or operate as a generator to charge the battery pack.

During low-speed and low-load driving conditions, the vehicle operates in full-electric mode, drawing power from the battery pack and electric motor. As the vehicle speed increases, the gasoline engine turns on and supplements the electric motor to provide additional power to the wheels. During high-speed and high-load conditions, the engine provides most of the power to the wheels while the electric motor/generator supplements the engine and recharges the battery pack.

One of the main advantages of Serial-Parallel Hybrid Electric Vehicles is their improved fuel efficiency compared to conventional gasoline-powered vehicles. The combination of electric and gasoline power allows for better fuel economy and reduced emissions. They also have the ability to operate in full-electric mode for short distances, reducing dependence on gasoline.

However, Serial-Parallel Hybrid Electric Vehicles can be more complex and expensive to manufacture than other types of hybrid electric vehicles due to the additional components required. They also require more maintenance than conventional gasoline-powered vehicles due to the complexity of the powertrain. Additionally, the battery pack may require replacement after a certain number of years or miles, adding to the overall cost of ownership (Moawad et al., 2023).

Some examples of Serial-Parallel Hybrid Electric Vehicles include the Toyota Prius, Ford C-Max, and Chevrolet Volt. The Toyota Prius, in particular, has become synonymous with the hybrid electric vehicle market and has been popular among consumers for its reliability, fuel efficiency, and low emissions (Thyagarajan, 2011).

2.2.3 Plug-in Hybrid Electric Vehicles

Plug-in hybrid electric vehicles (PHEVs) are an increasingly popular form of transportation that combines the functionality of both electric vehicles and hybrid electric vehicles. Unlike conventional hybrid electric vehicles, PHEVs have larger battery packs that can be recharged from an external source, such as a wall socket or charging station. This allows them to operate in all-electric mode for longer periods of time and with higher speeds. PHEVs are designed to use both electric and gasoline power sources to optimize efficiency and reduce emissions. When the battery is depleted, the vehicle will automatically switch to a hybrid mode, which combines the use of both electricity and gasoline to power the vehicle.

There are two main types of PHEVs: series and parallel. In a series PHEV, the gasoline engine is used to generate electricity for the electric motor, which in turn powers the wheels. The gasoline engine is not connected directly to the wheels, which means that the vehicle can be driven in all-electric mode for a longer period of time. In a parallel PHEV, both the electric motor and the gasoline engine are connected to the wheels and can power the vehicle simultaneously or individually. This provides more power and a longer driving range compared to a series PHEV. A third type of PHEV is the series-parallel PHEV, which combines the features of both series and parallel PHEVs to optimize efficiency and performance.

PHEVs have many advantages over conventional gasoline-powered vehicles. They emit fewer greenhouse gases and pollutants, which helps to reduce air pollution and improve public health. They also reduce dependence on oil and can save consumers money on fuel costs.

Additionally, PHEVs have a longer range than fully electric vehicles, making them more practical for longer trips.

However, there are also some disadvantages to PHEVs. They are typically more expensive than conventional gasoline-powered vehicles, due to the cost of the battery pack and other components. The battery pack also adds weight to the vehicle, which can reduce overall performance and handling. Additionally, the availability of charging infrastructure is still limited in many areas, which can make it difficult for drivers to find a charging station when needed.

Despite these drawbacks, PHEVs are gaining popularity as a viable alternative to conventional gasoline-powered vehicles. Major automakers such as Toyota, Ford, and General Motors have introduced PHEV models, and many new models are expected to hit the market in the coming years. With advances in battery technology and an increase in charging infrastructure, PHEVs have the potential to become a mainstream form of transportation and play a significant role in reducing greenhouse gas emissions and improving air quality (Figure 2.8)

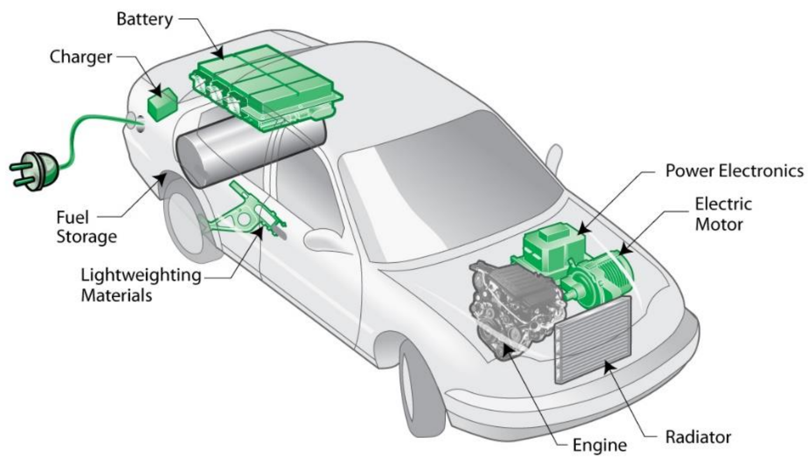


Figure 2.8. Plug-in hybrid electric vehicle (PHEV) diagram (URL-6)

2.3 Types of Motor Used in Hybrid and Electric Vehicles

Hybrid and electric vehicles are becoming increasingly popular as people seek to reduce their carbon footprint and dependence on fossil fuels. One of the key components of these vehicles is the electric motor, which converts electrical energy stored in the battery into mechanical energy to power the vehicle. There are several types of electric motors used in hybrid and electric vehicles, each with their unique features, advantages, and disadvantages. In this article, the most common types of electric motors used in these vehicles and their characteristics was discussed (Bairwa, Supraja, Pratiksha, & Sumanth, 2023).

2.3.1. DC Motors

DC motors, also known as brushed motors, are one of the most commonly used types of motors in electric and hybrid vehicles. These motors convert electrical energy into mechanical energy by creating a magnetic field in the stator, which interacts with the magnetic field produced by the rotor to generate torque. The stator of a DC motor consists of a series of coils that are arranged in a circular pattern around the motor's axis. The rotor, on the other hand, is made up of a series of permanent magnets that are arranged in a cylindrical shape.

One of the main advantages of DC motors is their simplicity and low cost, making them an attractive option for use in hybrid and electric vehicles. They are also highly efficient, with efficiency levels of up to 95%, meaning that they convert almost all of the electrical energy supplied to them into mechanical energy. This results in better performance, longer driving range, and improved fuel economy.

However, DC motors also have some disadvantages. One of the most significant drawbacks is their limited speed range, which can limit their usefulness in certain applications. They also require regular maintenance due to the brushes, which can wear out over time and require replacement. Additionally, DC motors are not as durable as some other types of motors, such as AC motors or switched reluctance motors, which can be a concern for vehicle manufacturers.

Despite these drawbacks, DC motors remain a popular choice for hybrid and electric vehicles due to their cost-effectiveness and reliability. They are commonly used in smaller vehicles, such as electric bicycles and scooters, as well as in some larger vehicles, such as hybrid buses and trucks.

2.3.1.1 Series-Wound DC Motors

Series-wound DC motors are the oldest type of DC motor and have been used in electric vehicles for several decades. These motors are highly efficient and can provide high torque at low speeds, making them optimal for use in electric vehicles. However, they have a low power-to-weight ratio and require regular maintenance due to the wear and tear on their brushes and commutators.

2.3.1.2 Permanent Magnet DC Motors

Permanent magnet DC motors are the most commonly used type of DC motor in electric vehicles due to their high power-to-weight ratio and low maintenance requirements. These motors use a permanent magnet to create a magnetic field that drives the rotor, eliminating the need for brushes and commutators. They are highly efficient, reliable, and offer excellent torque characteristics. However, they can be more expensive than series-wound DC motors.

2.3.2 AC Motors

AC motors are another common type of electric motor used in hybrid and electric vehicles. These motors operate using alternating current (AC) and are more commonly found in high-performance electric vehicles due to their ability to provide high power outputs. AC motors can be further classified into two types: synchronous and asynchronous motors.

Synchronous AC motors are widely used in electric vehicles due to their high-power density and efficiency. These motors have a rotor that rotates at the same speed as the magnetic field generated by the stator winding. This results in the rotor having a fixed position with respect to the stator, making it more efficient in converting electrical energy to mechanical energy. Synchronous AC motors are also known for their high torque output, making them suitable for use in high-performance electric vehicles (URL-7).

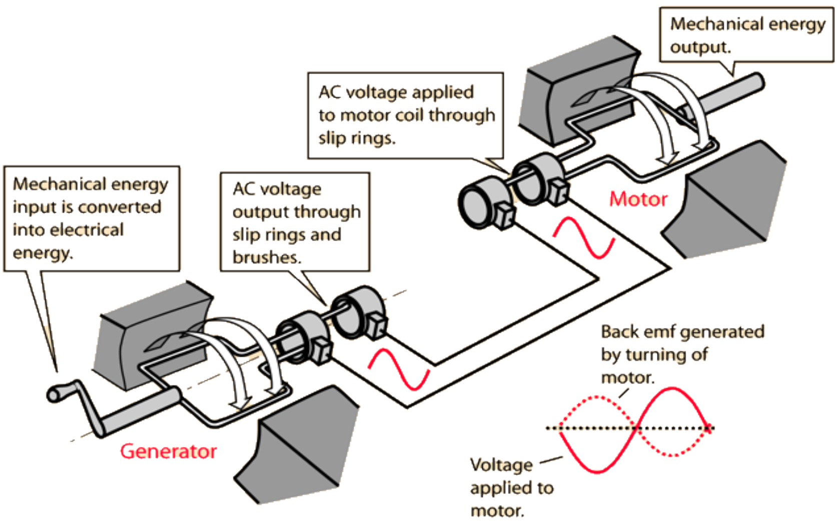


Figure 2.9. AC Motor (URL-7)

Asynchronous AC motors are also known as induction motors. These motors have a rotor that rotates at a slightly slower speed than the magnetic field generated by the stator winding. This difference in speed results in a rotating magnetic field that induces a current in the rotor, causing it to rotate. Asynchronous AC motors are commonly used in smaller electric vehicles and hybrid vehicles due to their lower cost and simplicity in design (Iqbal, Moinoddin, & Reddy, 2021).

One of the advantages of AC motors is their ability to operate over a wider range of speeds compared to DC motors. This makes them optimal for use in electric vehicles as they can provide sufficient torque at both low and high speeds, resulting in better acceleration and overall performance. Additionally, AC motors are more efficient compared to DC motors, resulting in longer battery life and a higher driving range.

However, one of the disadvantages of AC motors is their more complex control systems. Synchronous AC motors require more complex control systems, such as a variable frequency drive, to maintain a constant speed, resulting in higher costs. Asynchronous AC motors, on the other hand, have a simpler control system, but are less efficient compared to synchronous AC motors, resulting in lower overall performance.

2.3.2.1 Induction Motors

Induction motors are the most commonly used type of AC motor in electric vehicles due to their high efficiency, low cost, and simple design. These motors use a rotor that does not have any permanent magnets, making them less expensive than synchronous motors. However, they have lower power density and torque density than synchronous motors and are less efficient at high speeds (Iqbal, Moinoddin, & Reddy, 2021).

2.3.2.2 Synchronous Motors

Synchronous motors are another type of AC motor used in hybrid and electric vehicles. These motors use permanent magnets to create a magnetic field that drives the rotor. They are highly efficient, have a high power-to-weight ratio, and provide excellent torque characteristics. However, they are more expensive than induction motors and require a more complex control system.

2.3.3. Switched Reluctance Motors

Switched reluctance motors (SRMs) are gaining popularity as a viable option for use in electric and hybrid vehicles due to their high efficiency, low cost, and robustness. SRMs operate by utilizing the magnetic attraction and repulsion between the rotor and stator poles. Unlike permanent magnet motors, SRMs have no permanent magnets and instead rely on the magnetic reluctance of the ferromagnetic materials in the rotor and stator to produce torque.

One of the main advantages of SRMs is their simple construction, which makes them less expensive to manufacture than other motor types. They also have a higher power density than other motors, which means they can deliver the same power output with a smaller size and weight. Additionally, SRMs have a wide operating range, making them suitable for a variety of applications.

Another advantage of SRMs is their high efficiency. SRMs have fewer losses than other motor types due to their simple construction, lack of permanent magnets, and ability to operate at high speeds without generating excessive heat. This high efficiency translates into longer driving ranges and lower energy consumption, making SRMs an attractive option for electric and hybrid vehicles.

SRMs are also highly reliable due to their robust construction. Unlike other motor types, SRMs do not have permanent magnets that can demagnetize over time. Additionally, SRMs have fewer moving parts, reducing the risk of mechanical failure. These characteristics make SRMs optimal for use in harsh environments or applications that require high reliability.

Despite these advantages, SRMs also have some disadvantages. One of the main challenges of SRMs is their high torque ripple, which can lead to unwanted vibrations and noise. To reduce torque ripple, designers often implement complex control algorithms or use additional hardware, which can increase the cost of the motor.

Another challenge of SRMs is their limited speed range. Unlike other motor types, SRMs have a maximum operating speed, beyond which the motor becomes unstable. This limits the maximum power output of the motor and makes it less suitable for high-performance applications.

2.4. Battery Types Used in Electric Vehicles

Electric vehicles rely heavily on their batteries as their primary source of power. The choice of battery technology plays a crucial role in determining the performance, cost, and range of electric vehicles. Currently, lithium-ion batteries are the most widely used batteries in electric vehicles due to their high energy density, longer life span, and low self-discharge rate. However, there are still some limitations and challenges that need to be addressed, such as battery capacity, charging time, number of discharge cycles, durability, and cost.

One of the key challenges in battery technology is improving the energy density of the battery. High energy density is essential to increase the range of electric vehicles and reduce the battery weight and size. Researchers are exploring different chemistries to develop batteries with higher energy density. One of the promising battery technologies is lithium-sulfur batteries, which have the potential to provide higher energy density than lithium-ion batteries. Another promising technology is lithium-metal or lithium-ion polymer batteries, which offer higher energy density and faster charging times.

The choice of battery technology also depends on the type of electric vehicle and its drive system. For example, plug-in hybrid electric vehicles (PHEVs) typically use smaller battery packs as they rely on both the battery and the internal combustion engine for power. On the other hand, battery electric vehicles (BEVs) rely solely on the battery for power and require larger battery packs with higher energy density to achieve longer driving ranges (Singh, & Tiwari, 2019).

In addition to the technical challenges, the cost of batteries is also a significant factor that affects the adoption of electric vehicles. The cost of batteries has been declining in recent years, but it still accounts for a significant portion of the overall cost of an electric vehicle. The high cost of batteries is due to the complex manufacturing process and the high cost of raw materials such as lithium, cobalt, and nickel. Researchers are exploring new materials and manufacturing processes to reduce the cost of batteries and make electric vehicles more affordable.

2.4.1. Lead – Acid Battery

Lead-acid batteries are a type of rechargeable battery that has been in use for over 150 years. They are known for their low cost, high reliability, and ease of maintenance. Although lead-acid batteries are widely used in traditional vehicles, they have also found their way into electric vehicles due to their relatively low cost and easy availability.

The lead-acid battery is composed of lead plates and an electrolyte solution consisting of sulfuric acid. The plates are placed in cells and then submerged in the electrolyte solution, which activates the battery. When an electric current is applied, lead ions in the electrolyte are attracted to the lead plates, creating a chemical reaction that generates electricity. Lead-acid batteries are relatively heavy, but they can provide high power output and are well-suited for short-range electric vehicles, such as golf carts and forklifts.

Lead-acid batteries have several advantages. First, they are widely available and relatively low-cost compared to other battery technologies. Second, they have a long-life span and can be recharged many times. Third, lead-acid batteries are easy to maintain and can be serviced by most automotive technicians. Finally, lead-acid batteries are reliable and have been used in the automotive industry for many years.

However, lead-acid batteries also have several disadvantages. They are relatively heavy and have a low energy density, which means they have limited range and are not well-suited for long-range electric vehicles. Lead-acid batteries are also sensitive to high temperatures and require careful temperature control during charging and operation. Furthermore, they contain toxic materials that require careful handling and disposal, which can increase their overall cost.

Despite these disadvantages, lead-acid batteries remain an important technology for electric vehicles, particularly in low-speed applications such as golf carts, forklifts, and other similar vehicles. In recent years, some companies have developed advanced lead-acid batteries that have improved energy density and longer cycle life, making them more suitable for use in electric vehicles. Overall, while lead-acid batteries may not be the most advanced or high-performing technology available, they are still an important part of the electric vehicle landscape and are likely to remain so for many years to come.

2.4.2. Nickel-Metal Hydrite Battery

Nickel-metal hydride (NiMH) batteries are another type of rechargeable battery commonly used in electric vehicles. NiMH batteries use a nickel oxyhydroxide positive electrode and a hydrogen-absorbing negative electrode. They have a higher energy density than lead-acid batteries and are less toxic than their predecessor, nickel-cadmium (NiCad) batteries. NiMH batteries have been used in electric vehicles since the 1990s, and they continue to be used in some hybrid electric vehicles today (Besenhard, 2008).

One of the advantages of NiMH batteries is that they have a higher energy density than lead-acid batteries. This means that they can store more energy in the same amount of space, allowing for longer driving ranges in electric vehicles. NiMH batteries also have a higher cycle life than lead-acid batteries, meaning they can be charged and discharged more times before they need to be replaced. Additionally, NiMH batteries are less toxic than NiCad batteries, making them a more environmentally friendly option.

However, there are also some disadvantages to NiMH batteries. One of the main drawbacks is that they are more expensive than lead-acid batteries. This higher cost is due to the more complex manufacturing process and the higher cost of the raw materials used in NiMH batteries. NiMH batteries also have a lower power density than lithium-ion batteries, which means that they cannot deliver as much power in a short amount of time. This can affect the performance of electric vehicles, particularly during acceleration (Besenhard, 2008).

2.4.3. Lithium-ion Battery

Lithium-ion (Li-ion) batteries have become the most popular and widely used type of battery in electric vehicles. Li-ion batteries are composed of a cathode, an anode, and an electrolyte. The cathode is typically made of a metal oxide, such as lithium cobalt oxide (LCO), lithium nickel manganese cobalt oxide (NMC), or lithium iron phosphate (LFP). The anode is usually made of graphite, and the electrolyte is a lithium salt in an organic solvent (Besenhard, 2008).

One of the main advantages of Li-ion batteries is their high energy density, which means they can store a large amount of energy in a relatively small and lightweight package. This makes them optimal for use in electric vehicles, where weight and space are important factors. Li-ion batteries also have a long cycle life, meaning they can be charged and discharged many times before they begin to degrade (Besenhard, 2008).

Another advantage of Li-ion batteries is their high efficiency. They can convert more than 90% of the energy stored in them into usable electricity, which means less energy is wasted as heat. Li-ion batteries also have a low self-discharge rate, which means they can hold their charge for a long time when not in use.

However, Li-ion batteries also have some drawbacks. They can be expensive to produce, especially if they use high-quality materials. Li-ion batteries can also be sensitive to temperature, which can affect their performance and lifespan. In addition, they can be prone to thermal runaway, which is a rapid, uncontrollable increase in temperature that can cause the battery to catch fire or explode.

2.4.4. LiFePO4 battery

Lithium Iron Phosphate (LiFePO4) is a type of lithium-ion battery that has been gaining popularity in recent years, particularly in electric vehicle applications. LiFePO4 is a type of cathode material that offers several advantages over other types of lithium-ion batteries, such as higher energy density, longer cycle life, and improved safety (Besenhard, 2008).

One of the main advantages of LiFePO4 batteries is their high energy density. This means that they can store more energy in the same amount of space as other types of batteries. As a result, LiFePO4 batteries are a popular choice for electric vehicles, where space is at a premium and energy density is critical to achieving longer driving ranges (Besenhard, 2008).

Another advantage of LiFePO4 batteries is their longer cycle life. Unlike other types of lithium-ion batteries, LiFePO4 batteries can be cycled up to 2,000 times without significant loss of capacity. This means that they can last much longer than other types of batteries, making them a cost-effective choice in the long run.

Safety is another important advantage of LiFePO4 batteries. They are much less prone to overheating and thermal runaway than other types of lithium-ion batteries, making them less likely to catch fire or explode. This is because LiFePO4 is a very stable and non-reactive material, even at high temperatures.

One potential disadvantage of LiFePO4 batteries is their lower voltage and specific energy compared to other types of lithium-ion batteries. This means that they may not be suitable for applications that require high power output or high energy density, such as some electric vehicles. However, advancements in LiFePO4 technology are addressing these issues, and they are becoming more widely used in electric vehicle applications.

2.4.5. LMO batteries

LMO (Lithium Manganese Oxide) is another type of lithium-ion battery that has been used in electric vehicles. It has a higher energy density compared to lead-acid and NiMH batteries, making it more efficient and lighter. The cathode material of LMO batteries is made of manganese oxide and lithium, while the anode is made of graphite. LMO batteries have a higher operating voltage and longer cycle life than other types of lithium-ion batteries, which means they can be charged and discharged more times before they start to lose capacity (Besenhard, 2008).

One of the main advantages of LMO batteries is their thermal stability. They are less prone to overheating and thermal runaway than other lithium-ion batteries, making them safer and more reliable. This is because the manganese oxide in the cathode acts as a stabilizing agent, helping to prevent the formation of lithium dendrites that can cause short circuits and thermal runaway.

Another advantage of LMO batteries is their relatively low cost compared to other types of lithium-ion batteries. This is because manganese is abundant and inexpensive, making it a cost-effective material for battery production. Additionally, LMO batteries have a high power output, which makes them suitable for use in electric vehicles and other applications that require high power.

However, LMO batteries also have some disadvantages. One of the main drawbacks is their lower energy density compared to other lithium-ion batteries, which means they have a shorter range and may require more frequent charging. They are also less durable than other types of lithium-ion batteries, and may experience a drop in capacity after several hundred cycles of charging and discharging.

2.4.6. NCA batteries

Nickel Cobalt Aluminum (NCA) is a type of lithium-ion battery commonly used in electric vehicles. It is known for its high energy density, making it a popular choice among manufacturers. The NCA battery is composed of a cathode made of lithium nickel cobalt aluminum oxide, an anode made of graphite, and an electrolyte solution. The combination of these materials allows for the flow of lithium ions between the anode and cathode, creating an electrical current that powers the vehicle.

One of the main advantages of NCA batteries is their high energy density. This means they can store more energy per unit of weight than other types of batteries, allowing electric vehicles to travel farther on a single charge. NCA batteries also have a longer lifespan compared to other lithium-ion batteries, which reduces the need for replacement and ultimately lowers costs for the consumer.

Another advantage of NCA batteries is their ability to operate in extreme temperatures, both hot and cold. This is important for electric vehicles as they need to be able to operate in a variety of climates. NCA batteries are also relatively safe and stable, with low risk of overheating or combustion.

There are also some drawbacks to NCA batteries. One is their high cost compared to other types of batteries, which can make electric vehicles more expensive. NCA batteries are also less tolerant to overcharging and over-discharging, which can reduce their lifespan and potentially cause safety issues.

2.4.7. NMC batteries

Nickel Manganese Cobalt (NMC) is a type of lithium-ion battery chemistry that is commonly used in electric vehicles. It is a relatively new technology that was developed in the early 2000s as an improvement over the previously used lithium cobalt oxide (LCO) chemistry. NMC is known for its high energy density, which allows for a longer range on a single charge, and its long cycle life, which means it can last for many charging cycles without losing capacity.

The NMC battery chemistry typically consists of a mix of nickel, manganese, and cobalt in the cathode, and a graphite anode. The exact composition of the cathode can vary depending on the specific application and manufacturer, but the most common composition is around 33% nickel, 33% manganese, and 33% cobalt. The use of these three metals in the cathode allows for a balance between energy density, power output, and cost.

One of the key advantages of NMC batteries is their high energy density. This means that they can store a large amount of energy in a relatively small package, allowing for a longer range on a single charge. NMC batteries also have a relatively long cycle life, which means they can last for many charging cycles without losing capacity. This is due to the use of stable materials in the cathode, which reduces the rate of degradation over time.

Another advantage of NMC batteries is their high-power output. This allows them to provide the necessary power for acceleration and high-speed driving. NMC batteries also have a low self-discharge rate, which means they can hold their charge for a long time when not in use. This is useful for vehicles that are parked for extended periods of time, such as electric vehicles that are used for commuting or short trips.

However, there are also some disadvantages to NMC batteries. One of the biggest is their relatively high cost compared to other battery chemistries, such as lead-acid or nickel-metal hydride. This is due to the use of expensive materials in the cathode, such as cobalt, which is a limited resource. NMC batteries also have a higher risk of thermal runaway, which can lead to fires or explosions, although this risk can be mitigated with proper design and management.

In conclusion, NMC batteries are a promising technology for electric vehicles, offering a balance between energy density, power output, and cost. While they are more expensive than some other battery chemistries, they offer a longer range and longer cycle life, making them a good choice for electric vehicles that require high performance and reliability. As battery technology continues to improve, it is likely that NMC batteries will become even more efficient and cost-effective, further increasing their appeal for electric vehicle applications.

3. MATERIALS AND METHOD

3.1. Design and Manufacturing

The provided code is a MATLAB implementation for simulating the behavior of a standard sedan vehicle in a curved road with a given radius. The program takes inputs such as the weight of the vehicle and battery, wheel coefficient of friction, vehicle dimensions, battery position, vehicle speed, and curve radius. The program then computes the position of the vehicle's center of gravity, the loads on each wheel, the handling of each tire, and the centripetal force acting on the vehicle. It also calculates the maximum curve degree that the vehicle can handle without tipping over.

The program uses several formulas to calculate these values. Firstly, the program calculates the position of the vehicle's center of gravity using the weight and position of the vehicle and battery. It then calculates the loads on each wheel by dividing the total weight of the vehicle and battery by the area of each tire. The handling of each tire is then computed by multiplying the load on each tire by the coefficient of friction. The centripetal force acting on the vehicle is calculated using the formula $F = \frac{mV^2}{r}$, where F is the force, m is the mass of the vehicle and battery, V is the vehicle speed, and r is the radius of the curve.

The program then calculates the maximum curve degree that the vehicle can handle without tipping over. It uses the formula $F = \frac{mV^2}{r}$ to calculate the centripetal force acting on the vehicle and compares it with the handling of each tire. The program selects the minimum handling value and calculates the maximum curve degree using the formula $degree = atan(wheelbase/radius)$, where wheelbase is the distance between the front and rear axles of the vehicle.

In the case of drawing a graph, the program calculates the vehicle's center of gravity for 100 evenly spaced battery positions in the X, Y, and Z axes. It then calculates the maximum curve degree for each of these positions and generates a 3D graph showing the maximum curve degree for all battery positions.

3.2. Mathematical Modelling

Modelling an electric vehicle provides a way to accurately calculate the dynamic behavior and performance characteristics of the vehicle, allowing for necessary design revisions to be made based on these calculations. Additionally, simulations can be performed according to driving cycles to conduct tests on battery life and range, as well as examine the dynamic behavior of the vehicle's engines.

Another benefit of modeling and simulation is the ability to explore and evaluate various power transmission systems to establish a stable and optimal balance. This is particularly important for hybrid electric vehicles, where the level of hybridization can be determined and the performance/power balance of the engines can be optimized for more efficient operation. By using advanced modeling techniques, such as MATLAB/Simulink, it is possible to accurately simulate a wide range of scenarios and identify potential issues before they occur, allowing for faster and more effective design iterations.

One important aspect of electric vehicle modeling is the development of accurate mathematical models that capture the vehicle's dynamic behavior. These models can include factors such as the vehicle's mass, aerodynamics, rolling resistance, and powertrain characteristics. By using mathematical formulas, such as Newton's Second Law, it is possible to accurately predict the acceleration, speed, and range of the vehicle under different driving conditions.

In addition to modeling the vehicle itself, it is also important to model and simulate the various systems that contribute to the vehicle's overall performance, such as the suspension, differential, brake, and propulsion systems. By simulating these systems, it is possible to optimize their performance and identify potential issues before they occur. For example, the suspension system can be modeled to predict how the vehicle will respond to different road conditions, while the differential can be modeled to ensure that power is distributed evenly between the wheels.

The brake system is another important component of electric vehicle modeling, as it is responsible for bringing the vehicle to a stop. By accurately modeling the brake system, it is possible to predict stopping distances and optimize brake performance for maximum safety. The propulsion system, which includes the electric motors and power electronics, is also a critical component of electric vehicle modeling. By simulating the propulsion system, it is possible to optimize efficiency and performance, and ensure that the powertrain is able to meet the vehicle's power and torque requirements (Bairwa, Supraja, Pratiksha, & Sumanth, 2023).

3.2.1. Linear Motion

In order for a vehicle to move in a linear motion, the power generated by the engines must be able to overcome the various resistances that arise during the movement. These resistances can be categorized into several types such as wind resistance, rolling resistance, hill resistance, acceleration resistance, and driving force. The driving force is the net force available for the vehicle to move forward after subtracting all the resistances from the engine power.

Figure 3.1 illustrates the drag forces acting on the vehicle in the linear X-axis. The first resistance encountered by the vehicle is wind resistance, which is caused by the air pressure acting against the vehicle's movement. The second resistance is rolling resistance, which occurs due to the friction between the tires and the ground. The third resistance is hill resistance, which is caused by the incline of the road. The fourth resistance is acceleration resistance, which is the force required to increase the vehicle's speed. Finally, the driving force is the force that propels the vehicle forward.

Understanding and calculating these resistances are crucial in determining the performance and efficiency of the vehicle. Through proper calculation and analysis, the vehicle's powertrain and battery systems can be optimized to achieve the desired level of performance and range (URL-8).

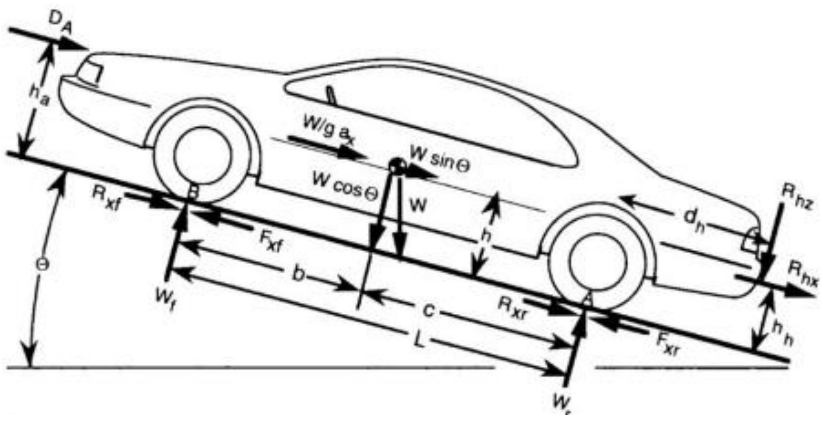


Figure 3.1. Drag forces on the vehicle (URL-8)

3.3. Mechanical Coupling

The driveline is a crucial component of an electric vehicle as it is responsible for transferring the mechanical force produced by the drive motor to the wheels. Compared to vehicles with internal combustion engines or hybrid EVs, the drivetrain in EVs is relatively simpler. In this study, a fixed ratio gearbox was utilized to ensure efficient power transmission.

Chart-3.1 illustrates the force components acting on the electric vehicle, as well as the drive force that counteracts these components to generate wheel speed. The force components include wind resistance, rolling resistance, hill resistance, and acceleration resistance. By subtracting these resistive forces from the drive force, the resulting force is used to drive the vehicle in linear motion. The block diagram in Chart-3.1 presents a clear overview of the entire process.

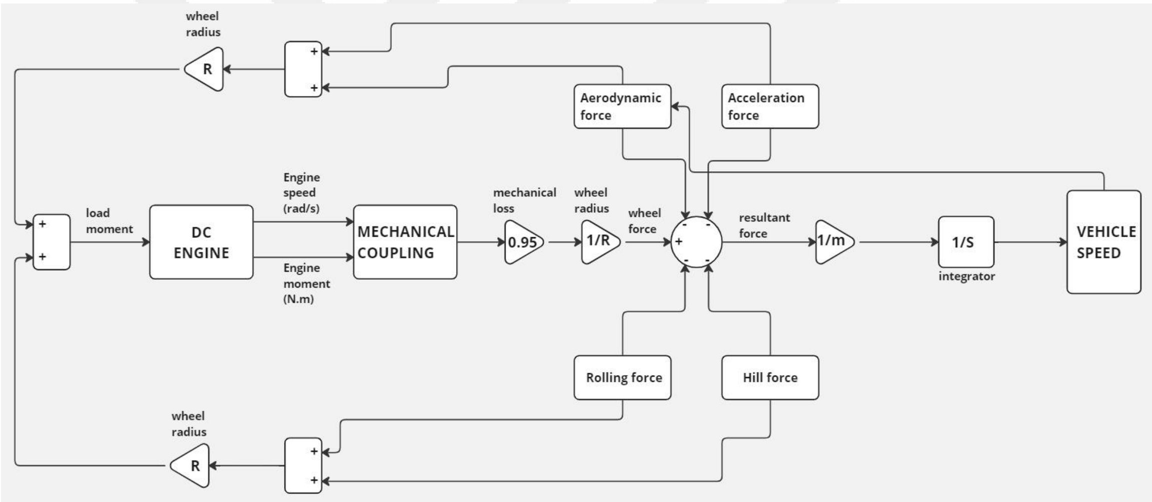


Figure 3.2. Example of Mathematical model of vehicle mechanics

The mechanical system of an electric vehicle is responsible for transferring the mechanical force generated by the electric motor to the wheels, allowing the vehicle to move. In comparison to internal combustion engines and hybrid EV's, the drivetrain of EV's is simpler, and therefore, a fixed ratio gearbox was used in this study. As shown in Chart-3.1, there are four fundamental forces acting on the vehicle, namely aerodynamic, acceleration, hill, and rolling forces. The load force that affects the engine is determined by subtracting these external forces from the force produced by the motor shaft. The load moment affecting the motor is then calculated by multiplying the load force by the wheel radius. In EV's, energy is supplied to the electric motor by the battery and the brake (regenerative braking) while the vehicle is accelerating. To achieve the necessary bidirectional flow of mechanical and electrical energy, mechanical coupling is necessary. The fixed ratio gearbox used in this study was considered sufficient, and a conversion ratio of 5 was determined.

To provide mechanical coupling in the simulation study in the MATLAB/Simulink environment, the "Speed Reducer" block was used from the "SimPowerSystems" toolbox of MATLAB, which enabled the mechanical coupling between the electric motor and the vehicle mechanics. By entering the engine speed and vehicle speed, the mechanical coupling produces the drive torque transmitted to the wheels at its output, inversely proportional to the conversion ratio. The calculation of all forces on the mathematical model was performed by reducing them to a single wheel. The force obtained from the motor is calculated by dividing the torque value obtained from the motor torque by the wheel radius. The conversion ratio of the gearbox was chosen as 5, taking into account the mechanical loss in the gearbox output shaft. Since mechanical parts such as differential and axle are not used in this system, an adequate rate of 5% was accepted. Finally, the force transmitted to the wheel is obtained by multiplying the motor torque by 0.95 and dividing by the wheel radius (Zou, Li, Hu, & Chamaillard, 2018).

4. RESULTS AND DISCUSSIONS

To test this code in several different scenarios, some tests will be performed and their outputs will be analyzed.

Calculation of total vehicle mass:

This calculation simply adds the mass of the vehicle (m1) to the mass of the battery (m2) to determine the total mass of the vehicle and battery, which is denoted as "topmass".

$$topmass = m1 + m2$$

Calculation of center of gravity coordinates:

The x, y, and z coordinates of the center of gravity are important parameters that can be used to determine the handling and stability of a vehicle. To calculate these coordinates, total mass (topmass) and the position of the battery (xposition, yposition, and zposition) to calculate the x-coordinate of the center of gravity (centerx) was used first. Then, using this x-coordinate, along with the total mass and the y- and z-coordinates of the battery, to calculate the y- and z-coordinates of the center of gravity (centery and centerz, respectively).

$$centerx = xposition - (\left(\frac{xposition}{topmass}\right) m1)$$

$$centery = yposition - (\left(\frac{yposition}{topmass}\right) m1)$$

$$centerz = zposition - (\left(\frac{zposition}{topmass}\right) m1)$$

Calculation of weight distribution on each tire:

The weight distribution on each tire is determined by considering the mass of the vehicle and battery, as well as the position of the center of gravity. The calculation involves dividing the vehicle's weight into four parts (left forward, right forward, left backward, and right backward) and calculating the weight on each tire based on its distance from the center of gravity. The equations provided for $left_{forward_{handling}}, right_{forward_{handling}}, left_{backward_{handling}}, and\ right_{backward_{handling}}$ take into account the length and width of the vehicle, as well as the x- and y-coordinates of the center of gravity.

$$left_{forward_{mass}} = \left(\frac{\left(\frac{topmass}{length}\right)\left(\left(\frac{length}{2}\right) + centerx\right)}{width}\right)\left(\left(\frac{width}{2}\right) + centery\right)$$

$$right_{forward_{mass}} = \left(\frac{\left(\frac{topmass}{length}\right)\left(\left(\frac{length}{2}\right) + centerx\right)}{width}\right)\left(\left(\frac{width}{2}\right) - centery\right)$$

$$left_{backward_{mass}} = \left(\frac{\left(\frac{topmass}{length}\right)\left(\left(\frac{length}{2}\right) - centerx\right)}{width}\right)\left(\left(\frac{width}{2}\right) + centery\right)$$

$$right_{backward_{mass}} = \left(\frac{\left(\frac{topmass}{length}\right)\left(\left(\frac{length}{2}\right) - centerx\right)}{width}\right)\left(\left(\frac{width}{2}\right) - centery\right)$$

Calculation of handling force on each tire:

The handling force on each tire is the force that is generated when the tire grips the road surface during cornering. This force is proportional to the weight on the tire and the coefficient of friction between the tire and the road surface (u). The handling force on each tire is simply the weight on that tire multiplied by the coefficient of friction (u). The equations provided for $left_{forward_{handling}}, right_{forward_{handling}}, left_{backward_{handling}}, and\ right_{backward_{handling}}$ use the weight distributions calculated in step 3, along with the coefficient of friction, to determine the handling force on each tire.

$$left_{forward_{handling}} = left_{forward_{mass}}\ u$$

$$right_{forward_{handling}} = right_{forward_{mass}}\ u$$

$$left_{backward_{handling}} = left_{backward_{mass}}\ u$$

$$right_{backward_{handling}} = right_{backward_{mass}}\ u$$

Calculation of centripetal force on the vehicle:

During cornering, a vehicle experiences a force that pulls it towards the center of the turn. This force is known as the centripetal force and can be calculated using the equation below where Fcenter_m is the centripetal force, topmass is the total mass of the vehicle and battery, speed is the speed of the vehicle, and radius is the radius of the turn.

$$Fcenter_m = topmass\ \frac{speed^2}{radius}$$

Calculation of maximum turn angle:

The maximum turn angle that a vehicle can safely take without tipping over is determined by the handling force on the weakest tire, which is the tire that generates the least amount of handling force during cornering. To calculate this, the minimum handling force on the tires by taking the minimum of the four handling forces calculated. Then, with this this minimum handling force, along with the total mass and speed of the vehicle, to calculate the radius of the turn at which the handling force on the weakest tire equals the centripetal force on the vehicle. Finally, this radius value to calculate the maximum turn angle using the equation $degree_m = atand\left(\frac{width}{radius_m}\right)$, where width was the width of the vehicle was used.

$$Fmin = min([left_{forward_{handling}}, right_{forward_{handling}}, left_{backward_{handling}}, right_{backward_{handling}}])$$

$$radius_m = topmass\ \frac{speed^2}{Fmin}$$

$$degree_m = atand\left(\frac{width}{radius_m}\right)$$

4.1. Scenarios

Using the MATLAB program, various scenarios were analyzed and vehicle dynamics were calculated based on multiple inputs. Thanks to the calculation, thousands of scenarios could be created and vehicle dynamic calculated. Also, the calculation can be developed later and can be integrated all the forces, drag forces, vehicle power systems etc. By this, all types of vehicles and all scenarios can be considered and test before product of the vehicle.

This study shows that the lower the battery in the vehicle, the more successful the vehicle dynamics. It can also be seen that the lighter the battery, the better the dynamics of the vehicle. As known; vehicle speed, curve radius, vehicle dimensions are also very important for vehicles cornering performance.

Scenarios obtained using MATLAB were interpreted through graphs. By inputting variables such as battery position and certain vehicle dynamics, the vehicle's cornering capability and tilt over condition were evaluated using five different graphs. The definitions of these graphs and the obtained data from the graphs are explained below.

Definition of Graph 1: Battery Position and Curve Angle on X Axis

Graph 1 shows the effect of battery position on X axis change. It represents the battery position on the X-axis. A point is drawn for each of the values and a graph is created by connecting the points.

Definition of Graph 2: Battery Position and Curve Angle on Y Axis

Graph 2 shows the effect of battery position on Y axis change. It represents the bend angle on the Y axis. A point is drawn for each of the values and a graph is created by connecting the points.

Definition of Graph 3: Battery Position and Curve Angle on X and Y Axis

Graph 3 shows the effect of battery position on X and Y axis change. It represents the battery position on the height change on the Y-axis. A point is drawn for each of the values and a graph is created by connecting the points. Graph 3 is actually a three-dimensional graph on the MATLAB program. That’s why, it has not used in the two dimensioned scenarios below.

Definition of Graph 4: Horizontal Acceleration and Bend Angle

Graph 4 shows the effect of horizontal acceleration on the cornering angle. It represents the horizontal acceleration on the X-axis and the bend angle on the Y-axis. A point is drawn for each of the values and a graph is created by connecting the points.

Definition of Graph 5: Vehicle Height and Balance Force

In graph 5, the effect of vehicle height on the turning angle is examined. It represents the cornering angle on the Y-axis and the height of the vehicle the Z-axis. A point is drawn for each of the values and a graph is created by connecting the points.

The inputs of fourteen different scenarios created by entering different data into the MATLAB program are given in Table 4.1. After that, these inputs are interpreted with their graphics and inferences and the scenarios are compared with each other.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11	Scenario 12	Scenario 13	Scenario 14
Vehicle Weight (kg)	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	600	1200	1200	1200
Battery Weight (kg)	300	540	540	540	540	540	540	300	540	540	540	300	300	300
Wheel Coeff. Friction	0.4	0.4	0.9	0.9	0.9	0.9	0.9	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Vehicle Lenght (m)	5	5	5	5	5	5	5	3	3	3	3	5	5	5
Vehicle Width (m)	3	3	3	3	3	3	3	1	1	1	1	3	3	3
Vehicle Height (m)	2	2	2	2	2	2	2	2	2	2	2	2	2	3
Battery Min X Position (m)	0	0	0	1.5	-2	2	-2.5	0	0	2	0	0	0	0
Battery Max X Position (m)	0.4	0.4	0.4	2.5	0	2.5	-2	0.5	0.5	2.5	0.5	0.5	0.5	0.5
Battery Min Y Position (m)	0	0	0	0	0	2	-2.5	0	0	0	0	0	0	0
Battery Max Y Position (m)	0.5	0.5	0.5	0.5	0.5	2.5	-2	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Battery Min Z Position (m)	0	0	0	0	0	0	0	0	0	1	0	0	0	-1.5
Battery Max Z Position (m)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1.5	0.5	0.5	0.5	-1
Min Vehicle Speed (m/s)	15	15	15	15	15	15	15	15	15	15	15	15	30	15
Max Vehicle Speed (m/s)	25	25	25	25	25	25	25	25	25	25	25	25	40	25
Curve Radius (m)	40	40	40	40	40	40	40	40	40	40	40	25	25	40

Table 4.1. Test inputs of scenarios.

4.1.1. Scenario 1

Enter the Vehicle Weight (kg) : 1200

Enter the Battery Weight (kg) :300

Enter the Wheel Coefficiency of Friction :0.4

Enter the Vehicle Length (m) :5

Enter the Vehicle Width (m) :3

Enter the Vehicle Height (m) :2

Enter the Minimum Battery X Position (m) :0

Enter the Maximum Battery X Position (m) :0.4

Enter the Minimum Battery Y Position (m) :0

Enter the Maximum Battery Y Position (m) :0.5

Enter the Minimum Battery Z Position (m) : 0

Enter the Maximum Battery Z Position (m) : 0.5

Enter the Minimum Vehicle Speed (m/s) :15

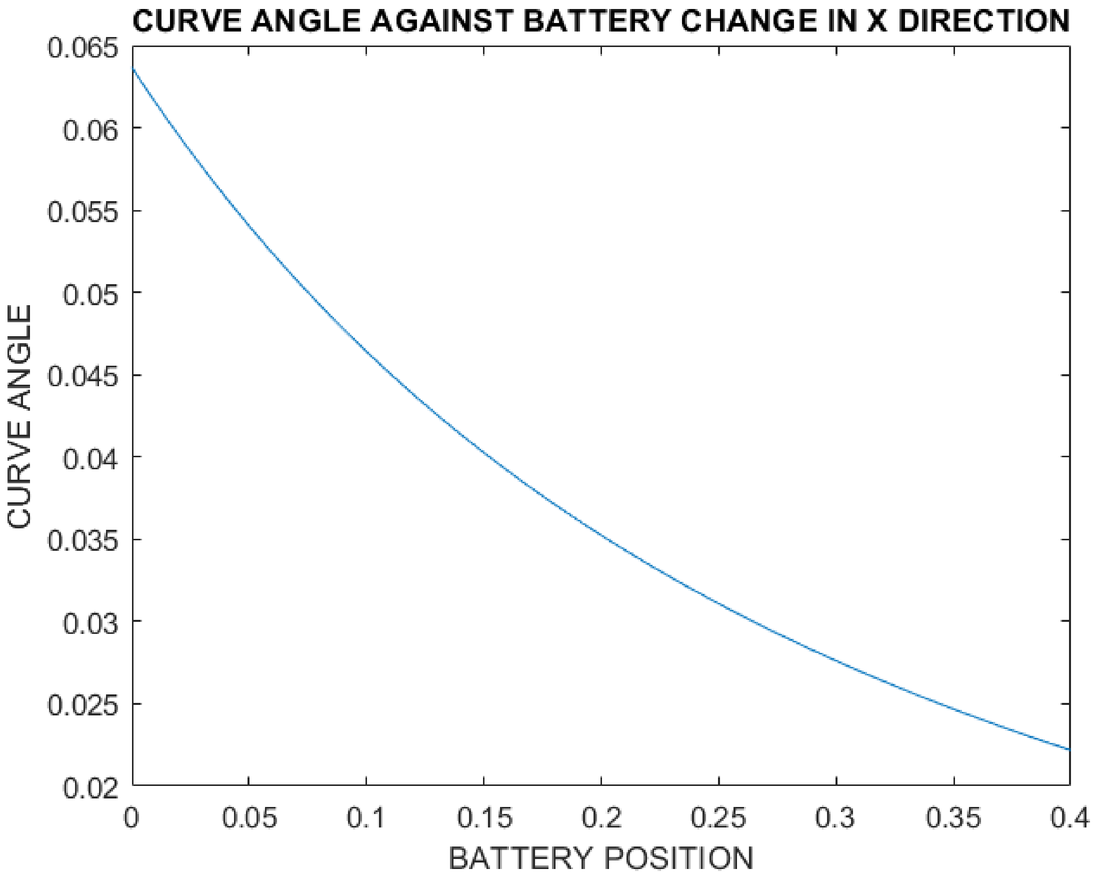
Enter the Maximum Vehicle Speed (m/s) :25

Enter the Curve Radius (m) :40

Inferences

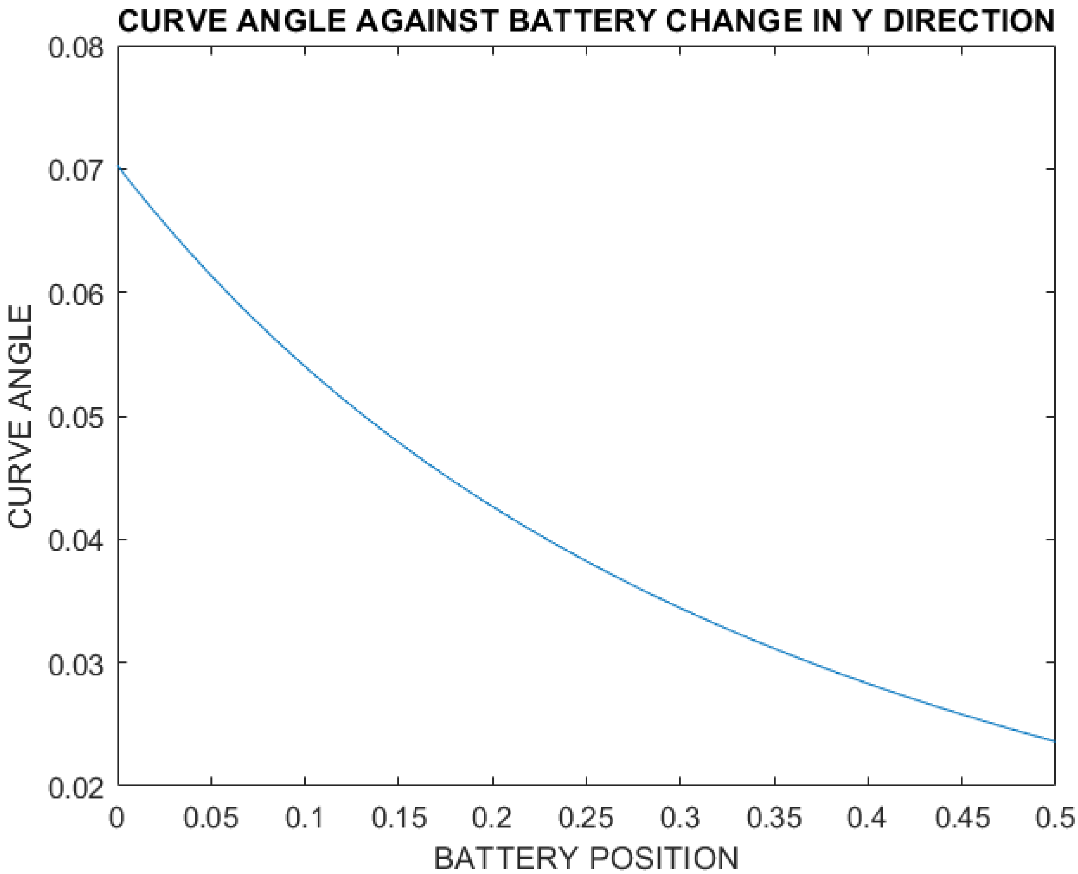
In first scenario, vehicle has 1200 kilograms of weight. Also, vehicle has 300 kilograms battery weight which is lighter than a standard vehicle. In example, Tesla Model S has 540 kilograms of battery. Battery is right into the middle of the center of gravity of the vehicle. Vehicle speed is between 15-25 m/s. Curve has average sharpness, radius of 40 meters.

Graph 4.1 is the graph of the relation between curve radius and battery position according to its X axis. The battery is at the middle of the vehicle; radius has average sharpness and the vehicle speed is average. According to these inputs, this result is an average result for a standard vehicle.



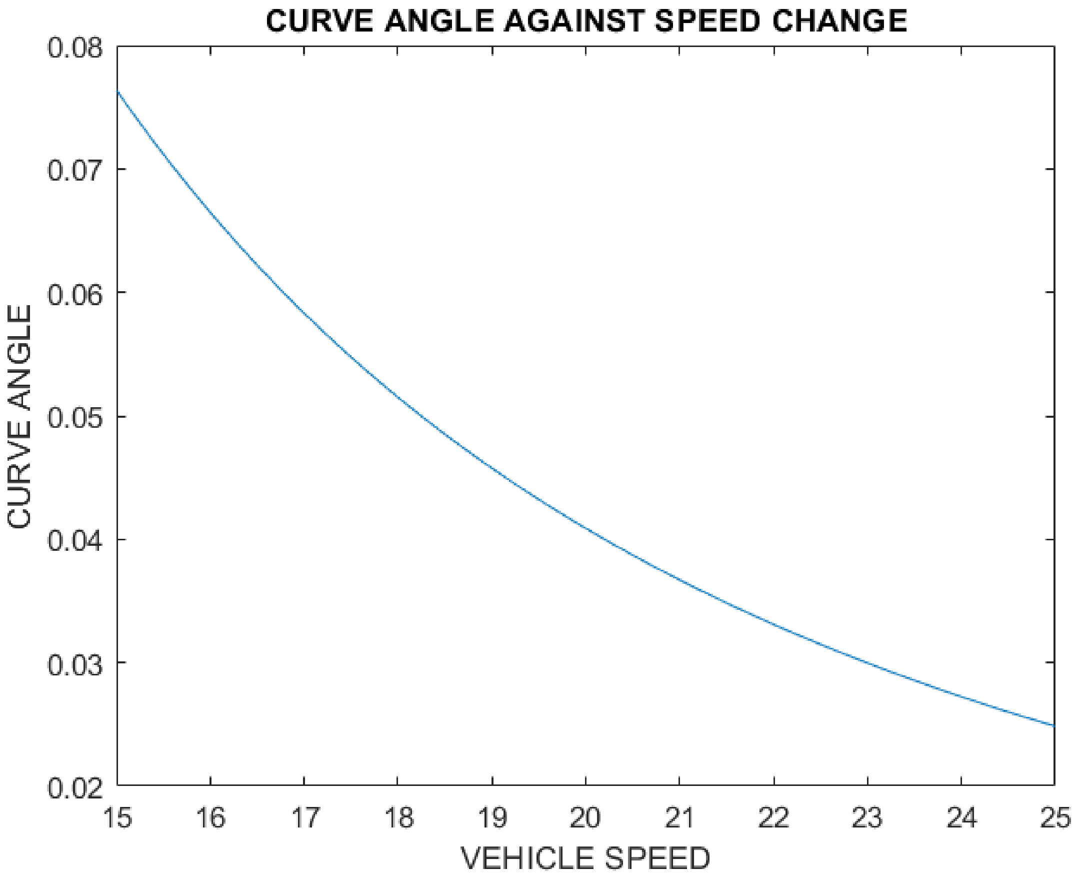
Graph 4.1. Battery Position and Curve Angle on X Axis

Graph 4.2 is the graph of the relation between curve radius and battery position according to its Y axis. The battery is at the middle of the vehicle; radius has average sharpness and the vehicle speed is average. According to these inputs, this result is an average result for a standard vehicle.



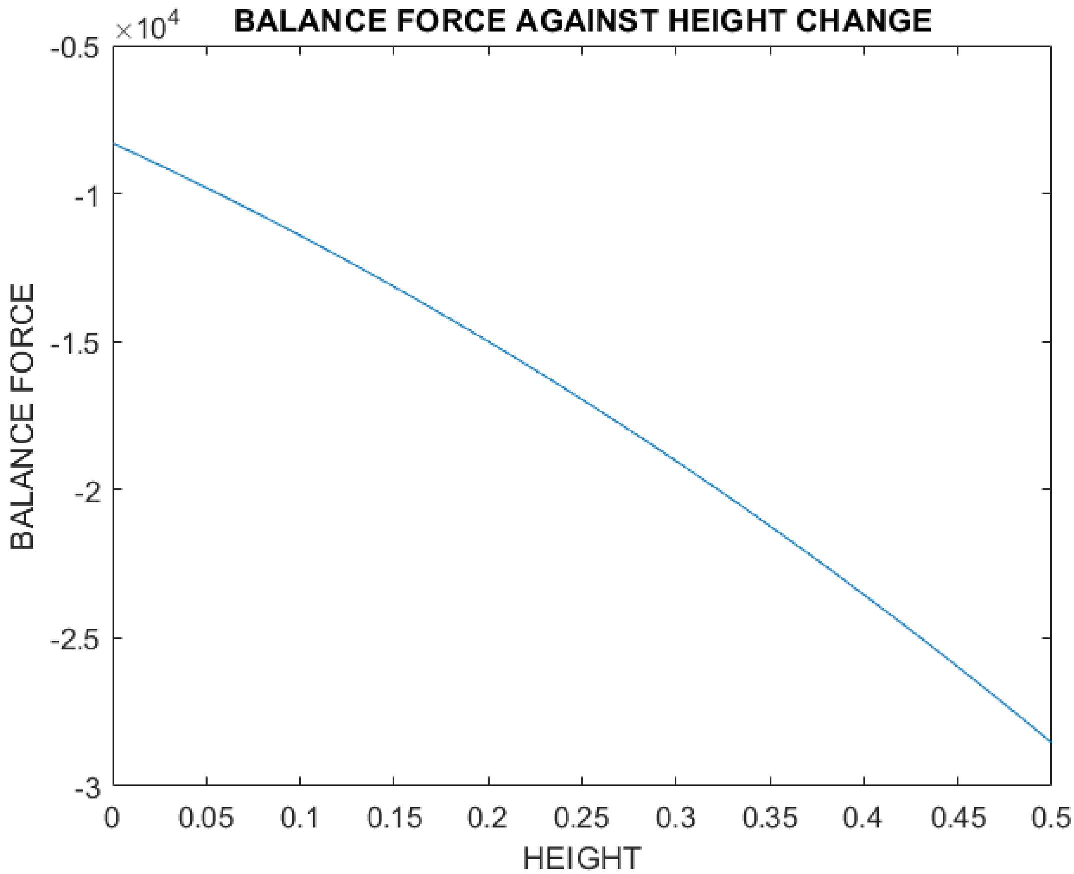
Graph 4.2. Battery Position and Curve Angle on Y Axis

Graph 4.3 represents the relation between curve angle and vehicle speed. In this scenario, inputs are average as a standard vehicle dynamic. So, output graphic is average as the other ones.



Graph 4.3. Horizontal Acceleration and Bend Angle

Graph 4.4 represents the relation between height of the vehicle and cornering performance. Vehicle has 2 meters height and curve has 40 meters radius. According to these, vehicle has average cornering performance.



Graph 4.4. Vehicle Height and Balance Force

4.1.2. Scenario 2

Enter the Vehicle Weight (kg) : 1200

Enter the Battery Weight (kg) :540

Enter the Wheel Coefficiency of Friction :0.4

Enter the Vehicle Length (m) :5

Enter the Vehicle Width (m) :3

Enter the Vehicle Height (m) :2

Enter the Minimum Battery X Position (m) :0

Enter the Maximum Battery X Position (m) :0.4

Enter the Minimum Battery Y Position (m) :0

Enter the Maximum Battery Y Position (m) :0.5

Enter the Minimum Battery Z Position (m) : 0

Enter the Maximum Battery Z Position (m) : 0.5

Enter the Minimum Vehicle Speed (m/s) :15

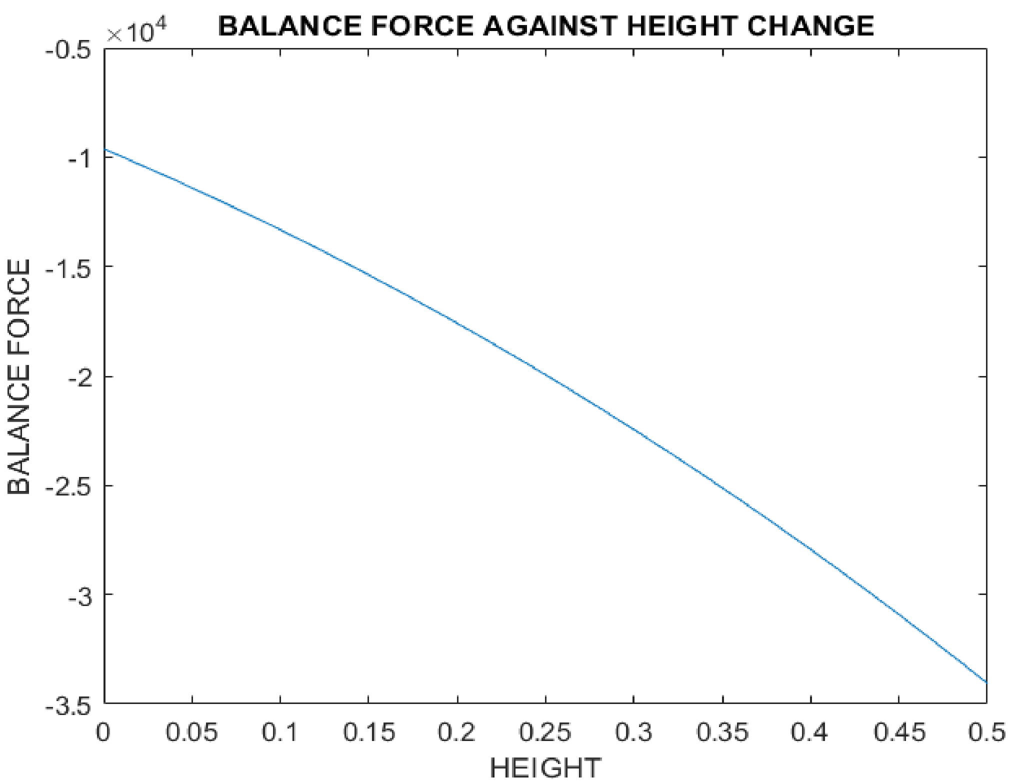
Enter the Maximum Vehicle Speed (m/s) :25

Enter the Curve Radius (m) :40

Inferences

Only difference between first and this scenario is battery weight. Vehicle has 540 kilograms of battery weight, same as Tesla Model S. The rest of the inputs are the same. By that, it can be seen the effect of the battery weight on vehicle dynamics.

In balance force against height change graph 4.5 as below, there is a slightly difference on graph than previous scenario. Because the battery is heavier, total vehicle gets heavier. This causes handling and cornering performance worse than the first scenario.



Graph 4.5. Vehicle Height and Balance Force

4.1.3. Scenario 3

Enter the Vehicle Weight (kg) : 1200

Enter the Battery Weight (kg) :540

Enter the Wheel Coefficiency of Friction :0.9

Enter the Vehicle Length (m) :5

Enter the Vehicle Width (m) :3

Enter the Vehicle Height (m) :2

Enter the Minimum Battery X Position (m) :0

Enter the Maximum Battery X Position (m) :0.4

Enter the Minimum Battery Y Position (m) :0

Enter the Maximum Battery Y Position (m) :0.5

Enter the Minimum Battery Z Position (m) : 0

Enter the Maximum Battery Z Position (m) : 0.5

Enter the Minimum Vehicle Speed (m/s) :15

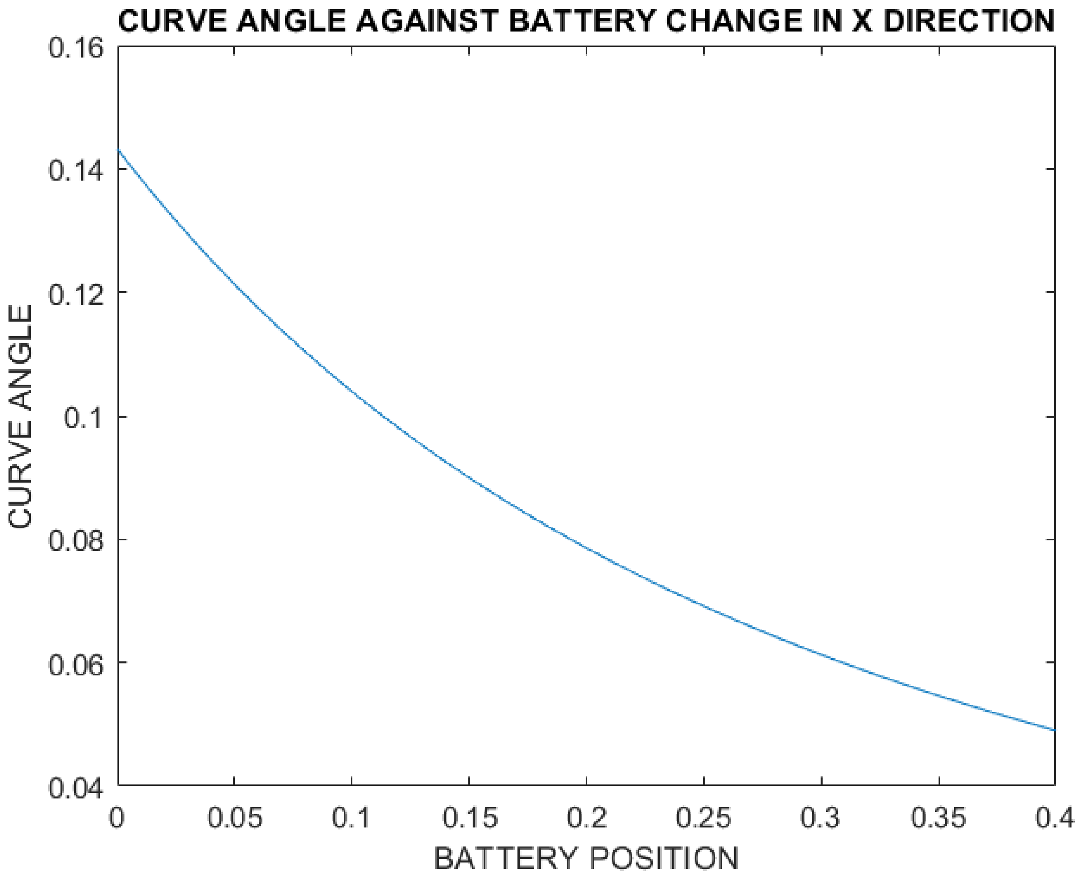
Enter the Maximum Vehicle Speed (m/s) :25

Enter the Curve Radius (m) :40

Inferences

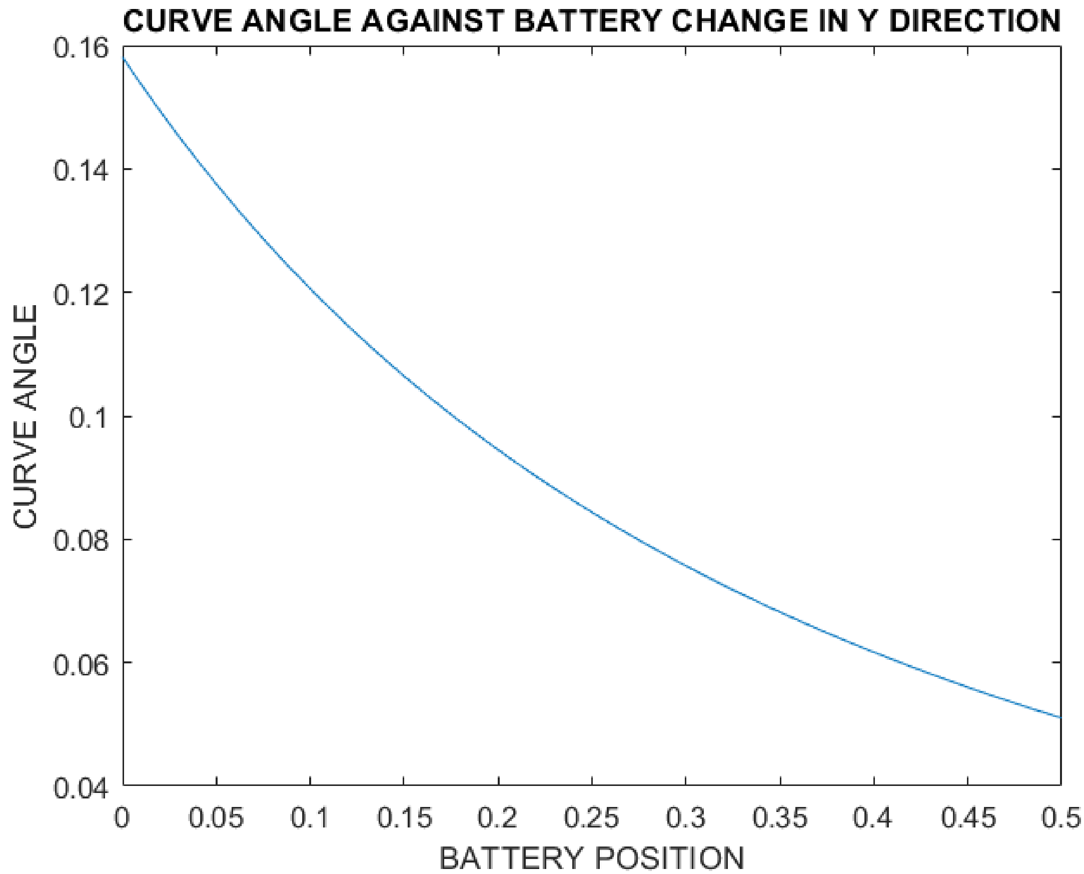
In this scenario, vehicle has more friction. It has 0.9 friction coefficient instead of 0.4. It can be caused by tires, ground type etc. The rest inputs are all the same as the first scenario. This would cause much higher fuel consumption because of high friction.

According to graph 4.6; curve angle increases because of the high friction. Vehicles cornering performance increases significantly. But this would cause high fuel consumption.



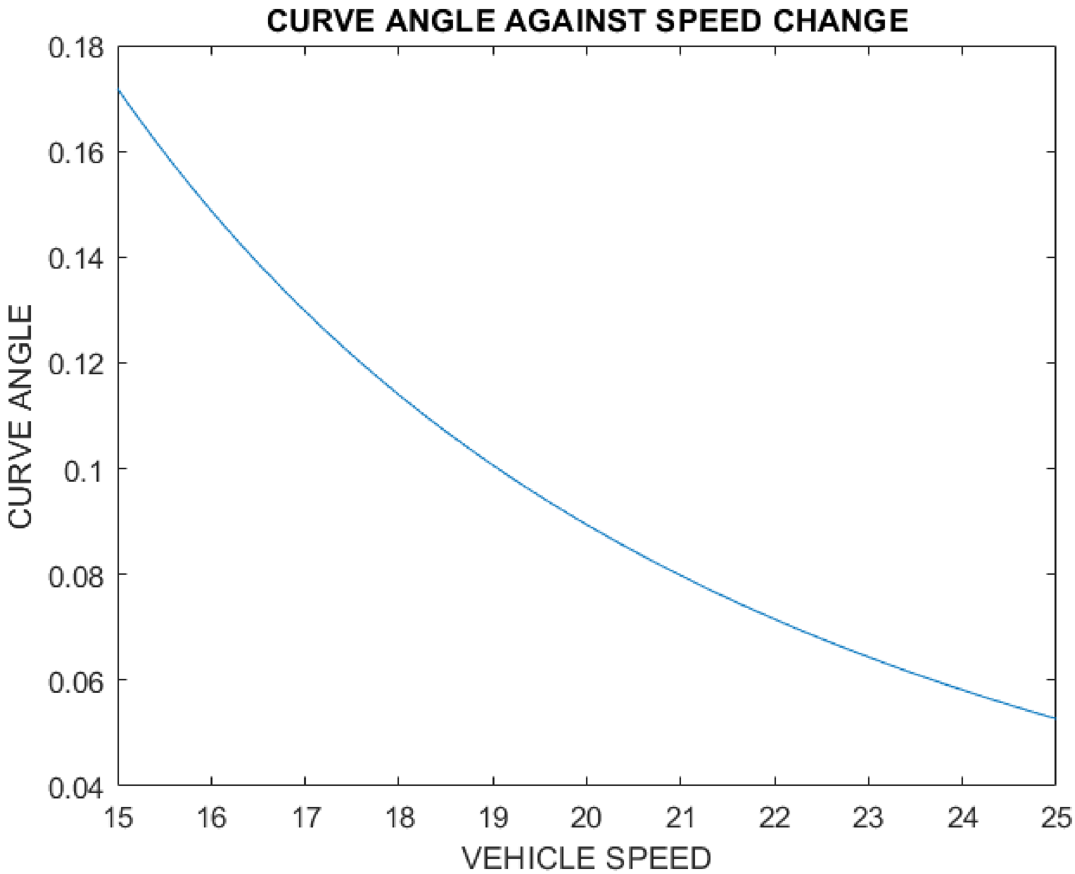
Graph 4.6. Battery Position and Curve Angle on X Axis

As the same input, in graph 4.7 curve angle increases from 0.07 to 0.16 when battery position is zero. This is caused thank to high friction.



Graph 4.7. Battery Position and Curve Angle on Y Axis

Also, as in graph 4.8 vehicle can go faster on same curve thank to high friction. But it would cause much more fuel consumption.



Graph 4.8. Horizontal Acceleration and Bend Angle

4.1.4. Scenario 4

Enter the Vehicle Weight (kg) : 1200

Enter the Battery Weight (kg) :540

Enter the Wheel Coefficiency of Friction :0.9

Enter the Vehicle Length (m) :5

Enter the Vehicle Width (m) :3

Enter the Vehicle Height (m) :2

Enter the Minimum Battery X Position (m) :1.5

Enter the Maximum Battery X Position (m): 2.5

Enter the Minimum Battery Y Position (m) :0

Enter the Maximum Battery Y Position (m) :0.5

Enter the Minimum Battery Z Position (m) : 0

Enter the Maximum Battery Z Position (m) : 0.5

Enter the Minimum Vehicle Speed (m/s) :15

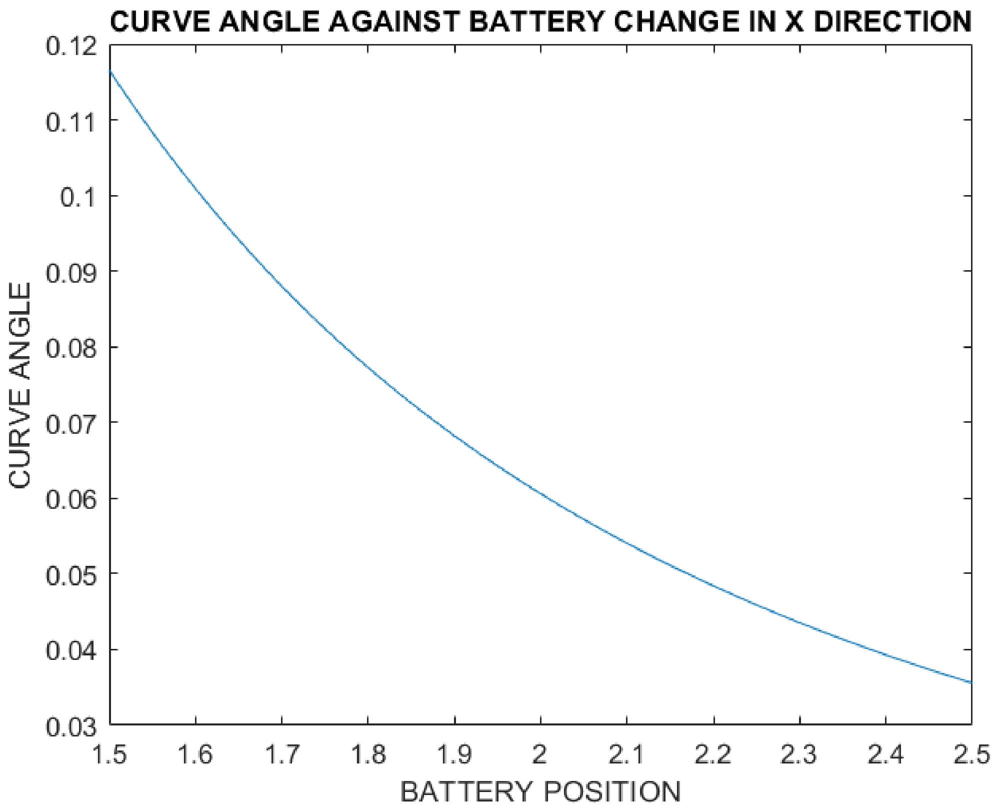
Enter the Maximum Vehicle Speed (m/s) :25

Enter the Curve Radius (m) :40

Inferences

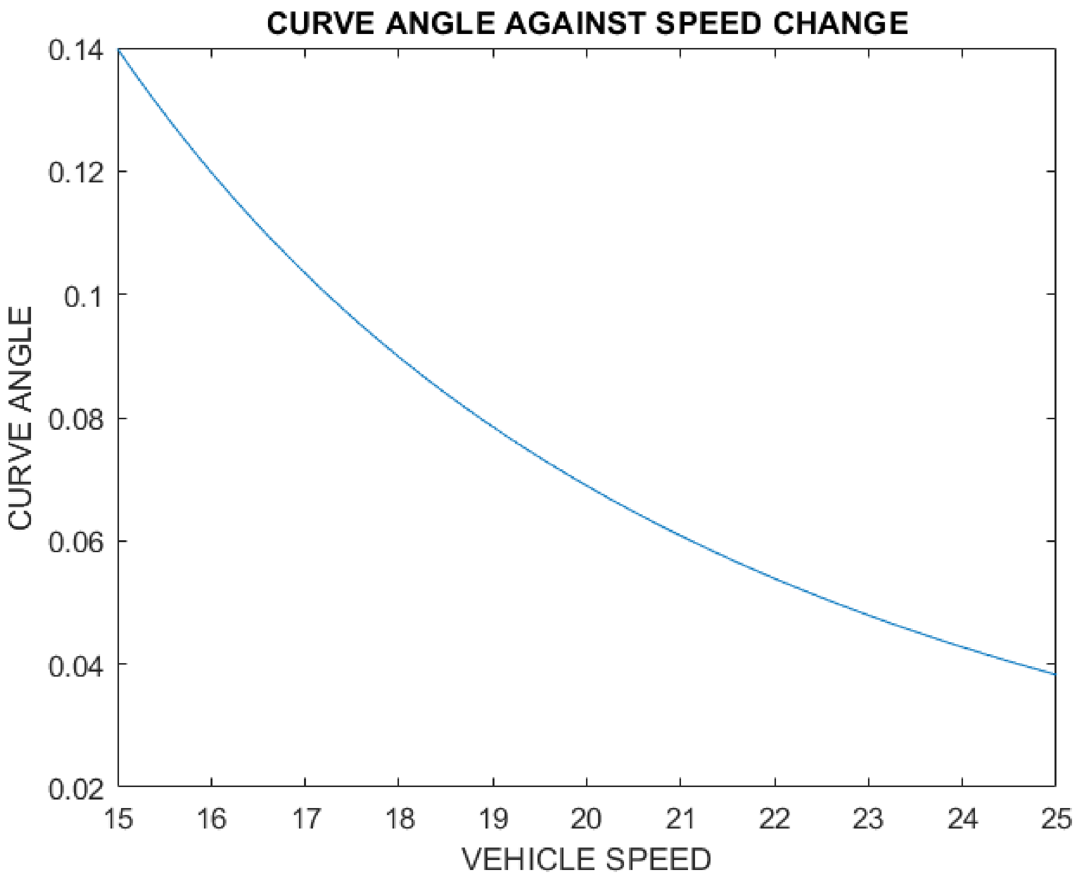
In this scenario, the battery is one-meter front side the vehicle center of gravity than the previous scenario. All other inputs are the same. This scenario would cause understeer of the vehicle. It will decrease the oversteer. But cornering performance will not change dramatically.

As in graph 4.9**,** more the battery stands front side of the vehicle about 1-meter more, curve angle decreases because of understeering.



Graph 4.9. Battery Position and Curve Angle on X Axis

As in graph 4.10, cornering performance would be worse because of the understeer. When the battery is on the front-hand site of the vehicle at the speed of 15m/s; maximum curve angle would be 0.14 degree. But in previous scenario, it was about 0.17 degree per meter.



Graph 4.10. Horizontal Acceleration and Bend Angle

4.1.5. Scenario 5

Enter the Vehicle Weight (kg) : 1200

Enter the Battery Weight (kg) :540

Enter the Wheel Coefficiency of Friction :0.9

Enter the Vehicle Length (m) :5

Enter the Vehicle Width (m) :3

Enter the Vehicle Height (m) :2

Enter the Minimum Battery X Position (m) :-2

Enter the Maximum Battery X Position (m): 0

Enter the Minimum Battery Y Position (m) :0

Enter the Maximum Battery Y Position (m) :0.5

Enter the Minimum Battery Z Position (m) : 0

Enter the Maximum Battery Z Position (m) : 0.5

Enter the Minimum Vehicle Speed (m/s) :15

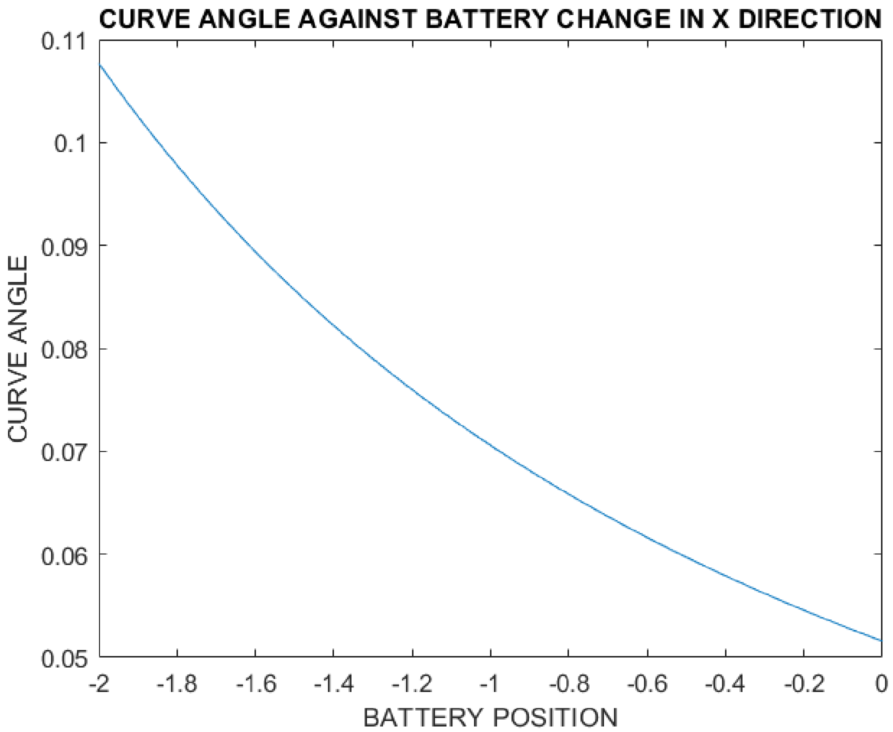
Enter the Maximum Vehicle Speed (m/s) :25

Enter the Curve Radius (m) :40

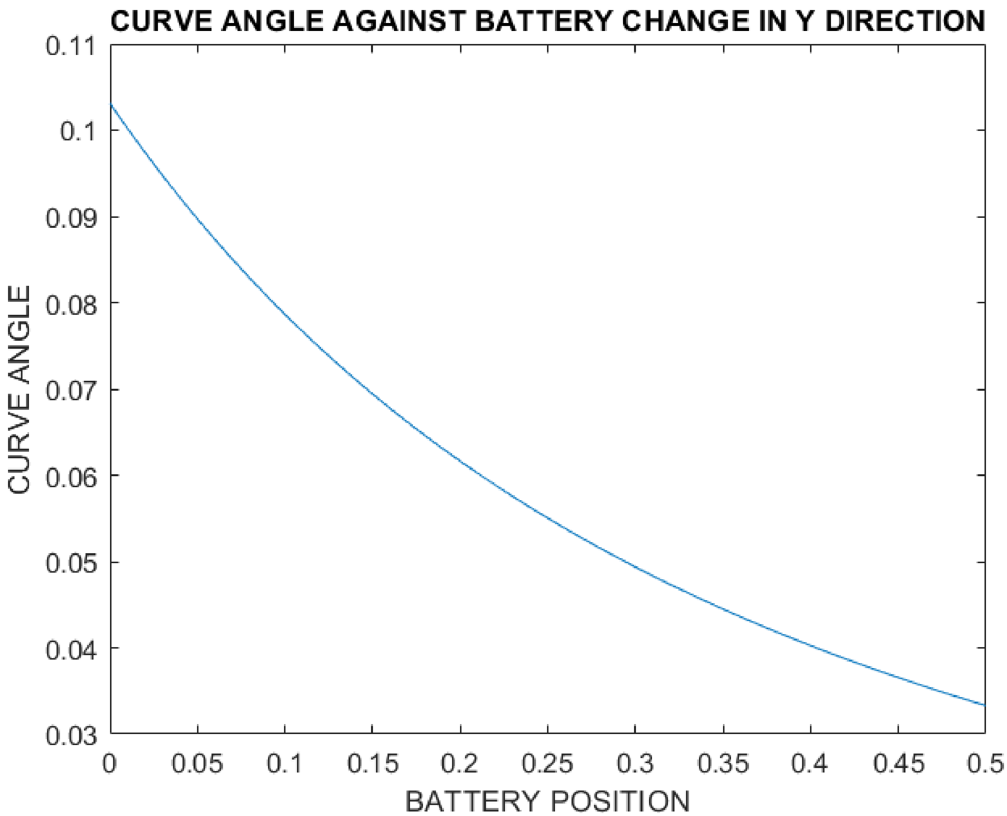
Inferences

In this scenario, vehicle have all the same inputs as previous one. Only difference is, battery in back-hand site of the vehicle(X-axis). This would cause the oversteer, because the center of gravity will be back side of the vehicle.

As in graph 4.11 and graph 4.12**,** vehicles curving performance is almost the same as previous. Only vehicle would oversteer more because of the weight distribution. When the battery goes back on X-axis, the cornering performance will be slightly worse. Because it's always better when the weight is at the middle of the center of gravity. Also, skidding on first move of the vehicle would be more.

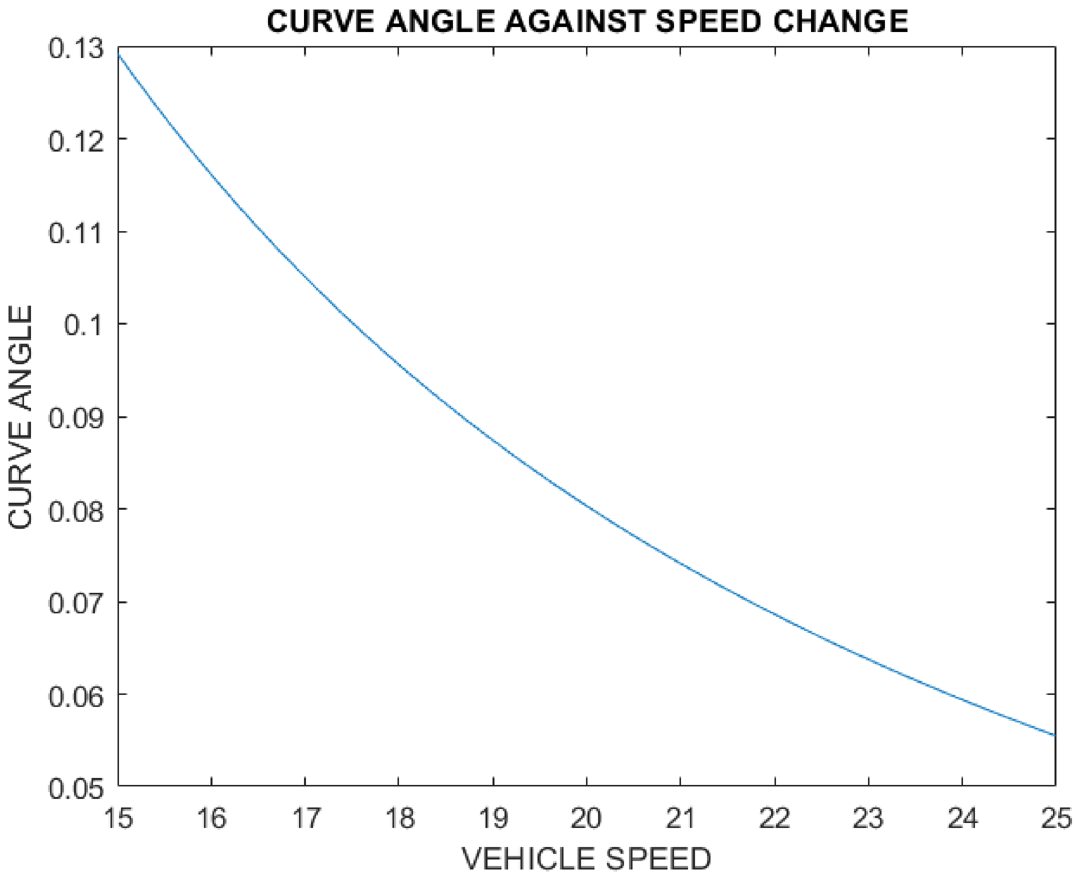


Graph 4.11. Battery Position and Curve Angle on X Axis



Graph 4.12. Battery Position and Curve Angle on Y Axis

As in graph 4.13; curve angle and vehicle speed are not changed so dramatically. Cornering performance just got a little worse.



Graph 4.13. Horizontal Acceleration and Bend Angle

4.1.6. Scenario 6

Enter the Vehicle Weight (kg) : 1200

Enter the Battery Weight (kg) :540

Enter the Wheel Coefficiency of Friction :0.9

Enter the Vehicle Length (m) :5

Enter the Vehicle Width (m) :3

Enter the Vehicle Height (m) :2

Enter the Minimum Battery X Position (m) :2

Enter the Maximum Battery X Position (m): 2.5

Enter the Minimum Battery Y Position (m) :2

Enter the Maximum Battery Y Position (m) :2.5

Enter the Minimum Battery Z Position (m) : 0

Enter the Maximum Battery Z Position (m) : 0.5

Enter the Minimum Vehicle Speed (m/s) :15

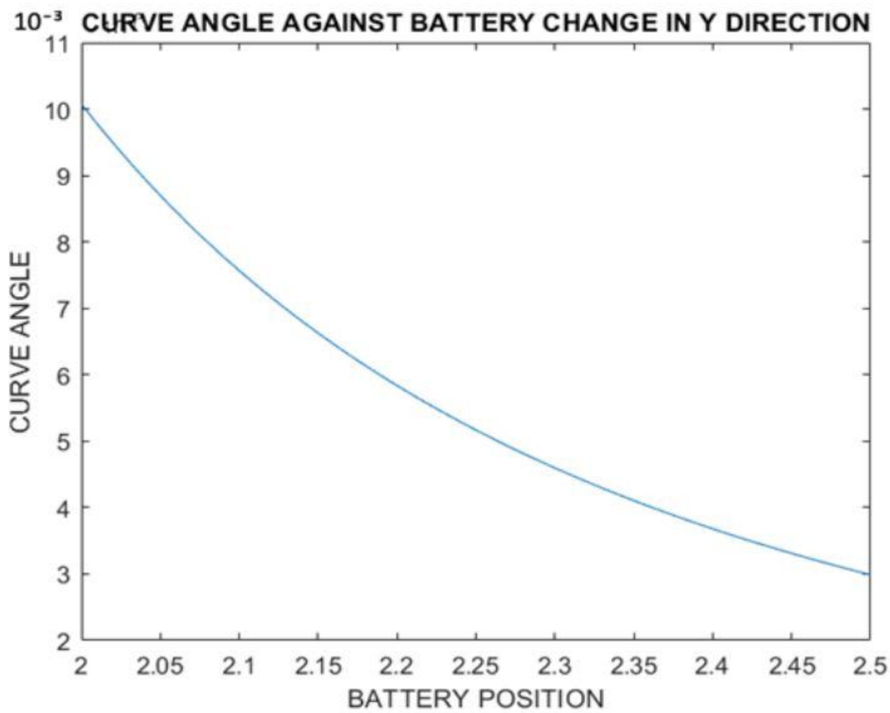
Enter the Maximum Vehicle Speed (m/s) :25

Enter the Curve Radius (m) :40

Inferences 6

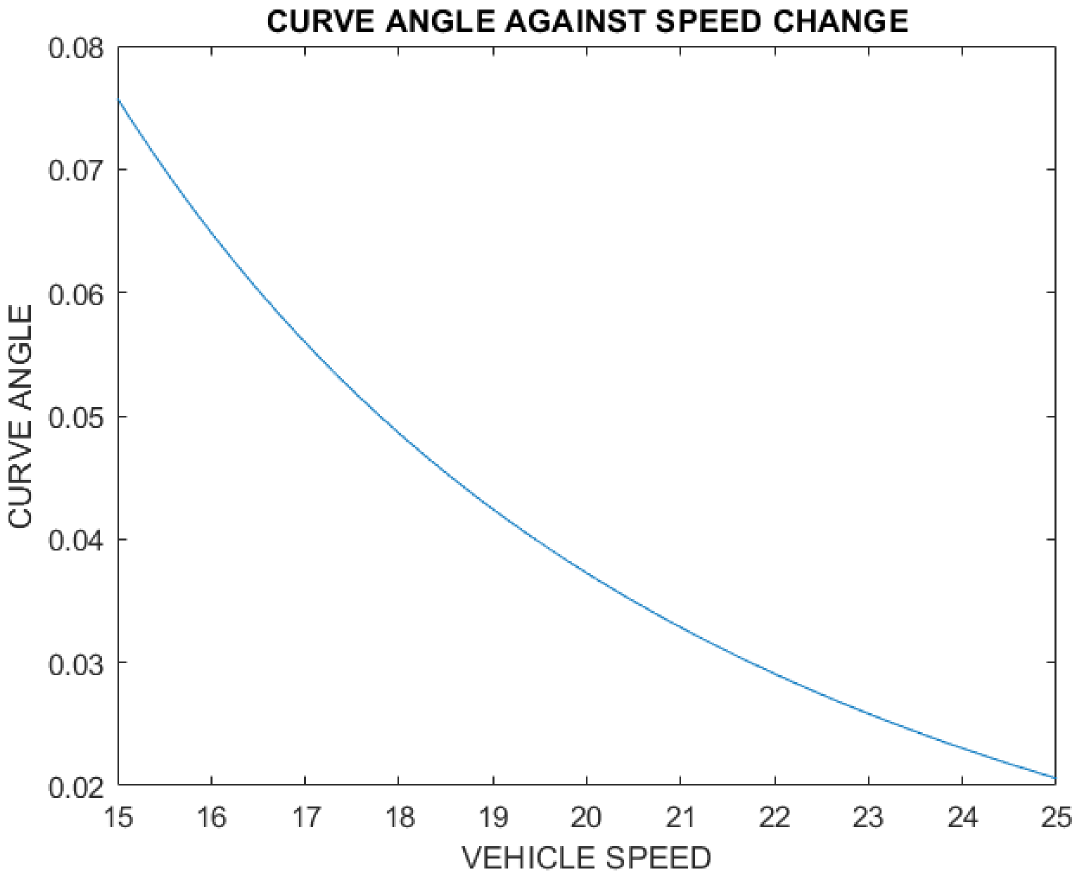
In this scenario, vehicle's battery position has changed. Battery is on the front-end site of the vehicle; and it's on the right-hand site of the vehicle about 2 meters(Y-axis). The rest is as the same with previous scenario. Results are as below:

As in graph 4.14; battery position is on the right-hand site of the vehicle. According to this, if the battery goes by side of the vehicle, cornering performance would get worse significantly. Because balance of the vehicle would be disrupted.



Graph 4.14. Battery Position and Curve Angle on Y Axis

As in graph 4.15, cornering performance would be decreased. In this scenario, at the speed of 15m/s, vehicle can corner 0.075 degree. But in previous scenario, vehicle could corner 0.13 degree with the same speed. This shows that if the battery is right or left-hand side of the vehicle, cornering performance would decrease dramatically. That's why batteries preferred to put middle of the vehicle on Y-axis.



Graph 4.15. Horizontal Acceleration and Bend Angle

4.1.7. Scenario 7

Enter the Vehicle Weight (kg) : 1200

Enter the Battery Weight (kg) :540

Enter the Wheel Coefficiency of Friction :0.9

Enter the Vehicle Length (m) :5

Enter the Vehicle Width (m) :3

Enter the Vehicle Height (m) :2

Enter the Minimum Battery X Position (m) :-2.5

Enter the Maximum Battery X Position (m): -2

Enter the Minimum Battery Y Position (m) :-2.5

Enter the Maximum Battery Y Position (m) :-2

Enter the Minimum Battery Z Position (m) : 0

Enter the Maximum Battery Z Position (m) : 0.5

Enter the Minimum Vehicle Speed (m/s) :15

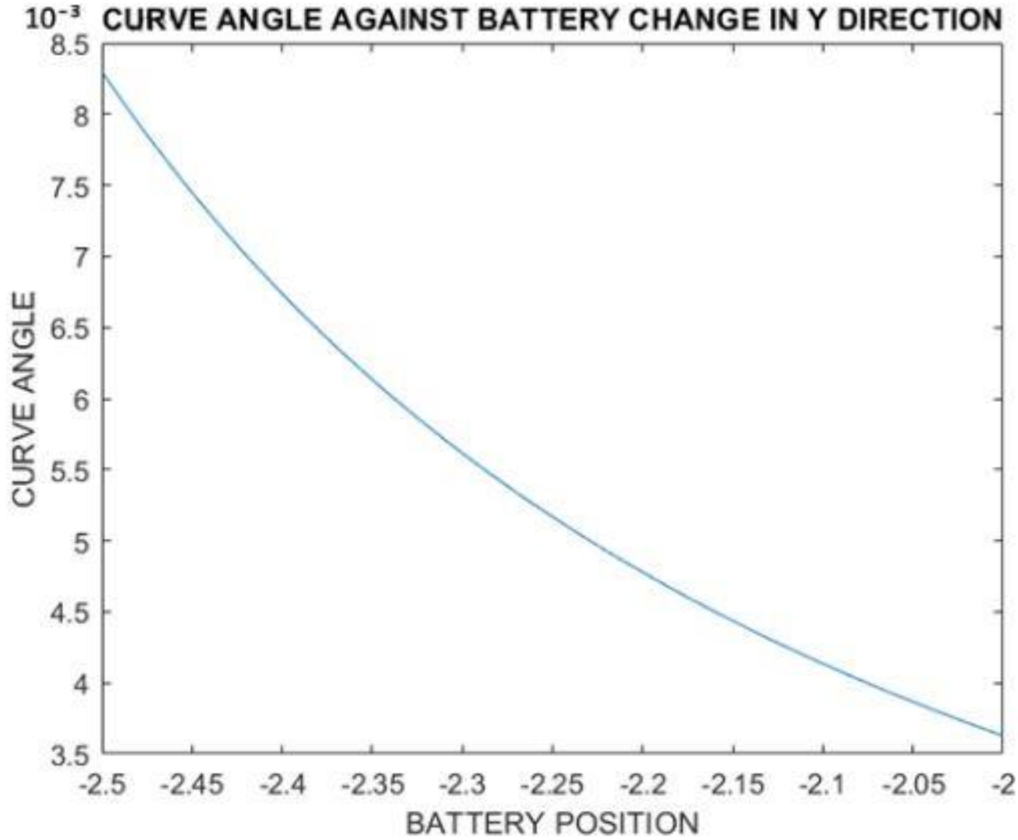
Enter the Maximum Vehicle Speed (m/s) :25

Enter the Curve Radius (m) :40

Inferences 7

In this scenario, battery’s position has changed. Battery is on the back side of the vehicle(2meters), and also left-hand side (2 meters) of the vehicle. All other inputs are the same as previous scenario.

As can be seen in graph 4.16, vehicles cornering performance wouldn’t change significantly. Because of battery is back side of the vehicle, cornering performance is better. But battery is left-hand side of the vehicle, so cornering is not as successful as scenario 5.



Graph 4.16. Battery Position and Curve Angle on Y Axis

4.1.8. Scenario 8

Enter the Vehicle Weight (kg) : 1200

Enter the Battery Weight (kg) :300

Enter the Wheel Coefficiency of Friction :0.4

Enter the Vehicle Length (m) :3

Enter the Vehicle Width (m) :1

Enter the Vehicle Height (m) :2

Enter the Minimum Battery X Position (m) :0

Enter the Maximum Battery X Position (m): 0.5

Enter the Minimum Battery Y Position (m) :-0

Enter the Maximum Battery Y Position (m) :0.5

Enter the Minimum Battery Z Position (m) : 0

Enter the Maximum Battery Z Position (m) : 0.5

Enter the Minimum Vehicle Speed (m/s) :15

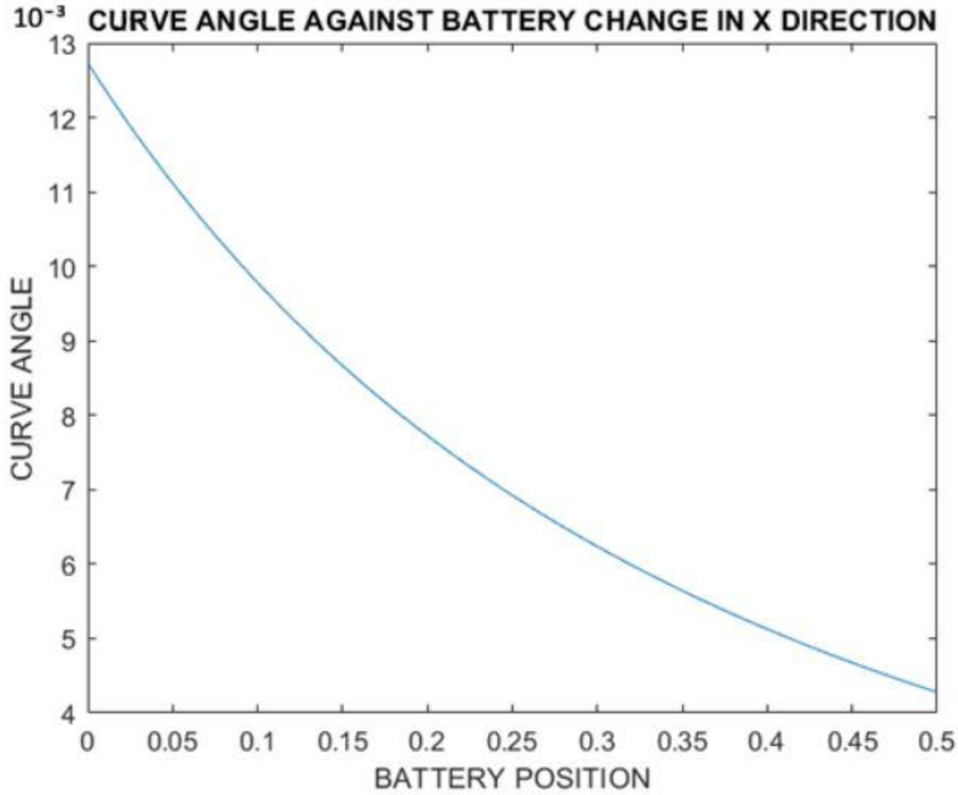
Enter the Maximum Vehicle Speed (m/s) :25

Enter the Curve Radius (m) :40

Inferences 8

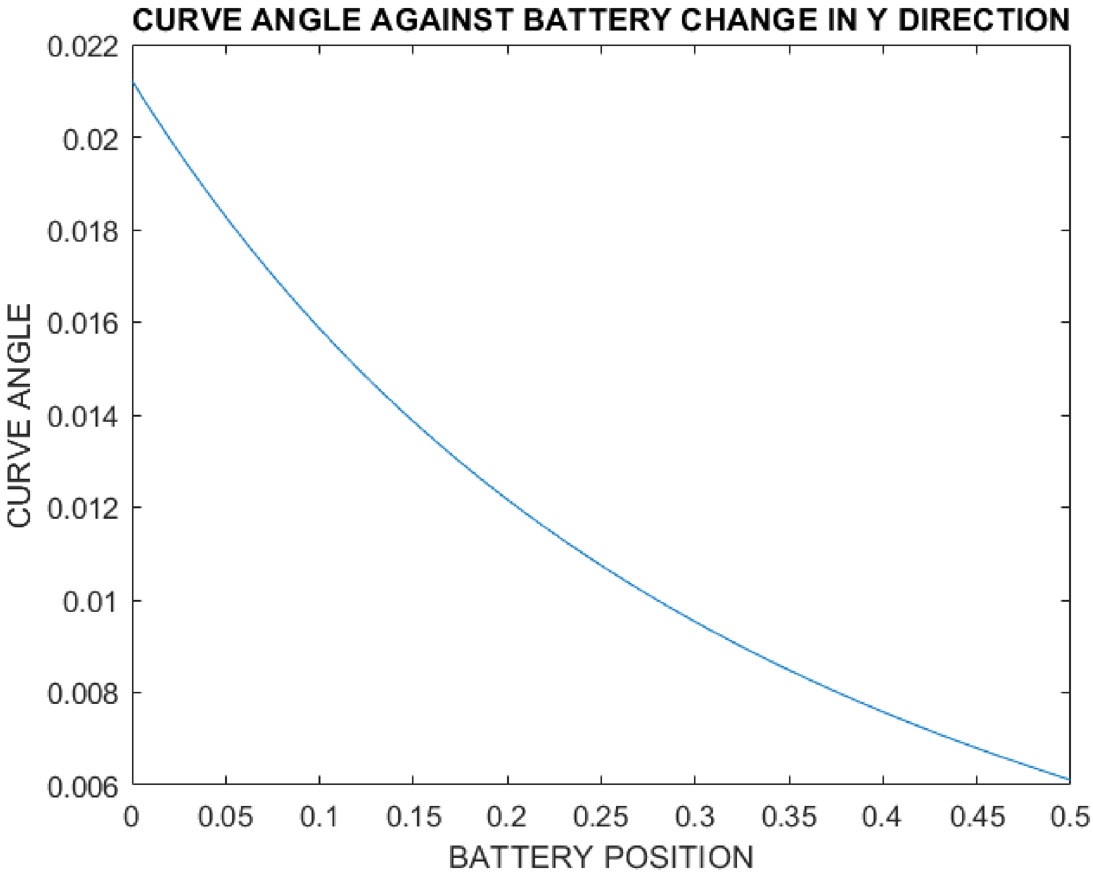
In this scenario, most of the scenarios were like scenario 1. Only difference is vehicle has smaller dimensions. It has 3 meters length instead of 5. 1-meter width instead of three. The height is still same, 2 meters. Depending on smaller vehicle has same weight, the handling gets worse. Slipping chance is much more than large vehicle. Because center of gravity is higher and also axles are closer to it.

In graph 4.17, vehicle has much less cornering capacity than the first scenario. Because with same weight, vehicle has smaller dimensions. Tilting over or losing grip is so possible in this scenario.

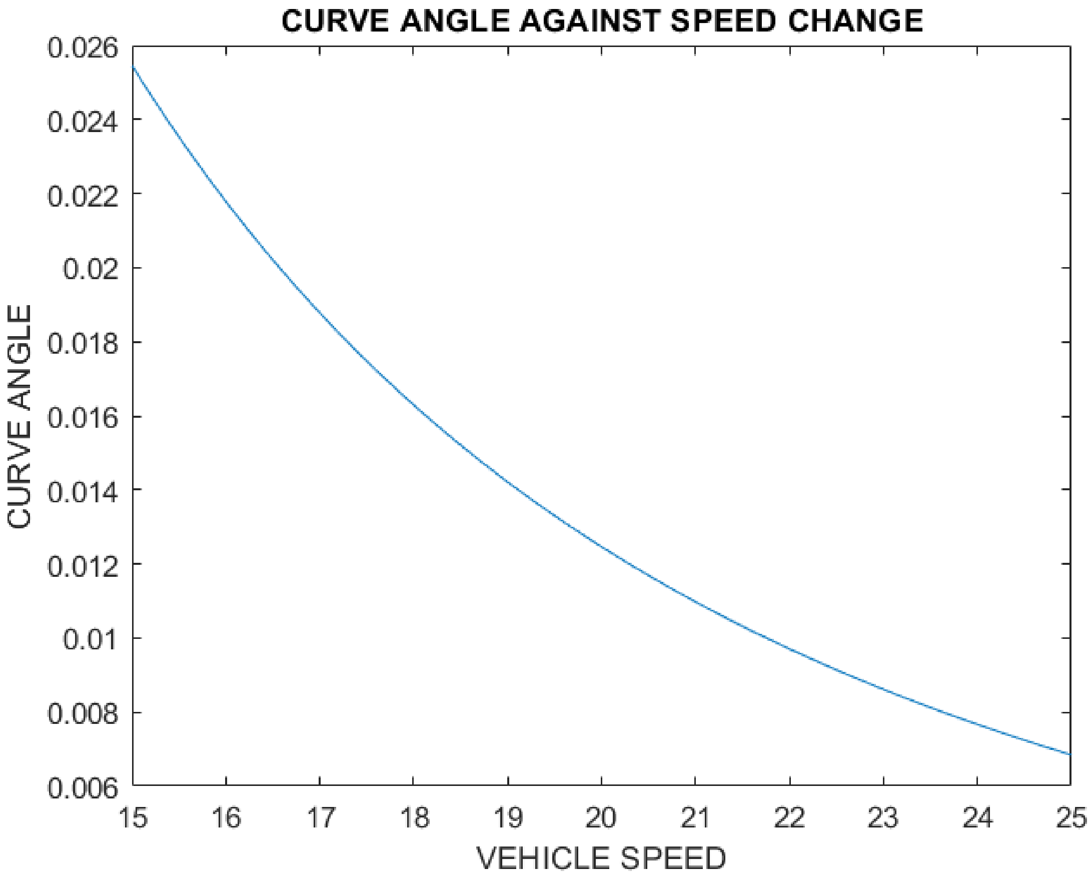


Graph 4.17. Battery Position and Curve Angle on X Axis

As in graph 4.18 and 4.19, vehicles cornering capacity is very low. The cornering angle is about 0.025 degrees in battery's zero position. It was about 0.07 degrees in the first, larger vehicle scenario. This type of vehicle is dangerous, because height measure is larger than width measure.



Graph 4.18. Battery Position and Curve Angle on Y Axis



Graph 4.19. Horizontal Acceleration and Bend Angle

4.1.9. Scenario 9

Enter the Vehicle Weight (kg) : 1200

Enter the Battery Weight (kg) :540

Enter the Wheel Coefficiency of Friction :0.4

Enter the Vehicle Length (m) :3

Enter the Vehicle Width (m) :1

Enter the Vehicle Height (m) :2

Enter the Minimum Battery X Position (m) :0

Enter the Maximum Battery X Position (m): 0.5

Enter the Minimum Battery Y Position (m) :-0

Enter the Maximum Battery Y Position (m) :0.5

Enter the Minimum Battery Z Position (m) : 0

Enter the Maximum Battery Z Position (m) : 0.5

Enter the Minimum Vehicle Speed (m/s) :15

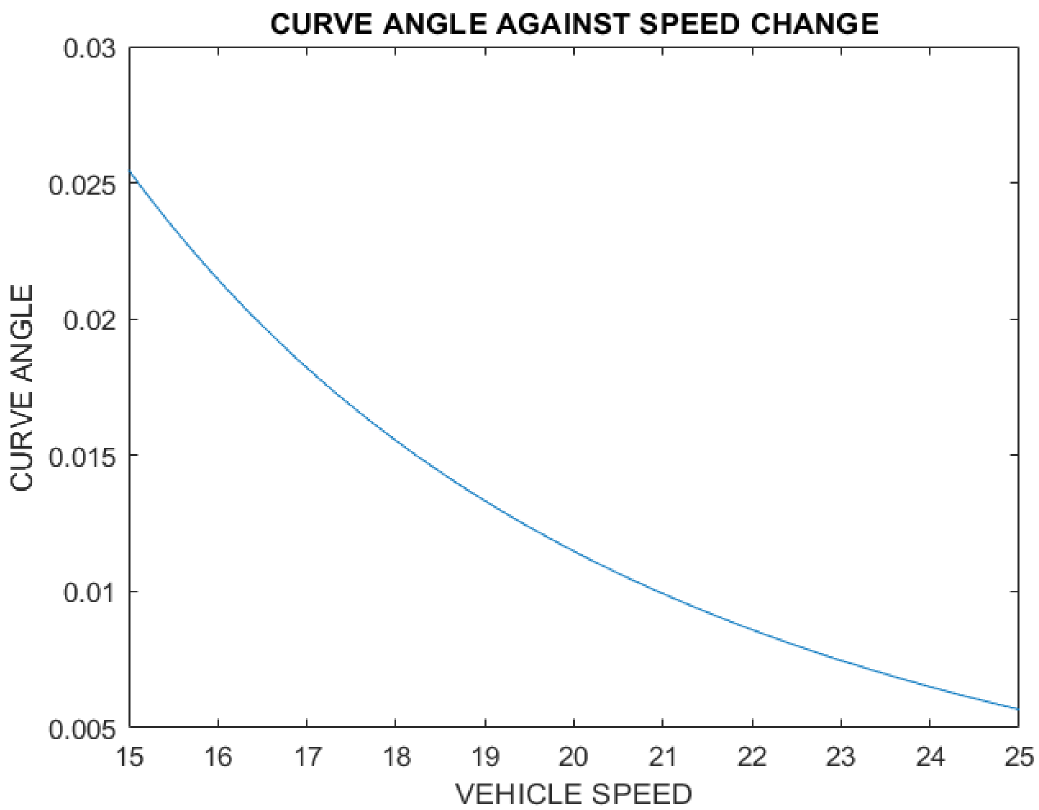
Enter the Maximum Vehicle Speed (m/s) :25

Enter the Curve Radius (m) :40

Inferences

In this scenario, vehicle has the same inputs with scenario 8. Only difference is battery weight. Battery is 540kg as first scenario. It's 240 kilograms heavier than previous scenario. According to these circumstances, vehicle has very bad cornering performance as previous. Actually, this vehicle is slightly worse than scenario 8.

In graph 4.20, cornering performance is slightly worse than previous vehicle. Because this vehicle has 240 kilograms more weight than the other. This shows the effect of weight on vehicles. That's why, if batteries are lighter, they would be smaller and vehicles would have better handling.



Graph 4.20. Horizontal Acceleration and Bend Angle

4.1.10. Scenario 10

Enter the Vehicle Weight (kg) : 1200

Enter the Battery Weight (kg) :540

Enter the Wheel Coefficiency of Friction :0.4

Enter the Vehicle Length (m) :3

Enter the Vehicle Width (m) :1

Enter the Vehicle Height (m) :2

Enter the Minimum Battery X Position (m) :2

Enter the Maximum Battery X Position (m): 2.5

Enter the Minimum Battery Y Position (m) :-0

Enter the Maximum Battery Y Position (m) :0.5

Enter the Minimum Battery Z Position (m) : 1

Enter the Maximum Battery Z Position (m) : 1.5

Enter the Minimum Vehicle Speed (m/s) :15

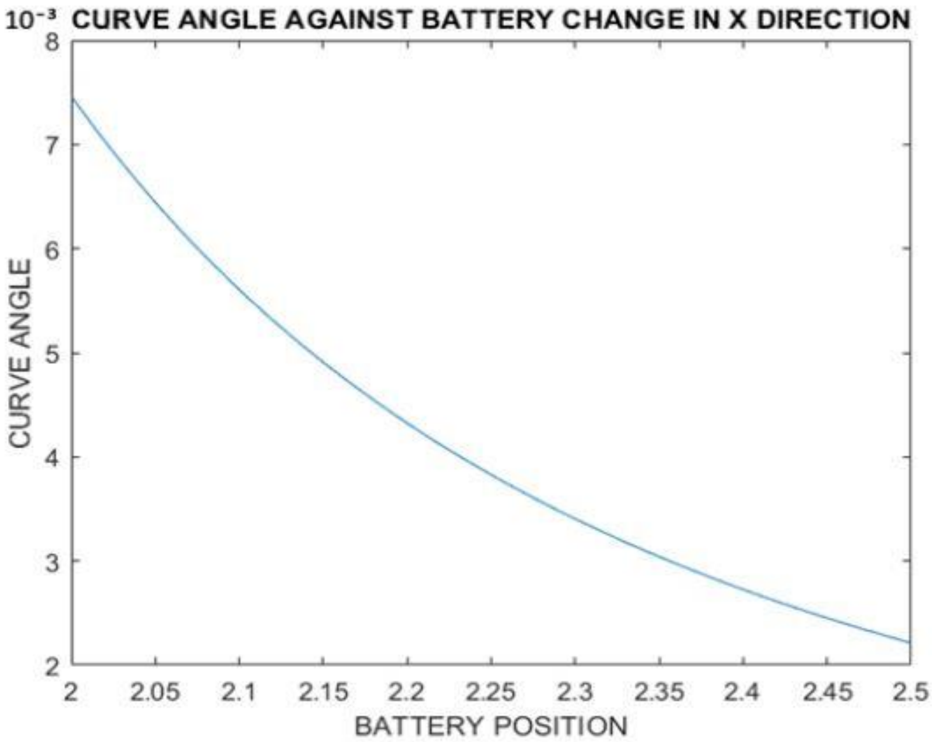
Enter the Maximum Vehicle Speed (m/s) :25

Enter the Curve Radius (m) :40

Inferences

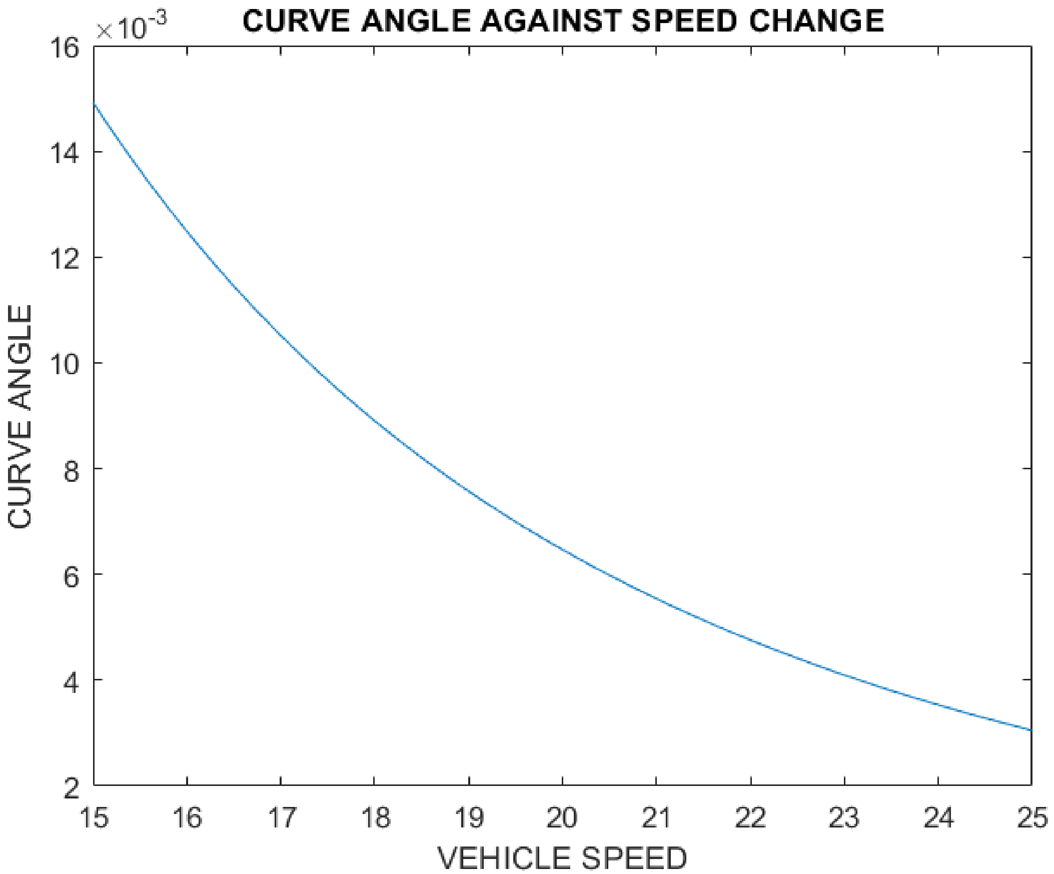
In this scenario, vehicle has 3 meters length and 1-meter width as previous. Also, battery is 2 meters front-hand side and 1-meter upper side of the vehicle. This scenario vehicle has the worst grip of all. Because of the battery position is high, center of gravity is higher. Also, vehicle has small dimensions. According to this, cornering is the worse than all previous scenarios in that virtually designed vehicle.

Because of battery changed location on X and Z axis, the graphics would change dramatically. Cornering was 0.013 degree on previous vehicle. According to graph 4.21 as below, cornering is about 0.008 at the battery position of 2 meters on X.



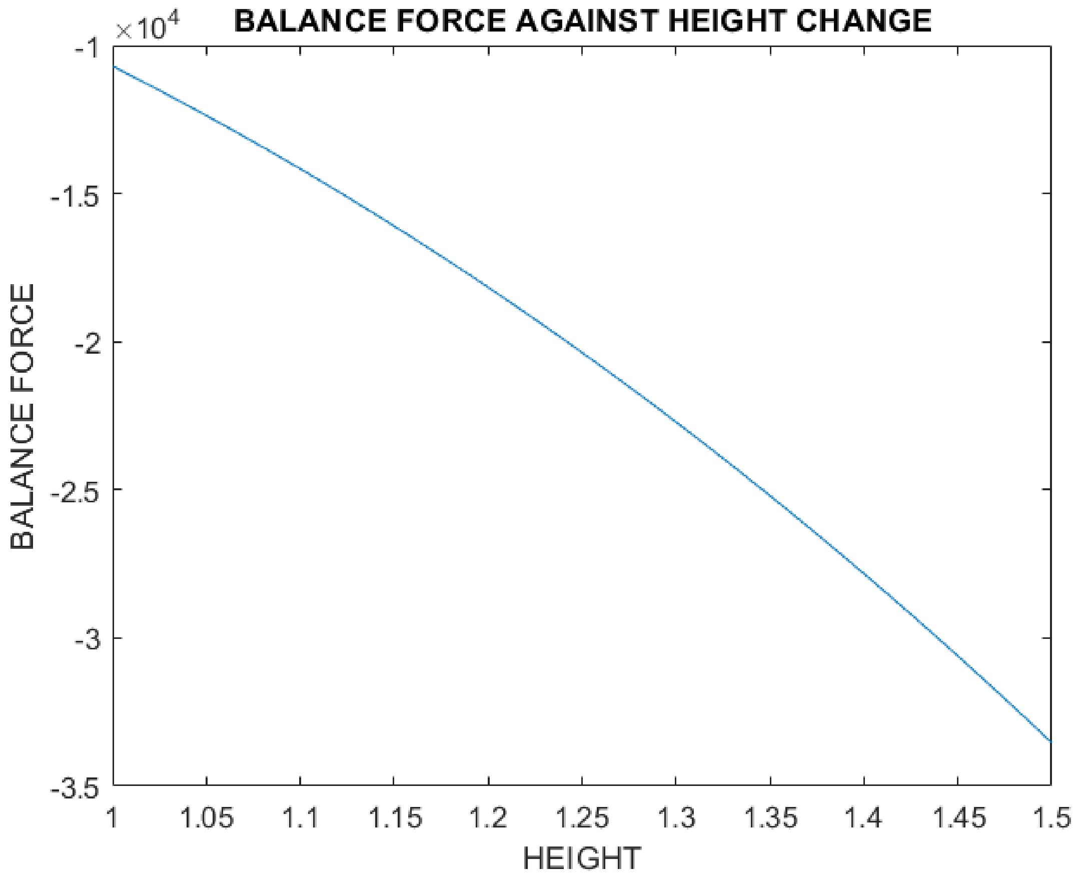
Graph 4.21. Battery Position and Curve Angle on X Axis

According to the graphic 4.22 below, curve angle is about 0.015 degree when the vehicle has 15m/s speed. In the previous scenario, curve angle was about 0.025. This shows that the closer the battery is to the center of gravity and the closer to the ground, vehicle has better handling.



Graph 4.22. Horizontal Acceleration and Bend Angle

As in graph 4.23 as below; on the 0.3 height of the battery, vehicle has about 0.000125 N balance force on negative side, which is the worst result so far. But at the scenario 9, vehicle had 0.0002 N balance force.



Graph 4.23. Vehicle Height and Balance Force

4.1.11. Scenario 11

Enter the Vehicle Weight (kg) : 600

Enter the Battery Weight (kg) :540

Enter the Wheel Coefficiency of Friction :0.4

Enter the Vehicle Length (m) :3

Enter the Vehicle Width (m) :1

Enter the Vehicle Height (m) :2

Enter the Minimum Battery X Position (m) :0

Enter the Maximum Battery X Position (m): 0.5

Enter the Minimum Battery Y Position (m) :-0

Enter the Maximum Battery Y Position (m) :0.5

Enter the Minimum Battery Z Position (m) : 0

Enter the Maximum Battery Z Position (m) : 0.5

Enter the Minimum Vehicle Speed (m/s) :15

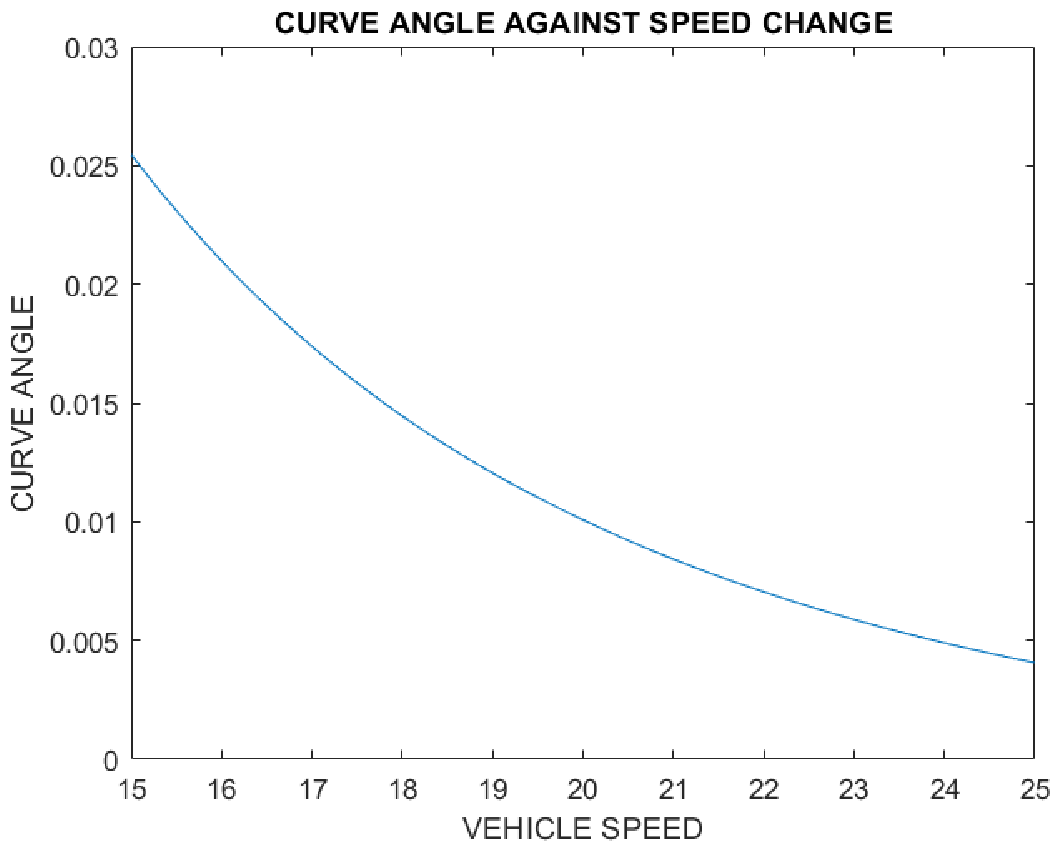
Enter the Maximum Vehicle Speed (m/s) :25

Enter the Curve Radius (m) :40

Inferences

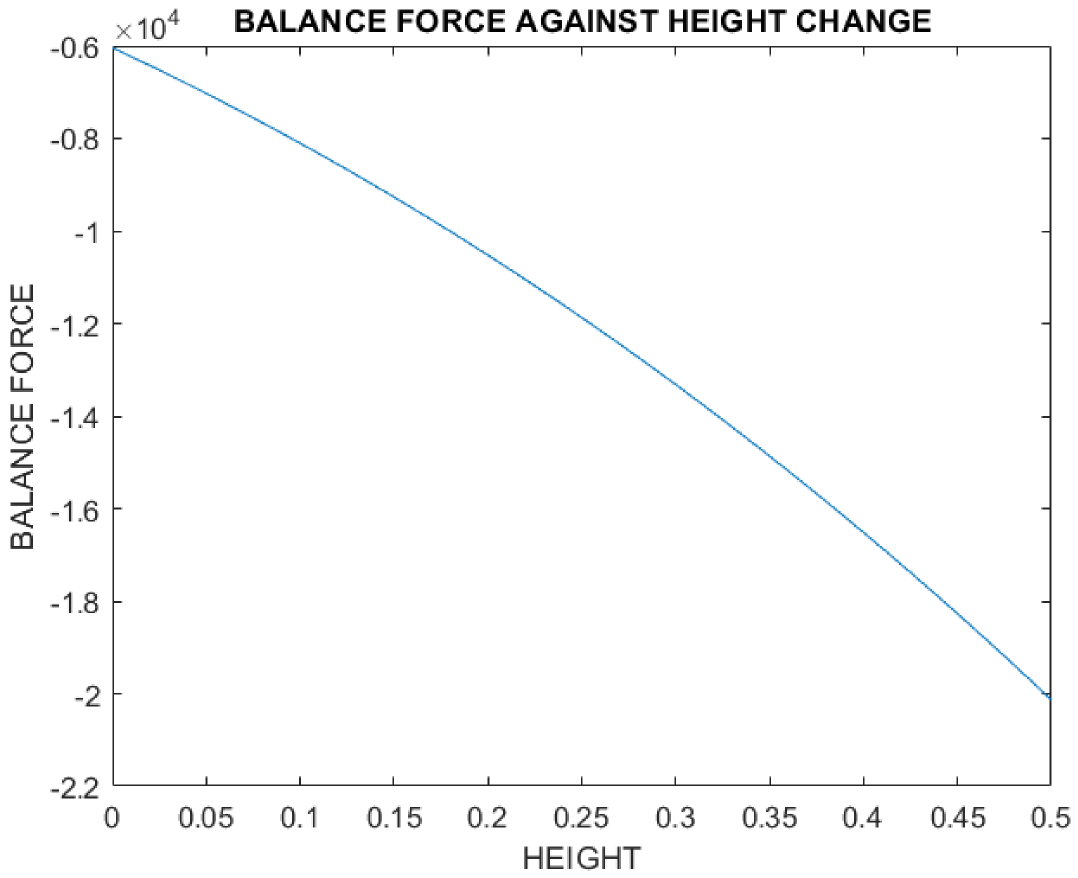
In this test, vehicle has same inputs with scenario 9; except vehicle weight. Vehicle is 600 kilograms instead of 1200. According to these inputs, vehicle has average cornering performance.

Comparing the scenario 9 and this, only difference is vehicle weight. According to that, at slow speeds, vehicle had not very different cornering performance compare to scenario 9. But if the speed increases, cornering performance slightly decreases.



Graph 4.24. Horizontal Acceleration and Bend Angle

In graph 4.25, balance force increases slightly as previous scenario, because the vehicle has lower mass.



Graph 4.25. Horizontal Acceleration and Bend Angle

4.1.12. Scenario 12

Enter the Vehicle Weight (kg) : 1200

Enter the Battery Weight (kg) :300

Enter the Wheel Coefficiency of Friction :0.4

Enter the Vehicle Length (m) :5

Enter the Vehicle Width (m) :3

Enter the Vehicle Height (m) :2

Enter the Minimum Battery X Position (m) :0

Enter the Maximum Battery X Position (m): 0.5

Enter the Minimum Battery Y Position (m) :-0

Enter the Maximum Battery Y Position (m) :0.5

Enter the Minimum Battery Z Position (m) : 0

Enter the Maximum Battery Z Position (m) : 0.5

Enter the Minimum Vehicle Speed (m/s) :15

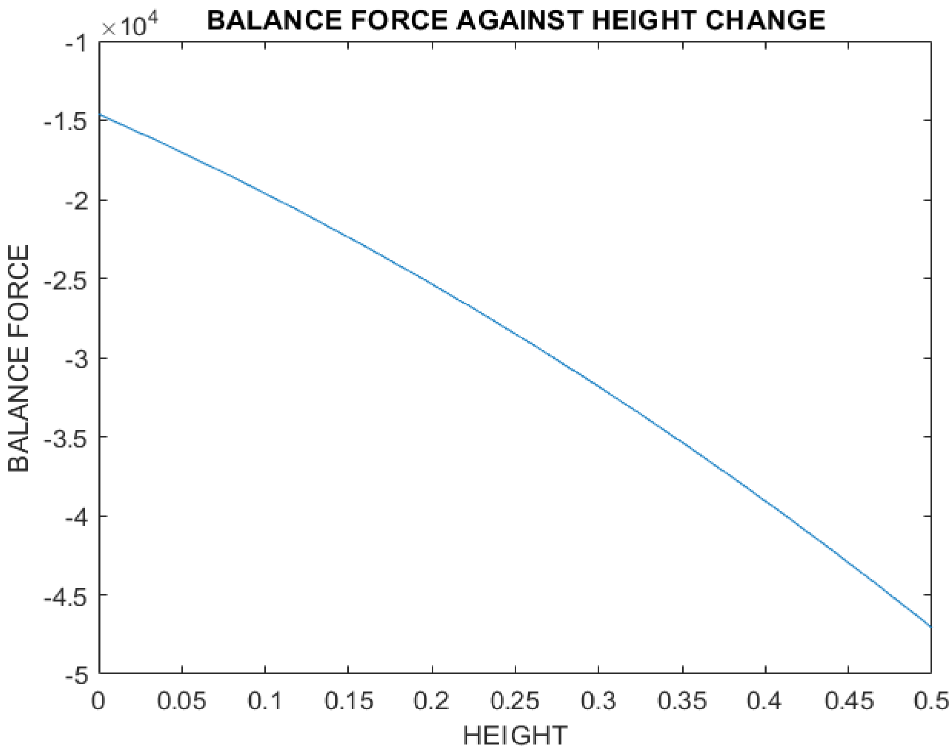
Enter the Maximum Vehicle Speed (m/s) :25

Enter the Curve Radius (m) :25

Inferences

In this scenario, all inputs are as the same with first scenario. Only radius of the curve is 25 meters. According to this, cornering is harder for the vehicle because the bend is sharp. Vehicle would lose the grip easily and oversteer.

As in graph 4.26 below, balance force is about 0.00015N in zero height. In first scenario, balance force was about 0.0001N. Balance force is 33% lower than the first scenario because the the sharp bend.



Graph 4.26. Vehicle Height and Balance Force

4.1.13. Scenario 13

Enter the Vehicle Weight (kg) : 1200

Enter the Battery Weight (kg) :300

Enter the Wheel Coefficiency of Friction :0.4

Enter the Vehicle Length (m) :5

Enter the Vehicle Width (m) :3

Enter the Vehicle Height (m) :2

Enter the Minimum Battery X Position (m) :0

Enter the Maximum Battery X Position (m): 0.5

Enter the Minimum Battery Y Position (m) :-0

Enter the Maximum Battery Y Position (m) :0.5

Enter the Minimum Battery Z Position (m) : 0

Enter the Maximum Battery Z Position (m) : 0.5

Enter the Minimum Vehicle Speed (m/s) :30

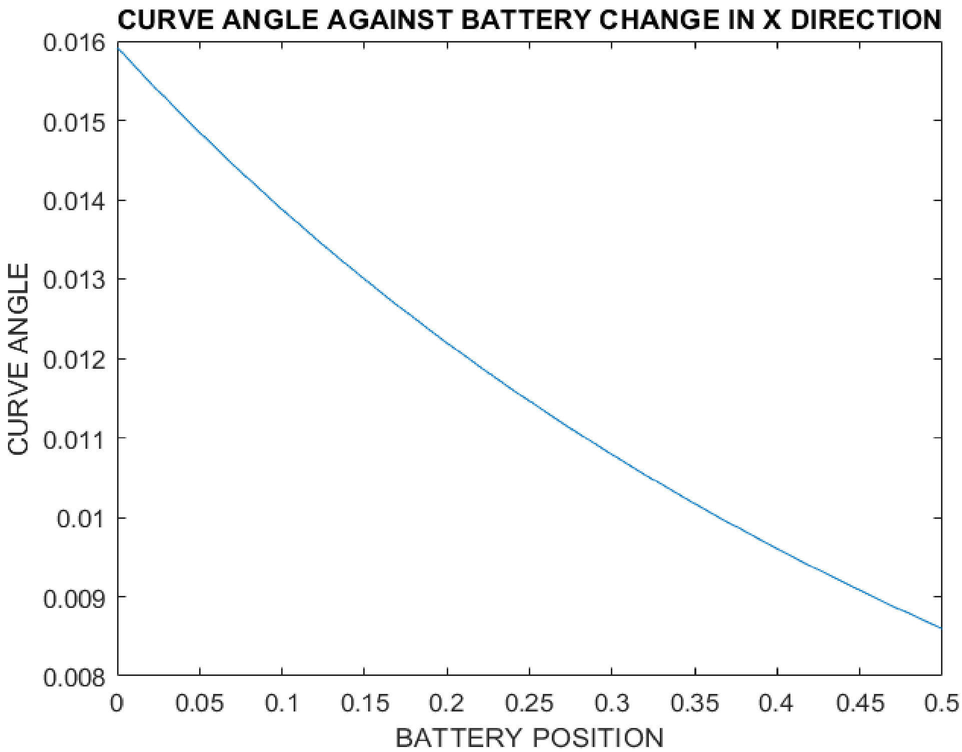
Enter the Maximum Vehicle Speed (m/s) :40

Enter the Curve Radius (m) :25

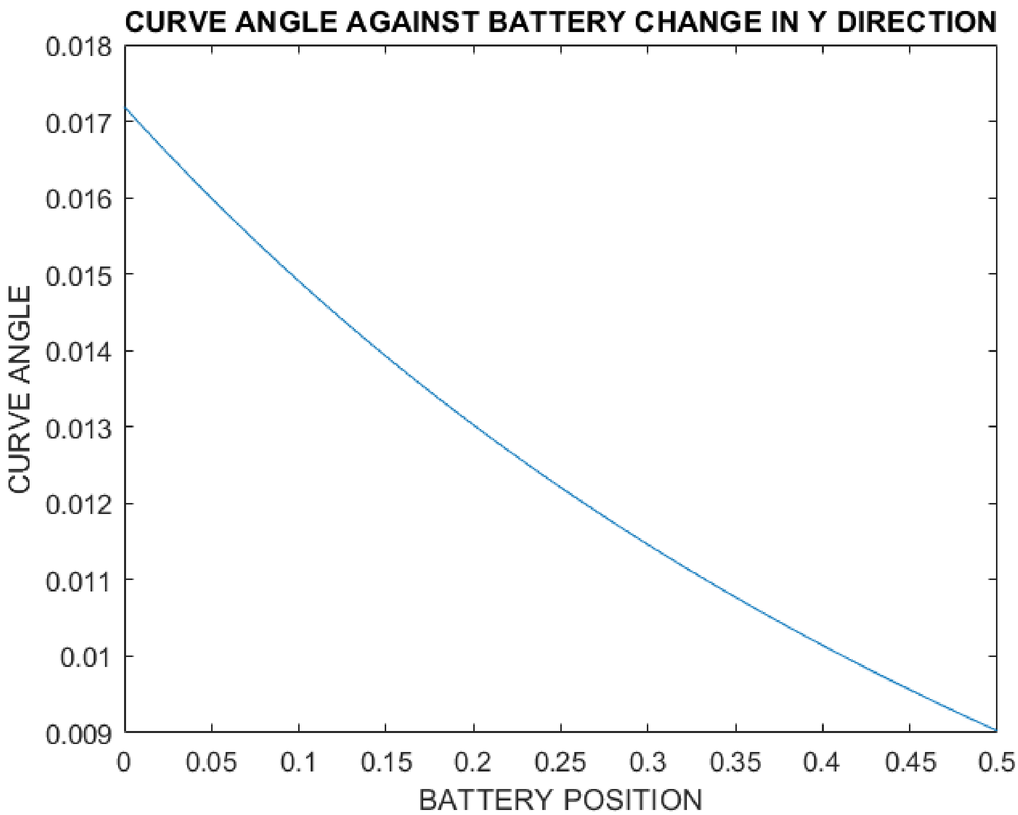
Inferences 13

In this scenario, all inputs are the same with the first scenario, except vehicle speed. Vehicle moves faster in this scenario. This will make cornering performance worse. This will affect the grip negatively.

As in graph 4.27 and 4.28, curve angle is less more than first scenario. On the zeroth battery position on X, curve angle is around 0.016 degree. But in first scenario, vehicle speed was between 15-25m/s. It'scurve angle was 0.065 degree.

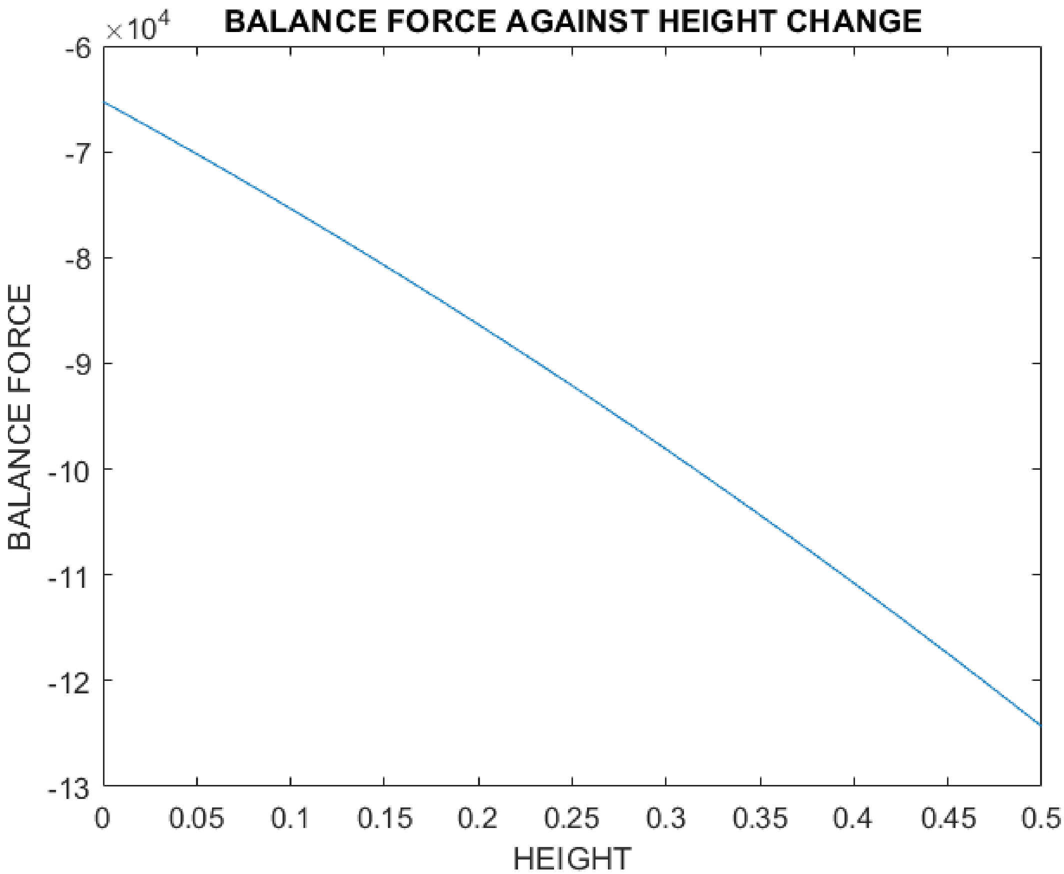


Graph 4.27. Battery Position and Curve Angle on X Axis



Graph 4.28. Battery Position and Curve Angle on Y Axis

As in graph 4.29, balance force is much more than first scenario. Because the speed is high, centrifugal would be higher and balance force would be high.



Graph 4.29. Vehicle Height and Balance Force

4.1.14. Scenario 14

Enter the Vehicle Weight (kg) : 1200

Enter the Battery Weight (kg) :300

Enter the Wheel Coefficiency of Friction :0.4

Enter the Vehicle Length (m) :5

Enter the Vehicle Width (m) :3

Enter the Vehicle Height (m) :3

Enter the Minimum Battery X Position (m) :0

Enter the Maximum Battery X Position (m) :0.5

Enter the Minimum Battery Y Position (m) :0

Enter the Maximum Battery Y Position (m) :0.5

Enter the Minimum Battery Z Position (m) :-1.5

Enter the Maximum Battery Z Position (m) :-1

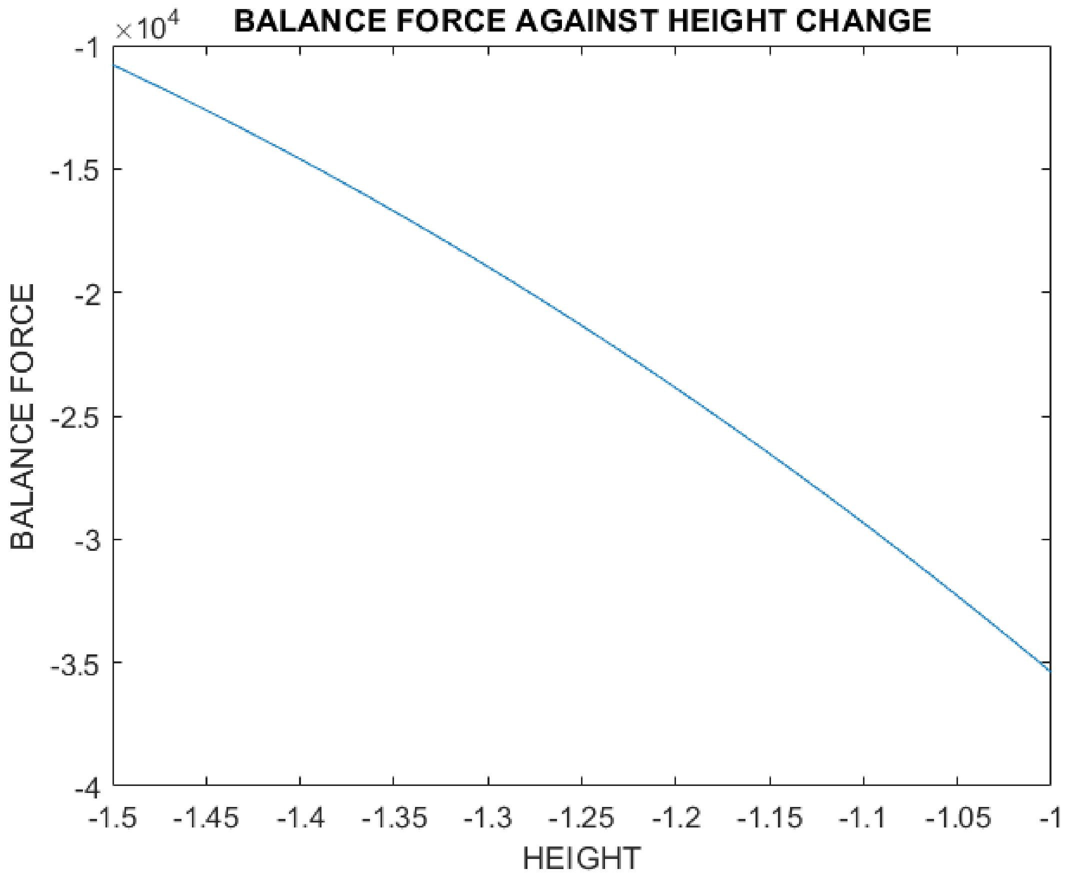
Enter the Minimum Vehicle Speed (m/s) :15

Enter the Maximum Vehicle Speed (m/s) :25

Enter the Curve Radius (m) :40

Inferences 14

In this scenario, all inputs are the same with the first one, except height of the battery on X-axis. Because the height of the battery is less, center of gravity would be lower; this causes better cornering performance. In first scenario, when the height of the battery is around 0.5-meter, balance force was about 3 Newton. In this scenario, when the battery height is 1 meter below the center of gravity, balance force would be around 3.5 Newton. (Graph 4.30)



Graph 4.30. Vehicle Height and Balance Force

4.2 Maximum Curve Calculation

In this section, the maximum cornering angle that the vehicle can turn with the inputs which entered was calculated. When the MATLAB code ran, the 1 key must be pressed. This helps to calculate maximum cornering capability of the vehicle by degree in a meter. If the cornering failures, the code gives “vehicle tilt over” error. If the vehicle corners the bend successfully, “vehicle not tilt over” code would be seen.

4.2.1. Scenario 1

Enter the Vehicle Weight (kg) : 1200

Enter the Battery Weight (kg) :540

Enter the Wheel Coefficiency of Friction :0.4

Enter the Vehicle Length (m) :5

Enter the Vehicle Width (m) :3

Enter the Vehicle Height (m) :2

Enter the Battery X Position (m) :0

Enter the Battery Y Position (m) :0

Enter the Battery Z Position (m) :-1

Enter the Vehicle Speed (m/s) :15

Enter the Curve Radius (m) :80

Vehicle Tilt Over

Maximum Curve Degree: 0.076394 .>>

In this scenario, vehicle could not corner the bend. Vehicle tilts over at the angle of 0.076 degree of the curve.

4.2.2. Scenario 2

Enter the Vehicle Weight (kg) : 1200

Enter the Battery Weight (kg) :300

Enter the Wheel Coefficiency of Friction :0.4

Enter the Vehicle Length (m) :5

Enter the Vehicle Width (m) :3

Enter the Vehicle Height (m) :2

Enter the Battery X Position (m) :0

Enter the Battery Y Position (m) :0

Enter the Battery Z Position (m) :-0.8

Enter the Vehicle Speed (m/s) :10

Enter the Curve Radius (m) :100

Vehicle Not Tilt Over

Maximum Curve Degree : 0.171887 .>>

In this scenario, vehicle does not tilt over; it travels cross the curve safely with about 0.172 degree.

4.2.3. Scenario 3

Enter the Vehicle Weight (kg) : 1200

Enter the Battery Weight (kg) :300

Enter the Wheel Coefficiency of Friction :0.9

Enter the Vehicle Length (m) :5

Enter the Vehicle Width (m) :3

Enter the Vehicle Height (m) :2

Enter the Battery X Position (m) :0

Enter the Battery Y Position (m) :0

Enter the Battery Z Position (m) :-0.8

Enter the Vehicle Speed (m/s) :10

Enter the Curve Radius (m) :100

Vehicle Not Tilt Over

Maximum Curve Degree : 0.386741 .>>

In this scenario, vehicle corners approximately 0.386-degree curve safely.

5. CONCLUSION

Electric vehicles (EVs) are becoming increasingly popular due to their potential to reduce emissions, save energy, and promote sustainable transportation. The purpose of this thesis was to design and develop a small electric vehicle using a mathematical model and simulation tools. The model was based on the fundamental forces acting on vehicles and the performance of the EV was analyzed using simulation software. This thesis contributes to the design and development of electric vehicles, as well as to the understanding of their performance characteristics.

The study began with a detailed review of electric vehicles components and their characteristics. The review included presuming an electric vehicles different road and design scenarios depending the battery’s location. The virtual design of the electric vehicle was then developed using MATLAB/Simulink software, which allowed the calculation of the dynamic behavior and performance values of the vehicle. The simulation study provided a platform for analyzing different scenarios and establishing a stable and optimum balance.

The simulation study showed that the electric vehicle designed in this study could overcome the resistances that occur during movement, including wind resistance, rolling resistance, hill resistance, and acceleration resistance. Those resistances would be integrated by friction coefficient. The forces acting on the vehicle were calculated by subtracting the external forces that oppose the force produced by the motor shaft, and the load moment that would affect the motor was determined. The mechanical coupling of the drive motor was provided through a fixed ratio gearbox with a conversion ratio of 5.

In addition, the simulation study showed that regenerative braking could be used to capture and store energy during braking, which could then be used to power the electric motor during acceleration. This was an important finding because it demonstrated the potential to improve the energy efficiency of electric vehicles. By regenerative braking, electric vehicles can go further distances by one full charge. Regenerative braking increases the range of the vehicle dramatically.

The design and simulation of the electric vehicle presented in this thesis has several implications for the future of electric vehicles. The study showed that electric vehicles can be designed and developed using simulation tools, which can provide insights into the performance characteristics of the vehicle. The study also showed that simple powertrain designs can be effective in achieving good performance characteristics in electric vehicles.

Overall, this thesis provides important insights into the design and development of electric vehicles and demonstrates the potential of simulation tools for analyzing the performance characteristics of these vehicles. The results of this study can be used to inform the design of future electric vehicles, and to promote the use of sustainable transportation.

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APPENDIX

Running code is as below:

```
clear
clc

p=input("If you want a single case to be calculated enter 1, if you want to draw
graph enter 2 :");
if p==1

    m1=input("Enter the Vehicle Weight (kg) : ");
    m2=input("Enter the Battery Weight (kg) :");
    u=input("Enter the Wheel Coefficiency of Friction :");
    length=input("Enter the Vehicle Length (m) :");
    width=input("Enter the Vehicle Width (m) :");
    height=input("Enter the Vehicle Height (m) :");
    xposition=input("Enter the Battery X Position (m) :");
    yposition=input("Enter the Battery Y Position (m) :");
    zposition=input("Enter the Battery Z Position (m) :");
    speed=input("Enter the Vehicle Speed (m/s) :");
    radius=input("Enter the Curve Radius (m) :");

    %% Weight Center Calculation

    topmass=m1+m2;
    centerx=xposition-((xposition/topmass)*m1);
    centery=yposition-((yposition/topmass)*m1);
    centerz=zposition-((zposition/topmass)*m1);

    %% Weight Calculation on Each Wheel


left_forward_mass=(((topmass/length)*((length/2)+centerx))/width)*((width/2)+cente
ry);
    right_forward_mass=(((topmass/length)*((length/2)+centerx))/width)*((width/2)-
centery);
    left_backward_mass=(((topmass/length)*((length/2)-
centerx))/width)*((width/2)+centery);
    right_backward_mass=(((topmass/length)*((length/2)-
centerx))/width)*((width/2)-centery);

    %% Calculating Handling of Each Tire

    left_forward_handling=left_forward_mass*u;
    right_forward_handling=right_forward_mass*u;
    left_backward_handling=left_backward_mass*u;
    right_backward_handling=right_backward_mass*u;

    %% Calculation of the centripetal force acting on the vehicle

    Fcenter_m=topmass*speed^2/radius;

    %% Curve Angle Calculation
```

```
    degree=atand(width/radius);

    %% Vertical Tipping Status

    y_degree=atand((centerz+height)/(centery+(width/2)));
    z_width=sqrt((centerz+height)^2+(centery+(width/2))^2);
    balance=(topmass*cosd(y_degree))*z_width-Fcenter_m*z_width/2;

    if balance>0
        disp('Vehicle Not Tilt Over');
    else
        disp('Vehicle Tilt Over');
    end


    %% Maximum bend radius calculation

    A=[left_forward_handling right_forward_handling left_backward_handling
right_backward_handling];
    Fcenter_m=min(A);
    radius_m=topmass*speed^2/Fcenter_m;
    degree_m = atand(width/radius_m);

    %% RESULTS

    fprintf('Maximum Curve Degree : %f .',degree_m);
end

if p==2
    m1=input("Enter the Vehicle Weight (kg) : ");
    m2=input("Enter the Battery Weight (kg) :");
    u=input("Enter the Wheel Coefficiency of Friction :");
    length=input("Enter the Vehicle Length (m) :");
    width=input("Enter the Vehicle Width (m) :");
    height=input("Enter the Vehicle Height (m) :");
    xminposition=input("Enter the Minimum Battery X Position (m) :");
    xmaxposition=input("Enter the Maximum Battery X Position (m) :");
    yminposition=input("Enter the Minimum Battery Y Position (m) :");
    ymaxposition=input("Enter the Maximum Battery Y Position (m) :");
    zminposition=input("Enter the Minimum Battery Z Position (m) :");
    zmaxposition=input("Enter the Maximum Battery Z Position (m) :");
    minspeed=input("Enter the Minimum Vehicle Speed (m/s) :");
    maxspeed=input("Enter the Maximum Vehicle Speed (m/s) :");
    radius=input("Enter the Curve Radius (m) :");

    xnomposition=abs(xmaxposition+xminposition)/2;
    ynomposition=abs(ymaxposition+yminposition)/2;
    nomspeed=abs(minspeed+maxspeed)/2;

    %% Center of gravity calculation

    topmass=m1+m2;
    j=1;
    for i=xminposition:abs(xmaxposition-xminposition)/100:xmaxposition
        centerx(j)=i-((i/topmass)*m1);
        j=j+1;
    end
    j=1;
```

```
    for i=yminposition:abs(ymaxposition-yminposition)/100:ymaxposition
        centery(j)=i-((i/topmass)*m1);
        j=j+1;
    end
    j=1;
    for i=zminposition:abs(zmaxposition-zminposition)/100:zmaxposition
        centerz(j)=i-((i/topmass)*m1);
        j=j+1;
    end
    %% CALCULATIONS
    for i=1:1:101

    %% Calculation of the load on the tires


left_forward_massx(i)=(((topmass/length)*((length/2)+centerx(i)))/width)*((width/2
)+ynomposition);

right_forward_massx(i)=(((topmass/length)*((length/2)+centerx(i)))/width)*((width/
2)-ynomposition);
        left_backward_massx(i)=(((topmass/length)*((length/2)-
centerx(i)))/width)*((width/2)+ynomposition);
        right_backward_massx(i)=(((topmass/length)*((length/2)-
centerx(i)))/width)*((width/2)-ynomposition);


left_forward_massy(i)=(((topmass/length)*((length/2)+xnomposition))/width)*((width
/2)+centery(i));

right_forward_massy(i)=(((topmass/length)*((length/2)+xnomposition))/width)*((widt
h/2)-centery(i));
        left_backward_massy(i)=(((topmass/length)*((length/2)-
xnomposition))/width)*((width/2)+centery(i));
        right_backward_massy(i)=(((topmass/length)*((length/2)-
xnomposition))/width)*((width/2)-centery(i));


left_forward_massxy(i)=(((topmass/length)*((length/2)+centerx(i)))/width)*((width/
2)+centery(i));

right_forward_massxy(i)=(((topmass/length)*((length/2)+centerx(i)))/width)*((width
/2)-centery(i));
        left_backward_massxy(i)=(((topmass/length)*((length/2)-
centerx(i)))/width)*((width/2)+centery(i));
        right_backward_massxy(i)=(((topmass/length)*((length/2)-
centerx(i)))/width)*((width/2)-centery(i));

    %% Calculation of the grip of individual tires

        left_forward_handlingx(i)=left_forward_massx(i)*u;
        right_forward_handlingx(i)=right_forward_massx(i)*u;
        left_backward_handlingx(i)=left_backward_massx(i)*u;
        right_backward_handlingx(i)=right_backward_massx(i)*u;

        left_forward_handlingy(i)=left_forward_massy(i)*u;
        right_forward_handlingy(i)=right_forward_massy(i)*u;
        left_backward_handlingy(i)=left_backward_massy(i)*u;
        right_backward_handlingy(i)=right_backward_massy(i)*u;
```

```
        left_forward_handlingxy(i)=left_forward_massxy(i)*u;
        right_forward_handlingxy(i)=right_forward_massxy(i)*u;
        left_backward_handlingxy(i)=left_backward_massxy(i)*u;
        right_backward_handlingxy(i)=right_backward_massxy(i)*u;

    %% Calculation of the centripetal force acting on the vehicle

        Fcenterspeed(i)=topmass*(minspeed+((maxspeed-minspeed)/100)*(i-
1))^2/radius;

    %% Bend angle calculation

        degree=atand(width/radius);

    %% Vertical Tipping Status

        y_degree(i)=atand((centerz(i)+height)/(centery(i)+(width/2)));
        z_width(i)=sqrt((centerz(i)+height)^2+(centery(i)+(width/2))^2);
        balance(i)=(topmass*cosd(y_degree(i)))*z_width(i)-
Fcenterspeed(i)*z_width(i)/2;

    %% Maximum bend angle calculation

        Ax=[left_forward_handlingx(i) right_forward_handlingx(i)
left_backward_handlingx(i) right_backward_handlingx(i)];
        Ay=[left_forward_handlingy(i) right_forward_handlingy(i)
left_backward_handlingy(i) right_backward_handlingy(i)];
        Axy=[left_forward_handlingxy(i) right_forward_handlingxy(i)
left_backward_handlingxy(i) right_backward_handlingxy(i)];

        Fcenter_mx(i)=min(Ax);
        Fcenter_my(i)=min(Ay);
        Fcenter_mxy(i)=min(Axy);

        radius_mx(i)=topmass*(minspeed+((maxspeed-minspeed)/100)*(i-
1))^2/Fcenter_mx(i);
        radius_my(i)=topmass*(minspeed+((maxspeed-minspeed)/100)*(i-
1))^2/Fcenter_my(i);
        radius_mxy(i)=topmass*(minspeed+((maxspeed-minspeed)/100)*(i-
1))^2/Fcenter_mxy(i);

        degree_mx(i)=atand(width/radius_mx(i));
        degree_my(i)=atand(width/radius_my(i));
        degree_mxy(i)=atand(width/radius_mxy(i));

    end

    x=xminposition:abs(xmaxposition-xminposition)/100:xmaxposition;
    figure(1)
    plot(x,degree_mx);
    title('CURVE ANGLE AGAINST BATTERY CHANGE IN X DIRECTION');
    xlabel('BATTERY POSITION');
    ylabel('CURVE ANGLE');

    y=yminposition:abs(ymaxposition-yminposition)/100:ymaxposition;
    figure(2)
    plot(y,degree_my);
```

```
    title('CURVE ANGLE AGAINST BATTERY CHANGE IN Y DIRECTION');
    xlabel('BATTERY POSITION');
    ylabel('CURVE ANGLE');

    figure(3)
    plot3(x,y,degree_mxy);
    title('CURVE ANGLE AGAINST BATTERY CHANGE IN X & Y DIRECTION');
    xlabel('BATTERY POSITION X');
    ylabel('BATTERY POSITION Y');
    zlabel('CURVE ANGLE');

    velocityz=minspeed:abs(maxspeed-minspeed)/100:maxspeed;
    figure(4)
    plot(velocityz,degree_mxy);
    title('CURVE ANGLE AGAINST SPEED CHANGE');
    xlabel('VEHICLE SPEED');
    ylabel('CURVE ANGLE');

    z=zminposition:abs(zmaxposition-zminposition)/100:zmaxposition;
    figure(5)
    plot(z,balance);
    title('BALANCE FORCE AGAINST HEIGHT CHANGE');
    xlabel('HEIGHT');
    ylabel('BALANCE FORCE');

end
```