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MASTER

In **Control**

Option: **Control**

Title:

Speed Control Method of Electric Vehicle for Improving Passenger Ride Quality

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Registration Number:………/2019

Dedications

I would like to dedicate this work to my lovely supportive family,

To my Grand-parents may their souls rest in peace,

To my parents, who have been a source of encouragement and inspiration to me throughout my life,

To everyone whom whenever I felt down they helped me to stand up again and work harder.

Acknowledgement

There have been many people who have walked alongside us during this year, this long busy year. They have guided me, placed opportunities in front of me and showed me the doors that might be useful to open. I would like to thank every one of them. Without hesitation I would especially like to thank my supervisor ***Dr.Saliha Boutora***, ***Dr.Youcef Grainat***. Without your encouragements, your belief in me, your help and inspiration this thesis would not have been possible.

Even though I found some difficulties during the simulation of this thesis but my supervisor ***Dr S.Boutora*** as strict as She was but with good attention that I could understand only at the end gave me faith in myself and in my skills, She showed me not to be scared and to try, to think and take risks as an engineer, to try to find solution to any obstacles I might face as I faced a lot.

So thank you again as we learnt a lot of technical skills during this amazing experience.

Abstract

In This project, we are applying new speed control method of electric vehicles (EVs) which consists of the longitudinal speed pattern for improving the ride comfort against the longitudinal acceleration/deceleration. Since the longitudinal acceleration/ deceleration of EVs causes the discomfort of passengers, reducing such bad effect of acceleration/deceleration acting on passengers is very important for not only the ride comfort of them, but also vehicle running safety. By applying the general optimal control theory, We generate the speed pattern for improving the passenger ride quality based on evaluating the variations of acceleration. The effectiveness of the present method is demonstrated through numerical experiments using MATLAB compared with some conventional methods.

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List of abbreviations

EV : Electric Vehicle.

HV : Hybrid Vehicle.

ICEV : Internal Combustion Engine Vehicle.

PRT : Personal Rapid Transit.

ICE : Internal Combustion Engine.

PHEV : Plug-in Hybrid Electric Vehicle.

PI : Proportional Integral.

DC : Direct Current.

Chapter I : Overview of Electric Vehicle

Chapter II : Passenger Ride Quality

Chapter III : Speed Control Method

Chapter IV : Simulation Results

General Introduction

In recent years, with the wide spread of internal-combustion engine vehicles (ICEVs) all over the world, the environment and energy problems are going severely. Therefore, the development of next-generation vehicles such as hybrid vehicles (HVs) and electric vehicles (EVs) has been focused. Especially, EVs have attracted great interests as a powerful solution against the problems. EVs are automobiles which are propelled by electric motors, using electrical energy stored in batteries or another energy storage device. Electric Motors have several advantages over ICEs [1] [2] [3] [4]:

- Energy efficient. Electric motors convert 75% of the chemical energy from the batteries to power the wheels—ICEs only convert 20% of the energy stored in gasoline.
- Environmentally friendly. EVs emit no tailpipe pollutants, although the power plant producing the electricity may emit them. Electricity from nuclear-, hydro-, solar-, wind-powered plants causes no air pollutants.
- The input/output response is faster than for gasoline/diesel engines. It is said that the motor torque response is 2 orders of magnitude faster than that of the engine. E.g., if engine torque response costs 500 ms, the response time of motor toque will be 5 ms.
- The torque generated in the wheels can be detected relatively accurately. For engine, the output torque varies along with the temperature and revolutions; even it has high-nonlinearity. Consequently, the value of torque is too difficult to be measured accurately. However, the value of motor torque is surveyed easily and accurately from the view of current control.
- The motor can be made small enough, then the vehicles can be made smaller by using multiple motors placed closer to the wheels. The drive wheels can be controlled fully and independently. E.g., it becomes easily achievable to control the differences of driving force developed between the left and right wheel.

From these good points of EVs, we can realize the superior running of vehicle with the good ride quality by using appropriate speed control. Such superior speed control is very useful for autonomous vehicle and some types of autonomous vehicle can also be applied, for example, PRT (Personal Rapid Transit) [5] and so on. From the point of view of preventing a motion sickness and an accident, the ride comfort of the car is also very important [6].

Because vertical vibration influences the ride comfort of passengers, many studies are performed about the relation of vertical vibration and ride quality from the past few decades. For example, [7] or [8] are typical works for investigating the analyses, the ride discomfort caused by vertical vibration. Furthermore, an active suspension control system [9] is a typical control system for preventing the vertical vibration. As well as the vertical vibration, it is important to reduce the influence on lateral speed change for improving overall ride quality. However, unfortunately, there are few studies on ride discomfort due to longitudinal acceleration/deceleration. Therefore, in this project, we used the speed control method by generating the longitudinal speed pattern using the jerk which is time derivative of the acceleration and the acceleration as the evaluation index, for improving the ride comfort against the longitudinal acceleration/deceleration. We apply the method by using the general optimal control theory and also based on the techniques proposed in [10] [11] [12] [13]. The method aims to contribute to improve the beginner driver's driving skill from the viewpoint of passenger's comfortability by showing the ideal running pattern and checking the driving.
The rest of this project is organized as follows: Chapter1 describes the electric vehicle; Chapter 2 states the evaluation of ride comfort. In Chapter 3, the proposed generation method of speed pattern is presented. The extended proposed method is shown. The simulation results are discussed in chapter 4. Finally, we end the project with some conclusions.

Chapter 1

Overview of Electric Vehicle

1.1. Introduction

An electric vehicle (EV) is a vehicle powered by an electric motor, instead of an internal combustion engine (ICE), and the motor is run using the power stored in the batteries. The batteries have to be charged frequently by plugging into any main (120 V or 240 V) supply. EVs are known as zero emissions vehicles (ZEVs) and are much environment friendly than gasoline- or LPG-powered vehicles. As EVs have fewer moving parts, maintenance is also minimal. With no engine there are no oil changes, tune-ups, or timing and there is no exhaust. EVs are also far more energy efficient than gasoline engines and they are very quiet in operation.

Electric vehicle (EV) are based on electric propulsion system. No internal combustion engine is used. All the power is based on electric power as the energy source. The main advantage is the high efficiency in power conversion through its propulsion system of electric motor. Recently there has been massive research and development work reported in both academic and industry. Commercial vehicle is also available. Many countries have provided incentive to users through lower tax or tax exemption, free parking and free charging facilities.

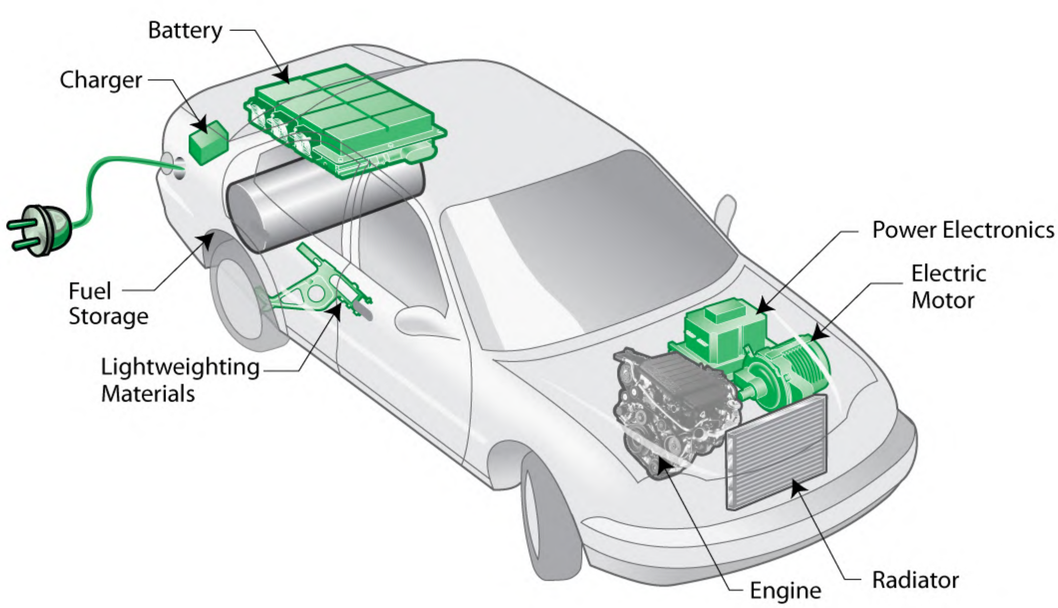

Fig 1: PHEV Diagram.

1.2. The key components of an EV

The electric vehicle is rather simple in structure. The key components are the propulsion parts. Fig 2 shows the configuration.

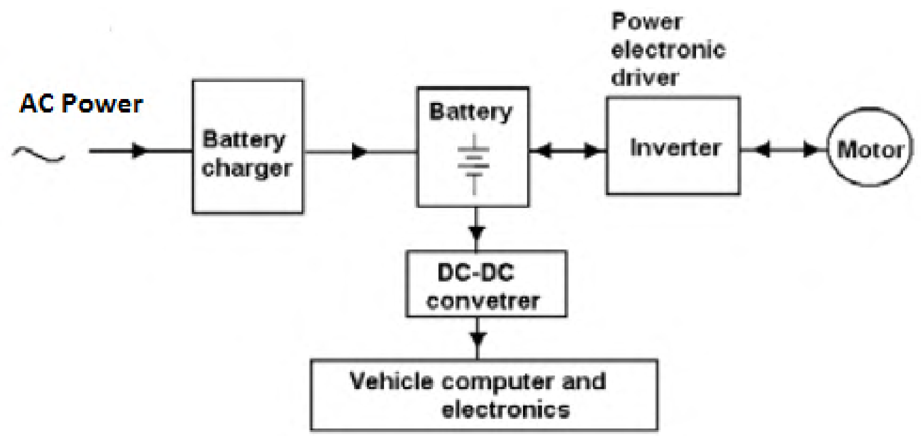

Fig 2: The key components of an Electric Vehicle.

The battery is the main energy storage. The battery charger is to convert the electricity from mains to charge the battery. The battery voltage is DC and I is inverted into switched-mode signal through power electronic inverter to drive the motor. The other electronic components in a vehicle can be supplied to the battery through DC-DC converter that step down the voltage from the battery pack to lower voltage such as 5V-20V.

1.2.1. Batteries

Battery stores the electricity required to run the vehicle. The battery supplies electric current to the motor. And thus, the vehicle runs. The higher the capacity of the battery the higher is the range of the electric vehicle. Most modern electric vehicles use Lithium-ion type batteries. These batteries have higher energy density. It means they are capable of storing more energy. Figure 3 shows the different types of batteries.

Fig 3: The different types of batteries used in EVs.

The table below shows the characteristics of each battery.

Battery Type	**Energy/Weight** **Watt-hours/Kg**	**Energy/Volume** **Watt-hours/L**	**Power/Weight** **Watt/Kg**	**Energy/US$** **Watt-hr/$**
Lead-acid	30-40	60-75	180	4-10
Nickel-Zinc	60-70	170	900	2-3
Lithium-Ion	160	270	1800	3-5
Lithium-Polymer	130-200	300	2800	3-5

Table 1: Properties of batteries used in EVs.

1.2.2. Motors

The motor is the main component of an EV. It is very important to select proper type of motor with suitable rating. For example, it is not accurate to simply refer to a 10 hp motor or a 15 hp motor, because horsepower varies with volts and amps, and peak horsepower is much higher than the continuous rating .There are a number of motors available for electric vehicle: DC motors, Induction motor, DC brushless motor, Permanent magnetic synchronous motor and Switched reluctance motor.

The figure below show the different types of motors used in EVs.

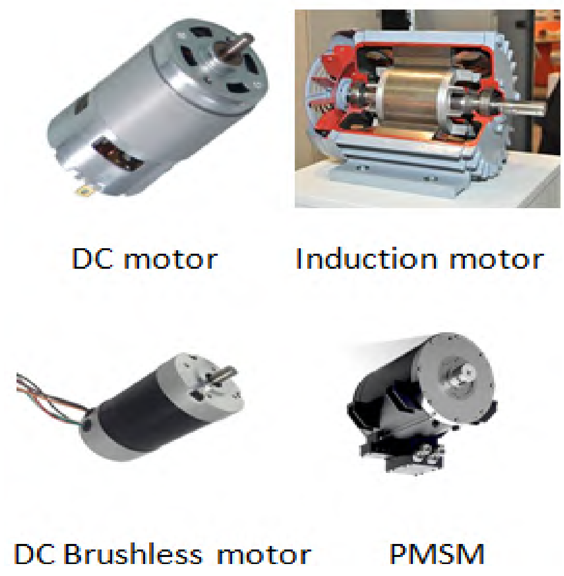

Fig 4: The different types of motors.

1.2.3. Inverter

Battery stores the electric current in the form of Direct Current (DC). But, the majority of the motors used in the electric vehicles run on Alternating Current (AC). So, the inverter performs the function of converting DC to AC.

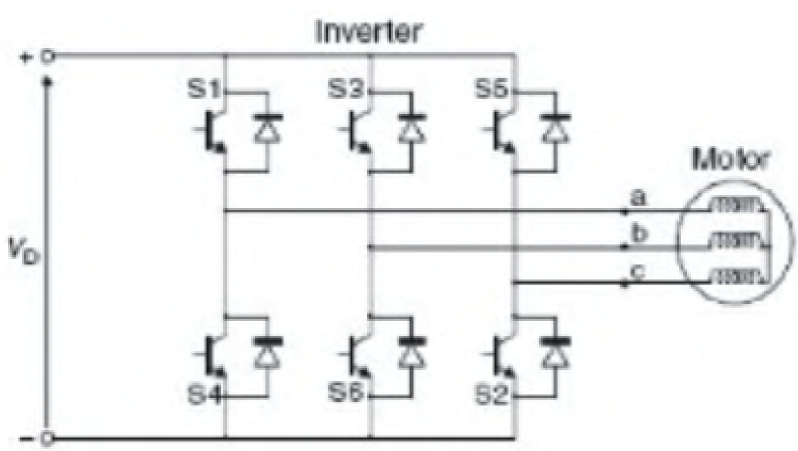

Fig 5: A three phase inverter.

Using six sets of power transistors, the controller takes in 300 volts DC and produces 240 volts AC, 3-phase.

1.2.4. DC-DC Converter

DC to DC converter is a category of power converters and it is an electric circuit which converts a source of direct current (DC) from one voltage level to another, by storing the input energy temporarily and then releasing that energy to the output at a different voltage.

Fig 6: The suitable DC/DC Converter for EVs.

1.2.5. Battery Charger

The charger needed for the battery system for slow charging or fast charger are both required to handle high power. Modern chargers can sense the level of charge in the battery pack, and taper the charging current accordingly.

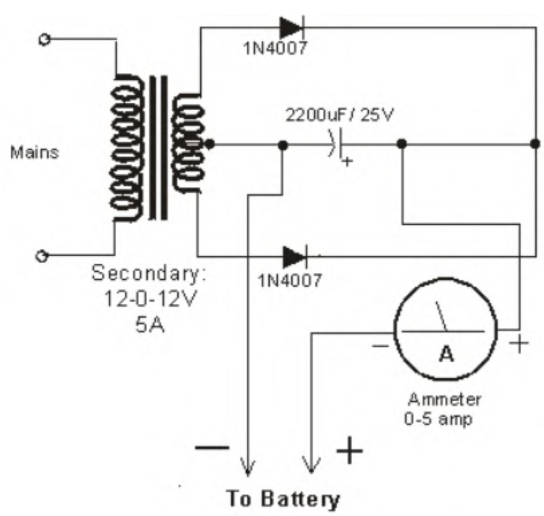

Fig 7: The equivalent Circuit of Charger used in EV

Remarks:

- Charging done from power grid (household/ charging station).
- A good charger monitors battery voltage, current flow and battery temperature to minimize charging time.

Fig 8: Delta Q Charger.

1.3. How do Electric Vehicles work

Instead of a fuel tank, an electric vehicle has an on-board battery that gets charged through an electricity supply and then stores and uses that energy to power an electric motor and set the wheels in motion. It means the cars have no need for a clutch and gearbox or an exhaust pipe and it makes them much quieter and, many say, smoother to drive.

On a full charge, a standard electric car can now run more than 400km before needing to be recharged. That might not be as far as you could get on one tank of petrol, but most journeys could still easily be accomplished in an electric car.

1.4. The different types of Electric Vehicles

Electric vehicles come in three types and they are classed by the degree that electricity is used as their energy source. Fig 9 shows the different types of electric vehicle.

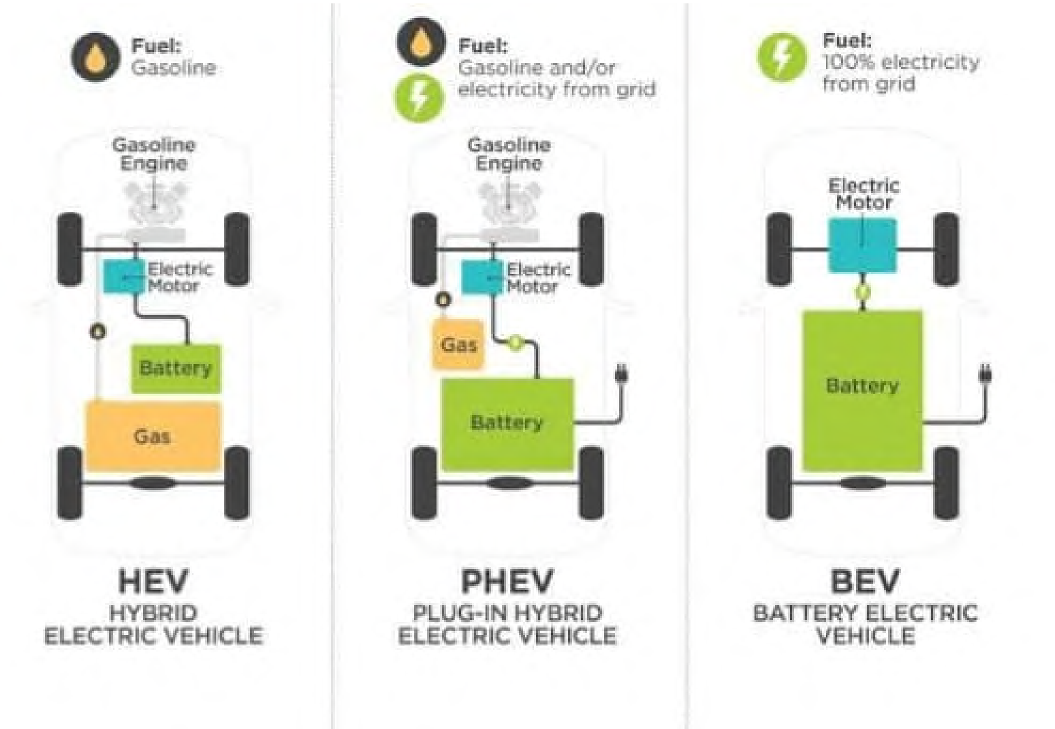

Fig 9: Different types of electric vehicles.

1.4.1. Battery Electric Vehicles or BEV

This type is fully electric with rechargeable batteries and does not have a gasoline engine. It stores electricity onboard with high-capacity battery packs. Battery power is used to run the electric motor of the vehicle and as well as all onboard electronics. Battery electric vehicles do not emit harmful emissions and hazards, unlike traditional gasoline-powered vehicles. They are charged with electricity from an external source.

1.4.2. Plug-In Hybrid Electric Vehicles or PHEV

This type of electric vehicle is also known as Extended-Range Electric Vehicles and it is powered by both petrol and electricity. Its battery can be recharged through both regenerative braking and “plugging in” to an external source of electrical power. This type of electric car can go anywhere from 10 to 40 miles before its gas engine provides assistance, unlike standard hybrids which can only go about 1 to 2 miles before the gasoline engine turns on.

1.4.3. Hybrid Electric Vehicles or HEV

This type of electric car is also powered by both petrol and electricity. Its electric energy is generated by its own braking system to recharge the battery. That process is called "regenerative braking". In that process, the electric motor helps to slow the vehicle and uses some of the energy normally converted to heat by the brakes. It starts off using the electric motor and then the gasoline cuts in as load or speed arises. The two motors of a hybrid electric vehicle are controlled by an internal computer, ensuring the best economy for the driving conditions.

1.5. The main safety components in an EV

1.5.1. Circuit Breakers

A circuit breaker provides a fail-safe manual interruption of the battery power in event of a drive system malfunction. It also provides a convenient way to shut off battery power during routine servicing of the system. It must be installed in a location where it can be operated by the driver. It allows the driver to manually isolate the power train components from the battery pack in an emergency or while working on the car, even if the ignition switch fails.

1.5.2. Ignition Key Main Contractor

Contactors are used to switch high currents remotely by means of a low-level control voltage. In EVs high voltages, inductive loads, and extremely high current loads are encountered. To switch a current under these conditions requires specifically designed equipments. Contactors have continuous duty coils, silver-cadmium-oxide contacts to prevent welding, and magnetic blowouts, which extinguish electrical arcing.

1.5.3. Potbox

The potbox is the interface between the throttle pedal and the speed controller. It sends a variable resistance signal to the controller to specify the amount of electricity to be released to the motor. It interfaces directly with any vehicle's existing throttle control cable or linkage. It comes with many safety features, such as deadman switches for emergency disconnect and high pedal lockout to prevent unintentional acceleration.

1.5.4. Fusible Link

A fusible link should be inserted in the traction battery circuit in each pack in the vehicle. It will break the circuit in case of a short circuit.

1.6. Theory of Operation of EV

When the driver steps on the pedal, the potentiometer activates and provides the signal that tells the controller how much power it is supposed to deliver. There are two potentiometers for safety. The controller reads the setting of the accelerator pedal from the potentiometers, regulates the power accordingly, takes the power from the batteries and delivers it to the motor. The motor receives the power (voltage) from the controller and uses this power to rotate the transmission. The transmission then turns the wheels and causes the car to move forward or backward.

If the driver floors the accelerator pedal, the controller delivers the full battery voltage to the motor. If the driver takes his/her foot off the accelerator, the controller delivers zero volts to the motor. For any setting in between, the controller chops the battery voltage, thousands of times per second to create an average voltage somewhere between 0 and full battery pack voltage. The drive train can also add charge to the battery if the motor is operated as a generator during regeneration. This can occur during braking

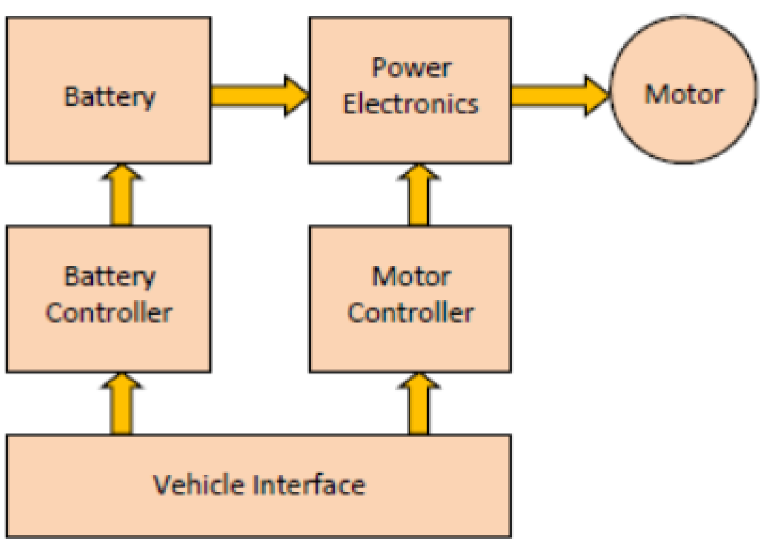

Fig 10: Electric Vehicle Drive Train.

Or if the vehicle is being powered by an Internal Combustion Engine (ICE). In the diagram, the battery is frequently constructed of Lithium Ion cells, and supplies 300+ volts and high current to the power electronics. A battery controller monitors key battery parameters and controls the battery pack.

The power electronics unit inverts the DC battery voltage into three-phase AC voltage at the proper frequency and voltage for the motor to meet the requested speed and torque. The Vehicle Interface communicates with the Battery Controller and Motor Controller, and provides an interface with the vehicle-level controls and sensors.

Potentiometer: It is circular in shape and it is hooked to the accelerator pedal. The potentiometer, also called the variable resistor, provides the signal that tells the controller how much power is it supposed to deliver.

1.7. Electric Vehicle Mathematical Modeling and Simulation

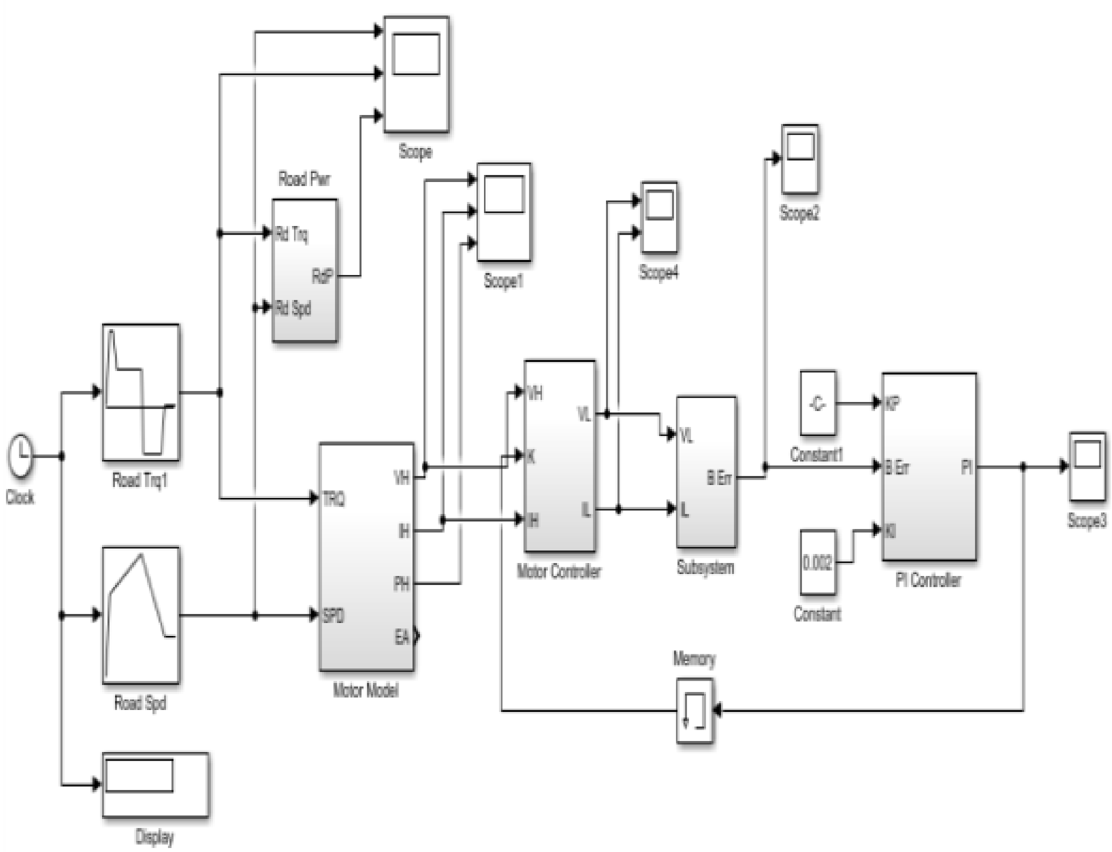

Fig 11. Simulink Model of Electric Vehicle.

The road speed and torque values are taken and simulated using MATLAB/Simulink. The battery voltage required is calculated and the torque and speed conditions during motoring and regeneration were simulated to determine the energy flow and performance of the drive.

This simulation results can be used for electric vehicle applications. Determining the equations and their corresponding variables and parameters is a necessary first step in model development. Each block in this simplified model represents one or more major equations as listed below

Motor Model

Developed motor torque: Td(Nm) =Km*IA(Amp) (1)

Developed motor voltage: V_D(Volt) = W_D (rad/sec)/Km (2)

The motor High Side voltage :

V_H(Volt)= I_H(Amp)*R_A(Ohm)+ L_H(Henry)*di(t)/dt(A/s) + V_D(V) (3)

The motor physical constant, Km, is a physical parameter that depends upon the construction of the motor.

The developed electrical power: P = I_A* V_D* Km (4)

in the motor model the mechanical friction and inertia as well as the magnetic power losses have been set to zero.

Motor Controller Model

The motor controller is assumed to be an ideal controller with no power loss and no time lag. High side voltage: V_H =K*V_L (5)

Controller High Side Current: I_H = (1/K)*V_L (6)

Battery Model

The battery is modelled as a voltage source with an internal resistance. The battery is assumed to have a constant internal voltage, EB.

Battery model calculation: V_L (Volt) = I_L (Amp) *R_A (Ohm) + E_B (Volt) (7)

The battery model uses the current and voltage information from the Motor Controller to calculate the required battery's internal voltage. This voltage is compared with the actual EB value to create a battery voltage error, BErr, and that error is used by the PI controller model to adjust the loop gain.

BE_{RR} = EB (actual) - EB (calculated) (8)

Proportional Integral (PI) Controller Model

The PI controller accepts the BE_{RR} signal from the Battery Model and uses proportional (Kp) and integral (Ki) to calculate the gain K value that is used by the MotorController.

$$K = (Kp + s*KI)*BE_{RR} \quad (9)$$

Simulation Results:

The simulation that is presented assumes known speed and torque values.

Speed values= [0 2000 3000 1000 1000]

Speed time= [0 5 50 85 100]

Torque values = [0 330 330 160 160 -220 -220 0 0]

Torque time = [0 5 10 15 50 55 80 85 100]

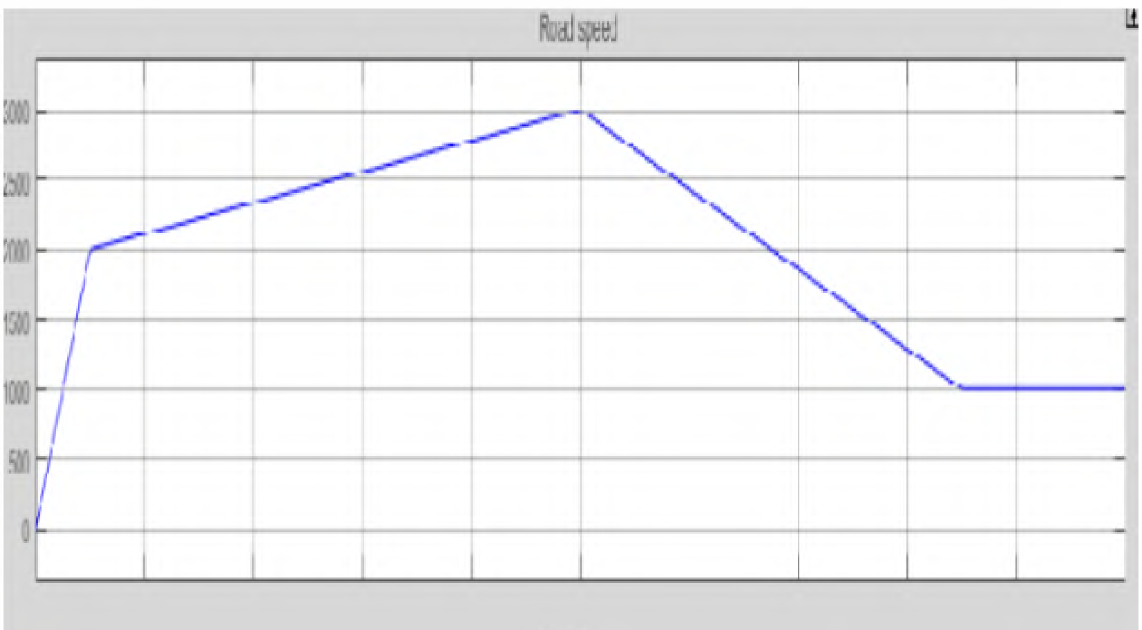

Fig 12: Road Speed Characteristics.

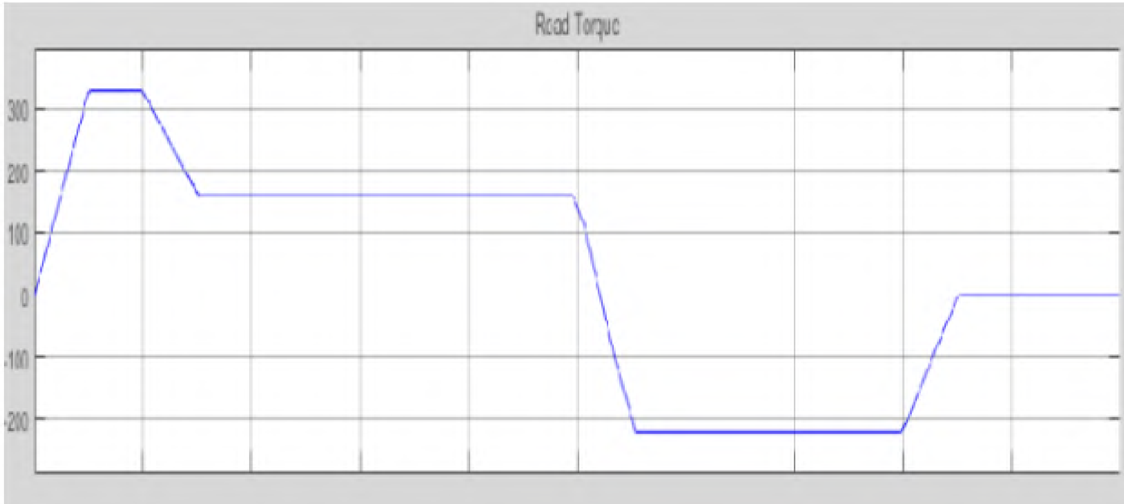

Fig 13: Road Torque Characteristics.

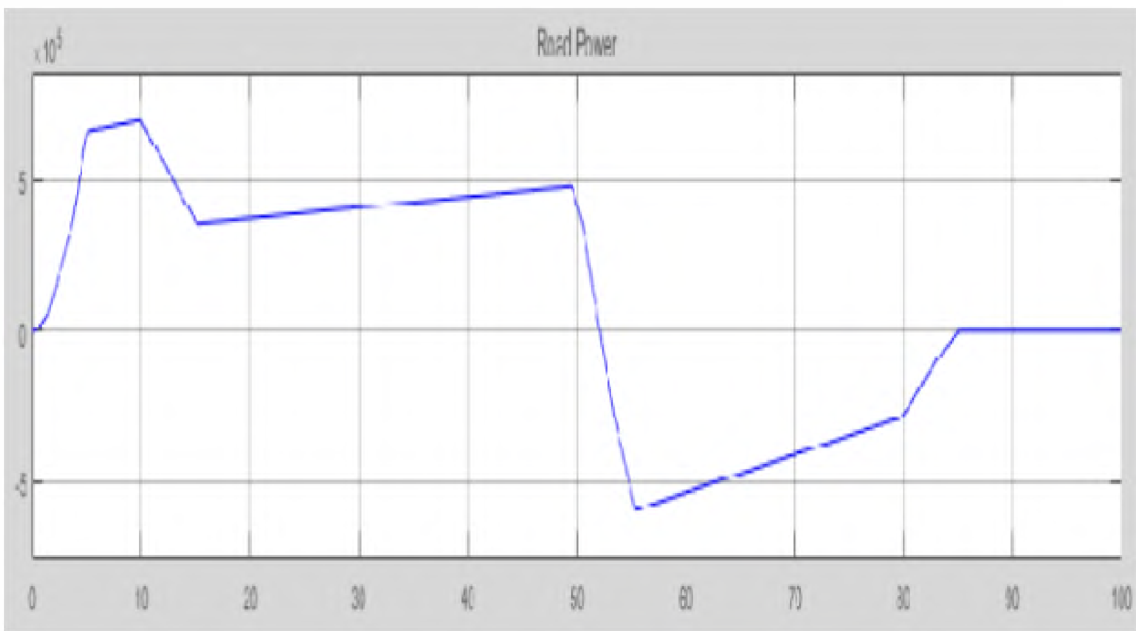

Fig 14: Road Power Characteristics.

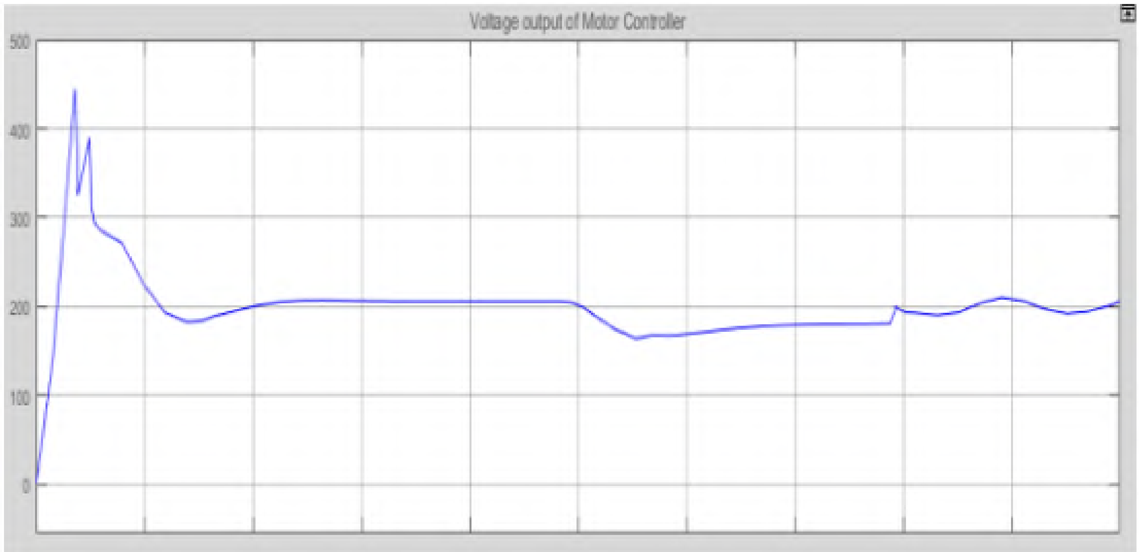

Fig 15: Voltage Output of Motor Controller.

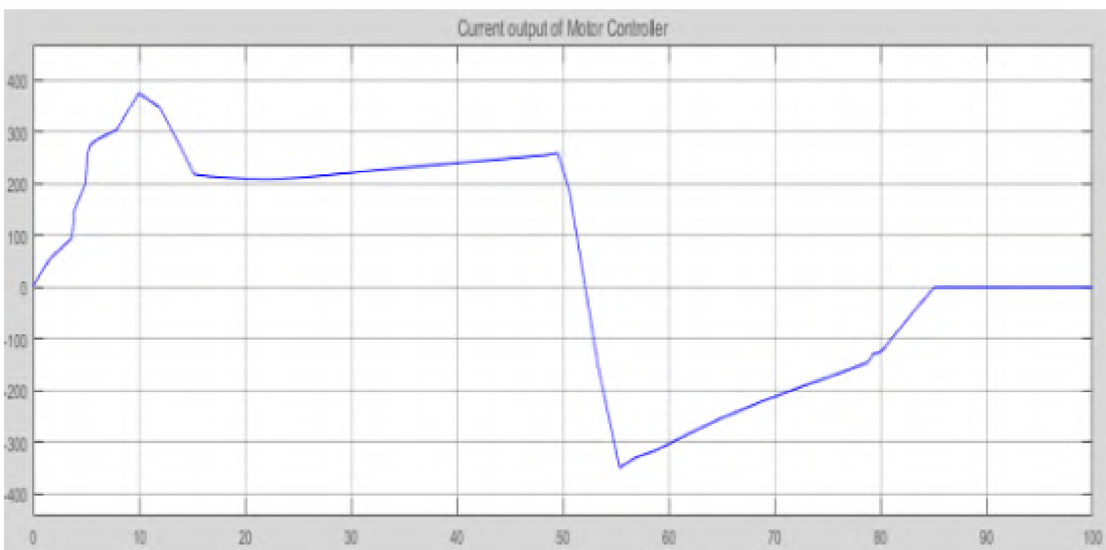

Fig 16: Current Output of Motor Controller.

When both torque and speed are positive values the DC Motor is providing torque in the direction of rotation. This is normal motoring operation. However, when the motor torque is in the opposite direction to the speed, then the motor is being pushed and acting as a generator.

When both current and voltage are positive values then the DC Motor is providing torque in the direction of rotation and power is being transferred to the load. This is normal motoring operation. However, when the motor current is in the opposite polarity of the voltage at T=50 ms then the motor is being pushed and acting as a generator with current flow back into the battery.

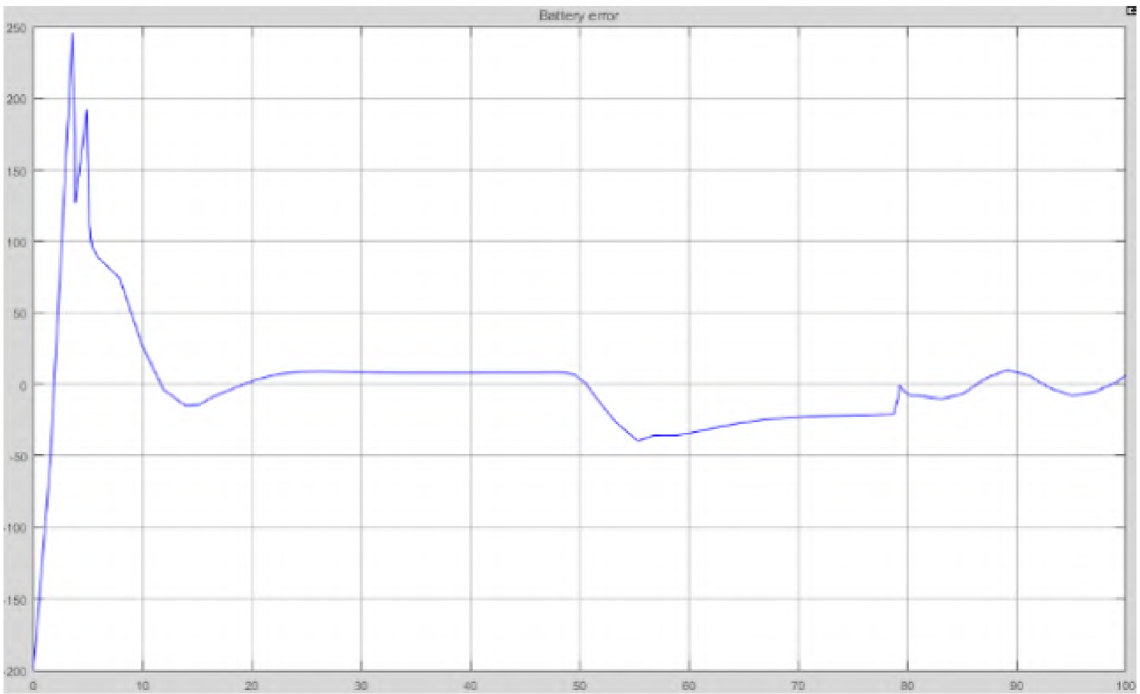

Fig 17: Battery Voltage Error.

The simulation model adjusts the controller gain (K) to meet drive torque and regeneration
requirements. The simulation compared the nominal battery internal voltage, VB =200 volts or Vbatt (actual), with a calculated battery voltage based on the motor voltage and current values to get VBatt (calculated). The difference, V_{Berr}, was used as an error signal input to the Proportional Integral (PI) Controller.

The maximum error of -200 occurs at the very beginning of the simulation. This large error is a natural response to starting the simulation. The simulation quickly recovers and holds an error of about +76 during the initial starting of the motor. It is normal to have a higher error here because the motor developed voltage, V_D (Volt) = W_D (rad/sec)/Km, is low during startup, especially when the current is increasing.

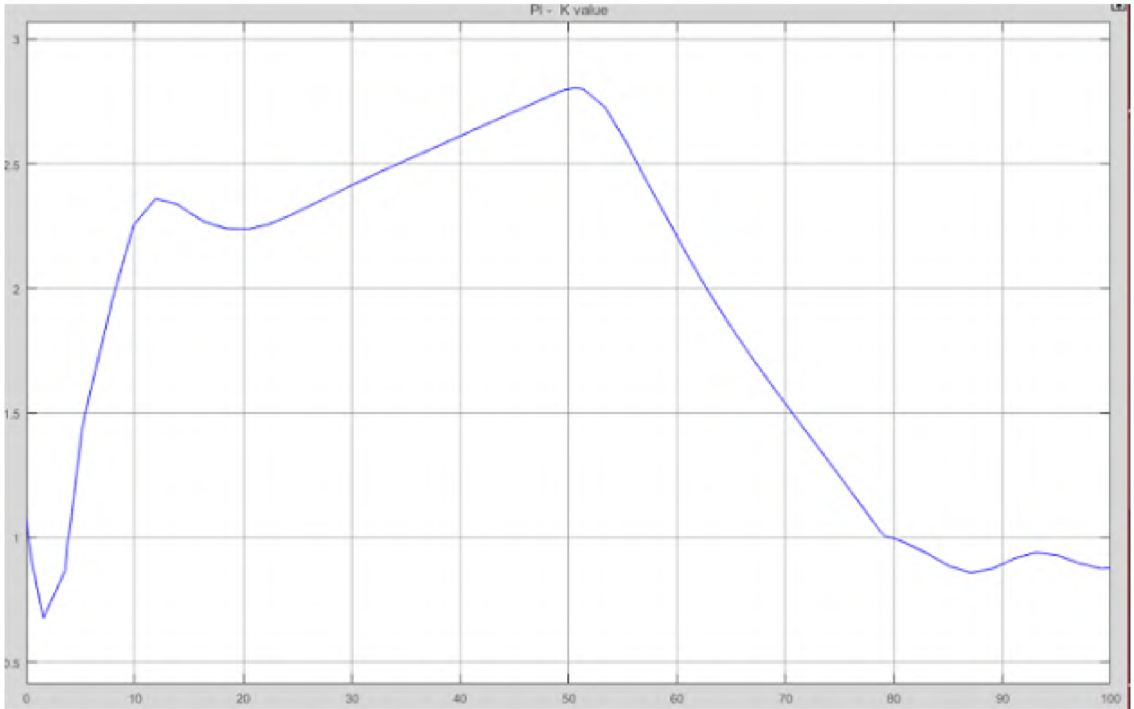

Fig18. PI controller -K value.

The minimum value of Gain K is 0.4 and maximum value of gain K is 2.8. The battery in electric vehicle is producing sufficient electric power required to overcome the road speed and torque in the simulated results.

1.8. Limitations of an Electric Vehicle:

1.8.1. High price:

The production of electric-vehicles is not yet done completely on a commercial basis. Hence, these vehicles are costly than conventional cars running on petrol or Diesel.

1.8.2. Low range:

Range of an electric-vehicle is the distance that it can cover on a single charge. There have been recent advances in the battery technology. However, the range of these vehicles is still not on par with that of the regular vehicles. Also, some of these vehicles are suitable only for low-speed applications.

1.9. Advantages of using an Electric vehicle:

- Less air pollution: There is an absence of any combustion process. Hence, these vehicles do not emit polluting gases into the atmosphere. So, they cause less harm to the environment compared to traditional IC engine powered vehicles.
- Less noise pollution: The electric motor runs quietly. Hence, the noise level while operating these vehicles is much lower than that of the petrol or diesel engine powered cars. Thus, it results in very less noise pollution.
- Higher efficiency: The efficiency of operation of an electric vehicle is much higher. For e.g. the efficiency of an electric motor is nearly 90% compared to an internal combustion engine. Hence, in all, an electric-vehicle is more efficient than petrol or Diesel vehicle.
- Low maintenance cost.
- Low fuel and operating cost.

1.10. Bibliographical survey on electric vehicles:

Electric vehicles, encompassing electric motors, batteries, and power electronics, have important advantages over today's gasoline-powered internal combustion engines. They are quieter, virtually nonpolluting, and more energy efficient, reliable, and durable. Major advances have been made in various electric drive technology components since the late 1980s. For example, advances in power electronics have resulted in small, lightweight DC/AC inverters that, in turn, make possible AC drives that are cheaper, more compact, more reliable, easier to maintain, more efficient, and more adaptable to regenerative braking than the DC systems used in virtually all electric vehicles through the early 1990s. The electric vehicle motor-controller combination is now smaller and lighter than a comparable internal combustion engine, as well as cheaper to manufacture and maintain. A large number of papers have appeared on EVs during past 15 years.

1.11. Conclusion:

This chapter has reviewed the structure of Electric Vehicle, especially in Battery Electric Vehicles and its types which is classified depends on from where it absorbs its energy, and showed what are the safety components in it and how can we work with it. We have seen also the limitations of the EVs which are the price (high cost) and the low range which is the main problem that has a relation with the battery use.

Chapter 2

Passenger Ride Quality

2.1. Introduction

With the development of society and economy, people's living standards have been continuously improved, and there is a higher requirement for the comfort of the car's riding environment [14]. To ensure that the car's vibration is within a certain range, so that the driver can have good psychological and physiological conditions under long-term driving conditions. Excellent ride comfort is not only the guarantee to improve the riding comfort, but also important to the safe driving [15].

Ride comfort is an important factor to measure the performance of automobiles. It is subjected to some effects of parameters related to suspension, wheels and tires, and acceleration which is our focus in this study. The figure below shows how the passenger sits in the vehicle.

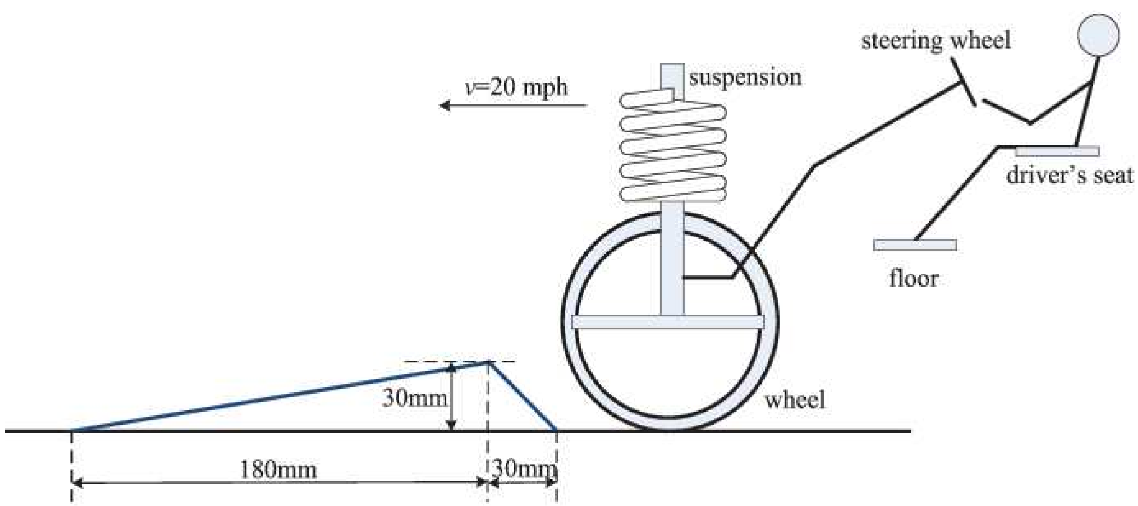

Fig 19: The schematic of Ride Comfort.

The ride comfort is one of the most important rail vehicle assessment standards. The ride comfort is given by several different adverse effects which passengers are subject on. These effects include mainly noise, air humidity, lighting, temperature, ventilation and vehicle vibration. The ride comfort is one of fundamental assumptions of a rail vehicle achievement and popularity for passengers and transport operators. For this reason a big emphasis is given on the rail vehicle analysis before its operation. For analysis computer simulations and detailed analysis of measured experimental values are widely used.

2.2. Ride Comfort for Passenger

The passenger ride comfort can be evaluated by the so-called indirect method [16]. For this method there is necessary to know acceleration values of the vehicle in analyzed points. Acceleration values are filtered and weighted by functions that take into account the human sensitivity to the vibration in 25 reference directions. Such modified values are statistically evaluated subsequently and comfort indices for the floor and for the standing or seated person standing and seated are numerically calculated. Acceleration inputs to the calculation can be obtained by measurement [17].

During a wagon running dynamic movements of wagon body arise. These movements effect as vibrations. Passengers are subjected to these negative effects during a rail vehicle operation [18, 19]. The ride comfort is the total sensation which is generated in the passenger body by the rail vehicle body movements. These rail vehicle body movements are to the whole passenger body transmitted in passenger – vehicle points (Fig.20) to the passenger position:

- Standing position: floor – feet,
- Seated position: headrest – neck, arm rest – arms, seat – hip, backrest – back, floor – feet.

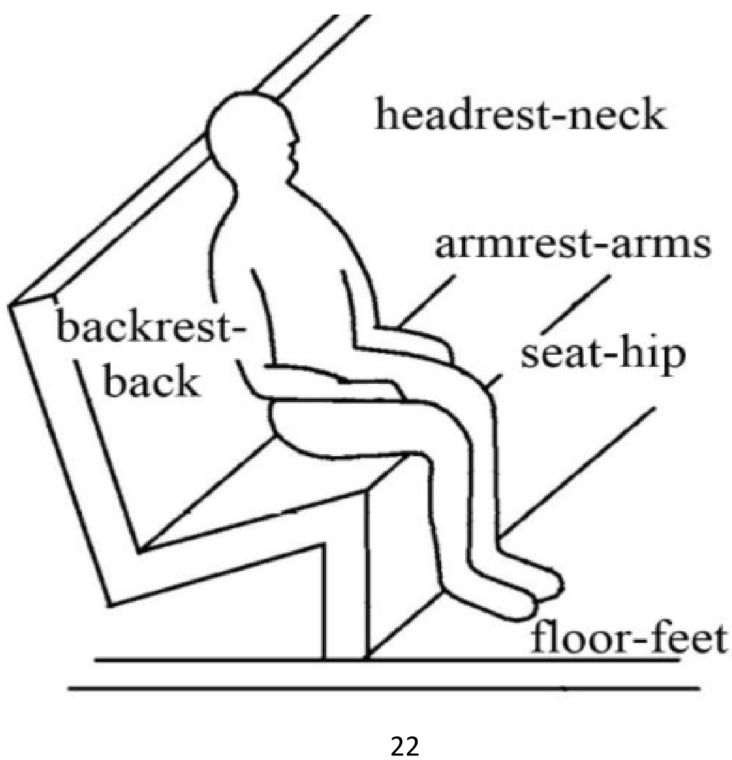

Fig 20: Interfaces points.

2.3. Effect of Suspension System on Vehicle Ride Comfort

The vehicle suspension system is generally consisted of spring, damper, oriented framework and anti-roll bar.

2.3.1. Suspension Stiffness

Suspension stiffness determines the natural frequency of the suspension system. The car has high requirements for ride comfort, and usually chooses a relatively low body natural frequency to obtain smaller acceleration. The general frequency range of a car is within 1~1.5Hz. On the contrary, off-road vehicles and trucks usually have poor road conditions, and a relatively high natural body frequency must be selected. Generally, the frequency range selected is 1.5 to 2 Hz.

2.3.2. Suspension Static Deflection

Suspension static deflection directly affects the body natural frequency. When the elastic properties of the suspension used are linear changes, the static deflection of the front suspension f c_1 can be expressed as follows.

$$\boldsymbol{f}_{\boldsymbol{c}_1} = \frac{\boldsymbol{m}_1 \boldsymbol{g}}{\boldsymbol{k}_1} \tag{10}$$

Equation (2) is the static deflection of the rear suspension fc_2.

$$\boldsymbol{f}_{\boldsymbol{c}_2} = \frac{\boldsymbol{m}_2 \boldsymbol{g}}{\boldsymbol{k}_2} \tag{11}$$

Where k_1, k_2 are the suspension stiffness of front and rear suspension respectively, m_1, m_2 are the sprung mass of front and rear suspension respectively and g is the gravitational acceleration [20].

2.3.3. Unsprung Mass

When the unsprung mass is large, the impact load received by the suspension system and transmitted to the vehicle body is also large. When the unsprung mass of the independent suspension is small, the impact and vibration from the road surface can reduced and the ride comfort of the car improved. The effect of unsprung mass on ride comfort is often evaluated by the ratio of unsprung mass to sprung mass. The smaller the value, the better.

2.3.4. Relative Damping Ratio

When the vehicle suspension has only elastic elements and no vibration damping device, the vibration of the vehicle suspension mass will continue for a long time, making the passenger feel uncomfortable. Therefore, there must be damping force in the suspension to damp vibration. After the suspension stiffness is determined, the damping force must be properly selected in order to give full play to the damping effect of the suspension. When the damper of the suspension system is linear, the speed of vibration attenuation can be evaluated by the relative damping ratio. The expression is shown as follows [21].

$$\zeta = \frac{c}{2\sqrt{km}} \qquad (12)$$

Where c is the equivalent damping coefficient of the suspension damper, k is the suspension stiffness and m is the suspension mass.

2.4. Quantifying Ride Comfort

Ride comfort is evaluated based on different phenomena that occur on varying road surfaces and in specific driving situations. In the digital prototype, the phenomenon known as stuttering, or vibration, is viewed as part of standard procedure [22], whereby several defi nitions for the vibrational effect have been derived from literature and practical applications. Most of the time, engine vibrations are what is being referred to an upset the otherwise smooth control and stability of the front end of the vehicle as a result of the engine block starting to resonate with the body at a coupling frequency [22]. The term can also be expanded in scope, however, to cover the vibrations exhibited in the chassis and suspension, engine and detachable parts. When this definition is applied, the vibrational effect encompasses frequencies ranging from approximately 4 to 25 Hz. Ride comfort and the phenomena associated with it are evaluated primarily in a subjective manner.

When vibration is very noticeable, for example, it is perceived as an unpleasant hopping of the vehicle as it travels down the road. To realize a numerically-based simulation exercise, however, objective characteristic variables must be derived that accurately represent, or characterize, the subjective evaluation. An overview of the different processes and procedures for objectively assessing perceived vibration is provided in [23].

Many automakers evaluate vibrational performance by targeting the driver seat console or seat assembly under maximum vehicle acceleration to define an objective criterion, as the main area in which forces are transferred from the vehicle to its occupants is the seats they sit on. Maximum acceleration continues to be used as an objectivity variable within the scope of the reliability analysis. The limits for the design criteria can be set in variable fashion, depending on the market position of the vehicle and manufacturer, and are specific end in relation to the target design state for a vehicle in the vehicle technical specifications. These limits directly correlate with the levels of tolerable acceptance on the part of the vehicle occupants and are routinely validated with customers. In the context of reliability engineering, exceeding the defined limits can be viewed as an active occurrence of the phenomenon and compromise the overall operative function of the vehicle as a result.

2.5. Ride Comfort Testing

There are generally two types of tests for comfort criteria, which are objective and subjective tests. Objective test is related to medical test in which human fatigue is considered as an indication. Several investigations were discussed and can be concluded that it is very difficult to establish good relation between fatigue and the vibration characteristics of the vehicle. Subjective testing is widely used in comfort criteria and a reasonably good correlation has been established between comfort criteria and the vehicle’s vibration characteristics. The test is generally to study the influence of the various vibrations on the human subject. Several criteria proposed by various researchers were discussed like Reiher-Meister criteria, Jacklin-Liddel criteria, Janeway criteria, Sperling criteria, Mauzin-Sperling criteria, and Dieckmann criteria. These criteria were compared carefully and modified classification of limits for different groups of vibrations. However, the limits are still disputable.

2.6. Evaluation of Ride Quality

There are various factors which have an influence on ride quality, but the index of the ride quality depends on individuals. About the railroad carriage, various research about the evaluation of the ride comfort with respect to the frequency of vibrations in vertical and horizontal directions have been reported in [24].

However, most of these deal with the evaluation of ride quality with respect to the sustained vibration of the steady run or vibration in the vertical direction. In the case of EVs, it is important to evaluate the ride comfort with respect to later- al speed change. In relation to this point, there are [25] and [26] as the study which investigated the relation between the acceleration/deceleration, the jerk (time derivative of the acceleration) and ride quality. In [25] and [26], subjectivity rating of the ride comfort tests about a start, a stop, immediate start, a run including the hitting the brakes for the resting posture and the reading posture and derive the following linear multiple regression model for the ride quality index.

$$d(t) = \beta_0 + \beta_1\alpha_{p+}(t) + \beta_2\alpha_{p-}(t) + \beta_3 j_{r+}(t) + \beta_4 j_{r-}(t) + \epsilon(t) \tag{13}$$

Where parameters in (1) are defined in the table below. And where $\alpha_{p+}(t), \alpha_{p-}(t), j_{r+}(t), j_{r-}(t)$ in $T = (t-3, t)$ are given as follows:

$$\alpha_{p+}(t) = \begin{cases} max_{t\in T}\alpha(t), & |max_{t\in T}\alpha(t)| \geq |min_{t\in T}\alpha(t)| \\ 0, & |max_{t\in T}\alpha(t)| \leq |min_{t\in T}\alpha(t)| \end{cases} \tag{14}$$

$$\alpha_{p-}(t) = \begin{cases} 0, & |max_{t\in T}\alpha(t)| \leq |min_{t\in T}\alpha(t)| \\ min_{t\in T}\alpha(t), & |max_{t\in T}\alpha(t)| \geq |min_{t\in T}\alpha(t)| \end{cases} \tag{15}$$

$$j_{r+}(t) = \begin{cases} \sqrt{\frac{1}{3}\int_{t-3}^{t} j^2(\tau)d\tau} \ , j(T) \geq 0 \\ 0, j(T) < 0 \end{cases} \tag{16}$$

$$j_{r-}(t) \begin{cases} 0, j(T) \geq 0 \\ \sqrt{\frac{1}{3}\int_{t-3}^{t} j^2(\tau)d\tau} \ , j(T) < 0 \end{cases} \tag{17}$$

. .

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$d(t)$	Ride comfort index at time t
$\alpha_{p+}(t)$	Peak value of acceleration in $T = (t-3,t)$ (3 seconds just before time t)
$\alpha_{p-}(t)$	Peak value of deceleration in $T = (t-3,t)$ (3 seconds just before time t)
$j(T)$	Average value of jerk in T
$j_{r+}(t)$	Effective value of jerk in the case of positive value of j(T)
$j_{r-}(t)$	Effective value of jerk in the case of negative value of j(T)
$\in(t)$	Error term
β_0	Constant term
β_k	Partial regression coefficient

Table 1.Definition of parameters.

Unfortunately, it is not possible to derive the speed pattern by using d(t) directly since the d(t) is ride comfort index at the specific time t derived based on the acceleration and the jerk in the real time. It can't show overall evaluation. Then we need to consider another index for speed control for overall ride comfort. In [25] and [26], we can see that the value of deceleration, the value of jerk in deceleration, the value of jerk in acceleration and the value of acceleration have big influence on the ride quality by their order. Therefore, it is important to suppress both of the acceleration/deceleration and the jerk to improve the ride quality and we construct the speed control method on these facts.

2.7. Conclusion

In this chapter, we have defined the ride comfort and how it is formulated for the passenger. And also we have seen the factors that effect on the ride comfort. And how to evaluate it based on different phenomena.

Chapter 3

Speed Control Method

3.1. Introduction

The variation in longitudinal acceleration has great influence on ride comfort [4][5]. In usual travelling, a car accelerates or decelerates constantly. Therefore, suppression of the vibration is supposed to improve ride comfort in whole travelling of vehicle. We attempt to achieve suppression of the vibration in a wide range of vehicle velocity by applying speed pattern to motion control of EVs.

Generation of speed pattern for EVs is consisted of three steps [27]:

- Estimation of driver's intention and calculation of torque input.
- Generation of speed pattern using torque input, vehicle velocity and acceleration.
- Motion control of vehicle utilizing generated speed pattern.

At the moment of switching between acceleration and deceleration, it is important to suppress variation in acceleration/deceleration. Smooth travelling can be realized by generating speed pattern which has continuity in both acceleration and jerk. Using a large value of acceleration within the bounds of good ride comfort makes speedy acceleration/deceleration possible.The driver's evaluation of ride comfort is improved by generating speed pattern which is in accordance with driver's intention of travelling and motion of car based on the pattern. Driver's intention of travelling which is estimated from driver's operation of accelerator pedal and brake pedal is utilized for generation of speed pattern.

3.2. Generation of speed pattern

It's important for speed control method to consider the speed pattern. The speed pattern is defined as the ideal speed plan to satisfy various demands/limits for ride comfort, energy efficiency at acceleration, position, time and so on. In [28], the speed pattern is derived based on the SMART control method [29] by using following evaluation function.

$$J_0 = \int_0^{t_f} \left(\frac{da}{dt}\right)^2 dt \quad (18)$$

Where a is the acceleration and t_f is the terminal time, and where the state space vehicle model is as

$$\begin{pmatrix}\dot{v}\\ \dot{a}\end{pmatrix} = \begin{pmatrix}0 & 1\\ 0 & 0\end{pmatrix}\begin{pmatrix}v\\ a\end{pmatrix} + \begin{pmatrix}0\\ 1\end{pmatrix}u \tag{19}$$

However, the acceleration, which is one of the most important factor influenced to the ride quality as I mentioned in chapter 2, does not include directly in this evaluation function. In addition, a vehicle position is not included in this model. It's important factor for realizing the automatic driving in the near future. From these facts, the state space model and the evaluation function in this project is defined as follows.

$$\begin{pmatrix}\dot{x}\\ \dot{v}\\ \dot{a}\end{pmatrix} = \begin{pmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}x\\ v\\ a\end{pmatrix} + \begin{pmatrix}0\\ 0\\ 1\end{pmatrix}u \tag{20}$$

$$J_1 = \int_0^{t_f}\left[\left(\frac{da}{dt}\right)^2 + (qa)^2\right]dt \tag{21}$$

Where (20) is written as $\dot{x} = A\bar{x} + Bu$ with;

$$\bar{x} = \begin{pmatrix}x\\ v\\ a\end{pmatrix}, A = \begin{pmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ 0 & 0 & 0\end{pmatrix}, B = \begin{pmatrix}0\\ 0\\ 1\end{pmatrix}$$

It's also possible to control the vehicle position to add x in the state space variables for automatic driving. Furthermore, we can derive the speed pattern which emphasized the ride comfort against the acceleration and deceleration by adding the weighted qa to evaluation function. (q is the weighting constant).Then, by using the generalized optimal control theory, we can derive the following Hamiltonian H from (20) and (21).

$$H = \frac{1}{2}(u^2 + a^2) + \lambda^T(A\bar{x} + Bu) = \frac{1}{2}(u^2 + \bar{x}^T Q\bar{x}) + \lambda^T(A\bar{x} + Bu) \tag{22}$$

Where λ is the Lagrange multiplier and where

$$Q = \begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & q^2\end{pmatrix} \tag{23}$$

The solution minimized J_1 is obtained from $\frac{\partial H}{\partial u} = 0$ as

$$u = -b^T\lambda \tag{24}$$

From $\dot{x} = \frac{\partial H}{\partial \lambda}$ and $\dot{\lambda} = -\frac{\partial H}{\partial x}$, we can obtain

$$\begin{pmatrix} \dot{x} \\ \dot{\lambda} \end{pmatrix} = \begin{pmatrix} A & -BB^T \\ -Q & -A^T \end{pmatrix} \begin{pmatrix} x \\ \lambda \end{pmatrix} \tag{25}$$

This equation is expressed as

$$\begin{pmatrix} \dot{x} \\ \dot{v} \\ \dot{a} \\ \dot{\lambda}_1 \\ \dot{\lambda}_2 \\ \dot{\lambda}_3 \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & -q^2 & 0 & -1 & 0 \end{pmatrix} \begin{pmatrix} x \\ v \\ a \\ \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{pmatrix} \tag{26}$$

From (26),

$$\dot{\lambda}_2 = -C^n \tag{27}$$

Is obtained. Where C^n is given constant. Furthermore, the following state space equation is derived

$$\begin{pmatrix} \dot{a} \\ \dot{\lambda}_2 \\ \dot{\lambda}_3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & -1 \\ 0 & 0 & 0 \\ -q^2 & -1 & 0 \end{pmatrix} \begin{pmatrix} a \\ \lambda_2 \\ \lambda_3 \end{pmatrix} + \begin{pmatrix} 0 \\ -C^n \\ 0 \end{pmatrix} \tag{28}$$

The time response of this system expressed as (28) is

$$x_1(t) = e^{A_1 t} x_1(0) + \int_0^t e^{A_1(t-\tau)} B_1 u_1(\tau) d\tau \tag{29}$$

Where:

$$x_1 = \begin{pmatrix} \dot{a} \\ \dot{\lambda}_2 \\ \dot{\lambda}_3 \end{pmatrix}, A_1 = \begin{pmatrix} 0 & 0 & -1 \\ 0 & 0 & 0 \\ -q^2 & -1 & 0 \end{pmatrix}, B_1 = \begin{pmatrix} 0 \\ -C^n \\ 0 \end{pmatrix}, u_1 = 1$$

Then, from (20), we can derive $x_1(t)$ as follows.

$$\begin{pmatrix} a \\ \lambda_2 \\ \lambda_3 \end{pmatrix} = \begin{pmatrix} (e^{qt}+e^{-qt}) & \frac{1}{q^2}(-2+e^{qt}+e^{-qt}) & \frac{1}{q}(-e^{qt}+e^{-qt}) \\ 0 & 1 & 0 \\ q(-e^{qt}+e^{-qt}) & \frac{1}{q}(-e^{qt}+e^{-qt}) & (e^{qt}+e^{-qt}) \end{pmatrix} \times \begin{pmatrix} a(0) \\ \lambda_2(0) \\ \lambda_3(0) \end{pmatrix} + \frac{-C^n}{2} \begin{pmatrix} \frac{1}{q^2}\left(-2t+\frac{1}{q}e^{qt}-\frac{1}{q}e^{-qt}\right) \\ 2t \\ \frac{1}{q}\left(\frac{2}{q}-\frac{1}{q}e^{qt}-\frac{1}{q}e^{-qt}\right) \end{pmatrix} \tag{30}$$

Also $a(t)$ is obtained as follows.

$$a(t) = \left(\frac{1}{2}a(0)+\frac{1}{2q^2}\lambda_2(0)-\frac{1}{2q}\lambda_3(0)-\frac{C^n}{2q^3}\right)e^{qt} + \left(\frac{1}{2}a(0)+\frac{1}{2q^2}\lambda_2(0)-\frac{1}{2q}\lambda_3(0)-\frac{C^n}{2q^3}\right)e^{-qt}+\frac{C^n}{q^2}t + \frac{\lambda_2(0)}{q^2} \tag{31}$$

Where $q, a(0), \lambda_2(0), \lambda_3(0), C^n$ are given constants. Expressing constant terms in (31) as $C_j^n (j = 0,1,2,3)$, (31) is described as follows.

$$a(t) = C_0^n e^{qt} + C_1^n e^{-qt} + C_2^n t + C_3^n \tag{32}$$

Finally we can derive the following speed pattern after deformation of equations with state space equation: $\dot{x} = \frac{\partial H}{\partial \lambda}$, co-state space equation: $\dot{\lambda_2} = -\frac{\partial H}{\partial x}$, and stationary equation $0 = -\frac{\partial H}{\partial u}$.

$$\begin{aligned} x(t) &= C_0 e^{qt} + C_1 e^{-qt} + C_2 t^3 + C_3 t^2 + C_4 t + C_5 \\ v(t) &= qC_0 e^{qt} - qC_1 e^{-qt} + 3C_2 t^2 + 2C_3 t + C_4 \\ a(t) &= q^2 C_0 e^{qt} + q^2 C_1 e^{-qt} + 6C_2 t + 2C_3 \end{aligned} \quad (33)$$

Where C_j (j = 0,1, 2,3, 4,5) are constant coefficients. These values can be decided from initial and terminal conditions of t, x, v and a.

This speed pattern includes the method by [28]. This fact is shown as follows. Firstly, since the evaluation function of the proposed method, (9), is added $(qa)^2$to the one using in [28], (6), we can see that both equations are same if $q = 0$. But, the speed pattern is unable to derived (it should be indefinite solution) if q = 0. Then, let's do Maclaurin's expansion of the proposed speed pattern with neighborhood of q = 0 and derive the 4-th order approximated polynomial, which same order of [28].

One example is shown. Let's consider the following initial and terminal conditions.

$$\begin{cases} t_0 = 0, x_0 = 0, v_0 = 10, a_0 = 1 \\ t_f = 10, x_f = 100, v_f = 0, a_f = 0 \end{cases}$$

(34)

These conditions show the situation that the vehicle runs from a state running in speed 10 m/s and acceleration 1 m/s^2 to the 100 m spot ten seconds later, and to stop. Figure 21 shows the difference values of between the proposed speed pattern and the one in [28] is $-3 \times 10^{-14} \sim 8 \times 10^{-14}$. It may be considered to be the same, not little difference. Therefore, we can see that the proposed method includes and extends the method in [28]. In Figure 22 and Figure 23, red line indicates the result by the conventional method in [28] and blue line indicates the result by the proposed method with q= 3.5 which minimized total sum of d(t). Figure 23 shows the time response of vehicle speed and acceleration respectively.

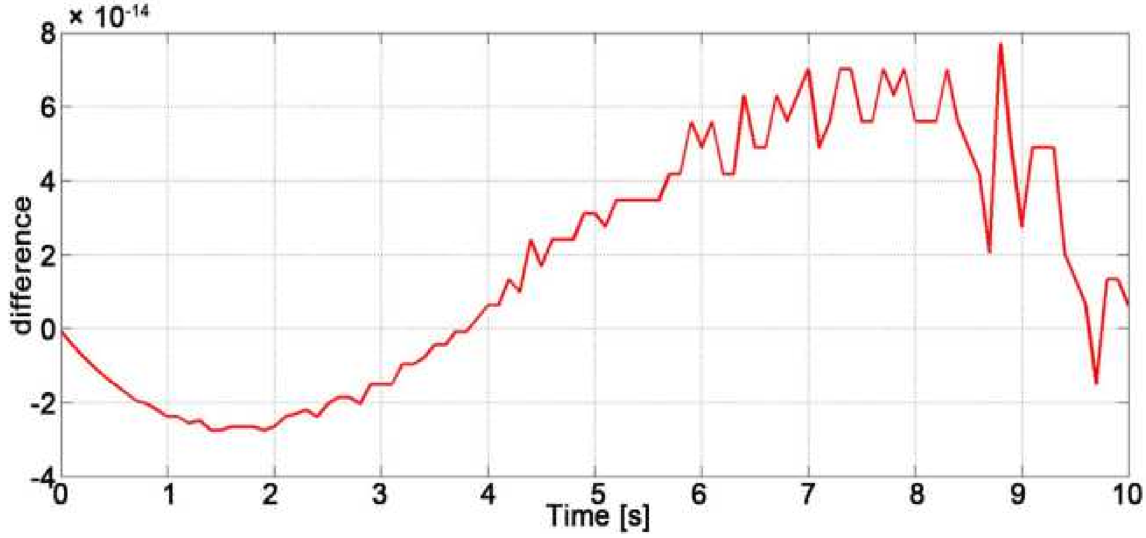
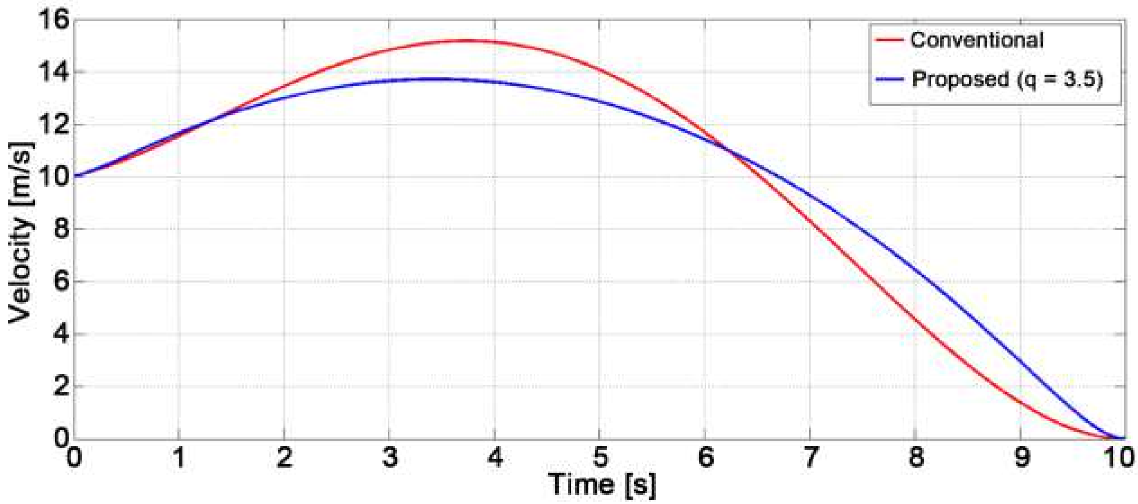
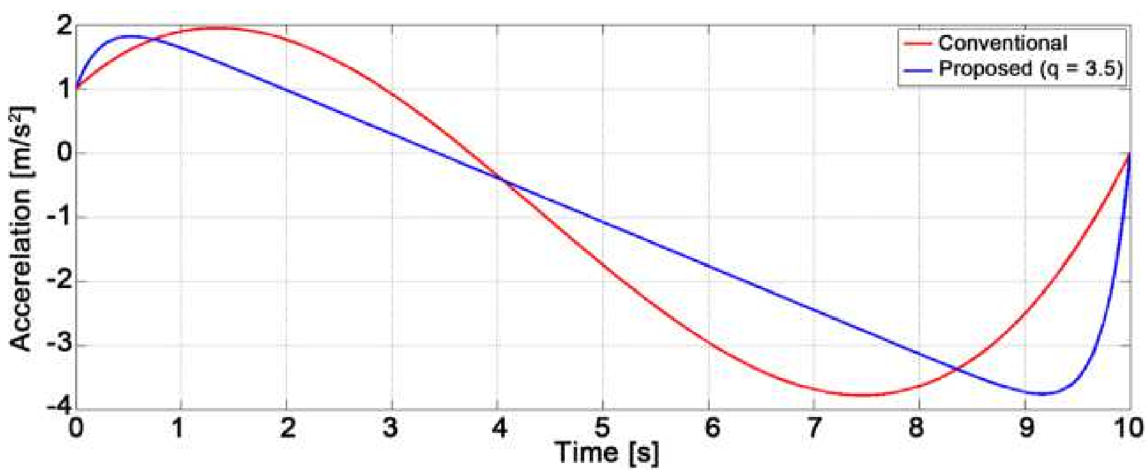


Figure 21.Difference values of speed pattern between the proposed one and [28].



(a)



(b)

Figure 22.Time response of (a) vehicle speed and (b) acceleration.

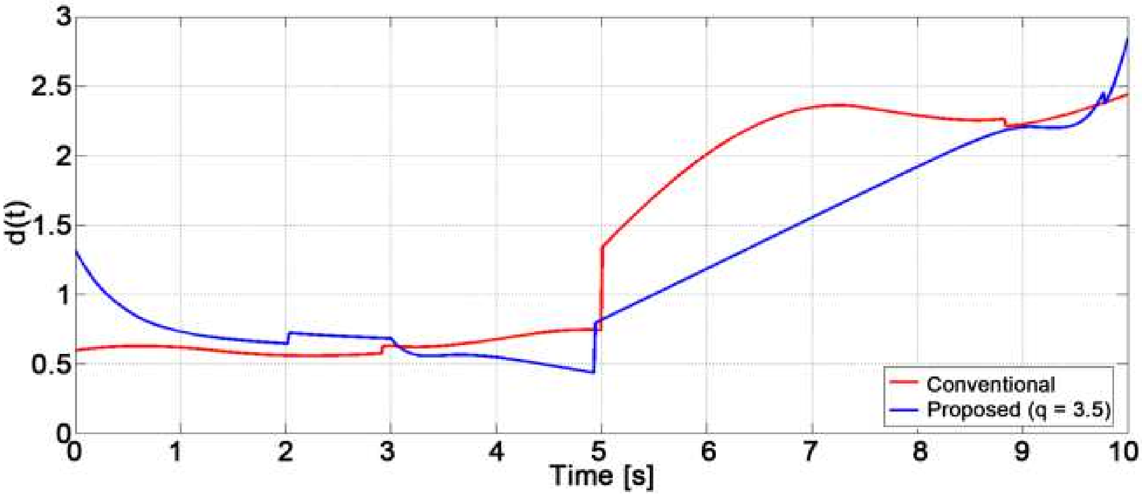


Figure 23.Time response of ride comfort index d(t).

From this Figure, We can see that both methods (the proposed and the method in [28] can generate the speed pattern satisfied initial and terminal conditions. Figure 14 shows time response of d (t). We can see that the proposed method can suppress the value of d (t) lower than the method in [28] in the most part of the whole running period. Therefore, we find out that the proposed method can improve the ride comfort than the method in [28].

3.3. Extended Generation Method

The proposed method is extended to the flexible generation method which can cope with the change of terminal conditions in the way of the run for practical use. For example, the method is extended to be able to deal with the situation that it is necessary to shorten a stop spot by some kind of factors such as other vehicles getting into the way. In such situation, the speed pattern should be re-generated flexibly in real-time accordance with the change of conditions. As the result of many simulations, we see that the remaining run time after the pattern re-generated greatly influenced the quality of ride comfort. Since the change of the run time brings the sudden change of the jerk. Therefore, the following evaluation function (J_2) is introduced to decide appropriate remaining run time.

$$J_2 = rx + sy \tag{35}$$

Where x is the absolute value of the difference of the value of the jerk just before and after the pattern re-generated, y is the absolute value of the difference of the derivative value of the jerk just before and after the pattern change, and r, s are constant weights. Because it was a problem that the jerk suddenly changes in before and after the pattern re-generated, appropriate values of the weight q of J_1 in (19) and the remaining run time are decided by using this evaluation function J_2 in (35) for the change of jerk consecutively and smoothly as much as possible. A flow of rough processing of this method is shown in Figure 24.

In addition, a search range at remaining run time is set. For example, the search range is set as not exceeding the whole running time set beforehand. If the running distance becomes long, remaining run time is able to be increased and search the best values of q and the remaining run time in the enlarged range.

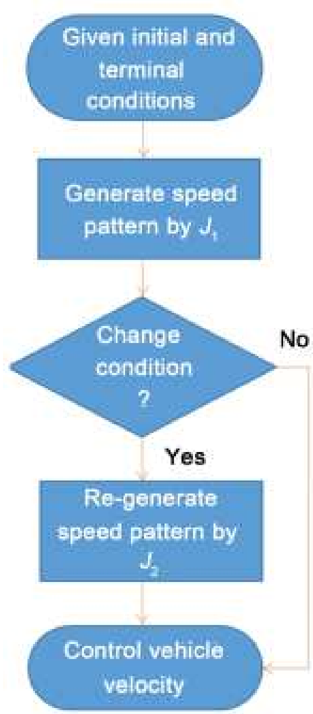


Figure 24.Flow of rough processing of the proposed method.

Then, it becomes possible to derive the speed pattern with best ride comfort, which minimize the total d (t) in whole running time, against the change of terminal conditions.

3.4. Conclusion

In this chapter, we generate a speed pattern for EVs based on the Hamiltonian theory for improving ride comfort. And also creating a flow chart which resume the extended generation method and doing a small comparison between the the proposed method and conventional method.

Chapter 4

Simulation Results

Let's confirm the effectiveness of the proposed extended method in some simulations.

4.1. Simulation I

Firstly, let's consider the situation that the stop spot is shortened after starting off. The first condition is as follows

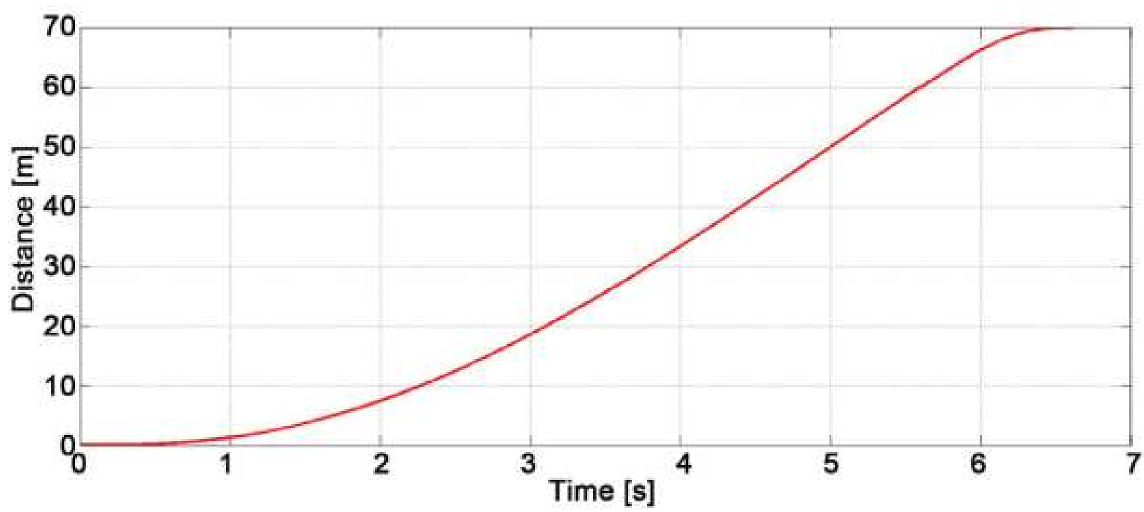
$$\begin{cases} t_0 = 0;\ x_0 = 0; v_0 = 0, a_0 = 0 \\ t_f = 10; x_f = 100; v_f = 0; a_f = 0 \end{cases} \quad (36)$$

Then, at running 60 m spot, the stop spot is shortened from 100 m to 70 m as follows

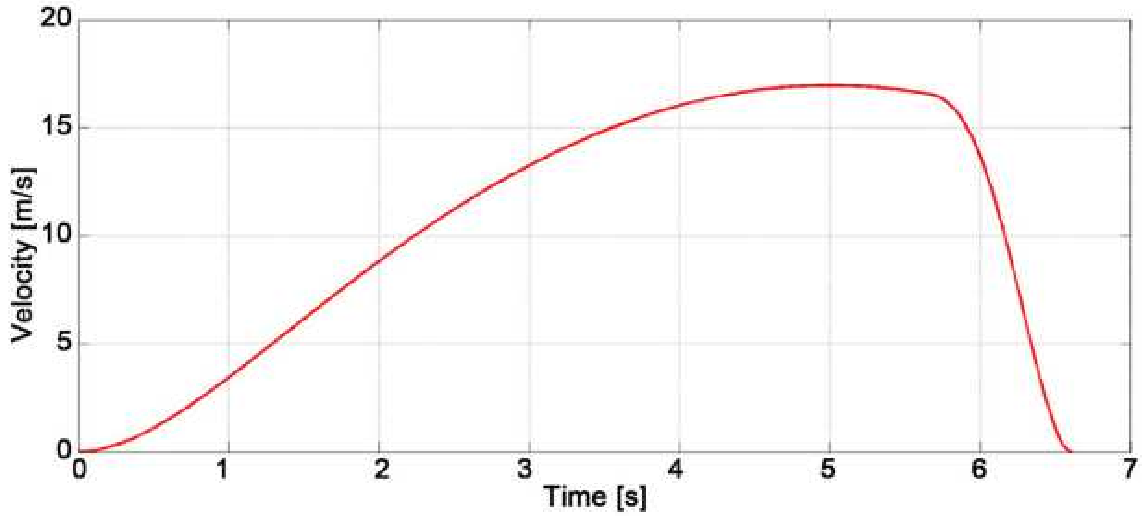
$$\begin{cases} t_0 = 0; x_0 = 0; v_0 = v_s; a_0 = a_s \\ t_f = [search]; x_f = 70; v_f = 0; a_f = 0 \end{cases} \quad (37)$$

Where v_s is final speed value before re-generate the speed pattern and a_s is final acceleration value before re-generate the pattern.

The results by the proposed method are shown as Figure 25 and Figure 26. In this simulation, the pattern is re-generated at 5.61 s, weights are q = 2.20, r = 1.00, s = 0.00 and remaining run time after regeneration of pattern is 1.00 s. So, we can see that the method can cope with the sudden change of stop spot from Figure 25.



(a)



(b)

Figure25. Time response of (a) vehicle position and (b) speed acceleration.

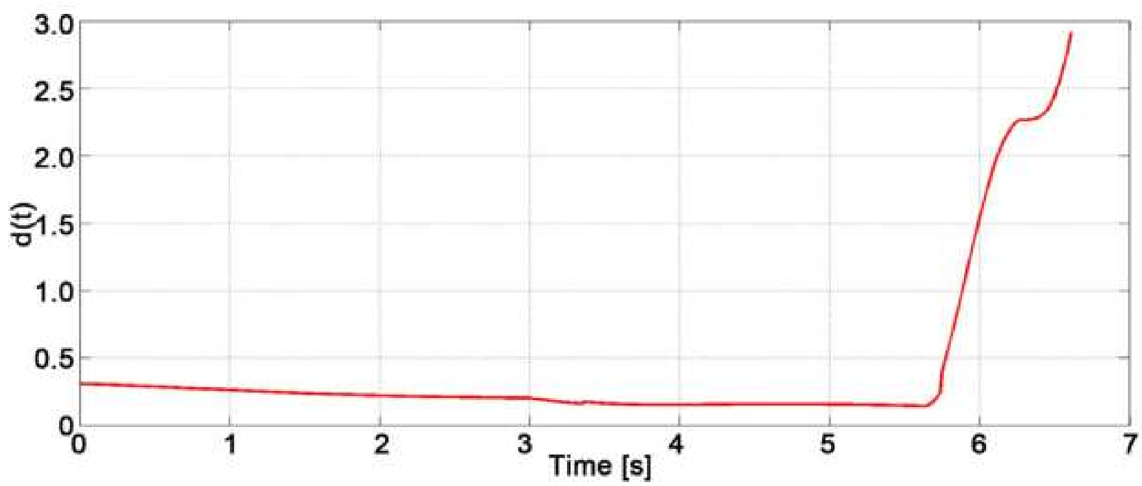


Figure 26. Time response of ride comfort index d(t).

From Figure 26, the ride comfort becomes worse at the time of shortening the stop spot at 5.61 s. But it’s natural response due to the sudden shortening of stop distance for safety. Therefore, we can say that the proposed method shows the good performance totally.

4.2. Simulation II

Let's consider the situation that the stop spot is lengthened after starting off.

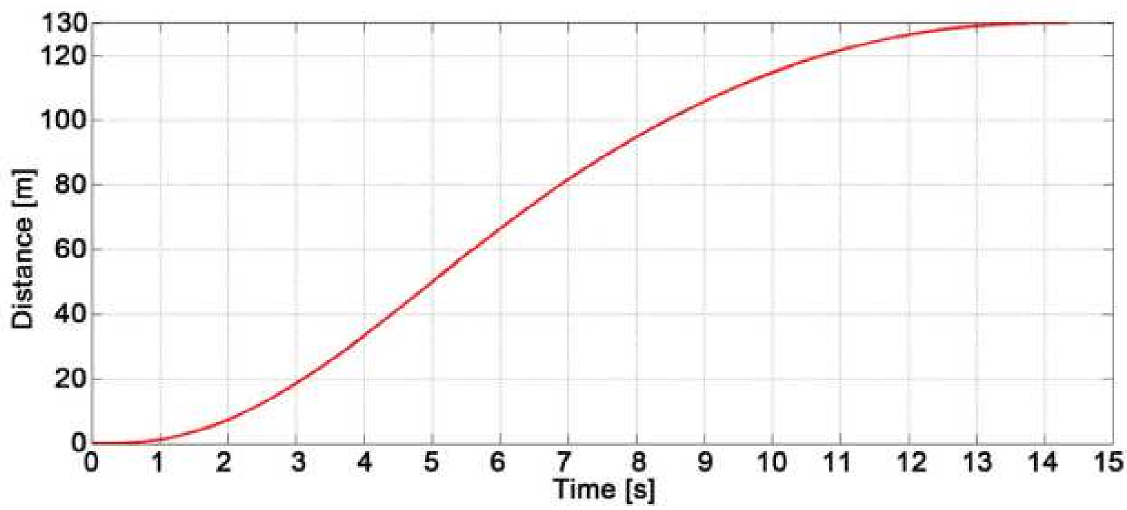
The first conditions as follows.

$$\begin{cases} t_0 = 0;\ x_0 = 0; v_0 = 0, a_0 = 0 \\ t_f = 10; x_f = 100; v_f = 0; a_f = 0 \end{cases} \quad (38)$$

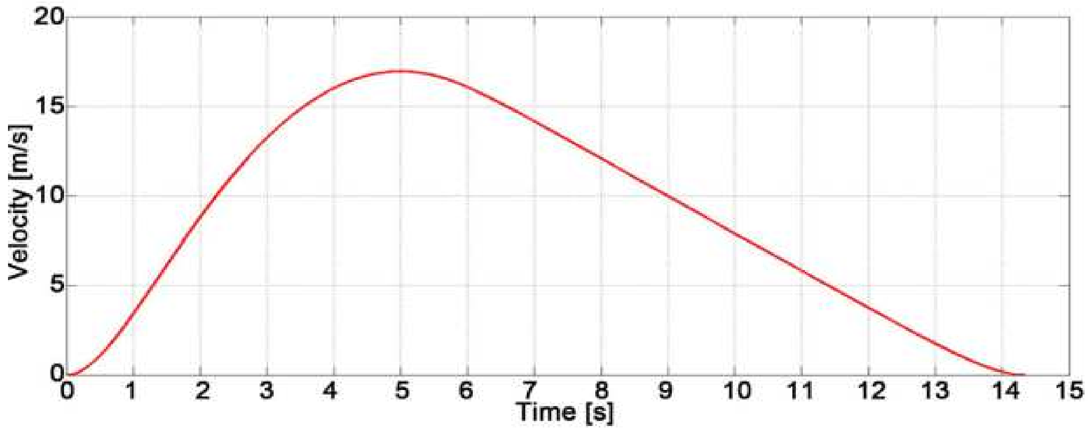
Then, at running 60 m spot, the stop spot is lengthened from 100 m to 130 m as follows.

$$\begin{cases} t_0 = 0;\ x_0 = 60; v_0 = v_s, a_0 = a_s \\ t_f = [search]; x_f = 130; v_f = 0; a_f = 0 \end{cases} \quad (39)$$

The results by the proposed method are shown in Figure 27. In this simulation, the pattern is re-generated at 5.61 s, weights are q = 1.90, r = 1.00, s = 0.00 and remaining run time after pattern re-generated is 8.18 s. From this figure, we can see that the method can cope with the situation of lengthening the stop spot**.**



(a)



(b)

Figure 27. Time response of (a) vehicle position and (b) speed acceleration.

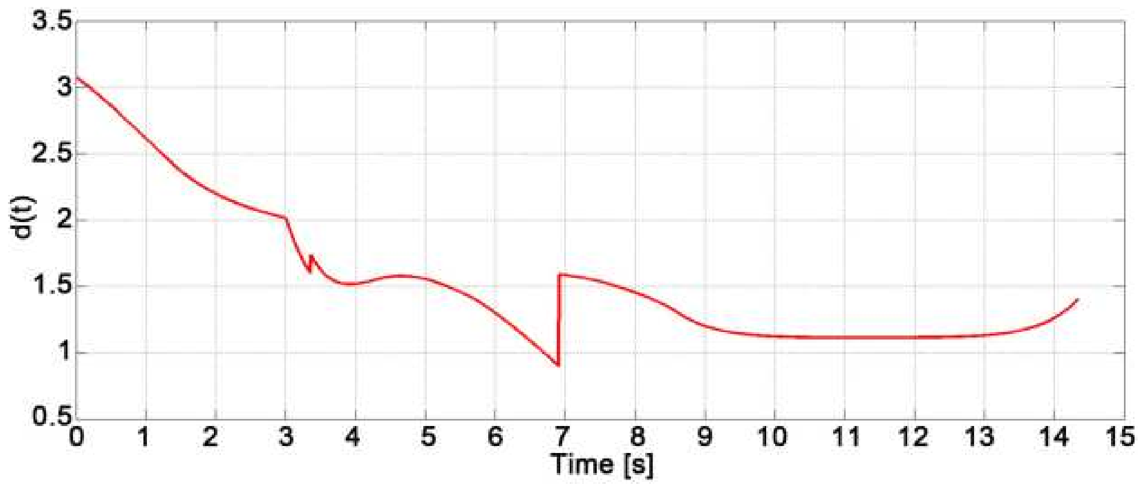


Figure 28. Time response of ride comfort index d (t).

From Figure 28, the ride comfort index d (t) turns worse suddenly at about 6.90 s.This is because the absolute value of the acceleration is bigger here, and it has a big influence on the d (t). But, after 6.90 s the value of d (t) is suppressed gradually. Therefore, the proposed method shows the good performance.

4.3. Simulation III

In this simulation, let's consider the situation that the stop spot is changed two times.

The first conditions as follows.

$$\begin{cases} t_0 = 0;\ x_0 = 0; v_0 = 0, a_0 = 0 \\ t_f = 10; x_f = 100; v_f = 0; a_f = 0 \end{cases} \tag{40}$$

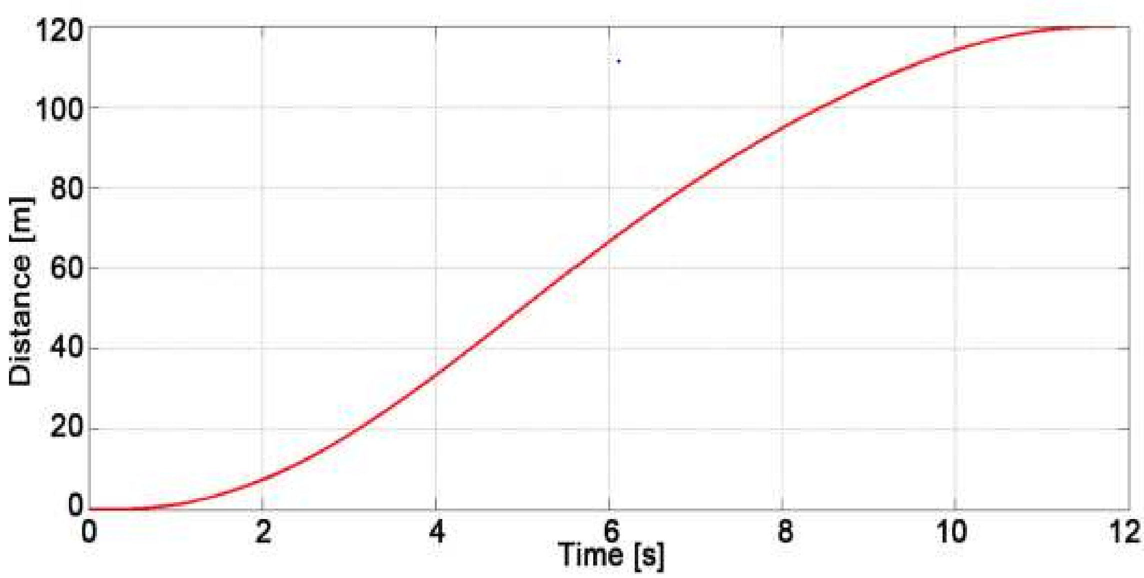
Firstly, at running 60 m spot, the stop spot is lengthened from 100 m to 130 m as follows.

$$\begin{cases} t_0 = 0;\ x_0 = 60; v_0 = v_s, a_0 = a_s \\ t_f = [search]; x_f = 130; v_f = 0; a_f = 0 \end{cases} \tag{41}$$

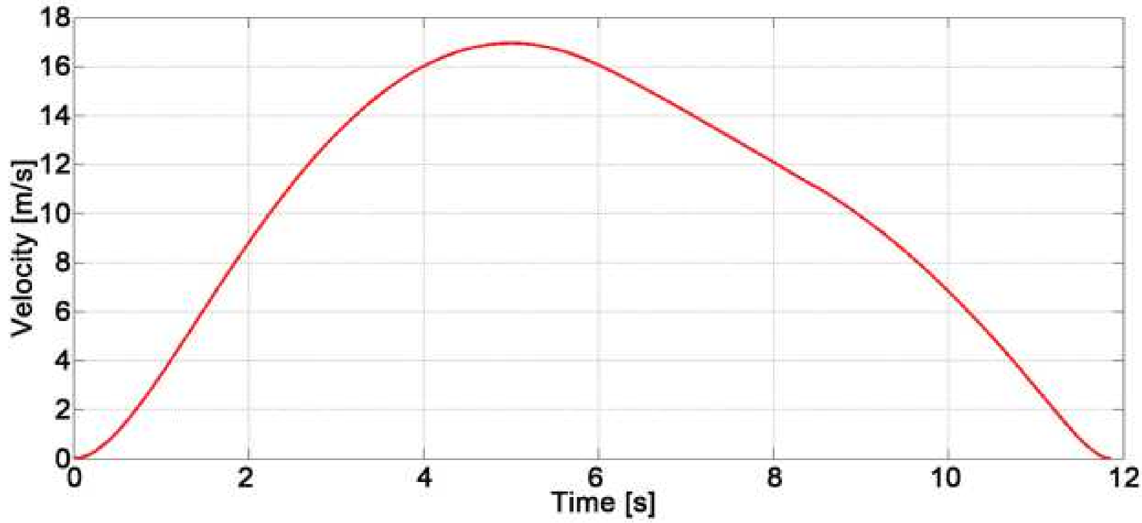
Then, at running 100 m spot, the stop spot is shortened from 130 m to 120 m as follows.

$$\begin{cases} t_0 = 0;\ x_0 = 100; v_0 = v_s, a_0 = a_s \\ t_f = [search]; x_f = 120; v_f = 0; a_f = 0 \end{cases} \tag{42}$$

The results by the proposed extended method are shown in Figure 29. In this simulation, the pattern is regenerated at 5.61 s and 8.36 s. The weights are q = 1.90, r = 1.00, s = 0.00 and q = 4.10, r = 0.40, s = 0.20 respectively. Total running time is 12.11 s. From this figure, we can see that the method can cope with the situation of change the stop spot two time.



(a)



(b)

Figure 29. Time response of (a) vehicle position and (b) speed acceleration.

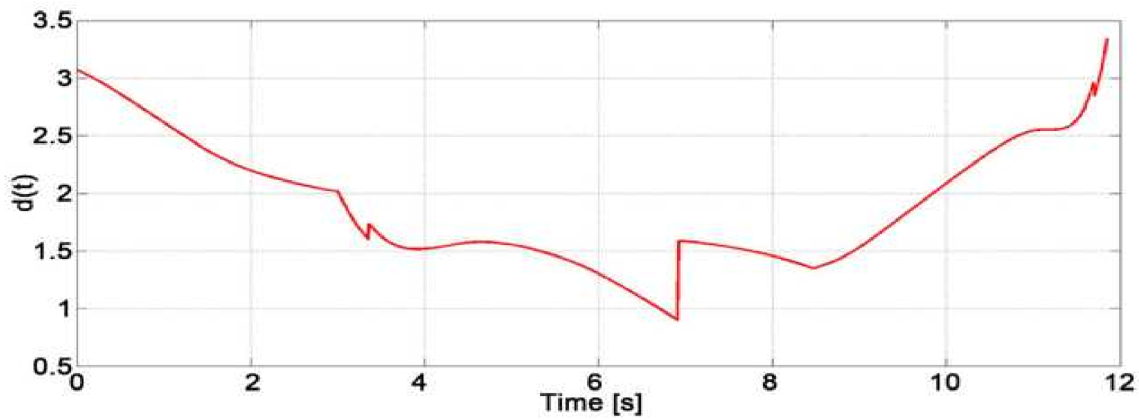


Figure 30. Time response of ride comfort index d (t).

From Figure30, the ride comfort index d (t) turns worse slightly at about 7.00 s. This is because the absolute value of the acceleration is bigger here, and it has a big influence on the d (t). Since the condition is changed again at 8.30 s, d (t) turns worse gradually after this time due to the influence of suddenly shortened stop point.

4.4. Simulation IV

In this section, the proposed extended method is compared with the conventional method [28] in the situation that the stop spot is shortened after starting off.

$$\begin{cases} t_0 = 0;\ x_0 = 0; v_0 = 0, a_0 = 0 \\ t_f = 10; x_f = 100; v_f = 0; a_f = 0 \end{cases} \tag{43}$$

Then, at running 40 m spot, the stop spot is shortened from 100 m to 90 m as follows.

$$\begin{cases} t_0 = 0;\ x_0 = 40; v_0 = v_s\ , a_0 = a_s \\ t_f = [search]; x_f = 90; v_f = 0; a_f = 0 \end{cases} \tag{44}$$

The result of comfort index d (t) is shown as Figure 31. In this simulation, the conventional method got worse the ride quality after situation changes. On the other hand, the proposed extended method can cope with the change. So, we can see the good performance of the proposed method.

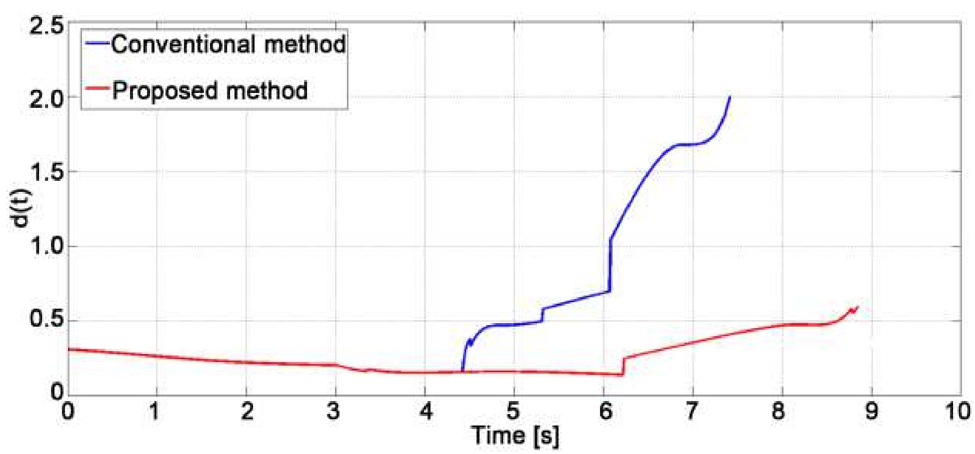


Figure 31. Time response of ride comfort index d (t)

4.5. Conclusion

In this chapter, we have a numerical examples using MATLAB to show the effect of acceleration/deceleration on the ride comfort in different cases. And in the end we have done a small comparison between the proposed method and the conventional one.

General Conclusion

In this Project, we have proposed the speed control method based on general optimal control theory for improving the passenger ride comfort of electric vehicles. The method is applying the general optimal control theory and also based on the conventional techniques. Furthermore, it includes the conventional method and extends the flexible speed-pattern-generation method which can cope with the change of terminal conditions in the way of the run. The method also aims to contribute to improving the beginner driver's driving skill from the viewpoint of passenger's comfortability by showing the ideal running pattern and checking the driving. The proposed method can expect to be also useful for the run which emphasized ride comfort of the automatic operation car which would come to practical use in the future. In future work, the suitability of the method must be studied not only the longitudinal run but also for overall driving situations. Furthermore, it is necessary to verify the effectiveness by actual experiments. Let's confirm the effectiveness.

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